



A Deep Near InfraRed Survey Along The Norma Wall

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Abstract

The galaxy distribution hidden behind the Zone of Avoidance (ZOA) contributes to the streaming motion of our Local Group and hence the dipole observed in the Cosmic Microwave background. The ZOA, an artifact of dust and star crowding in the Milky Way obscures about 20% of the optical extragalactic sky and 10% of the near-infrared sky. The ZOA also veils a massive ($\sim 2.7 \times 10^{16} h^{-1} M_{\odot}$) galaxy distribution centred at $\ell = 320^{\circ}$, $b = 0^{\circ}$, $v = 4500 \text{ km s}^{-1}$ known as the the Great Attractor (GA). The GA was first realised from the systematic distortion of velocities over and above the uniform Hubble flow of 400 elliptical galaxies within $40 h^{-1} \text{ Mpc}$. Due to its unfortunate position behind the ZOA the galaxy distribution contributing to the GA is difficult to map and hence to quantify.

Dedicated optical, near-infrared, far-infrared, X-ray and radio surveys were undertaken by many researchers to unveil the galaxy distribution in the ZOA, especially in the GA region. These multi-wavelength surveys led to the current understanding that the GA is a wall-like structure, the Norma Wall, centred on the Norma cluster (Abell 3627); $(\ell, b, v) = (324.3, -7.2, 4848 \text{ km s}^{-1})$. The Wall extends from the Pavo II cluster ($332^{\circ}, -24^{\circ}, 4200 \text{ km s}^{-1}$) at low Galactic latitudes to the Norma cluster. It then crosses the Galactic Plane (GP) at $\ell \sim 320^{\circ}$ and continues all the way to the Abell S0639 cluster ($281^{\circ}, 11^{\circ}, 6194 \text{ km s}^{-1}$) and includes the clusters CIZA J1324.7-5736 ($307.4, +5.0, 5700 \text{ km s}^{-1}$), Cen-Crux ($305.5^{\circ}, +4.8, 6214 \text{ km s}^{-1}$) and the overdensity around PKS 1343-601 ($309.7, +0.7, 3800 \text{ km s}^{-1}$). The Norma, CIZA J1324.7-5736, Cen-Crux and PKS 1343-601 clusters compose the high density peaks in the Norma Wall. The Norma cluster is up to date the most massive cluster in the Norma Wall. It also comprise the center of Norma Wall described above.

The multi-wavelength surveys have improved our understanding of the extent and shape of the Norma Wall. However, the most central part of the Norma Wall ($|b| < 7^{\circ}$) remains poorly understood because of the high levels of extinction and star-crowding at these low Galactic latitudes.

In this thesis, I present an imaging survey in the three near-infrared bands (J , H , K_s) along the most obscured part of the Norma Wall, the so called Norma Wall Survey (NWS). It has the goal to uncover the galaxy distribution in this area. The near-infrared waveband was selected because it is less affected by dust extinction than the optical. In addition, near-infrared surveys are sensitive to early-type galaxies which are better tracers of the mass in galaxies.

The survey used the InfraRed Survey Facility (IRSF) at the 1.4 m Japanese telescope of the

South African Astronomical observatory site in Sutherland. The telescope has the Simultaneous 3-colour InfraRed Imager for Unbiased Survey (SIRIUS) as its imaging instrument which has a spatial resolution of 0.45 pixel/arcsec and a field-of-view of $7'.7 \times 7'.7$.

The survey footprint covers an area of $37.5 \text{ } \square^2$ with 2793 individual pointings that have an average seeing of FWHM= $1''.38$ in the K_s band. The galaxy search in the survey images resulted in the NWS catalogue which contains 4360 galaxies. Galaxies listed in the catalogue have an astrometric accuracy of $\sigma = 0''.202$ in both Right Ascension and Declination and a K_s band isophotal magnitude reliability of $\sigma = 0^m.14$. Only 5.5% of the galaxies uncovered in the survey have counterparts in the shallower Two Micron All Sky Survey Extended Sources Catalog (2MASX).

Extinction in the near-infrared is significantly lower than in the optical (9% in the K_s band compared to the B band) but not negligible. For this reason, and before analysing the large-scale structures in the NWS area, I first investigated the effect of dust obscuration on the observed J , H and K_s isophotal magnitudes and radii. This study has led to two methods to correct for dust extinction.

Applying these corrections, the catalogue is found to be complete for the isophotal magnitudes $J^\circ = 15^m.6$, $H^\circ = 15^m.3$ and $K_s^\circ = 14^m.8$. These completeness limits are valid for galaxies found in regions with dust obscuration below $A_{K_s} < 1^m.0$. Approximately $33.2 \text{ } \square^\circ$ (89%) of the survey area lies at these foreground obscuration levels and has star-crowding of $\log(N_{(K_s < 14)}/\text{deg}^2) < 4.71$, 99.2% of the observed galaxies lie within this part of the survey area.

Comparing the number counts of galaxies in the NWS area to independent all-sky counts indicates that the survey area is overdense, more or less uniformly over the whole survey region. By comparing the galaxy counts in the survey area to over/under dense regions identified in the 2MASX sky at different redshift ranges suggests that the excess counts observed in the NWS area are caused by a galaxy overdensity at the GA distance. Within the homogeneous galaxy overdensity five density peaks were identified. Two of these peaks correspond to the CIZA J1324.7-5736 and Cen-Crux clusters. The three remaining peaks are more distant than the GA, at a redshift of $z \approx 0.1$.

The galaxy distribution was also investigated as a function of photometric redshifts. This confirmed the overdensity to be at the GA distance. This analysis also hinted at the existence of another large-scale structure at a redshift of $z \approx 0.1$.

The homogeneous galaxy distribution over the whole survey area suggests that the survey footprint maps a continuous structure across the GP, i.e. the so-called Norma Wall. Assuming the Norma Wall to be a cylindrical filament of $84.5h^{-1} \text{ Mpc}$ in length and a cross-sectional radius of $2h^{-1} \text{ Mpc}$ filled uniformly by the mean density of the Norma Wall Survey at the approximate GA distance, and including the Norma, Pavo II, CIZA J1324.7-5736, Cen-Crux and Abell S0639 clusters, the total mass in galaxies amount to $\approx 4 \times 10^{15}h^{-1} \text{ M}_\odot$. This mass is in good agreement with recent estimates for the mass of the Norma Wall from X-ray and HI observations but lower than the original estimate by Lynden-Bell et al. (1988).

Dedication

I would like to dedicate the work in this theses to the memory of my father, and to Professor Anthony Fairall.

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1

Introduction

Galaxies behind the disk of the Milky Way are obscured from our view by the thick layers of dust and high stellar density. This significantly affects 20% of the optical extragalactic sky and 10% of the near infrared sky and define as such the respective Zone of Avoidance (ZOA).

The galaxy/mass distribution in the ZOA is a key element in understanding the origin of the dipole observed in the Cosmic Microwave Background (CMB). The streaming motion of our Local Group (LG) and the systematic peculiar motions of 400 elliptical galaxies within $40h^{-1}$ Mpc over and above the uniform Hubble flow is expected to be largely determined by a massive galaxy overdensity dubbed “the Great Attractor” that extends over an area of $40^\circ \times 40^\circ$. Unfortunately, the predicted centre of this overdensity lies deep in the ZOA. Different multi-wavelength observations, dedicated to unveil the nature and extent of the Great Attractor (GA), have led to the conclusion that the GA is an extended wall-like structure. However the central parts of the GA have remained obscured and hidden from view.

In this introduction, I describe the ZOA and review the different observational tools that were used to uncover the galaxy distribution hidden by the ZOA. I will also describe the wall-like structure that forms the GA. Following an in-depth review of the various galaxy surveys in the ZOA that are performed at multiple wavelengths, it becomes obvious that deep and wide-area near-infrared survey may be optimally suited to unveil and characterize the remaining part of the GA at low Galactic latitudes. This survey has to go deeper have a higher spatial resolution than the current all-sky Two Micron All Sky Survey (2MASS) (Skrutskie et al., 2006). This thesis presents such a deep near-infrared survey in three bands (J , H , K_s) along the most obscured region of the GA. The aim of this survey is to map the galaxy density in the optically obscured

part of the wall.

1.1 The Zone of Avoidance

The first realization of the existence of a “Zone of few Nebulae” around the Galactic Plane (GP) was made by Proctor (1887) as he mapped 4630 nebulae from Sir John Herschel’s General Catalogue of Nebulae (Herschel, 1864). The later work by Charlier (1922), plotting nebulae from the more comprehensive New General Catalogue (NGC) by Dreyer (1888, 1895) made it clear that the region around the GP ($|b| \leq 10^\circ$) has a lower density of nebulae compared to the rest of the sky. This region now defines the optical ZOA. No connection was made at that time between the Milky Way and the ZOA because of the lack of knowledge that many of the nebulae were extragalactic sources and of the existence of light-absorbing dust.

The link between the ZOA and the Milky Way was only made after Hubble (1929) used Cepheid variables to recognize that many of the nebulae were extragalactic sources similar to our own Milky Way, next to the discovery by Trumpler (1930) of the obscuration of starlight by dust. It is now understood that the optical ZOA is mainly caused by the increased levels of dust extinction towards the GP.

The first quantitative definition for the ZOA was given by Shapley (1961). It was defined by him as the region with “the isopleth of five galaxies or less per square degree from the Lick and Harvard surveys”. In comparison, regions further away from the GP have a mean of 54 galaxies per square degree (Shane & Wirtanen, 1967).

The Milky Way is home to a huge number of stars that form our Galaxy. The increase in star counts towards the GP next to dust extinction causes an additional difficulty in detecting galaxies that lie behind the Milky Way. The increase in extinction and stellar density makes it hard to derive accurate parameters for galaxies residing in the ZOA.

The following sections describe how Galactic dust and stellar density affect our view of the extragalactic sky and shape the ZOA in the different wavebands.

1.1.1 Galactic extinction

Interstellar dust scatters and absorbs light along the line-of-sight from stars within the Galaxy and from extragalactic sources. Extinction is the term used to describe the obscuration by dust of light coming from other sources. Due to the abundance of dust close to the GP compared to other regions further away, dust obscuration can be as high as 70 mag in the optical B band in some regions within the ZOA.

Extinction is wavelength dependent and more prominent at the shorter wavelengths. Compared to the optical, the Near InfraRed (NIR) extinction in the J , H and K_s bands is 21%, 13% and 9% respectively of that in the B band (Cardelli, Clayton & Mathis, 1989). Extinction also depends on the line-of-sight towards an object as light from different sources transverses

different column densities of dust with varied composition and dust particles size. Obscuration by dust affects the observed properties for galaxies, such as isophotal magnitudes and radii, total magnitudes and even galaxy classification. Hence, statistical results and conclusions derived from magnitudes and radii limited galaxy catalogues are unreliable if they are not corrected for extinction.

Even though extinction in the NIR is significantly less than in the optical it can still reach high levels in some regions very close to the GP ($|b| \lesssim 1^\circ$). This makes the understanding of how Galactic extinction varies over the whole-sky essential when making accurate deductions from galaxy surveys. This is particularly important for galaxy surveys in the ZOA.

An average extinction law in the optical and NIR, is given by Cardelli, Clayton & Mathis (1989). The absolute extinction at a particular wavelength $A(\lambda)$, normalized to the extinction in the visual $A(V)$, is a function of the parameter R_V which is line-of-sight dependent. R_V is defined as the ratio of the visual $A(V)$ to selective extinction $E(B - V)$ or colour excess,

$$R_V = \frac{A(V)}{E(B - V)}. \quad (1.1)$$

A typical value for R_V is 3.1 (Cardelli, Clayton & Mathis, 1989) (this value is used throughout this thesis for calculating extinction in different wavebands from $E(B_V)$). According to Cardelli, Clayton & Mathis (1989) the mean extinction in the optical B ($0.44 \mu\text{m}$) and R ($0.70 \mu\text{m}$) bands and the NIR J ($1.26 \mu\text{m}$), H ($1.63 \mu\text{m}$) and K_s ($2.14 \mu\text{m}$) is, (the values in brackets after the filters correspond to the central wavelength of those respective filters)

$$\begin{aligned} A_B &= 4.107 E(B - V), \\ A_R &= 2.325 E(B - V), \\ A_J &= 0.863 E(B - V), \\ A_H &= 0.570 E(B - V), \\ A_{K_s} &= 0.368 E(B - V). \end{aligned} \quad (1.2)$$

The reddening map of Schlegel et al. (1998) is widely used to gauge $E(B - V)$ along a line-of-sight to an extragalactic source and, in combination with Eqn. 1.2, to derive Galactic extinction in different passbands.

Figure 1.1 displays an all-sky Galactic reddening $E(B - V)$ map in Galactic coordinates and centred on the Galactic Centre. The Galactic reddening distribution was produced from the Schlegel et al. (1998) dust maps (image is taken from the Legacy Archive for Microwave Background Data Analysis (LAMBDA) data products¹). The map shows the values for $E(B - V)$ on a logarithmic scale from $0^{\text{m}}004$ to $6^{\text{m}}3$. The yellow/red band running along the GP indicate region of high extinction compared to the other regions in blue.

¹http://lambda.gsfc.nasa.gov/product/foreground/f_images.cfm

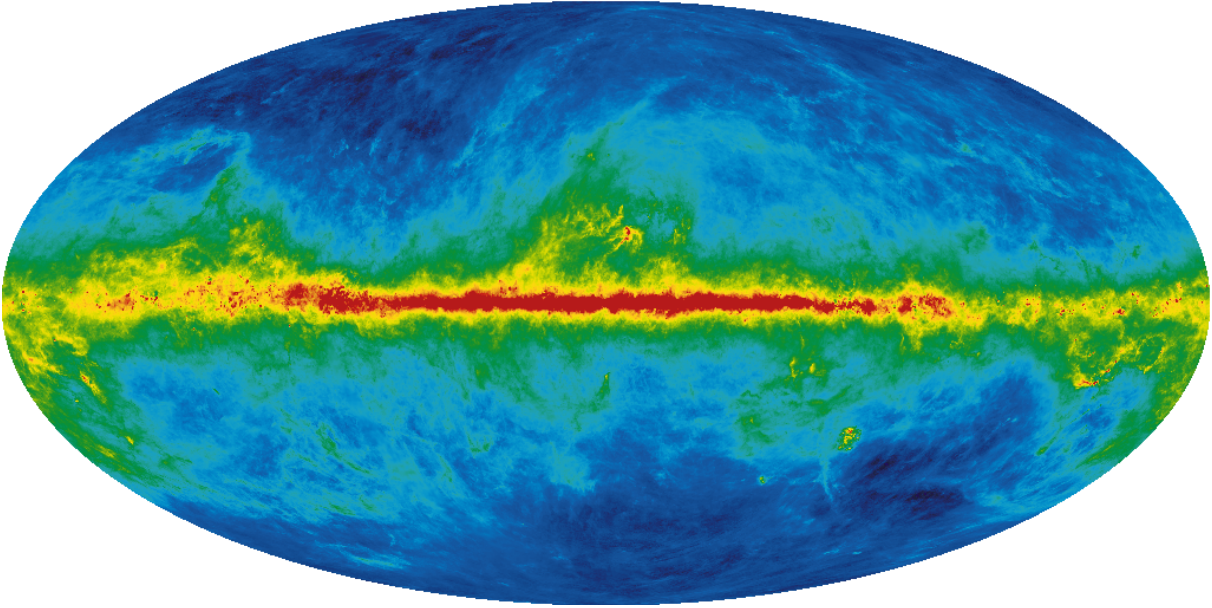


Figure 1.1: An all-sky projection of the Schlegel et al. (1998) reddening $E(B - V)$ map in Galactic coordinates and centred on the Galactic Centre. The values for $E(B - V)$ are shown on a logarithmic scale from 0^m004 to 6^m3 . The image is taken from the LAMBDA data products.

The Schlegel reddening map was created from the $100\,\mu\text{m}$ observations by the Diffuse Infrared Background Experiment (DIRBE) on board the Cosmic Background Explorer (COBE) satellite (Hauser et al., 1991) and the all-sky Infrared Astronomical Satellite Sky Survey Atlas IRAS/ISSA (Neugebauer et al., 1984; Wheelock et al., 1994).

The DIRBE infrared maps have a coarse resolution of $0^\circ7$ which fails to resolve the fine details of the infrared sky. The better resolved IRAS/ISSA (Neugebauer et al., 1984; Wheelock et al., 1994) $100\,\mu\text{m}$ map with a resolution of $5'$ was used to improve the resolution of the DIRBE dust map to $6'.1$. For more details on the processing and calibration of the reddening maps see Schlegel et al. (1998).

The $100\,\mu\text{m}$ map was first transformed into a dust column density using the dust temperature map produced from the 100 , and $240\,\mu\text{m}$ DIRBE observations. The resultant dust column density was then reddening-calibrated using colours of elliptical galaxies Schlegel et al. (1998).

1.1.2 Stellar density

Extinction is not the only source of confusion hampering observations in the ZOA. As the stellar density increases it becomes harder to detect galaxies in the ZOA due to confusion. Furthermore the rise in star density also causes an increase in the sky background noise thereby making it

1.1 The Zone of Avoidance

difficult to detect faint galaxies. The higher star density also implies larger errors in galaxy photometry.

Figure 1.2 shows the stellar density metric $\log(N_{(K_s < 14)}/\text{deg}^2)$ where $N_{K_s < 14}$ is the number of stars brighter than 14^m in the NIR K_s band from the 2MASS Point Source Catalog (2MPSC) (Skrutskie et al., 2006). For the key to this plot see Table 1.1. The map and table are taken from 2MASS Extended Source Catalog (2MASX) Jarrett et al. (2000a; Algorithms, Analysis, and Results¹).

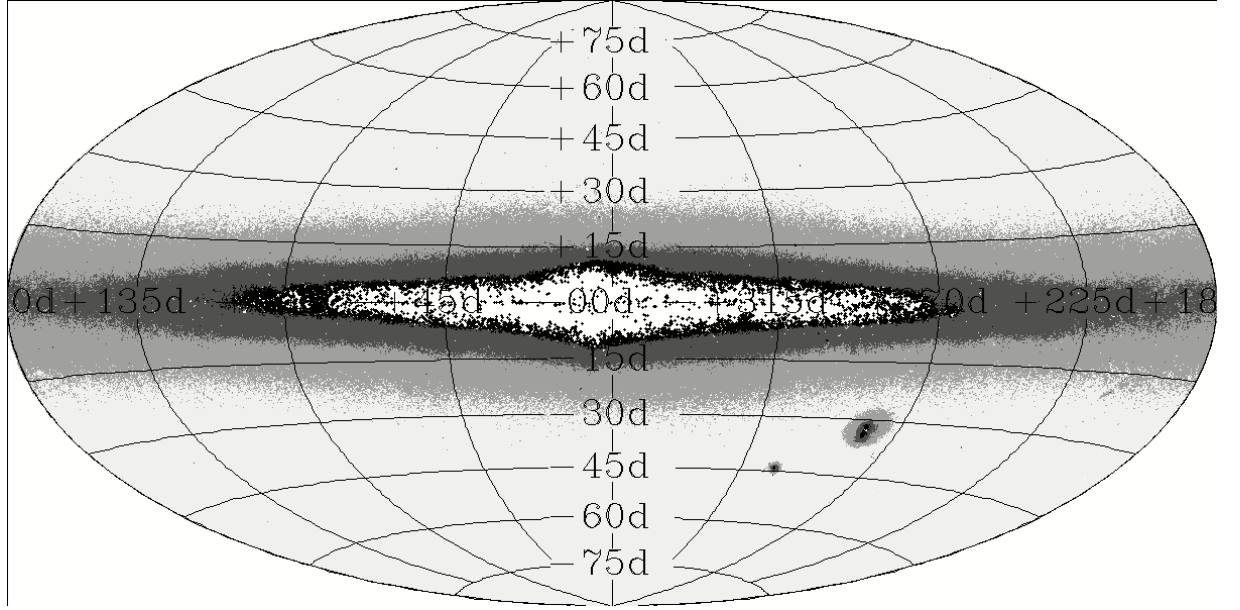


Figure 1.2: The 2MASS stellar density metric projected on Galactic coordinates. The metric was calculated as $\log(N_{(K_s < 14)}/\text{deg}^2)$ for stars brighter than 14^m in the NIR K_s band from the 2MPSC. The map and table are taken from 2MASX (Jarrett et al., 2000a).

Table 1.1: 2MASS stellar density metric (key for Fig. 1.2).

$\log(N_{(K_s < 14)}/\text{deg}^2)$	$ b $	Colour code
0.0 - 3.2	$\sim 25^\circ - 90^\circ$	light gray
3.2 - 3.6	$\sim 10^\circ - 25^\circ$	gray
3.6 - 4.0	$\sim 5^\circ - 10^\circ$	dark gray
4.0 - 4.5	$\sim 0^\circ - 5^\circ$	black
> 4.5	$\sim 0^\circ - 5^\circ$	white

¹http://web.ipac.caltech.edu/staff/jarrett/2mass/XSC/jarrett_density.html

From both Fig. 1.2 and Table 1.1 we can see that regions around the GP $b \leq |10^\circ|$ (coloured in dark gray, black, white) have high stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) > 3.6$ compared to the other regions that are further away. The Galactic Bulge, the white region around the centre, has the highest stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) > 4.5$. It is clear that galaxy surveys in the ZOA will be strongly affected by the high stellar density, particularly for the region around the Galactic Bulge ($300^\circ < \ell < 60^\circ$).

1.2 The ZOA at different wavebands

The Universe looks very different at different wavebands, as the different wavebands are sensitive to different objects, physical processes, and radiation mechanisms. As such is the ZOA, which is an artifact of our Milky Way galaxy, looks increasingly different at different wavebands. The two major effects that shape the optical and NIR ZOA are obscuration by interstellar dust and confusion by stellar density. The HI column density defines the ZOA in the X-ray as it absorbs X-ray radiation coming from extragalactic sources. In the following sections I will outline the shape of the ZOA in the different passbands.

1.2.1 Optical

The optical ZOA is largely determined by Galactic dust extinction. By merging and homogenizing data from different optical catalogues like the Uppsala General Catalog UGC (Nilson, 1973), the ESO Uppsala catalog (Lauberts, 1982), and the Morphological Catalog of Galaxies MCG (Vorontsov-Velyaminov & Archipova, 1963-74), an optical whole-sky galaxy catalogue was defined; see Fouqué & Paturel (1985); Lahav (1987). According to Hudson & Lynden-Bell (1991) this catalogue is complete for galaxies with observed diameters $D \geq 1'.3$. This diameter D corresponds to an isophote of 24.5 mag/arcsec² in the B band. Plotting this whole-sky catalogue shows a mostly empty region along the Galactic equator $|b| \lesssim 10^\circ$ (see Fig. 1.3). Using the Schlegel dust maps and plotting the extinction contour at $A_B = 1^m0$, it was found that the empty band correlates extremely well with this extinction contour (Kraan-Korteweg & Lahav, 2000). To further investigate the optical ZOA, deeper optical surveys were completed that covered almost the whole band $|b| \lesssim 10^\circ$ around the GP (see Kraan-Korteweg & Lahav 2000 for a complete review of these surveys and their results). Complementing these deep surveys after correcting their magnitudes, and radii for dust extinction using the recipe by Cameron (1990) with galaxies from the UGC, ESO, and MCG catalogues, resulted in a deep optical whole-sky catalogue. This enhanced galaxy catalogue narrowed the optical ZOA to the region $|b| \lesssim 5^\circ$ around the GP, a region very well demarcated by $A_B \gtrsim 3^m0$ contours. Figure 1.4 (from Kraan-Korteweg & Lahav 2000) shows the galaxy distribution from the whole-sky deep galaxy catalogue to be complete for galaxies with extinction-corrected radii $D^\circ \geq 1'.3$ for extinction levels of $A_B \lesssim 3^m0$.

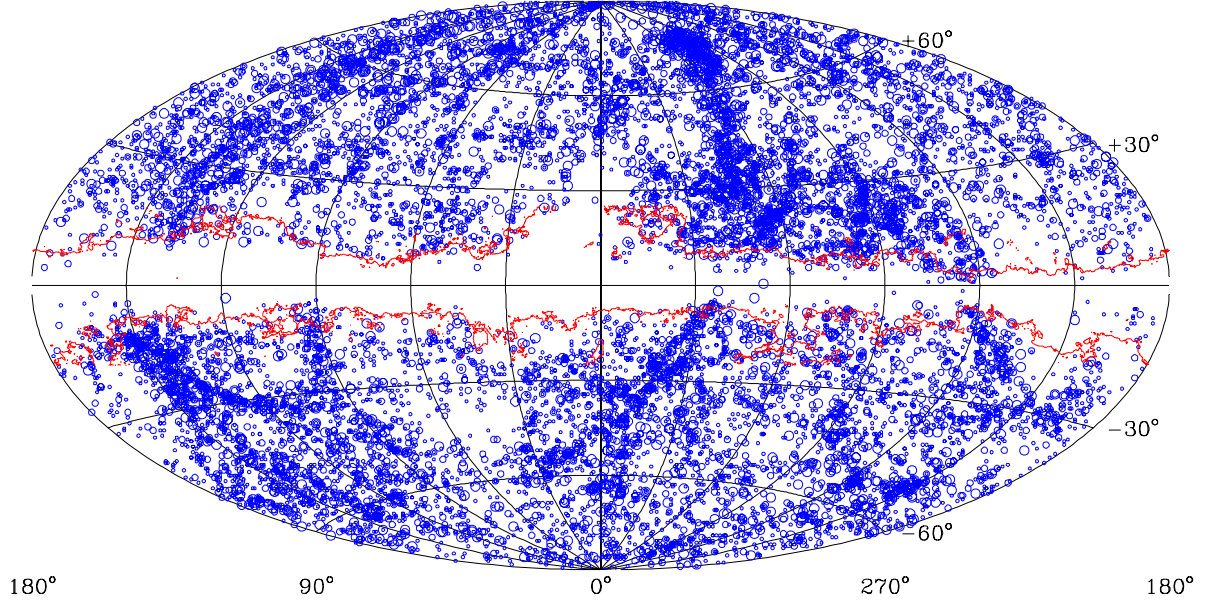


Figure 1.3: The whole-sky optical galaxies complete to $A_B = 1^m0$. The contour line marks extinction of $A_B = 1^m0$. The empty region $|b| \lesssim 10^\circ$ defines the optical ZOA. The plot clearly shows the strong link between the optical ZOA and dust obscuration. The map is reproduced from Kraan-Korteweg & Lahav (2000).

In Fig. 1.4 the link between the shape of the reduced optical ZOA and the extinction contour at $A_B \lesssim 3^m0$ is quite strong. At higher levels of dust extinction, the optical surveys are incapable of tracing galaxy structures behind the ZOA in any details.

1.2.2 Near infrared

As the Milky Way is more transparent at NIR wavelengths ($0.9\text{--}5.0\ \mu\text{m}$) it is a more reliable tool for detecting galaxies and structures obscured by the Milky Way, especially in the reduced optical ZOA as defined in Fig. 1.4. NIR surveys are more sensitive to detecting early-type, which are good indicators of galaxy clusters and stellar mass, than late-type galaxies. Even though surveys at NIR wavelengths perform better than those at optical in regions of increased dust extinction $|b| \lesssim 5^\circ$, their efficiency decreases with the increase in stellar density close to the Galactic Bulge. The shape of the NIR ZOA was found to strongly depend on the distribution of the stellar content in the Milky Way (Kraan-Korteweg, 2005). This is demonstrated here with the 2MASS stellar density metric in Table 1.2, and Fig.1.2. This table lists the density metric for stars that are brighter than $K_s = 14^m0$ in the 2MPSC, with the percentage of 2MASS extended sources that were found in those regions. The gray scale colours listed in this table act as a

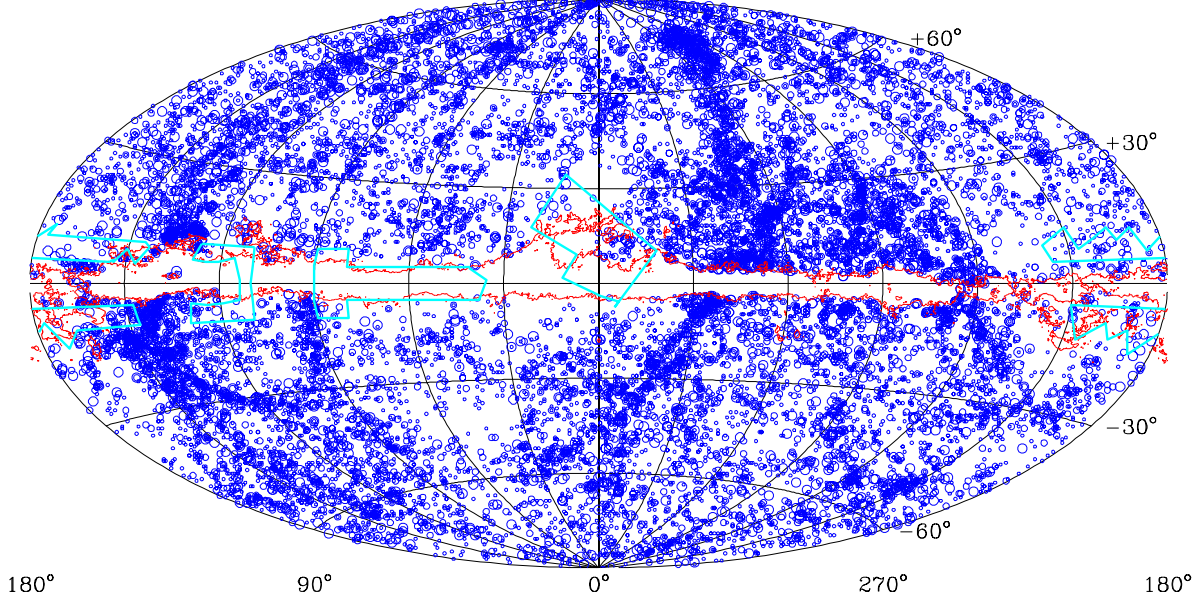


Figure 1.4: The whole-sky optical galaxy distribution complete to $A_B = 3^m0$. The contour line marks extinction of $A_B = 3^m0$. The empty region $|b| \lesssim 5^\circ$ defines the optical ZOA. The map is reproduced from Kraan-Korteweg & Lahav (2000).

key for Fig. 1.2. It is clear from Table 1.2 that the region $|b| \lesssim 5^\circ$ or $\log(N_{(K_s < 14)}/\text{deg}^2) \geq 4.0$ has the lowest galaxy count compared to the other regions. The region marked in white around the Galactic Centre is the region of highest stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) \geq 4.5$ where no galaxies were found. The figure and the table are taken from the 2MASX: “Algorithms, Analysis and Results web-page”.

Table 1.2: 2MASS stellar density metric and galaxy number counts.

$\log(N_{(K_s < 14)}/\text{deg}^2)$	galaxies	$ b $	Colour code
0.0 - 3.2	73.4%	$\sim 25^\circ - 90^\circ$	light gray
3.2 - 3.6	19.0%	$\sim 10^\circ - 25^\circ$	gray
3.6 - 4.0	6.9%	$\sim 5^\circ - 10^\circ$	dark gray
4.0 - 4.5	0.7%	$\sim 0^\circ - 5^\circ$	black
≥ 4.5	0.0%	$\sim 0^\circ - 5^\circ$	white

Efforts to systematically observe the whole-sky in three NIR bands J , H and K_s resulted in the above mentioned 2MASS (Skrutskie et al., 2006). The 2MASS survey started in June 1997, and was completed in February 2001. It used twin 1.3 meter telescopes, one at Mountain

Hopkins, Arizona for the north, and the other at Cerro Tololo, Chile for the south. This resulted in the 2MASS Extended Source Catalogue (Jarrett et al., 2000a) with 1.5 million sources, and the 2MASS Point Source Catalogue of nearly 0.5 billion sources (Skrutskie et al., 2006). In Fig. 1.5 I display an all-sky 2MASS extended source distribution of 1.5 million sources. The distribution is projected on Galactic coordinates, with the map centred on the Galactic Centre. The white area around the Galactic Bulge has the least galaxy number count.

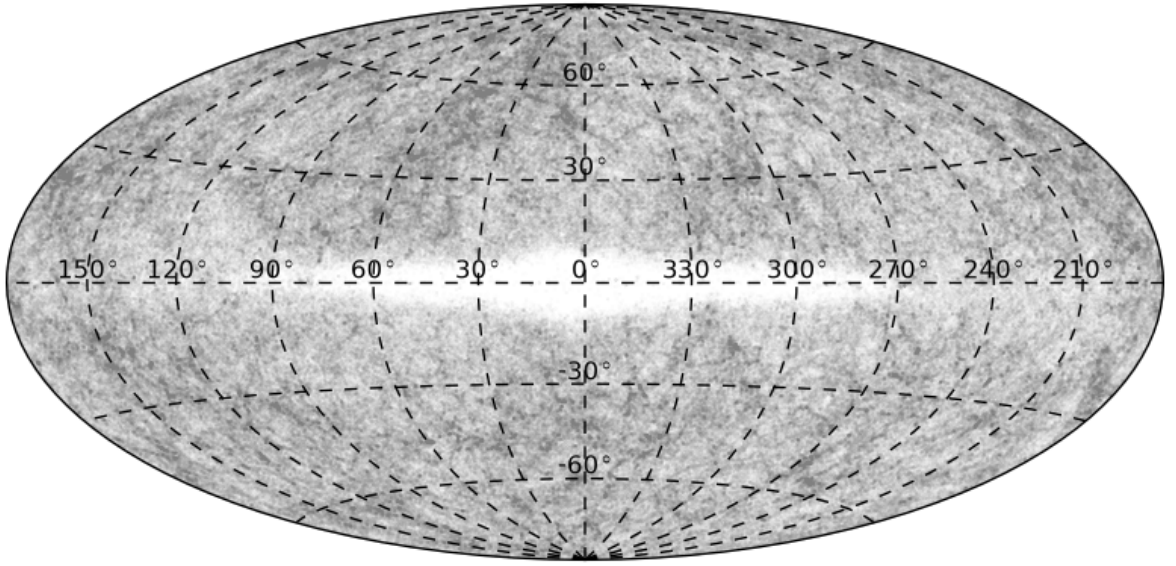


Figure 1.5: The 2MASS all-sky galaxy distribution. The map displays the 1.5 million extended sources identified in the 2MASS survey.

When comparing the 2MASS NIR galaxy distribution in Fig. 1.5 with the optical distribution in Figs. 1.3 and 1.4, it is evident that the NIR observations reduced the ZOA, in particular the regions that are far away from the Galactic Bulge, while the area around the Galactic Bulge ($300^\circ < \ell < 60^\circ$) remains devoid of galaxies. The latter is a direct result of the increased star-crowding and obscuration by dust in the Galactic Bulge. Deeper surveys with higher spatial resolution than 2MASS will significantly improve the capability of identifying galaxies in and around the Galactic Bulge region and hence in the GA region.

For completeness it is worth mentioning another large area NIR survey, the Deep Near-Infrared Southern Sky (DENIS) (Epchtein et al., 1997). DENIS was completed in 2000 and observed the southern sky in the three NIR bands I ($0.82 \mu\text{m}$), J and K_s using the European Southern Observatory (ESO) 1 meter telescope in Chile.

1.2.3 Mid and Far infrared

Mid infrared (MIR) radiation, 3-50 μm , arises from heated dust particles reprocessing absorbed starlight. Dust particles absorbing ultraviolet radiation from massive stars, are heated and then re-radiate this energy as thermal emission in the MIR waveband. The Far infrared (FIR), 50-350 μm radiation, is emitted by cold dust with temperatures $T \sim 10 - 50$ K. The MIR and FIR observations therefore favor the detection of late-type galaxies and starburst galaxies, as they are rich in cold dust. The MIR/FIR are less sensitive towards the dust-deficient ellipticals. The Milky Way is transparent in MIR and FIR which makes them very efficient for detecting spiral galaxies in regions where the Milky Way is opaque to the optical and (to a lesser extent) NIR light.

The Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984) surveyed 96% of the whole sky in the MIR/FIR bands centred on 12, 25, 60, and 100 μm . This resulted in a catalogue of 250 000 point sources (IRAS PSC; Joint IRAS Science Working Group 1988). The IRAS PSC was used to identify galaxies based on their flux ratios in the four observed MIR/FIR bands (Yamada et al., 1993). The high source count and confusion with galactic objects at low Galactic latitudes limited the identification of galaxies close to the GP, especially in the neighbourhood of the Galactic Bulge (Yamada et al., 1993).

Follow-up redshift surveys (PSCz) of extragalactic sources in the IRAS PSC by Saunders et al. (2000a) and which was later complemented by the Behind The Plane (BTP) survey (Saunders et al., 2000b) helped to reduce the IRAS ZOA. Figure 1.6 displays the distribution of PSCz and BTP surveys centred on the Galactic Centre. The shaded region on the map marks the incompleteness zone of both the PSCz (light gray) and BTP (dark gray) surveys.

From the PSCz and BTP distribution it can be seen that the IRAS ZOA is narrower than the optical ZOA (compare Fig. 1.4 with Fig. 1.6). Even though dust obscuration in the MIR/FIR wavebands is significantly lower than in the NIR, the IRAS PSCz and BTP ZOA is broader than the 2MASS NIR ZOA. This is due to the lower resolution of the IRAS survey and the increased source confusion by Galactic sources close to the GP.

Efforts to use a combination of MIR and FIR observations are currently pursued to pierce the highest dust obscured regions of the ZOA. The *Spitzer* Legacy program “Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE)” (Benjamin, 2003) surveyed the Galactic latitudes $|b| < 1^\circ$ for longitudes $\ell = 10^\circ - 65^\circ$ and $\ell = 295^\circ - 350^\circ$ with the InfraRed Array Camera (IRAC) at the MIR bands centred on 3.6, 4.5, 5.8, and 8.0 μm . Galaxy searches on the GLIMPSE images led to the discovery of various galaxy candidates in a highly obscured region, $A_{K_s} \approx 3^{\text{m}}0$. Two of these were confirmed as galaxies and lie in the GA (Jarrett et al., 2007a).

Figure 1.7, reproduced from Jarrett et al. (2007a), shows a colour composite image for the region $316^\circ.4 \lesssim \ell \lesssim 317^\circ.8$ and $-1^\circ.2 \lesssim b \lesssim 0^\circ.1$ where two galaxies in highly obscured region ($A_{K_s} \approx 3^{\text{m}}0$) at $\ell = 317^\circ.0$, $b = -0^\circ.5$ and $\ell = 316^\circ.9$, $b = -0^\circ.6$ were found. The image is a *Spitzer* colour composite of the four IRAC and Multiband Imaging Photometer for *Spitzer*

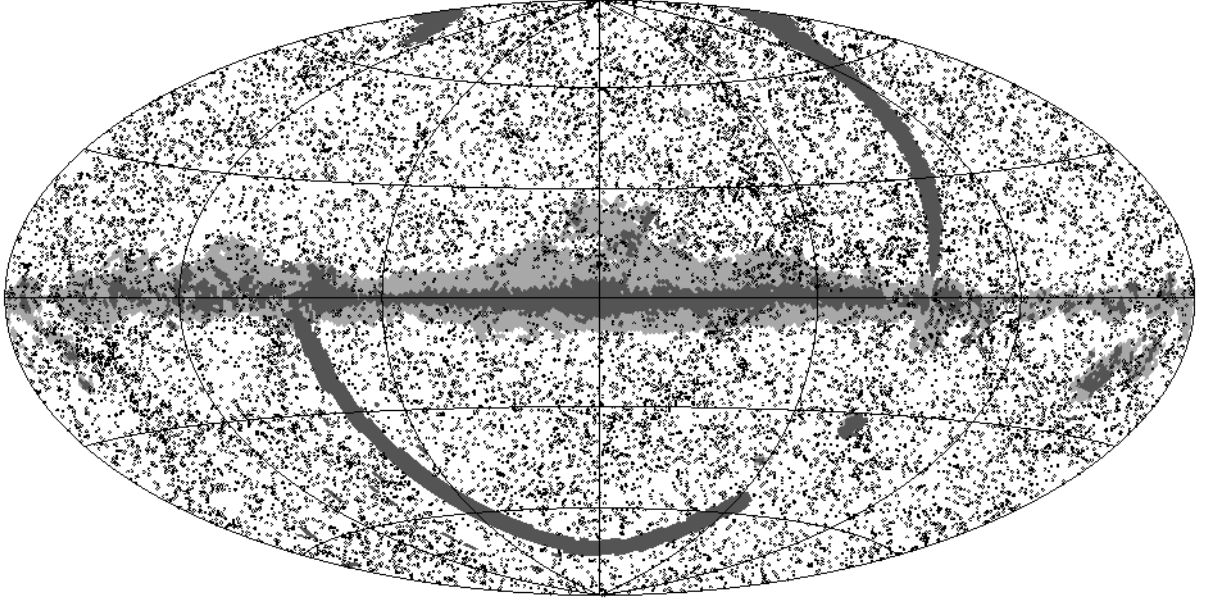


Figure 1.6: Source distribution for the IRAS PSCz, and BTP surveys centred on the Galactic Centre. The hatched region on the map is the incompleteness zone of both the PSCz (light gray) and BTP (dark gray) surveys (image is reproduced from Saunders et al. 2000a).

(MIPS) centred on $24.0\ \mu\text{m}$ images. The image demonstrates the ability of the MIR to penetrate through both the thick layers of stars and dust in the Milky Way and find galaxies. The insets are composite images for the two galaxies created from the deep NIR bands J , H , and K_s observed by the Infrared Survey Facility and combined with MIR images (image is taken from Jarrett et al. 2007a).

The success of using MIR and FIR wavebands to detect galaxies deeply embedded in the ZOA $|b| < 1^\circ$ was further demonstrated by Marleau et al. (2008) who identified 25 galaxies in the region $40^\circ \geq \ell \geq 65^\circ$, $|b| < 1^\circ$. Marleau et al. (2008) used images from GLIMPSE and the Multi-band Imaging Photometer for *Spitzer* Galactic Plane survey (MIPSGAL) that surveyed the same regions as GLIMPSE at two longer wavelengths centred on 24, and $70\ \mu\text{m}$.

1.2.4 Radio waveband

The Milky Way is transparent to the 21-cm line emissions from neutral hydrogen (HI) in galaxies. This makes observations in the radio domain efficient in tracing the large scale structures in the ZOA. HI observations have the extra benefit that redshifts and galaxies maximum rotational velocity can be derived directly from the detection without the need for follow-up redshift surveys. Radio observations depend on the HI content of galaxies. Hence radio observations are

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sensitive to spiral and gas rich dwarf galaxies, while gas-poor elliptical galaxies are missed from HI survey galaxy samples.

The first systematic blind HI galaxy survey behind the Milky Way was the Dwingeloo Obscured Galaxies Survey (DOGS). This survey used the 25 m Dwingeloo radio telescope to survey the northern ZOA ($30^\circ \leq \ell \leq 220^\circ$, $|b| \leq 5^\circ.25$) for galaxies out to 4000 km s^{-1} with an rms sensitivity of $\sigma = 40 \text{ mJy}$ (Kraan-Korteweg et al., 1994; Henning et al., 1998; Rivers et al., 1999).

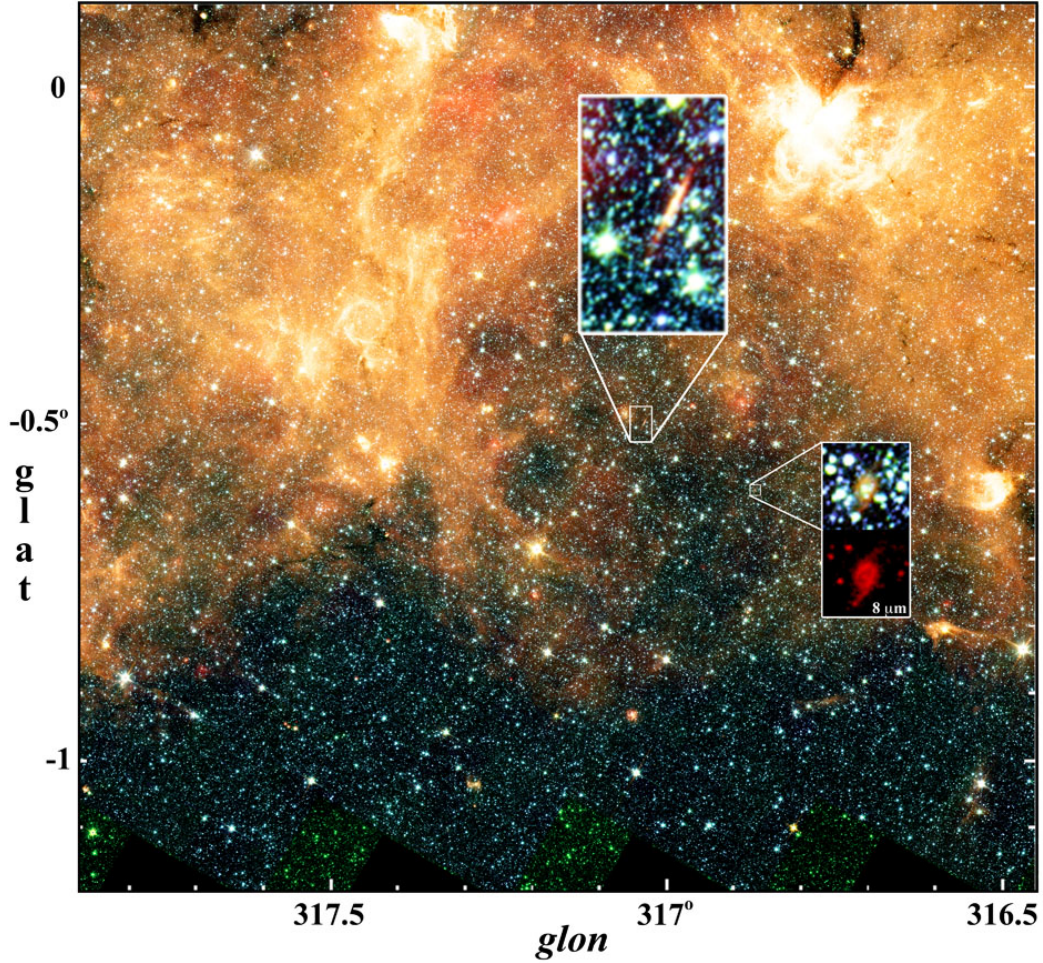


Figure 1.7: A composite of *Spitzer* IRAC ($3.6 \mu\text{m}$ [blue], $4.5 \mu\text{m}$ [green], $5.8 \mu\text{m}$ [yellow], and $8.0 \mu\text{m}$ [orange]), and MIPS $24.0 \mu\text{m}$ [deep red] images for the region $316^\circ.4 \lesssim \ell \lesssim 317^\circ.8$ and $-1^\circ.2 \lesssim b \lesssim 0^\circ.1$. This image demonstrate the ability of the MIR to penetrate through the thick veiling of stars and dust in the Milky Way and detect galaxies. The insets are the two galaxies at $\ell = 317^\circ.0$, $b = -0^\circ.5$ and $\ell = 316^\circ.9$, $b = -0^\circ.6$ that were discovered in the ZOA, and constructed from the deep IRSF J , H , and K_s images combined with the MIR images.

The HI Parkes All Sky Survey (HIPASS) is a blind HI survey of the southern sky from declination (δ) -90° up to $+25^\circ$. The rms noise of the survey is $\sigma = 13 \text{ mJy beam}^{-1}$. It covers a velocity range of $-1200 \leq cz \leq 12700 \text{ km s}^{-1}$, where cz is the Hubble recession velocity. This survey was then extended to the northern sky ($+2^\circ < \delta < +25^\circ$). HIPASS resulted in the detection of 5317 galaxies over the complete area surveyed (Meyer et al., 2004; Wong et al., 2006).

The deeper HI Parkes ZOA Survey (HIZOA) was completed as an extension to the shallower HIPASS survey (Henning, Kraan-Korteweg & Staveley-Smith, 2005; Donley, Staveley-Smith & Kraan-Korteweg, 2005). HIZOA has an average rms noise of $\sigma = 6 \text{ mJy beam}^{-1}$ and covers the region $212^\circ \leq \ell \leq 36^\circ$, $|b| \leq 5^\circ$ over the same velocity range $-1200 \leq cz \leq 12700 \text{ km s}^{-1}$ (Henning, Kraan-Korteweg & Staveley-Smith, 2005). HIZOA was extended to the northern sky in the region $36^\circ \leq \ell \leq 52^\circ$ and $196^\circ \leq \ell \leq 212^\circ$, $|b| \leq 5^\circ$ (Donley, Staveley-Smith & Kraan-Korteweg, 2005). This survey was further extended to include a region around the Galactic Bulge, $332^\circ \leq \ell \leq 36^\circ$, $5^\circ \leq |b| \leq 10^\circ$ and $352^\circ \leq \ell \leq 24^\circ$, $10^\circ \leq b \leq 15^\circ$ (Shafi, 2008). Figure 1.8 displays the galaxies detected in the HIZOA survey with its northern and Galactic Bulge extensions. Galaxies on this plot are colour-coded according to their redshift. The original HIZOA survey is outlined with the black dashed line, the northern extension with the red dashed line and the Galactic Bulge is outlined with the green solid line.

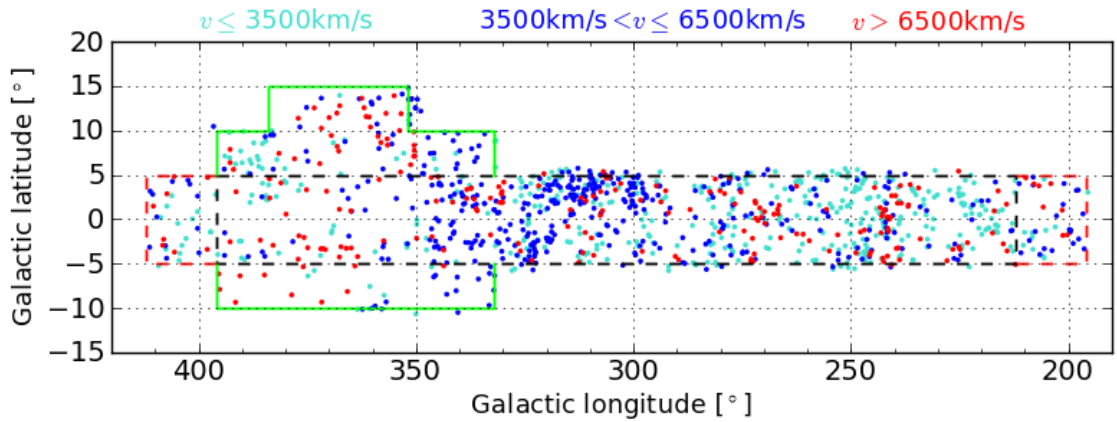


Figure 1.8: The distribution of HI galaxies from the extended HIZOA survey. Galaxies are colour-coded according to their redshift. The original HIZOA survey is outlined with the black dashed line, the north extension with the red dashed line and the Galactic Bulge is outlined with the green solid line. Galaxy positions and redshifts are from Kraan-Korteweg (private communication).

HI surveys have proved to be very effective in tracing HI rich galaxies in regions where optical and infrared observations fail. Unfortunately, the current HI ZOA surveys lack sensitivity and resolution to probe deep in the ZOA and recover the full galaxy distribution in the ZOA. The

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future MeerKAT (Kraan-Korteweg et al., 2008) and the Australian Square Kilometre Array Pathfinder (ASKAP) (Koribalski et al., 2009) will have improved sensitivity ($\sigma < 6 \text{ mJy beam}^{-1}$) and resolution ($< 1'$) to probe the most obscured and star-crowded regions of the ZOA.

1.2.5 X-ray observations

Rich clusters are strong emitters of X-ray radiation. The Milky Way is transparent to the hard X-ray emission above a few keV. This makes the X-ray a reliable tool for detecting clusters hidden in the most obscured regions of the ZOA. Rich clusters are also good tracers of large-scale structures as they are located at the centres of superclusters and great-wall like structures. For an extended review on the importance of X-ray observations to map clusters in the ZOA see Fabian (1994); Ebeling, Mullis & Tully (2002); Kraan-Korteweg & Lahav (2000). X-ray emission from clusters is not obscured by Galactic dust but by the heavy elements such as C and O found in the InterStellar Medium (ISM). While observations at optical wavebands are severely hampered by several magnitudes of extinction towards the GP, X-ray emission suffers the least compared to optical and infrared.

The “Clusters In the Zone of Avoidance” (CIZA) survey is the first systematic search for X-ray clusters in the ZOA (Ebeling, Mullis & Tully, 2002; Kocevski et al., 2007). The CIZA survey used X-ray data from the ROSAT All Sky Survey for initial target selection. Subsequent spectroscopic optical observations confirmed the cluster nature of the X-ray candidate sources. This resulted in over 250 rich clusters in the ZOA. Figure 1.9 (reproduced from Kocevski et al. 2007) displays the distribution of the CIZA clusters identified within the ZOA. The circles and stars represent the identified clusters in the first (Ebeling, Mullis & Tully, 2002) and second (Kocevski et al., 2007) published cluster lists compiled by CIZA, respectively. This map only shows the brightest 130 sources with X-ray fluxes higher than $3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The plot also shows contours for the Galactic neutral hydrogen density in units of 10^{20} cm^{-2} as a measure of the obscuring heavy elements in the ISM.

1.3 Peculiar velocity field

1.3.1 The CMB dipole

The studies of the CMB anisotropy ($\Delta T/T \sim 10^{-3}$) using the Differential Microwave Radiometers of the Cosmic Background Explorer (COBE) revealed a large angular scale dipole with an amplitude of $\Delta T = 3.365 \pm 0.027 \text{ mK}$ towards $\ell = 264^\circ.4$, $b = +48^\circ.4$ (Kogut et al., 1993). This dipole is explained as a Doppler shift in the CMB due to the streaming motion of our LG with respect to the CMB with a velocity of $v_{LG} = 627 \pm 22 \text{ km s}^{-1}$ in the direction $\ell = 276^\circ$, $b = +30^\circ$ (Kogut et al., 1993). It is now widely accepted that this motion is caused by the net gravitational field on the Local Group due to the irregular distribution of matter in the Universe (see e.g. Conklin 1969; Henry 1971 and Kolatt, Dekel & Lahav, 1995).

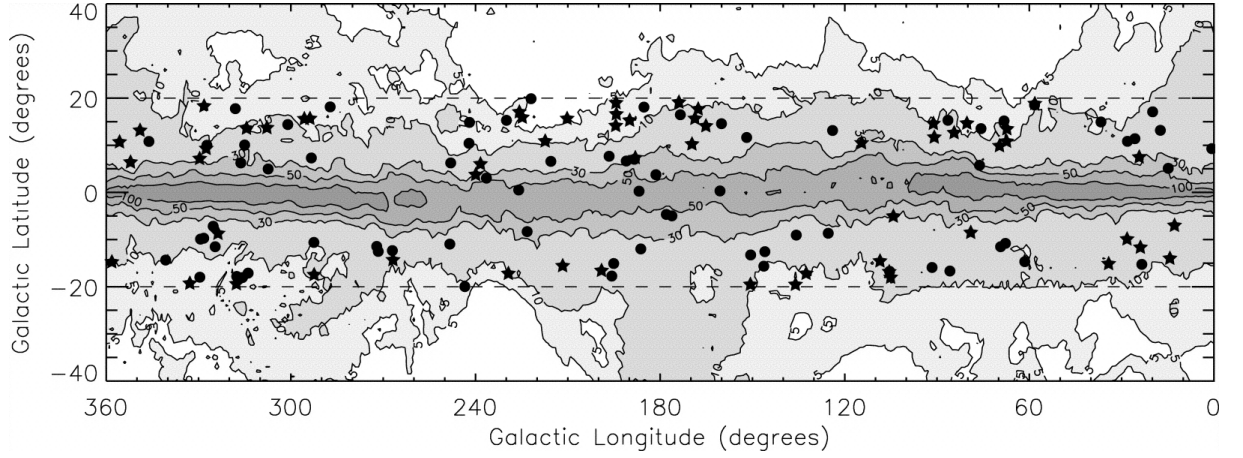


Figure 1.9: The distribution of CIZA clusters sample along the GP. The cluster distribution is overlaid on contours of Galactic neutral hydrogen column density in units of 10^{20} cm^{-2} . Circles denote the first CIZA sample (Ebeling, Mullis & Tully, 2002) and stars the second cluster sample (Kocevski et al., 2007) of the CIZA catalogue. The plotted sample contains 130 clusters with X-ray fluxes higher than $3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The plot is centred on the Galactic Anti-centre.

An aside on peculiar motions and the underlying mass density field

Assuming a linear gravitational field, the peculiar velocity ($\vec{v}_p$) of a reference frame is due to the gravitational acceleration induced by the mass distribution surrounding it by

$$\vec{v}_p \propto \frac{\Omega_m^{0.6}}{b} \sum \frac{M_i}{r_i^2} \hat{r}_i,$$

where $\Omega_m^{0.6}$ is the mass density, b the bias parameter, M_i and $\vec{r}_i$ are the mass and position vector respectively of the mass causing the peculiar velocity (Peebles, 1980).

Under the assumption of a constant mass-to-light ratio, galaxy magnitudes can be used as estimators for galaxy masses. Galaxy surveys were used to trace the mass density inhomogeneities that perturbs the motion of the LG, thus causing the CMB dipole. In a variety of studies [Yahil, Walker & Rowan-Robinson (1986) using the Revised Shapley-Ames catalogue; Lahav, Rowan-Robinson & Lynden-Bell (1988) adopting the UGC, ESO, MCG catalogues; and Maller et al. (2003) using the 2MASS extended source catalogue] it was found that the CMB dipole and LG peculiar motion apex come within $10^\circ - 30^\circ$ of each other. The poor knowledge of the galaxy distribution in the ZOA and the assumptions on the mass-to-light ratio are the major sources of inaccuracy in calculating the LG dipole.

Another approach, which is independent of a mass-to-light ratio, uses peculiar velocities of galaxies to reconstruct the density field free of the galaxy distribution (Bertschinger & Dekel, 1989; Bertschinger et al., 1990). This method uses the fact that a galaxy's velocity $v(x)$ is

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related to the potential $\Phi(x)$ via,

$$v(x) = -\nabla \Phi(x).$$

An implementation of this method is the Potential interpolation algorithm (POTENT) (Bertschinger & Dekel, 1989; Bertschinger et al., 1990; Dekel, Bertschinger & Faber, 1990; Kolatt, Dekel & Lahav, 1995). POTENT requires the peculiar velocities ($\vec{v}_p$) of galaxies defined as the difference between the observed galaxy velocity ($\vec{v}_{obs}$) and the Hubble velocity, which can be derived if both redshift and a redshift-independent distance is available. Distances independent of redshifts can be derived from, for instance, the Tully-Fisher relation (Tully & Fisher, 1977), the $D_n - \sigma$ relation for ellipticals (Lynden-Bell et al., 1988) or the Fundamental Plane method (Djorgovski & Davis, 1987; Dressler et al., 1987a). The Tully-Fisher relation is an empirical relation between the intrinsic luminosity of a spiral galaxy and its respective maximum rotational velocity while the $D_n - \sigma$ is a relation between the linear size of an elliptical galaxies and the central velocity dispersion. The Fundamental Plane correlates the distance dependent effective radius for a galaxy with the distance independent effective surface brightness and velocity dispersion. The effective radius is the radius of a galaxy within which half the total light is contained and the effective surface brightness is the surface brightness at this radius.

The peculiar velocity method has the advantage that it can infer the mass density in regions where the galaxy density is undersampled such as the ZOA. The largest sources of random uncertainty are the distance errors of individual galaxies and the bias due to the interpolation into the ZOA. Kolatt, Dekel & Lahav (1995) used the peculiar velocities in the neighbourhood of the ZOA to estimate the effect of the obscured galaxy density in the ZOA on the LG dipole. They concluded that the apex of the LG dipole changes by 31° when the mass density within of the $|b| \leq 20^\circ$ of the ZOA was included for the estimation of the LG dipole.

It is not only galaxy clusters, filaments and voids that can influence the gravitational field affecting the LG motion but also individual nearby galaxies. This is because the gravitational force scales as $1/R^2$ with R being the distance between the objects. The importance of nearby galaxies was first discussed by Kraan-Korteweg (1992) as she noted that $\approx 20\%$ of the LG dipole as determined from optically known galaxies within $v \lesssim 6000 \text{ km s}^{-1}$ is caused by eight apparently bright nearby ($v < 300 \text{ km s}^{-1}$) galaxies.

This effect of nearby galaxies on the dipole anisotropy in the All-Sky 2MASS Redshift Survey (2MRS) (Huchra et al., 2005) was studied by Erdoğan et al. (2006). In their work the five most luminous nearby galaxies (Maffei 1, Maffei 2, IC342, Dwingeloo1 and M81) were excluded from the reconstruction of the density field and then the misalignment angle ($\delta\theta$) between the LG and CMB dipole was recalculated. They showed that the exclusion of these galaxies has the effect of reducing this angle by 9° at a distance of 5000 km s^{-1} (see tables 1 and 2 in Erdoğan et al. (2006) for values of $\delta\theta$ as a function of distance). This significant change in the misalignment angle clearly shows that individual nearby galaxies at low Galactic latitudes are important in determining the effective gravitational field affecting the LG. It is worth pointing here that such nearby galaxies at low Galactic latitudes are missing from 2MRS which is only complete down

to $K_s = 11^m25$.

Even though the amplitude and direction of the CMB dipole is agreed upon, the structures that cause it are still controversial as is the convergence depth. The latter corresponds to the distance within which the contributing mass will affect to the LG dipole. Work by Strauss et al. (1992) using an IRAS sample, Lynden-Bell, Lahav & Burstein (1989) using an optical sample and Erdoğan et al. (2006) using 2MRS, concluded that major acceleration to the LG comes from structures within $\lesssim 60h^{-1}$ Mpc (6000 km s^{-1}) of the LG (here I use $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ where h is the dimensionless Hubble constant).

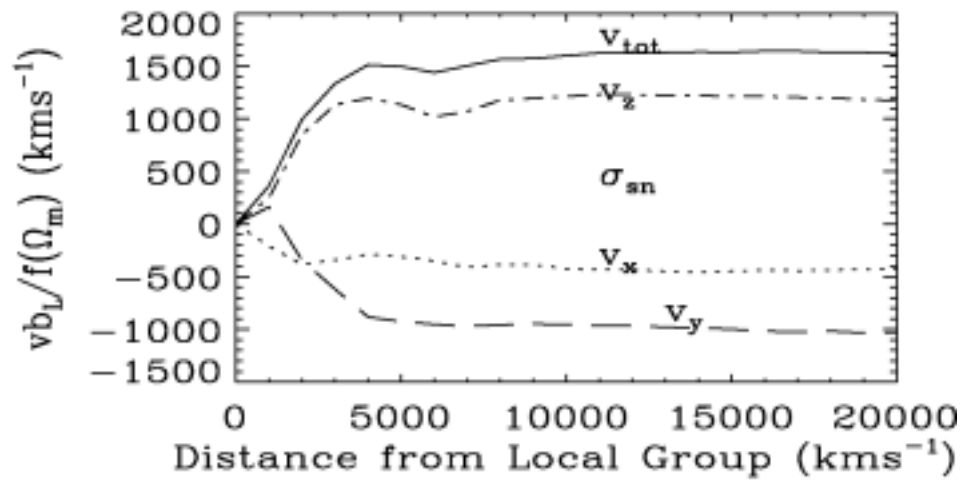


Figure 1.10: The three components and the magnitudes of the acceleration of the Local Group due to galaxies within a series of successively concentric spheres centred on the LG in the CMB frame. The plot is taken from Erdoğan et al. (2006).

Figure 1.10 shows the LG dipole velocity amplitude vb_L divided by the biasing parameter β ($D_{cL} = vb_L/\beta$) as a function of distance in km s^{-1} from the LG. From the plot we can see that the major contribution to the LG dipole comes from the mass distribution within a radius of $\approx 50h^{-1}$ Mpc (5000 km s^{-1}) from the LG, “the rising part of the curve”. Whereas the mass distribution further away only minimally affects the LG dipole amplitude, i.e. “the flat portion of the curve”. The structures with a distance of $\approx 50h^{-1}$ Mpc from the LG that are expected to contribute to the LG dipole, are the Virgo cluster (Jerjen & Tammann, 1993) and the Great Attractor (Lynden-Bell et al., 1988).

On the other hand, various galaxy cluster samples (Abell/ACO clusters: Scaramella, Vetolani, & Zamorani (1991); X-ray: Kocevski & Ebeling 2006) show that the galaxy distribution out to larger distances ($\lesssim 200h^{-1}$ Mpc) still influences the LG apex. In Fig. 1.11 the contributions to the dipole amplitude D_{cl} are shown as a function of the distance R in Mpc from the LG. The figure shows that even structures as far as 150 Mpc from the LG, i.e. at the distance

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of the Shapley superclusters (Shapley, 1930; Scaramella et al., 1989; Scaramella, Vettolani, & Zamorani, 1991) contribute significantly to the LG dipole (for a more elaborate discussion of this plot see Kocevski & Ebeling 2006).

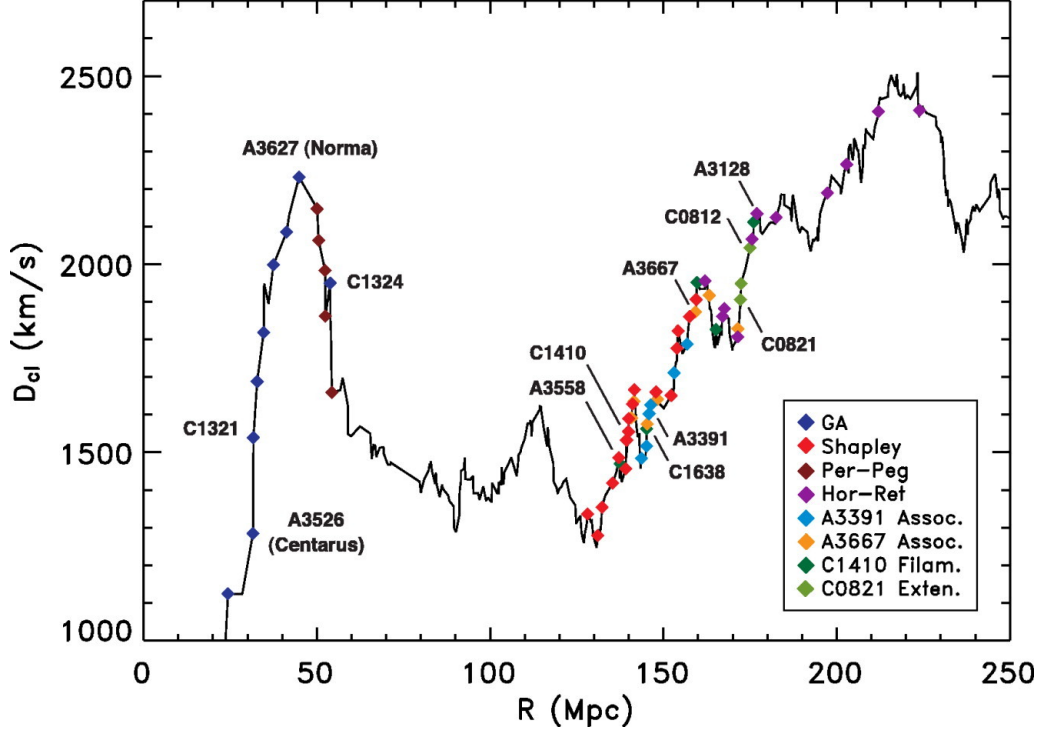


Figure 1.11: X-ray Local Group dipole profile. Cluster associations are grouped by symbol shading to highlight their impact on the overall dipole amplitude. Abell and CIZA clusters begin with the letters "A", and "C", respectively. Acronyms are GA: Great Attractor; Hor-Ret: Horologium-Reticulum; Per-Peg: Perseus-Pegasus. The plot is taken from Kocevski & Ebeling (2006).

The difference between these two plots clearly demonstrate the controversy about the structures and the sphere of influence that contribute to the LG dipole. This controversy is partly due to different galaxy samples, NIR for Erdoğan et al. (2006) and X-ray CIZA clusters for Kocevski & Ebeling (2006), completeness limits, survey depth and the sampling of galaxies within the ZOA. A better knowledge of the galaxy distribution in the most obscured and least mapped ZOA is vital for identifying structures that contribute to the LG dipole.

The cosmological relevance of determining the LG dipole as derived from the mass/galaxy distribution is the fact that it allows a comparison with the CMB dipole and therewith a determination of the bias parameter β . The LG dipole vb_L and the CMB dipole are related through

the biasing parameter as,

$$D_{cL} = vb_L/\beta.$$

1.3.2 Census of the Norma Wall

Originally the study of peculiar motions of 400 nearby ellipticals within $40h^{-1}$ Mpc led to the initial proposal of a hypothetical overdensity (Dressler et al., 1987b) termed the Great Attractor. Based on the same set of galaxies Lynden-Bell et al. (1988) estimated the mass of the GA to be $2.7 \times 10^{16} h^{-1} M_{\odot}$ centred at $\ell = 307^{\circ}$, $b = +9^{\circ}$, $v = 4500 \text{ km s}^{-1}$. The work by Kolatt, Dekel & Lahav (1995) based on a larger data set (ellipticals and spirals), and the POTENT method placed the centre of the GA at $\ell = 320^{\circ}$, $b = 0^{\circ}$, $v = 4500 \text{ km s}^{-1}$. No galaxy overdensity within the ZOA was known that accounted for the GA mass calculated by Lynden-Bell et al. (1988).

Complementary efforts aimed at penetrating the ZOA at multi-wavelengths resulted in the conclusion that the GA is an extended wall-like structure of moderately enhanced galaxy density. A deep optical galaxy survey in the Great Attractor region (Fairall, Woudt & Kraan-Korteweg, 1998; Woudt, 1998; Woudt, Kraan-Korteweg & Fairall, 1999; Woudt et al., 2004) gave a better view of the central part of the GA region. These surveys and a follow-up redshift survey identified the Norma cluster as a massive cluster at the centre of a wall-like structure (Kraan-Korteweg et al., 1996; Woudt, 1998; Radburn-Smith et al., 2006).

The Norma cluster lies within a great-wall-like structure now known as the Norma Wall (Woudt, 1998; Fairall, Woudt & Kraan-Korteweg, 1998; Kraan-Korteweg & Lahav, 2000; Radburn-Smith et al., 2006). The Wall extends from low Galactic latitudes encompassing the Pavo II cluster at $\ell = 332^{\circ}$, $b = -24^{\circ}$, $v = 4200 \text{ km s}^{-1}$ (Lucey & Carter, 1988) through the Norma cluster $\ell = 324^{\circ}.3$, $b = -7^{\circ}.2$, $v = 4848 \text{ km s}^{-1}$ (Kraan-Korteweg et al., 1996). The Wall then crosses the GP at $\ell = 320^{\circ}$ and continues all the way to Abell S0639 cluster centered at $\ell = 281^{\circ}$, $b = 11^{\circ}$, $v = 6194 \text{ km s}^{-1}$ (Stein, 1997) via the CIZA J1324.7-5736 cluster $\ell = 307^{\circ}.4$, $b = +5^{\circ}.0$, $v = 5700 \text{ km s}^{-1}$ (Ebeling, Mullis & Tully, 2002; Kocevski et al., 2007), the Cen-Crux $\ell = 305^{\circ}.5$, $b = +4^{\circ}.8$, $v = 6214 \text{ km s}^{-1}$ cluster (Woudt & Kraan-Korteweg, 2001) and the overdensity around PKS 1343-601 at $\ell = 309^{\circ}.7$, $b = +0^{\circ}.7$, $v = 3800 \text{ km s}^{-1}$ (Jones, Lloyd & McAdam, 2001). The Norma, CIZA J1324.7-5736, Cen-Crux and PKS 1343-601 clusters compose the high density peaks at the centre of the GA.

Figure 1.12 shows the distribution of galaxies that contribute to the GA. Clusters that form the Norma Wall are marked on the map. Only galaxies with known redshifts are shown. Galaxies are colour-coded according to their redshifts. The Norma Wall (roughly traced by the black contour line) is prominent in the redshift range $4000 \leq cz \leq 7000 \text{ km s}^{-1}$. The galaxy positions and redshifts were extracted from the HyperLeda galaxy database. On the same plot I show galaxies detected in HI (Kraan-Korteweg, private communication) from the deep Parkes HI ZOA survey (Henning, Kraan-Korteweg & Staveley-Smith, 2005; Donley, Staveley-Smith & Kraan-Korteweg, 2005) and its extension around the Galactic Bulge (Shafi, 2008).

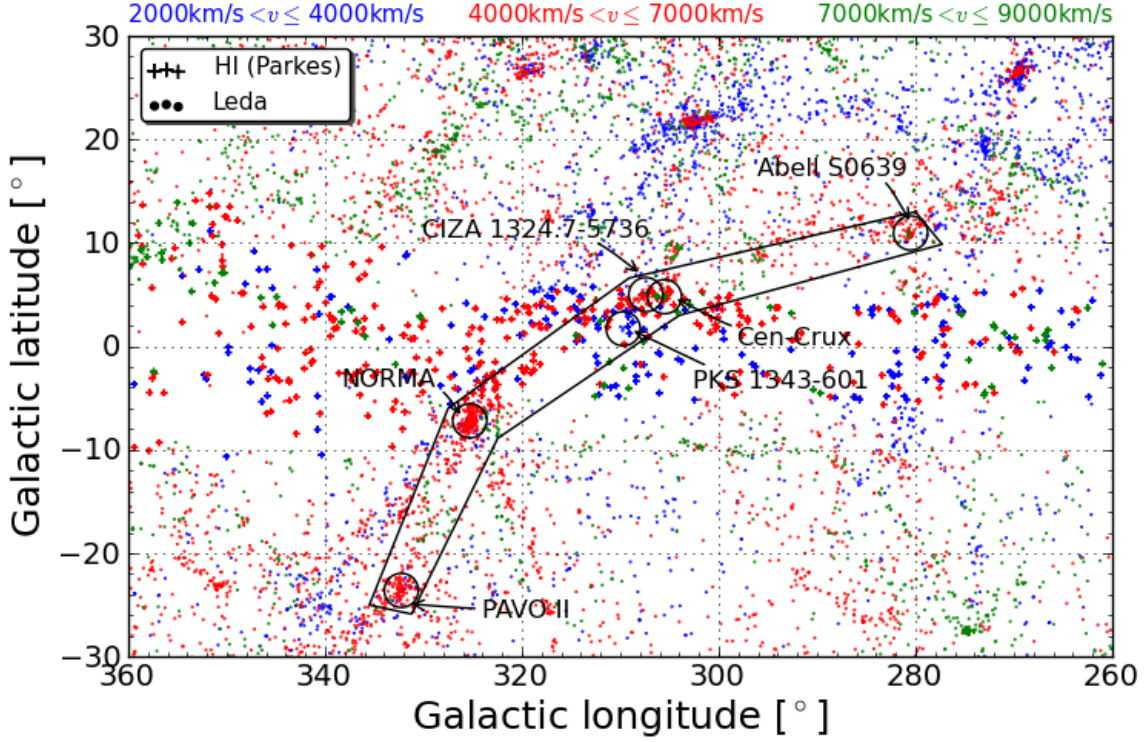


Figure 1.12: The Norma Wall. Clusters forming the Norma Wall are marked on the map are Pavo II at $\ell = 332^\circ$, $b = -24^\circ$, Norma $\ell = 324.3$ and $b = -7.2$, Abell S0639 at $\ell = 281^\circ$, $b = +11^\circ$, $v = 6194 \text{ km s}^{-1}$, through the CIZA J1324.7-5736 $\ell = 307.4$, $b = +5.0$, Cen-Crux $\ell = 305.5^\circ$, $b = +4.8$ and PKS 1343-601 $\ell = 309.7$, $b = +0.7$. The black contour line roughly marks the Norma Wall. The galaxy catalogue for the region was obtained from the HyperLeda database. Galaxies marked with crosses are HI observations (Kraan-Korteweg, private communication).

1.3.3 The high density peaks of the Great Attractor

The Norma cluster (Abell 3627) was identified as the most massive cluster in the GA region (Kraan-Korteweg et al. 1996; Woudt 1998). It has a mass of approximately $7.3-8.0 \times 10^{14} h^{-1} M_\odot$ within its Abell radius (Woudt et al., 2008). The Abell radius is defined as $R_A = \frac{1}{z}$, with z the cluster redshift (Abell, Corwin & Olowin, 1989). This high mass makes the Norma cluster the most likely bottom of the gravitational potential well of the GA.

The massive X-ray cluster CIZA J1324.7-5736 and the relatively lower-mass Cen-Crux cluster were also found to contribute to the GA dynamics. The X-ray total luminosity (0.1-2.4 ke V) of CIZA J1324.7-5736 is $3.12 \times 10^{44} h^{-2} \text{ ergs s}^{-1}$ which is 2/3 that of the Norma ($4.62 \times 10^{44} h^{-2} \text{ ergs s}^{-1}$) (Ebeling, Mullis & Tully, 2002). This is consistent with the dynamical mass of $(3.5 \pm 1.0) \times 10^{14} h^{-1} M_\odot$ of the CIZA J1324.7-5736 cluster, which is $\approx 30-50\%$ the mass of the Norma

Cluster (Radburn-Smith et al., 2006). This makes the CIZA J1324.7-5736 cluster the second most massive cluster in the Norma Wall.

The strong continuum radio source PKS 1343-601 (the fifth strongest extragalactic radio source in the sky (Jones, Lloyd & McAdam, 2001)) at $\ell = 309^\circ.7$, $b = +0^\circ.7$ and 3800 km s^{-1} was suspected by Kraan-Korteweg & Woudt (1999) to be the signature of a rich cluster hidden by galactic extinction $A_{K_s} = 4^m4$. Subsequent investigation of the region around the radio source by Nagayama et al. (2004) in the NIR only indicated an intermediate mass cluster centered around PKS1343-601. X-ray observations confirmed the absence of a rich cluster around PKS1343-601 (Ebeling, Mullis & Tully, 2002).

1.4 A motivation for a deep NIR survey

From the previous discussion it is evident that we understand the galaxy distribution for most of the Norma Wall fairly well, except for the highly-obscured and star-crowded region of the wall within the ZOA ($|b| \lesssim 7^\circ$). The galaxy distribution within of the Norma Wall that lies deep in the ZOA is important to map as it might host other Norma or CIZA J1324.7-5736 like clusters that can significantly add to the overall of mass of the Norma Wall. Furthermore by properly mapping the galaxy distribution in this region of the Wall and comparing it to the other regions of the Wall at high Galactic latitude, a mass estimate for the galaxy distribution within the filamentary structure of the Norma Wall can be made. This estimate for the mass in the GA will shed more light on the origin of the CMB dipole.

The core of the GA is situated at the heart of the ZOA where dust obscuration and star-crowding is severe. Figures 1.13 and 1.14 show the Galactic extinction and stellar-density respectively for the core region of the GA, here defined as $300^\circ < \ell < 330^\circ$ and $|b| < 8^\circ$. The extinction map shows contours of extinction in the K_s band (A_{K_s}). Extinction in the K_s band was calculated using the Schlegel reddening maps, and its relation to A_{K_s} is given in Eqn. 1.2. While Fig. 1.14 shows contours of stellar density $\log(N_{(K_s < 14)}/\text{deg}^2)$ taken from 2MASX. Both maps shows extinction contours (lines) at $A_{K_s} = 0^m3, 0^m6, 1^m0, 2^m0$ and 4^m0 . Even though the HI and MIR/FIR surveys can penetrate through the layers of dust quite effectively, both techniques are biased towards spiral galaxies, while elliptical galaxies are missed from these surveys. X-ray observations will not achieve the objective of mapping the extended galaxy distribution as they are sensitive only to high-density rich clusters. Furthermore due to the opacity of the atmosphere MIR/FIR observations are only possible from space-telescope.

This makes deep NIR survey an optimal way to trace the galaxy density distribution in the GA region. Unfortunately the currently available 2MASX survey is largely incomplete in the GA region. Figure 1.15 displays the all-sky 2MASS galaxy distribution, with the Norma Wall indicated on the map with the blue contour line as outlined in Fig. 1.12.

It is clear from the map that core of the GA remains largely devoid of 2MASS galaxies. This motivated us to perform a deep NIR survey in the GA region with a better resolution and

Introduction

increased depth than the current 2MASS survey.

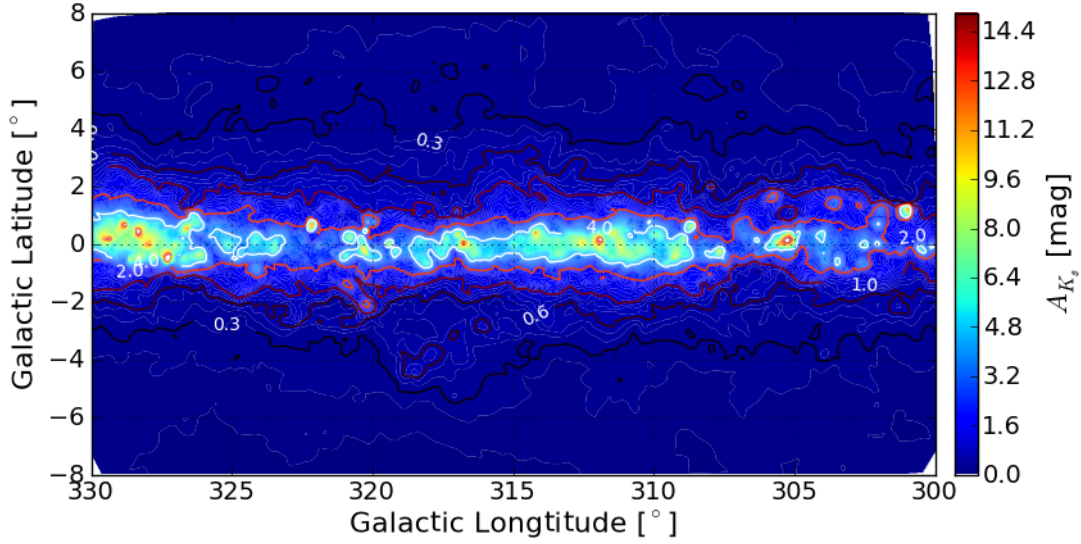


Figure 1.13: Galactic extinction in the K_s band. The map shows extinction in the K_s band. Solid contours are shown at $A_{K_s} = 0^m3$, 0^m6 , 1^m0 , 2^m0 , and 4^m0 .

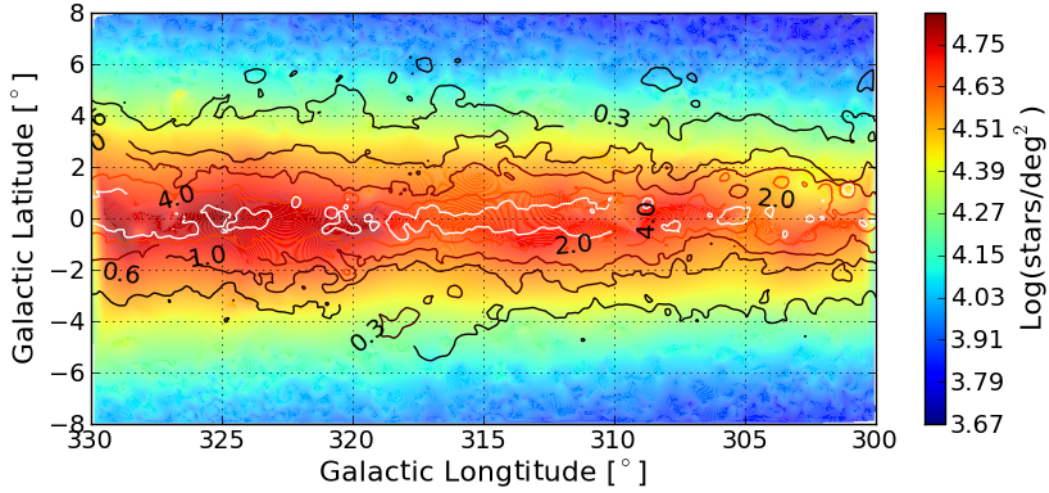


Figure 1.14: Contours of stellar density in the GA region. The stellar density used for this contour plot are taken from 2MASX. The solid line contours mark regions of constant Galactic extinction $A_{K_s} = 0^m3$, 0^m6 , 1^m0 , 2^m0 and 4^m0 .

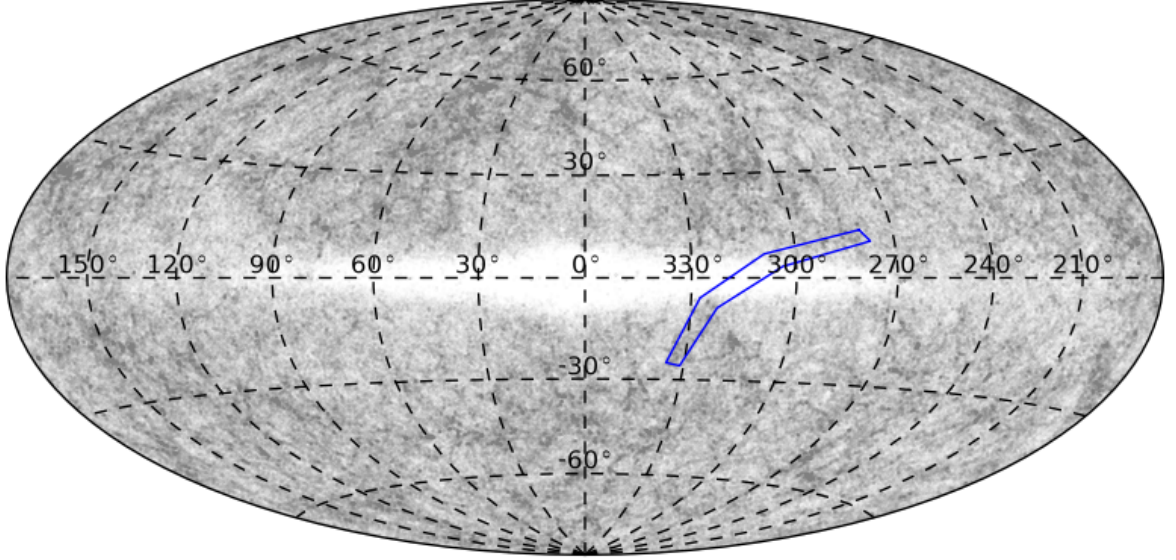


Figure 1.15: The map displays the 1.5 million extended source identified in the 2MASS survey. The blue contour line marks the Norma Wall. The plot shows that the core of the GA is devoid of 2MASS galaxies.

1.5 Outline of this thesis

In this thesis I discuss a deep NIR imaging (J , H , K_s) survey along the most obscured part of the Norma Wall aimed at identifying galaxies and galaxy clusters that contribute to the GA. Figure 1.16 displays the survey footprint that forms the basis of this thesis. The map shows galaxies in the GA region colour coded according to their redshifts. Galaxies marked with the circles are taken from the HyperLeda database, while galaxies marked with the crosses are HI galaxies (Kraan-Korteweg, private communications). The survey footprint is outlined by the black contour at the middle of the map.

This thesis is structured as follows. In Chapter 2, I describe the survey footprint, the telescope and the imaging instrument used for the survey. I also detail the image reduction steps and the subsequent image calibration procedures. Chapter 3 describes the algorithm that I followed to identify the galaxies on the survey images and the resulting galaxy catalogue. The chapter also discusses the galaxy parameters listed in the final catalogue. I then introduce the final survey catalogue and discuss its astrometric and photometric quality.

Chapter 4 studies the effect of dust extinction on the isophotal magnitudes and radii for galaxies that are observed in the band J , H and K_s and I hence derive extinction-corrections to the galaxies isophotal parameters. Chapter 5 analyse the observed galaxies statistically and the

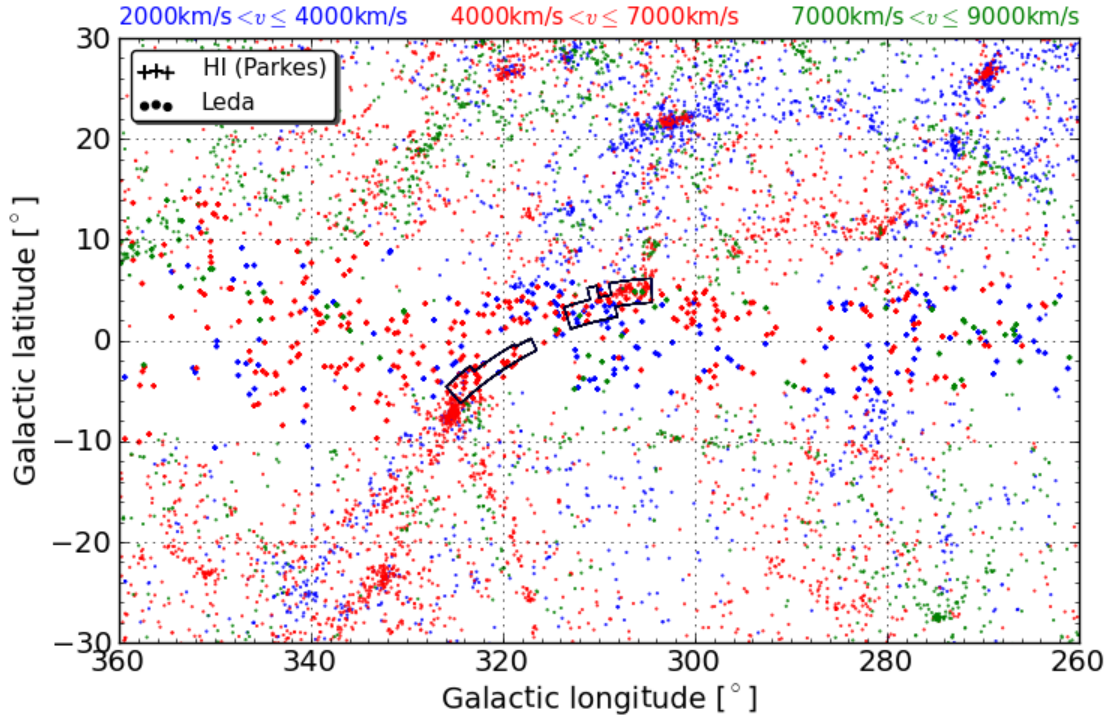


Figure 1.16: The Great Attractor region and the survey footprint. Galaxies are colour coded according to their redshift. Galaxies marked with circles are taken from the HyperLeda database, while galaxies marked with crosses are HI observations (Kraan-Korteweg, private communication). The survey footprint is denoted by the black outline (see Fig. 2.1 for a zoom in of the footprint).

survey completeness limits. The galaxy distribution within the survey footprint is investigated using galaxy density distributions and density maps to identify the large-scale structure within the survey area and compare it to other NIR field and cluster samples. I also attempt a mass estimate of the Norma Wall. Chapter 6 summarizes the conclusions and outlines future work.

2

Observation and Image Reduction

In this chapter I present a 37.5° deep imaging survey in three NIR passbands J , H , and K_s along the Norma Wall, henceforth called “The Norma Wall Survey” (NWS). The survey was carried out using the Infrared Survey Facility (IRSF), a 1.4 meter telescope. The survey images have a spatial resolution of 0.45 arcsec/pixel which is about four times higher than the 2.0 arcsec/pixel resolution of the currently available 2MASS survey. With an exposure time of 10 min per image the NWS is approximately 2 magnitudes deeper than 2MASS.

In the following sections, I will present details of the observations, image reduction and calibration. I will also discuss the astrometric and photometric quality of the survey images. All algorithms and codes that were applied for the different tasks were prepared by me unless otherwise stated.

2.1 Observations

The observations of the Norma Wall survey began in March 2006 and continued in 2007 and 2008 at a rate of 6-8 weeks/year. It was completed with a final observing run in July 2009 dedicated to filling in gaps and the re-observation of fields with unsatisfactory image quality (see Sect. 2.3.4). In Table 2.1 the allocated time slots on the IRSF are given. The table also lists the observers who contributed to the observing efforts. I myself carried out a total of six weeks of observations in 2007, 2008 and 2009.

Table 2.1: Time slots allocated for the ZOA survey on the IRSF.

Year	time slot	No. fields	No. of weeks	Observer
2006	March/April, June/July	700	6	RCKK, PAW, TN, KW
2007	March/April, June/July	819	6	RCKK, PAW, TN, KW, IFR
2008	March/April, June/July	829	6	TN, KW, IFR, PK
2009	March, June/July	288	5	TN, KW, IFR

*Nagayama, T. (TN) , Wakamatsu, K. (KW), Woudt, P. A. (PAW), Kraan-Korteweg, R. C. (RCKK), Kotze, P. (PK), Riad, I. F. (IFR).

2.1.1 The survey footprint

The Norma Wall is an extended wall-like structure running from below the GP, across the ZOA to regions above the GP (see chapter 1). For the purpose of this survey, and the goal to complete the survey within a reasonable time scale, only selected regions along the wall were observed systematically. The survey footprint is shown in Fig. 2.1. It was designed to effectively map galaxies and galaxy overdensities, where optical surveys become severely incomplete, and where the star-crowding is not so severe that the galaxy identification becomes impossible. The footprint consists of two branches, the upper defined by $305^\circ \lesssim \ell \lesssim 313^\circ$, and $1^\circ \lesssim b \lesssim 6^\circ$, while the lower branch is defined as $316^\circ \lesssim \ell \lesssim 325^\circ$, and $-6^\circ \lesssim b \lesssim 0^\circ$. The footprint is outlined in Fig. 2.1 by the black line.

Each cross within the footprint represents the centre of an individual IRSF field. The survey region encompasses 2793 individual pointings and covers an area of $37.5 \square^2$. Fields are colour-coded according to their year of observation.

Eighty one fields out of the 2793 fields (marked with blue crosses) were fields that failed the image quality control (see Sect. 2.3.5) but were good enough to be searched for galaxies. These 81 fields were not re-observed as no galaxies were found in them. For the purpose of investigating the astrometric, and photometric performance of the survey images and subsequent discussions, only the 2712 fields that passed the image quality control were used.

Marked on Fig. 2.1 as large filled blue circles are the centres of the Norma cluster ($\ell = 324^\circ.3$, $b = -7^\circ.2$), PKS 1343-601 ($\ell = 309^\circ.7$, $b = +1^\circ.7$), CIZA 1324.7-5736 ($\ell = 307^\circ.4$, $b = +5^\circ.0$), and Cen-Crux cluster ($\ell = 305^\circ.5$, $b = +4^\circ.8$). Contours of constant Galactic extinction at $A_{K_s} = 0^m1$, 0^m2 , 0^m3 , 1^m0 , 2^m0 , and 3^m0 are indicated. Extended sources from the 2MASX are also plotted in the figure (green circles). The correlation between the decrease in the galaxy number count, and the increase in extinction is quite obvious.

The upper branch starts approximately at $\ell = 304^\circ.8$, $b = +6^\circ.0$, encompasses the CIZA 1324.7-5736 and Cen-Crux clusters. It runs above the PKS 1343-601 cluster, which was observed in detail with the same instrument by Nagayama et al. (2004) and continues to $\ell \approx 314^\circ$, and $b \approx 1^\circ$. The region, $314^\circ \lesssim \ell \lesssim 317^\circ$, and $0^\circ \lesssim b \lesssim 2^\circ$, was not included in the survey footprint

as it was anticipated that our ability to detect galaxies in this region will completely deteriorate as a result of the high extinction ($A_{K_s} \gtrsim 2^m0$) and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) > 4.3$.

The lower branch starts at $\ell \approx 325^\circ$, $b \approx -6^\circ$ close to the Norma cluster. It does not form part of this work because it was previously observed with the same instrument (Woudt et al., 2005; Skelton et al., 2009). It then continues to $\ell \approx 316^\circ$, $b \approx 0^\circ$.

Galaxy detection in the region $316^\circ \lesssim \ell \lesssim 319^\circ$, $-2^\circ \lesssim b \lesssim 0^\circ$ is very difficult due to the high levels of extinction $A_{K_s} \gtrsim 2^m0$ and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) > 4.3$. The region was included to overlap with a region where 2 galaxies were detected in the GLIMPSE survey images (Jarrett et al., 2007a) at $\ell = 317^\circ 0$, $b = -0^\circ 5$, and $\ell = 316^\circ 9$, $b = -0^\circ 6$ and confirmed later to be part of the GA using the Australia Telescope Compact Array (ATCA) follow-up snapshots. Furthermore the region was also observed to overlap with a region surveyed by *Spitzer* (the orange box in Fig. 2.1) (Jarrett et al., 2007b).

2.1.2 The SIRIUS camera on the IRSF

The Norma Wall Survey was conducted using the Japanese IRSF telescope situated at the South African Astronomical Observatory (SAAO) site in Sutherland. The IRSF is a 1.4 meter Alt-Azimuth Cassegrain telescope. It is equipped with the Simultaneous 3-colour InfraRed Imager for Unbiased Survey (SIRIUS) as an imaging instrument. The SIRIUS camera has three 1024×1024 pixel HgCdTe detectors (HAWAII array) capable of taking simultaneous images in the J , H , and K_s passbands. The SIRIUS camera on the IRSF has a field of view of $7'.7 \times 7'.7$ with a resolution of $0''.45/\text{pixel}$, a gain of $5.5 e^-/\text{ADU}$ (Nagashima et al., 1999), and a read out noise of $30 e^-$.

Compared to other NIR survey telescopes and instruments like DENIS (Epchtein et al., 1997) or 2MASS (Skrutskie et al., 2006; Cutri et al., 2006), the IRSF telescope and the SIRIUS camera have a higher angular resolution. In Table 2.2, I compare the properties (e.g telescope diameter, field of view, and spatial resolution) of the IRSF+SIRIUS (Nagashima et al., 1999), 2MASS (Skrutskie et al., 2006) and DENIS (Epchtein et al., 1997) survey instruments. The improved resolution of the IRSF+SIRIUS instrument will greatly help in identifying faint extragalactic objects, and achieve better galaxy photometry by improving the quality of the star subtraction process. In the table I also list parameters for the Visible and Infrared Survey Telescope for Astronomy (VISTA) as a comparison to a prospective future near-infrared telescope. VISTA is an ESO 4 meter class wide field survey telescope in Chile which will survey the southern hemisphere.

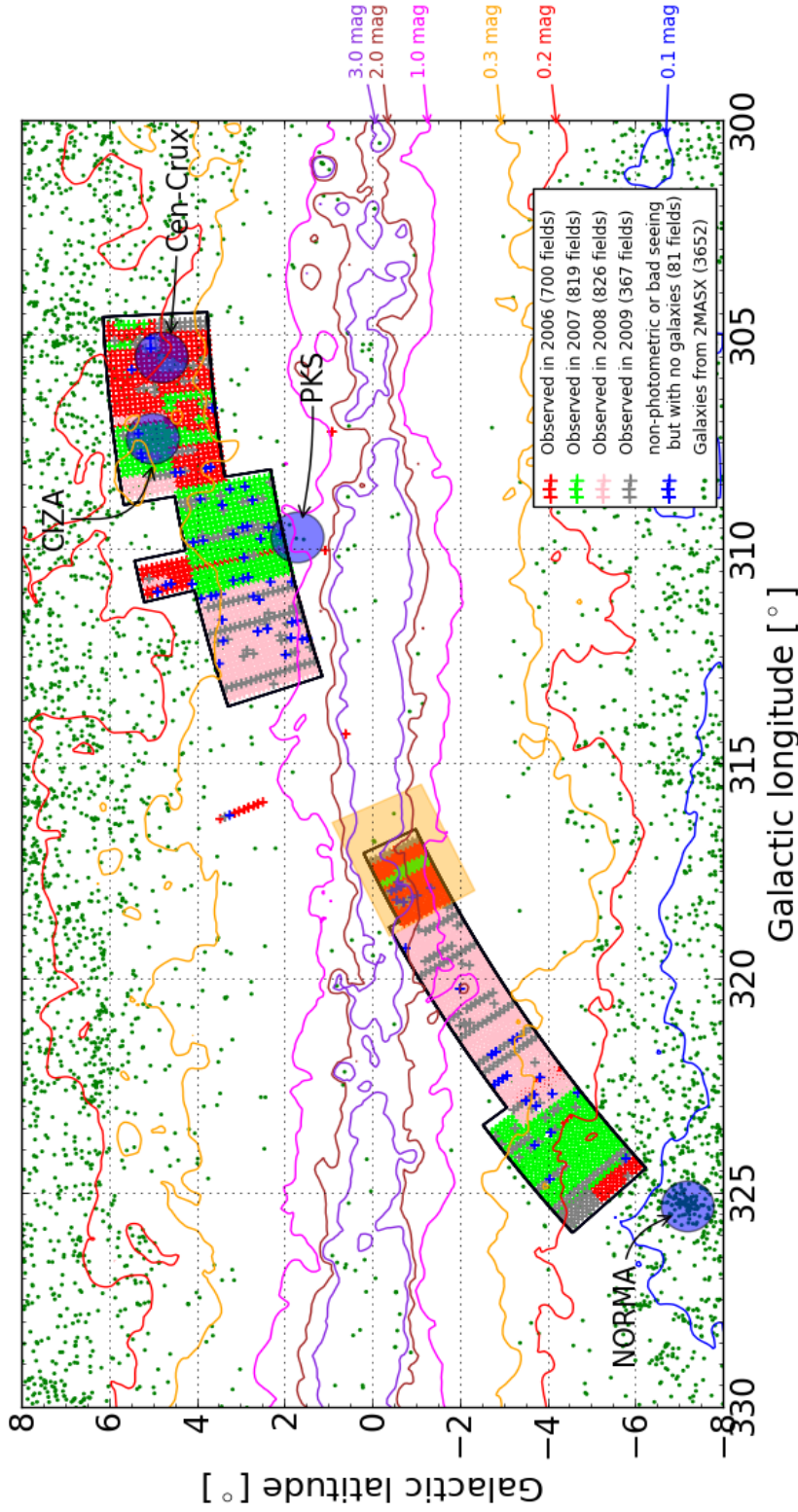


Figure 2.1: The survey footprint: 700 fields observed in 2006 (red), 819 fields observed in 2007 (green), 823 fields observed in 2008 (pink) and 223 observed in 2009 (black). The 81 fields (blue) either have bad seeing or non-photometric; they do not contain galaxies (these fields were not re-observed). The blue large circles mark the centres of the Norma cluster ($\ell = 324^\circ 3$, $b = -7^\circ 2$), PKS 1343-601 ($\ell = 309^\circ 7$, $b = +1^\circ 7$), CIZA 1324.7-5736 ($\ell = 307^\circ 4$, $b = +5^\circ 0$), and Cen-Crux clusters ($\ell = 305^\circ 5$, $b = +4^\circ 8$). Contours of constant extinction at $A_{K_s} = 0^m 1$, $0^m 2$, $0^m 3$, $1^m 0$, $2^m 0$, and $3^m 0$ are indicated. The green dots are galaxies from 2MASX. The $2^\circ \times 2^\circ$ orange box, centred on $\ell \approx 317^\circ 1$, $b \approx -1^\circ 0$, was surveyed by the IRAC, and MIPS Spitzer instruments.

2.1 Observations

Table 2.2: Telescope/instrument parameters for IRSF, 2MASS, DENIS, and VISTA.

Telescope	Diameter [m]	Field of View [']	Resolution ["]/pixel	Bandpass (central wavelength)			
				I/Y [μ m]	J [μ m]	H [μ m]	K_s [μ m]
IRSF+SIRIUS	1.4	7.7×7.7	0.45	- -	1.26	1.63	2.14
2MASS	1.3	8.5×8.5	2.0	- -	1.25	1.65	2.15
DENIS	1.0	12.0×12.0	1.0, 3.0, 3.0	0.82	1.25	- -	2.15
VISTA	4.0	90×60	0.34	1.02	1.25	1.65	2.15

The values quoted in the I/Y column is for DENISS I band and VISTA Y band.

Table 2.3 list parameters such as exposure time, limiting magnitudes, and survey area for surveys that were completed using those instruments. It also lists future surveys like the VISTA Hemisphere Survey (VHS) (see Emerson et al. 2004).

Table 2.3: Effective time and limiting magnitudes for the NWS, 2MASS, DENIS, and VISTA surveys

Survey	Inst.	effective time [sec]	limiting magnitude [mag]				Survey size [$\square^\circ$]
			I/Y	J	H	K_s	
NWS	IRSF+SIRIUS	600	- -	15.6	15.3	14.8	≈ 37.5
2MASS	2MASS	7.8	- -	14.7	13.9	13.1	All sky
DENIS	DENIS	9.0	16.5	14.8	- -	12.0	southern sky
VHS	VISTA	60	21.2	22.1	20.6	20.0	southern sky

The values quoted in the I/Y column is for DENISS I band and VISTA Y band. The limiting magnitudes in this table are the 10σ limiting magnitudes for the DENISS, 2MASS and NWS while it is the 5σ magnitudes for VISTA.

The limiting magnitudes listed in Table 2.3 reveal that the NWS survey is a significantly deeper survey of the GA than the currently available DENIS and 2MASS surveys. The limiting magnitudes for galaxies in DENIS (Mamon et al., 1998; Mamon, 2000) and 2MASS (Jarrett et al., 2000a) are estimates at high Galactic latitudes. The quoted NWS completeness limits are the extinction-corrected magnitudes for galaxies with foreground extinction below $A_{K_s} \leq 1^m0$ where most of the galaxies were found, see chapter 5 for a detailed discussion on the completeness limits of the current survey.

In Fig. 2.2 I compare the NWS and the 2MASS for image quality. The figure displays a field as observed in 2MASS (left panel) versus NWS (right panel). This field is centred at $\ell = 305^\circ09$, $b = +5^\circ53$. It is located at a relatively low extinction region ($A_{K_s} \approx 0^m14$). The stellar density of stars brighter than 14^m0 in the K_s band is $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.05$ in the NWS and $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.02$ in the 2MPSC. The stellar density difference translates into an excess of ≈ 749 stars/degree² or 7% per field-of-view for the NWS images over the 2MASS

images. This discrepancy between the stellar density given by 2MASS and the one calculated from the NWS images is due to the higher spatial resolution. Many of the blended stars in 2MASS can be resolved in the NWS images. Furthermore, the discrepancy can partially be due to the different algorithms used for the density calculation.

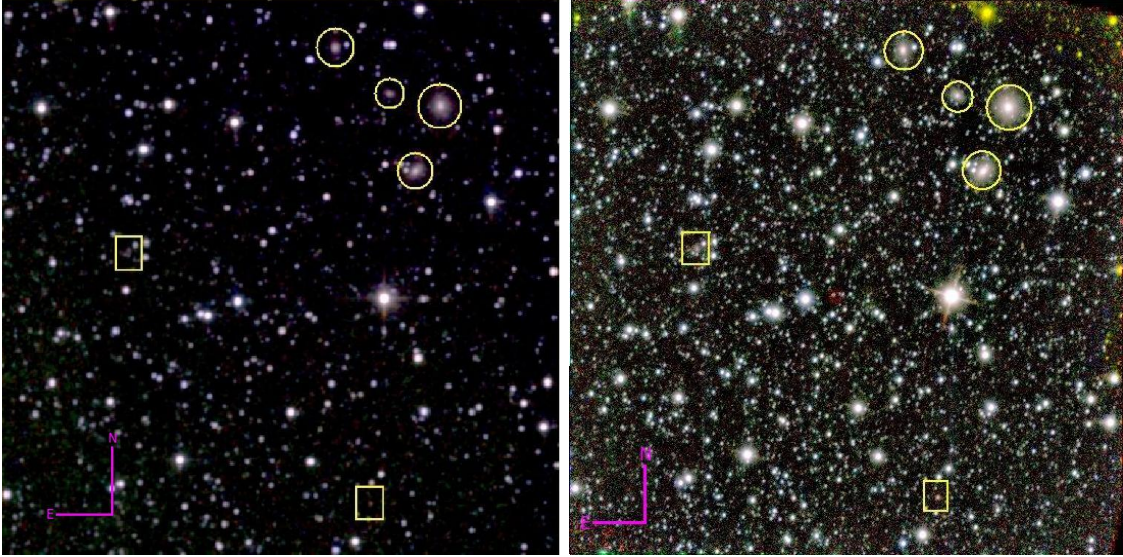


Figure 2.2: The $7'.7 \times 7'.7$ field centred at $\ell = 305^\circ 09$, $b = +5^\circ 53$. The average extinction in the field is $A_{K_s} = 0^m 14$, and the stellar density is $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.05$. Left: as seen in 2MASS. Right: as seen in NWS. The apparent difference in star counts between the two fields is due to the different integration times used in the two surveys. Galaxies marked with circles were catalogued in both the NWS, and the 2MASX, galaxies marked with boxes are only listed in the NWS.

The six galaxies marked with circles and boxes demonstrate the improved quality of our NWS images (right panel) over 2MASS (left panel). Only four of the galaxies (marked with circles) were catalogued previously in the 2MASX. The two galaxies marked by the boxes were not listed in the 2MASX, and are only now revealed as a result of the increased depth and spatial resolution of our survey compared to 2MASS.

Figure 2.3 displays a zoomed-in view of the galaxies as seen in 2MASS (columns 1 & 3) and NWS (columns 2 & 4). The two top rows display the four galaxies that are found in both the NWS and the 2MASS images. The bottom row shows the two galaxies that are only catalogued in the NWS.

The factor 4 improvement in the resolution of IRSF+SIRIUS over 2MASS also results in a more reliable morphological classification and better deblending of stars superimposed on galaxies, hence achieving a more reliable photometry. The longer integration times and improved

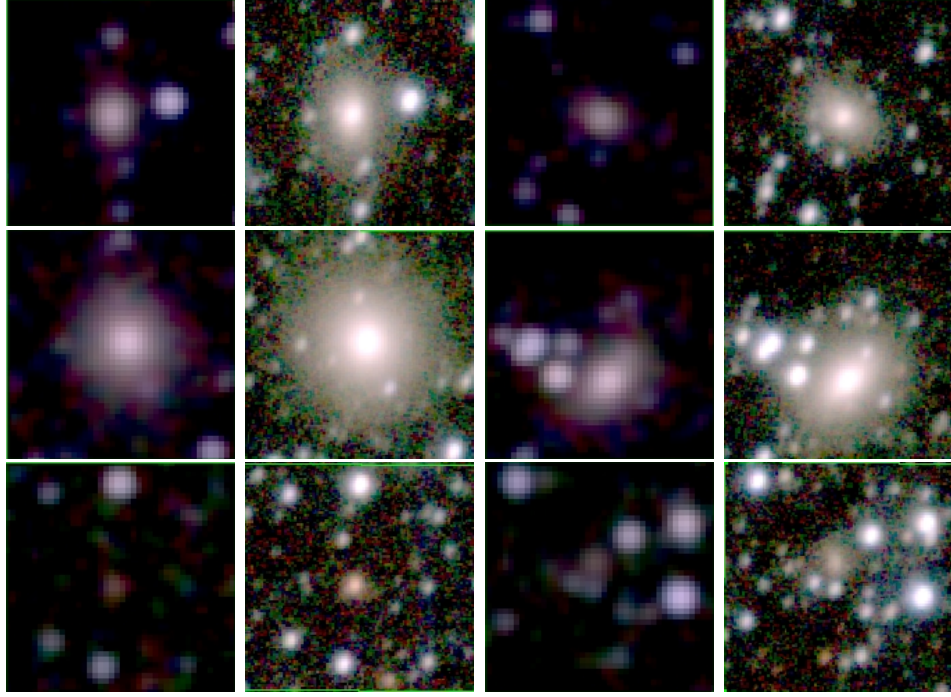


Figure 2.3: A zoom-in of the galaxies detected in the field displayed in Fig. 2.2. The 2MASX images are shown in columns 1 & 3. The SIRIUS ones are in columns 2 & 4. The first two rows show the galaxies detected in both the NWS and 2MASX. The bottom row galaxies that were only detected in the NWS images. The box size is $42'' \times 42''$. In these images North is up and East is left.

resolution also assist in the removal of faint stars that are blended with galaxies but are not resolved by 2MASS. This is best illustrated in Fig. 2.3 by comparing the galaxy images from 2MASS and SIRIUS. Many of the stars overlapping or blended with the galaxies are resolved in the SIRIUS images. This makes it easier to deblend nearby stars and hence better account for flux contamination from overlapping source. This will lead to more accurate galaxy photometry.

Another example is shown in Fig. 2.4 for a crowded field observed at $\ell = 316^\circ 99$, $b = -0^\circ 50$. The average extinction in this field is $A_{K_s} \approx 2^m 0$ while the stellar density in the field is $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.87$. The galaxy at $\ell = 317^\circ 0$, and $b = -0^\circ 50$ marked with the circle was detected on the NWS images and not in the 2MASS. This galaxy was first identified in the GLIMPSE survey (Jarrett et al., 2007a). Comparing the zoomed-in insets at the top right corner of Fig. 2.4, clearly shows a resolved star close to the core of the galaxy in the NWS image, while this star is completely washed out in the 2MASS images. This further substantiate our ability to detect highly obscured galaxies in very crowded fields close to the GP.



Figure 2.4: The field is centered on $\ell = 316^{\circ}99$, and $b = -0^{\circ}50$; the image size is $7'.7 \times 7'.7$. Left: as seen by 2MASS. Right: as seen by SIRIUS. The galaxy at $\ell = 317^{\circ}04$, $b = -0^{\circ}50$ marked with a circle, is deeply embedded in the GA region. This galaxy is detected in the Norma Wall survey but not in 2MASX. The galaxy was also detected by GLIMPSE (Jarrett et al., 2007a). (The insets are a zoom-in into the galaxy and the box size is $55'' \times 55''$).

2.1.3 Field imaging

The survey region was observed in strips of constant Right Ascension (RA), with adjacent strips separated by $7'.0$ in RA. Fields within each strip of constant RA are also separated by $7'.0$ in Declination (Dec). Given the field-of-view of $7'.7 \times 7'.7$, this configuration gives an overlap of $0'.7$ in RA and Dec between any neighbouring fields.

Infrared observations are fundamentally different from observations in the optical. This is due to the high sky-background in the infrared ($J \approx 16.5$ mag/arcsec², $H \approx 14.4$ mag/arcsec² and $K_s \approx 13.0$ mag/arcsec²) compared to the optical ($B \approx 22.6$ mag/arcsec² and $V \approx 21.6$ mag/arcsec²). The sky brightness values quoted here are for the ESO site at Paranal in Chile¹. For comparison the NIR sky-background for the SAAO site at Sutherland is $J \approx 16.3$ mag/arcsec², $H \approx 14.2$ mag/arcsec² and $K_s \approx 12.5$ mag/arcsec². These values were calculated as the median value of the sky brightness calculated for a set of 2693 fields (99.3% of the total number of the survey images). The sky brightness at the Sutherland is brighter than the Paranal site, specially in the K_s band, as Sutherland is warmer than Paranal.

The imaging of fields with exposure times longer than 1 min results in the saturation of the images, while using short exposures of $\lesssim 1$ min results in the images not having enough signal-

¹<http://www.eso.org/gen-fac/pubs/astclim/paranal/skybackground/>

to-noise to facilitate the detection of faint galaxies. It is hence customary to obtain multiple short exposure frames ($\lesssim 1$ min) and then combine them into a single image. This results in combined images with sufficiently high signal-to-noise to detect faint objects without the image being saturated.

For the purpose of our survey it was decided to image the fields with 25 consecutive frames of 24 sec exposure each. After combining the 25 frames, this leads to a total effective exposure time of 600 sec. The single frame exposure time and the total integration time were selected based on previous experience in using SIRIUS for observations in the ZOA (Woudt et al., 2005; Nagayama et al., 2004, 2006). The current values were selected as a trade-off between increasing our chances in detecting faint galaxies and contamination from faint stars.

A major difference between infrared and optical detectors is the higher proportion of faulty pixels in infrared detectors. This problem can be overcome by using a technique called dithering; a field is observed as a set of frames with the centre of each frame slightly shifted in a pattern around the centre of the field. Dithering ensures that objects in a field are located on different regions of the detector. In aligning and combining the dithered frames, the effect of faulty pixels is averaged out.

I used a dithering pattern displayed in Fig. 2.5 that consists of a 5×5 grid with individual spacings of $15''$. The 25 dithered frames are evenly distributed over the grid. These frames are denoted as (`self` frames) in the SIRIUS pipeline. The anomaly in the position of frame (11) is due to a flow in the code controlling the dithering pattern. This does not affect the final image as all frames will be aligned with the central frame and stacked together by the SIRIUS pipeline. As a result of this dithering, the final size of the image is $\approx 8'.6 \times 8'.6$. The central $\approx 7'.7 \times 7'.7$ region of the image has higher signal-to-noise compared to the outer region of the image.

2.1.4 Calibration observations: Flat fields, and dark frames

The pixel-to-pixel variations in the quantum efficiency of a detector array result in a different source count if an object is detected on different regions of the detector. To correct for that, the detector response to a uniform source of light needs to be measured. The process of correcting for this variation is called flat fielding. The correction uses specially observed frames of a uniform light source (flat-fields).

For the NW survey I used morning and evening twilight as the source of uniform light. On each night of an observing run, 100 flat-field frames of 5 sec exposures each were taken (weather conditions permitting) both in the morning and the evening. Flat-fields observed during the individual nights of a one-month observing run were then used to create one master flat-field (Sect. 2.2.2). This master flat-field was later used to correct all the raw images observed during that month.

Infrared detectors are sensitive to thermal noise. Even when the detector is not illuminated, it still shows a non-negligible signal. To correct for this, dark frames were taken with the

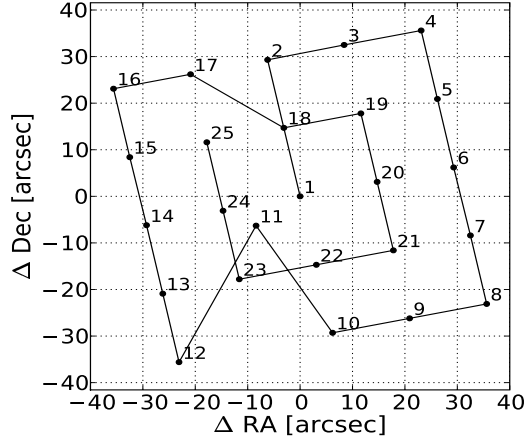


Figure 2.5: The dithering pattern around the centre (1) of the observed field. The outer box is $60'' \times 60''$ in size, and the inner box $30'' \times 30''$. The anomaly in the position of frame (11) is due to a flow in the code controlling the dithering pattern. This pattern was used for observing all the survey fields.

camera shutter closed. These frames model the thermal noise in the detector. Thermal noise is a function of exposure time. I took two sets of dark frames each of 10 frames. The first set with 24 sec. exposures for correcting the **self** frames and the second of 5 sec. exposures for correcting the flat field frames.

2.2 Image reduction

The raw images acquired with SIRIUS were reduced using the **SIRIUS** pipeline. The pipeline was developed, and maintained by Yasushi Nakajima¹. The pipeline is a dedicated **IRAF**² (Image Reduction and Analysis Facility) package for the automated reduction of raw images obtained with SIRIUS.

The pipeline uses the different sets of frames (**self**, **dark** and **flat**) to correct the raw frames for dark current and pixel-to-pixel quantum efficiency variation of the detector. The pipeline then combines all the corrected frames into a single image. The different steps of the reduction pipeline are described in the following sections.

¹Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya, Japan.

²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc, Under cooperative agreement with the National Science Foundation.

2.2.1 Dark current correction

The 10 dark frames with 24 sec. exposures were median combined into a single dark frame. The **self** frames were then corrected for dark current by subtracting the median dark frame from each **self** frame, resulting in a new frame **self_d**. Equally wells the 5 sec. exposures frames were also median combined and hence used to correct the flat fields.

2.2.2 Master flat field

Variations in the pixel-to-pixel efficiency (discussed in Sect. 2.1.4) are not significant on time scales of less than one month. To demonstrate this, I used flat-fields observed on three individual nights, on 23-03-2008, 07-04-2008 and 20-03-2009. The first two nights are approximately 2 weeks apart while the last night is almost one year later. For each individual night I created three flat-fields, one for each of the bands J , H and K_s . From these frames I produced three additional sets of frames. The first set (FLAT_λ^S) was produced as the difference between the flat-fields for the nights 23-03-2008, 7-04-2008. This field serves as a gauge to the short-time scale variation of the pixel-to-pixel variation in the detector efficiency. The second (third) set was created as the difference between the nights 20-03-2009 and 23-03-2008 (7-04-2008). The second and third sets were then mean combined (FLAT_λ^L). The FLAT_λ^L was created as an average field for the purpose of giving a better estimate for the long-term (1 year) variation in the detectors efficiency as it is anticipated that long term variations are higher than the short term.

Ideally, if the pixel-to-pixel efficiency is constant and does not vary with time, the two frames FLAT_λ^S and FLAT_λ^L should all have zero count rates. As this is not the case, it is expected that the detector pixel-to-pixel efficiency varies with time. This variation is demonstrated in Fig. 2.6 where I plot the mean offset along rows for the two fields FLAT_λ^S and FLAT_λ^L as a function of row number. In Fig. 2.6 the data points for the FLAT_λ^S frame are labeled with green stars and for FLAT_λ^L with red diamonds. The shifts for both fields were calculated for the same rows. On the plot the rows for the frame FLAT_λ^S were systematically shifted by 10 rows for easier comparison of the error bars. The shaded insets are a $5\times$ zoom-in for the data points in the rows 600 - 850.

Both fields FLAT_λ^S and FLAT_λ^L have an insignificant offset from the expected zero ADU level. The analysis shows that the J band varies the most with a standard deviation $\sigma = 0.013$ ADU and $\sigma = 0.051$ ADU over both the short and long-term scales respectively. The H and K_s has smaller dispersion compared to the J band. This conclusion is evident in Fig. 2.6 where the variation in the pixel-to-pixel efficiency is always smaller for the frame FLAT_λ^S compared to FLAT_λ^L . Table 2.4 lists the dispersion for each frame in all three bands.

The large variations detected in the J band compared to the other two bands are caused by three faulty regions on the J band detector. This also explains the significant variations seen in this band for the regions bound by the rows $\approx 240 - 440$ and $\approx 860 - 1024$. These regions are marked with red boxes on the J band sample flat-field displayed in the left panel of Fig. 2.7.

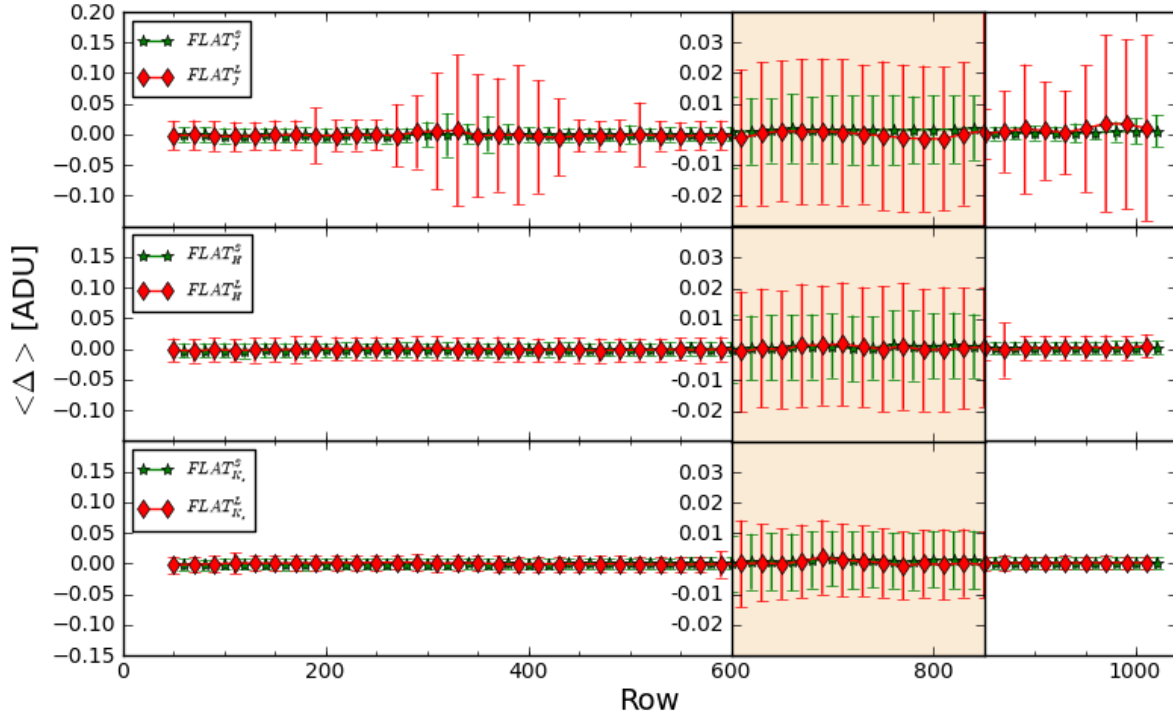


Figure 2.6: Time variation of the pixel-pixel quantum efficiency for the three NIR detectors used in SIRIUS. Top J , middle H , and bottom K_s . The plot shows the mean shifts Δ along lines of constant row numbers. The shaded insets are a $5\times$ zoom-in to the region with row numbers 600 - 850. The J band shows the most quantum variation over time. The regions defined by the rows $\approx 270 - 440$ and $\approx 860 - 1024$ in the J band show the most variation.

Table 2.4: J , H and K_s flat field time variation.

Band	$FLAT^S$ σ [ADU]	$FLAT^L$ σ [ADU]
J	0.013	0.051
H	0.011	0.020
K_s	0.009	0.012

This figure shows the flat fields $FLAT_J^L$, $FLAT_H^L$, and $FLAT_{K_s}^L$.

This results clearly support the decision of using flat fields observed over a period of one-month to correct frames observed in that month.

The *autotwflat* task of the **SIRIUS** package was used to create the master flat fields. The

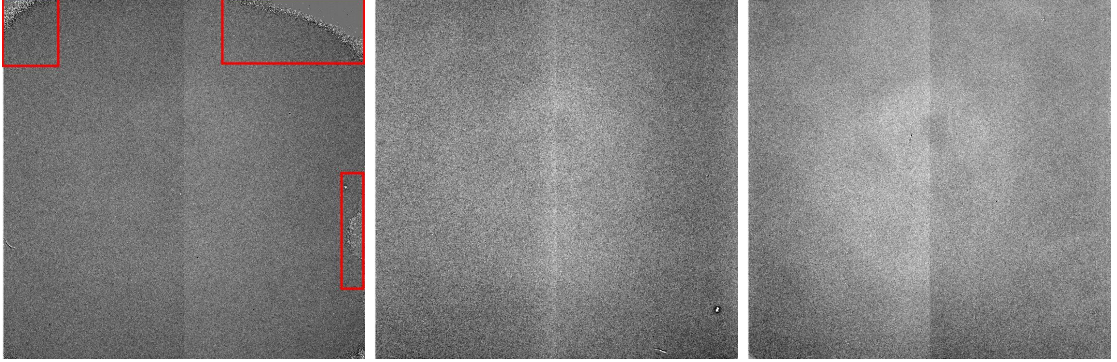


Figure 2.7: A sample of differential flats (FLAT_λ^L). Left J , middle H and right K_s band. The faulty regions on the J band detector between rows $\approx 240 - 440$ and $\approx 860 - 1024$ are marked with the red boxes.

task works by first creating individual flat fields from the frames of each night. The task selects pairs of frames that have a mean flux < 6000 counts ($\approx 30\%$ of the saturation level), and a mean flux difference > 2000 counts. Each pair is differentially combined, and then normalised by its median value. The differentially normalised frames from all nights within a one-month period are pixel-by-pixel median-combined creating a final master flat field. The master flat-fields are labeled **twilight**.

In the next step, the frames self_d are divided by the master flat field, removing the detectors response from the frames. This results in the new frames self'_d .

2.2.3 Sky subtraction

Imperfections, dirt, dust in the optical system of the telescope and emission from the atmosphere will imprint visual patterns on the observed frames. Usually no sky patterns are seen on the J band images. In the H band, diffraction patterns from OH emission in the atmosphere show up on the observed frames. For the K_s band, dust on the detector window is hot enough to radiate in this band and imprints its image on the detector. A sample of such patterns is shown in Fig. 2.8. These patterns contaminate the science images, resulting in confusion when extracting sources and performing photometry, unless the images are corrected for them. Another pattern that is clearly seen in the three bands is the division in halves of the frames. This pattern is artifact of the detectors readout system. Sky subtraction also corrects for this.

The process of correcting images for the sky-background is called sky subtraction. For each observed field, the mean flux of the dithered frames was scaled to the mean flux of the first frame in the ensemble of dithered frames by adding or subtracting a value equal to the difference of their mean flux. This process ensures that all frames have the same mean flux value. Those images were then pixel-by-pixel median combined. Since the sky patterns always occupy the

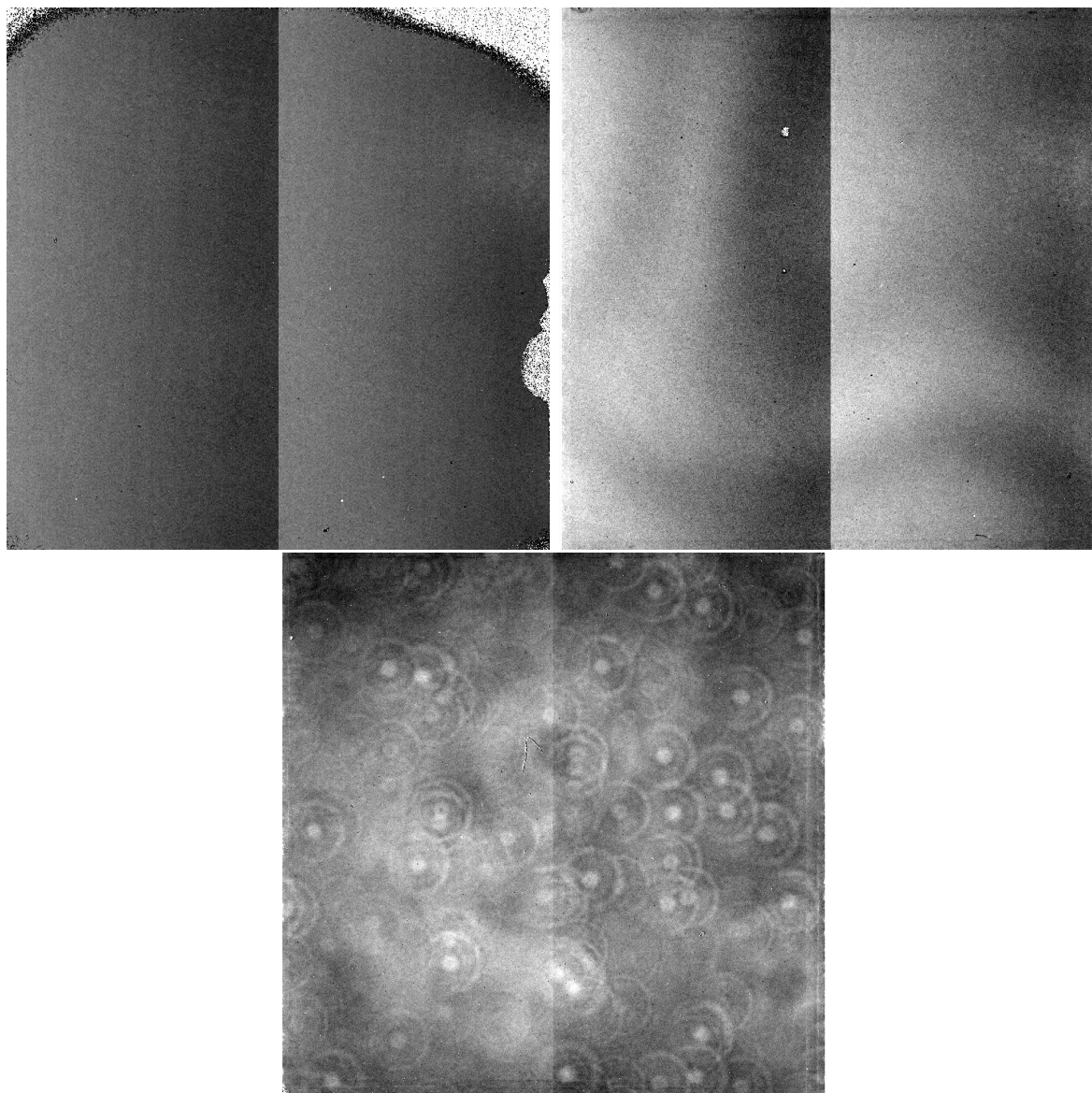


Figure 2.8: Sky background patterns. Top left J band: no sky pattern shows up in the J band, it is generally very uniform. Top right H band: diffraction patterns on the detector window from OH emission in the atmosphere. Bottom K_s band: dust hot enough to radiate in the K_s band.

same regions on the detector while the astronomical sources are shifted around because of the dithering, all sources in the combined frame are washed away except for the sky patterns. This new image, labeled as **sky**, will only have the imprint of the sky pattern. The **sky** frames were

also corrected with the `twilight` frames for the pixel-to-pixel variation in the quantum efficiency of the detectors.

The `sky` frame was then subtracted from each of the `selfa'` frames, resulting in new frames with the sky pattern removed. The sky-background of the new frame was re-set by adding the mean value of the sky-background `<sky>`. This gives the final image *SELF*. The previous image operations are summarised by,

$$SELF = \frac{\text{self}_a}{\text{twilight}} - \frac{\text{sky}}{\text{twilight}} + \langle \text{sky} \rangle. \quad (2.1)$$

2.2.4 The final image

The final image was created from the corrected dithered images *SELF* by aligning and average combining the dithered frames. For the alignment process, the dithered images were first processed by the IRAF procedures *daofind* and *phot*, creating a list of sources in each of the dithered images. Only stars with fluxes of 10σ above the sky-background and a magnitude error $\epsilon \leq 0^m.1$ detected within the region delimited by the pixels [51:900,51:900] were used for the alignment. Border regions were avoided because the lower signal-to-noise ratio. The aligned frames were then pixel-by-pixel average combined. The final combined images now have an enhanced gain of $Gain \times N$ and a reduced noise, scaling as $1/\sqrt{N}$, where N is the number of dithered frames, and $Gain$ is the single image gain. For our images the gain is $132 \text{ e}^-/\text{ADU}$.

2.3 Image calibration and quality control

Reduced images from the SIRIUS pipeline do not yet contain sufficient information to allow the extraction of photometric and astrometric information for the detected sources in the images. To extract such information, the images need to be calibrated astrometrically and photometrically. For this calibration process I used the 2MPSC (Skrutskie et al., 2006) as a calibration standard. The 2MPSC was favoured due to its overlap with our survey in all observed bands and the availability of point sources that are common in both the 2MPSC and our survey.

In this section, I first review the astrometric, and photometric quality of the 2MPSC. I will then describe the astrometric, and photometric calibration process of the NW survey images, and the resulting quality of the parameters.

2.3.1 The 2 Micron All Sky Survey (2MASS)

The 2MASS survey images were calibrated astrometrically using the Tycho 2 point source catalogue (Høg et al., 2000). A detailed description, and an in-depth assessment of the astrometric calibration of 2MASS images is given in Cutri et al. (2006).

A comparison between point sources that are found in both the 2MPSC and the Tycho 1 catalogue gave a mean position shift of $\langle \Delta \text{RA} \rangle = -0.87 \times 10^{-3}$ arcsec with $\sigma = 8.06 \times 10^{-2}$ arcsec and $\langle \Delta \text{Dec} \rangle = 4.76 \times 10^{-3}$ arcsec with $\sigma = 8.85 \times 10^{-2}$ arcsec.

The 2MASS source photometry is given in the internal 2MASS photometric system. 2MASS images were calibrated photometrically using the photon-counting relative spectral response curve for the 2MASS system (Cutri et al., 2006; Cohen, Wheaton & Megeath, 2003) and the calibrated spectrum of Vega from Cohen et al. (1992). The 2MPSC photometric quality is quantified using the “combined” photometric uncertainties, given as $[j h k]_{\text{cmsigcom}}$ (Cutri et al., 2006) in the 2MPSC. The variation of $[k]_{\text{cmsigcom}}$ with magnitude is shown in Fig. 2.9 (reproduced from Cutri et al. 2006).

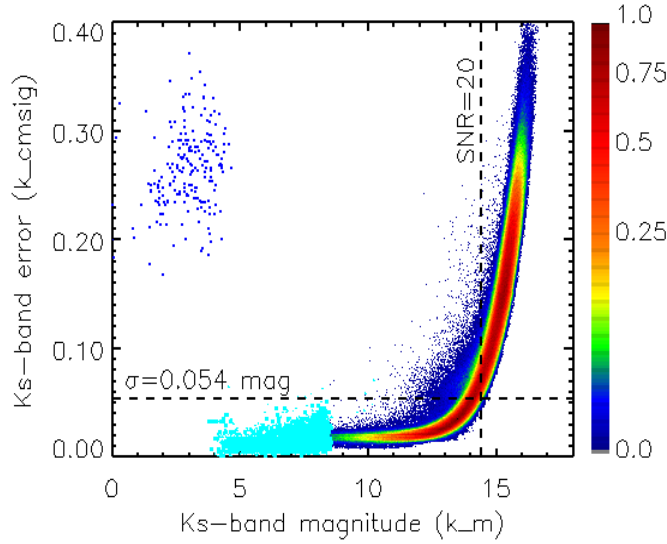


Figure 2.9: The 2MPSC combined photometric uncertainties. Plot is reproduced from Cutri et al. (2006). The plot shows 1.9 million points for the unconfused point sources lying within 15° of the north and south Galactic Poles. Photometry based on profile fits (Cutri et al., 2006) based on unsaturated stars is shown by a multi-colour density plot and photometry via aperture measures (Cutri et al., 2006) of unsaturated stars is shown by light blue dots. Saturated stars $m_{K_s} < 4^m0$, are shown by the dark blue points on the top left corner of the plot.

The plot shows 1.9 million points for unconfused point sources lying within 15° of the north and south Galactic Poles. Photometry based on profile fits (Cutri et al., 2006) of unsaturated stars is displayed with a multi-colour density plot, whereas photometry based on aperture measures (Cutri et al., 2006) of unsaturated stars is shown by light blue dots. Extremely bright (saturated) stars $m_{K_s} < 4^m0$ are shown by the dark blue points (the bunch of points at the top left corner of the plot). This figure demonstrates that stars with a signal-to-noise ratio higher

than 20 have photometric precision of $\epsilon = 0^m054$.

2.3.2 The astrometric calibration of the SIRIUS images

To calibrate the astronomical images astrometrically a subset of stars in the image is compared to their corresponding entries in a stellar catalogue. These are then used to define the transformation between the image coordinates and a World Coordinate System (WCS).

For the survey images coordinate conversion, a comparison with the 2MPSC was conducted using an implementation of the Optimistic Pattern Matching (OPM) algorithm proposed by Tabur (2007) and compiled by Dr. N. Matsunaga¹ (private communication). In the following, I provide more details about the OPM implementation.

List creation

The image for which a transformation is to be derived is first processed by a stellar detection routine (DoPHOT; Schechter et al. 1993) to construct a list of sources ordered by descending magnitudes. The $N = 50$ brightest sources are then selected to form the image stellar list $\mathfrak{S}$. Information about the image (field-of-view, scale and centre in equatorial coordinates) from the image Fits header were used to query the 2MPSC for the brightest 50 catalogue stars within the field. This list is denoted $\mathfrak{R}$.

Triangle construction

For all combinations (triplets) of stars in the two lists, triangles are created, with each triangle parametrised by two numbers (x_t, y_t) . This defines a triangle space with x_t the dot product between the two longest sides of the triangle, and y_t the ratio between the longest and the shortest sides of the triangle. For a list of n stars, $n(n-1)(n-2)/6$ unique triangles can be defined in this triangle space. An important feature of the (x_t, y_t) triangle space is that the least frequently occurring combination of a triangle with two nearby vertices and a third distant one, occupies the least dense region of this triangle space. This feature effectively reduces the overall computational time needed to find a good match between the two lists, $\mathfrak{S}$ and $\mathfrak{R}$, and hence a good astrometric solution. This will be explained in the following sections.

Matching triangles

Two triangles from $\mathfrak{S}$ and $\mathfrak{R}$ are deemed to match if their parameters (x_t, y_t) are within a certain tolerance $\epsilon = 0.02$ of each other. The matching process is time-consuming if all entries in the two lists are to be compared systematically. Limiting this process to the least dense regions of the triangle space and implementing an early exit mechanism from the process, once a good

¹Institute of Astronomy, School of Science, University of Tokyo

and reliable match is found between the two lists, significantly reduces the computational time needed by the process.

Astrometric solution and early exit mechanism

The early exit mechanism assumes that the subset of triangles in the least dense regions are rare. Any potential match is therefore probably a good match. The algorithm hence suspends the matching process to confirm the goodness of the candidate match. This candidate cross-correlation is checked by first applying a preliminary verification (Tabur, 2007). If successful, a preliminary astrometric solution is hence found. Astrometric solutions are found using the **IRAF** procedure *ccmap*, which finds a transformation between the image physical coordinates, and the catalogue WCS. The transformation is achieved using Eqns. 2.2.

$$\begin{aligned} X &= \text{coef}[0] * x + \text{coef}[1] * y + \text{coef}[2] \\ Y &= \text{coef}[3] * x + \text{coef}[4] * y + \text{coef}[5], \end{aligned} \quad (2.2)$$

where (x, y) is the position of a point source in the image physical coordinates and (X, Y) is the position of the matched pair in the WCS (J2000). ($\text{coef}[0] - \text{coef}[5]$) are the coefficients of the astrometric solution.

Using the preliminary solution, a final verification is conducted by cross-correlating the lists $\mathfrak{S}$ and $\mathfrak{R}$ to each other, thereby producing an improved astrometric solution. The mapping process is iterated three times, improving the quality of the solution with each iteration. The check is concluded as successful if 50% or more matches are found after the final iteration. The final astrometric solution is then determined and is written to the image fits-header. If any of the verification procedures results in a failure, the matching process is resumed to search for a better match.

2.3.3 The photometric calibration of the SIRIUS images

Due to the different filters and electronic arrangements used by the 2MASS and IRSF telescopes, a source observed by one instrument will have a different instrumental magnitude compared to the other. A source will also have different instrumental magnitudes under different photometric conditions. Instrumental magnitudes are magnitudes derived by counting a source flux and using Eqn. 2.3 to change it to magnitude,

$$m_{\lambda}^i = -2.5 \log \left(\frac{F_{\lambda}}{t_{exp}} \right), \quad (2.3)$$

where m_{λ}^i is the instrumental magnitude, t_{exp} is the single image exposure time and F_{λ} is the background-subtracted flux for a source in a given bandpass. Instrumental magnitudes are transformed to standard magnitudes using Eqn. 2.4,

$$m_{\lambda} = ZP_{\lambda} + m_{\lambda}^i + c_1 \times X + c_2 \times m_{col}, \quad (2.4)$$

where m_λ is the magnitude of the object in a standard magnitude system, ZP_λ the magnitude zero point (calibration constant) in a given bandpass, c_1 and X are the airmass extinction coefficient, and airmass respectively, c_2 is a colour coefficient and m_{col} is a colour term. Previous observations with the IRSF/SIRIUS showed that there is no colour dependence in Eqn. 2.4 and the coefficient c_2 is hence set to zero (Woudt; private communications).

Two methods are generally used to calibrate astronomical images photometrically. One method uses an observed set of standard stars. These stars are frequently observed over the course of the night at varying airmass to account for the variations in the photometric conditions, and airmass extinction over the night. Near-infrared standard stars can be found in Persson et al. (1998) or Carter & Meadows (1995) for faint and bright standard stars. This method requires extra time to observe these standard stars.

An alternative method uses stars in the field-of-view for which standardized magnitudes are available in a stellar catalogue. I implemented this method and used the 2MPSC as a standardized magnitude catalogue. This saves the time otherwise taken for observing the standard stars. This method is only applicable when the fields have enough stars that can be used for calibration, which is certainly the case for our ZOA fields.

The 2MASS, and SIRIUS use slightly different filters (see Fig. 2.10 for their transmission curves). The 2MASS curves are the solid lines and the SIRIUS curves are the dashed lines in Fig. 2.10. For the photometric calibration of our images, the 2MASS magnitudes were first converted to the SIRIUS filters magnitude system using the transformation relations given by (Yasushi Nakajima; private communications) before they were compared to the SIRIUS magnitudes.

$$\begin{aligned} J_{SIRIUS} &= J_{2MASS} + (-0.045 \pm 0.008)(J - H)_{2MASS} + (-0.001 \pm 0.008) \\ H_{SIRIUS} &= H_{2MASS} + (0.027 \pm 0.007)(J - H)_{2MASS} + (-0.009 \pm 0.008) \\ K_{sSIRIUS} &= K_{s2MASS} + (0.015 \pm 0.008)(J - K_s)_{2MASS} + (-0.001 \pm 0.008) \end{aligned} \quad (2.5)$$

Using the colour transformations given by Eqn. 2.5, Eqn. 2.4 now becomes

$$m_\lambda^{SIRIUS} = ZP_\lambda + m_\lambda^i \quad (2.6)$$

where m_λ^{SIRIUS} is the source magnitude in the IRSF/SIRIUS magnitude system and ZP_λ now is the combined term ($ZP_\lambda + c_1 \times X$).

I developed a code to automate the photometric calibration of the survey images. It relies on matching point sources in the image and the 2MPSC. Two sources were considered to be the same if they lie within a radius of $1''.35$ (3 pixels) of each other. Only stars flagged as having good photometric quality (AAA) and colour errors $(J - H)$, $(J - K_s)$ of $\epsilon \leq 0''.1$ in the 2MPSC (Cutri et al., 2006) were considered for the calibration.

The code was written as an IRAF procedure. This procedure uses the SExtractor algorithm ISOCOR (Bertin & Arnouts, 1996; Bertin, 1996; Holwerda, 1999) for finding the instrumental magnitudes of point sources in the images. SExtractor was also used to cross-identify sources in the NWS images, and the 2MPSC.

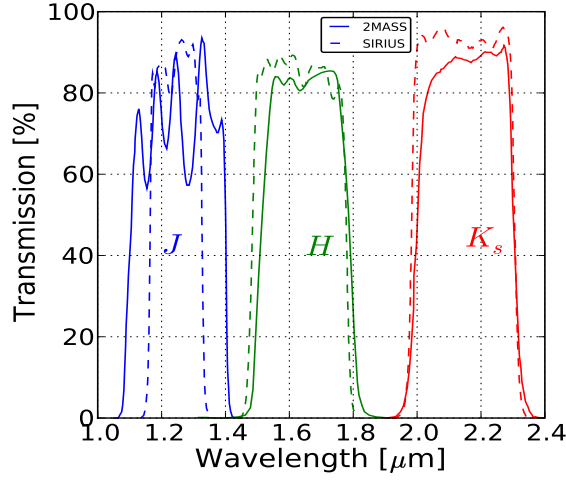


Figure 2.10: The 2MASS and SIRIUS colour filters transmission curves a function of wavelength. The 2MASS curves (Cutri et al., 2006) are shown with solid lines, the SIRIUS curves (Yasushi Nakajima; private communications) with the dashed lines. The displayed sensitivity curves do not account for the effect of other differences of the respective optical system.

For each matched pair, a value of ZP was calculated using Eqn. 2.6. On the average 10 star pairs/field were used for calculating the magnitude zero point in each image. The median value for all the pairs was hence determined and then written to the image fits header.

An aside on the ISOCOR algorithm The ISOCOR algorithm assumes that a source has a Gaussian light profile which is slightly distorted due to atmospheric seeing. The ratio between the flux within a threshold isophote I_{iso} to the total flux I_{tot} is then $\eta = \frac{I_{iso}}{I_{tot}}$, with η defined in Eqn. 2.7 (Bertin & Arnouts, 1996).

$$\eta \approx 1 - 0.1961 \frac{A \cdot t}{I_{iso}} - 0.7512 \left(\frac{A \cdot t}{I_{iso}} \right)^2. \quad (2.7)$$

Here A is the area within a threshold isophote t . The ISOCOR photometry was used for stellar magnitudes, since most of the galaxy light profiles are non-Gaussian.

2.3.4 Comparison with the 2MASS PSC

As a quality check of the calibration of the survey images I compared the positions and magnitudes of point sources that are found in both the NWS images and the 2MPSC. I report on the results of this comparison in the following two sections. Magnitude and position information for point sources in the survey images were found using SExtractor. The cross-identification of sources in 2MPSC and the NWS images was also performed using SExtractor. Two sources

were considered to be the same if they lie within a radius of $0''.45$ (1 pixel) of each other. Again only 2MPSC sources flagged as having good photometry (AAA) were used for the comparison. The comparison was made for the 2712 fields covering the NWS survey area.

Astrometry

The astrometric quality of the survey images is demonstrated by calculating the offsets in RA and Dec using Eqns. 2.8 and 2.9 for a subset of the correlated point sources.

$$\Delta\text{RA} = \text{RA}_{\text{NWS}} - \text{RA}_{\text{2MPSC}} \quad (2.8)$$

$$\Delta\text{Dec} = \text{Dec}_{\text{NWS}} - \text{Dec}_{\text{2MPSC}}. \quad (2.9)$$

Only sources with a FWHM $\leq 3''.15$ in the NWS images were used for the astrometric comparison. The number of cross-correlated pairs that satisfy this criteria and were used for the comparison were 949157. Table 2.5 lists the mean values for ΔRA and ΔDec with their respective standard deviations σ , and the number of pairs that were used for the comparison. The table also lists the standard error $SE = \sigma/\sqrt{N}$. The offsets and standard deviations listed in Table 2.5 are comparable to those quoted for the astrometric quality of the 2MPSC, see Sect. 2.3.1, and Cutri et al. (2006). These offsets are displayed in Fig. 2.11 where I plot ΔRA on the abscissa and ΔDec on the ordinate. The distribution density is colour coded as a function of $\log(N)$ where N is the number of data points in a unit area around the point (x_i, y_j) . The distribution in Fig 2.11, and the offsets of $\langle \Delta\text{RA} \rangle$ and $\langle \Delta\text{Dec} \rangle$ listed in Table 2.5, demonstrate that there are no systematic shifts in the position of point sources in our images. The circular shape characterizing the distribution is due to the imposed limiting radius of $\leq 0''.45$ used in the cross-correlation of the NWS and 2MPSC sources.

Table 2.5: Astrometric comparison for point sources in 2MASS with the NWS images.

Bandpass	$\langle \Delta\text{RA} \rangle$ $1'' \times 10^{-4}$	σ $1'' \times 10^{-2}$	SE $1'' \times 10^{-5}$	$\langle \Delta\text{Dec} \rangle$ $1'' \times 10^{-3}$	σ $1'' \times 10^{-2}$	SE $1'' \times 10^{-5}$	No. of pairs
<i>J</i>	4.9	8.9	9.3	1.5	9.3	9.7	949157
<i>H</i>	3.4	8.8	9.2	1.5	9.0	9.4	949157
<i>K_s</i>	3.6	8.4	8.7	1.2	8.7	9.0	949157

Photometry

For the photometric comparison, I determined the magnitude shift Δm_λ for a subset of stars found in both the NWS images and the 2MPSC. The magnitude shift Δm_λ is defined as,

$$\Delta m_\lambda = m_{\text{NWS}} - m_{\text{2MPSC}}, \quad (2.10)$$

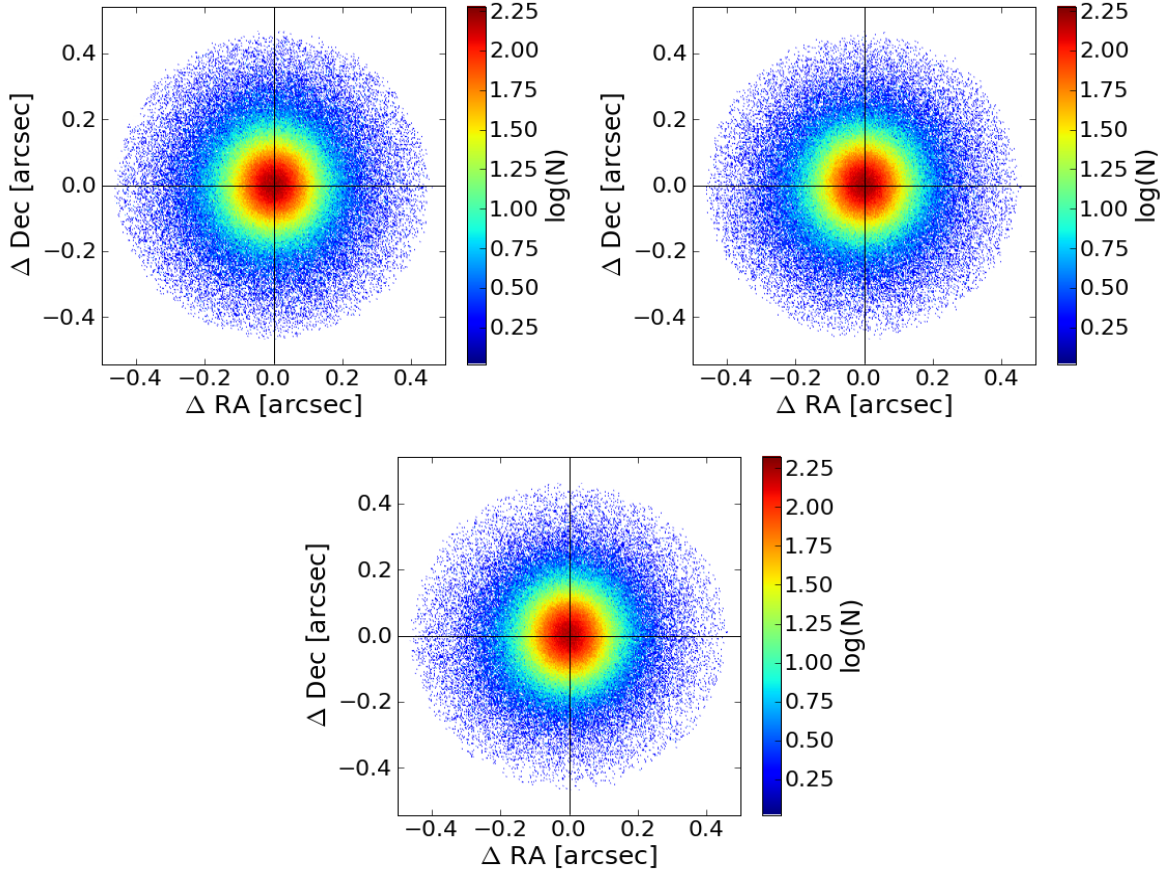


Figure 2.11: Astrometric comparison for point sources in 2MASS, and our survey. Top left: J band, top right: H and bottom K_s band. The circular shapes in the above distributions are due to the imposed correlation radius of $\leq 0''.45$ between the NWS survey images and 2MASS survey.

where m_{NWS} is the magnitude of the point sources as derived from the survey images by SExtractor and m_{2MPSC} is the magnitude of the matched source in the 2MPSC. The 2MPSC magnitudes were transformed to the NWS magnitude system using Eqn. 2.5 before being used for the comparison.

A pair in 2MPSC and NWS were selected to have a magnitude error $\epsilon \leq 0^m.04$ in the 2MPSC, while the NWS source was required to have a J band PSF with a $\text{FWHM} \leq 3''.15$ and not to be flagged by SExtractor as saturated or severely contaminated by a neighbouring sources. The number of pairs that satisfy this criteria is $N = 239731$. They were hence used for the comparison.

The SIRIUS magnitudes show a negligible mean offset of $\Delta m_J = -0.003 \pm 0.102$ mag in the

J band, $\Delta m_H = 0.001 \pm 0.099$ mag in the H band and $\Delta m_{K_s} = -0.007 \pm 0.126$ mag in the K_s band. The mean offsets, standard deviation, standard deviation error and the number of stars pairs that were used for this comparison are listed in Table 2.6.

Table 2.6: Photometric comparison of point sources in 2MASS with the NWS.

Bandpass	$\langle \Delta m \rangle$ [mag]	σ [mag]	SE [mag]	No. of pairs
J	0.0030	0.1028	0.0002	239731
H	0.0014	0.0993	0.0002	239731
K_s	-0.0071	0.1257	0.0003	239731

The uncertainties are illustrated in Fig. 2.12 (left panel) where I plot the magnitude shift Δm on the ordinate and the source magnitudes (NWS magnitudes) on the abscissa. On the same figure (right panel) I display the combined errors ($\sigma_{NWS} + \sigma_{2MPSC}$) for the points used in the comparison.

Even though the overall distribution in Fig. 2.12 has a negligible magnitude offset (see Table 2.6) it is evident that the bulk of the stars have systematic non-zero magnitude offsets. These offsets are marked in the distribution in Fig. 2.12 by the horizontal dashed lines. To investigate this systematic offset for the bulk of the star pairs, the pairs with magnitude shifts larger than $|\Delta m| > 0^m.3$ were excluded and the mean value for the clipped stars pairs was calculated. The mean magnitude offsets for the clipped sample is $\Delta m_J = 0.0452$ in the J band, $\Delta m_H = 0.0431$ in the H band and $\Delta m_{K_s} = 0.0561$ in the K_s band i.e. sources magnitudes derived from the survey images are fainter than their 2MASS counterparts. This is due to the photometric calibration algorithm being skewed by sources that had quite a large magnitude offset and were used to calculating the magnitude zero point. To correct for this artificial bias, the offset seen in the majority of the stars are subtracted from the sources magnitudes calculated by SExtractor.

Two further features are apparent on the Δm distribution: a small number of bright stars with very large negative errors and the bulgy shape of the distribution on the lower part of the plot. The first was found to be due to these stars being close to a saturated star or a spike from a saturated star. The latter is partially an artifact of the selection criteria applied to the comparison sample. The clear bias towards finding more stars in the NWS that are brighter than their 2MPSC counterparts is because of the increased depth of the NWS compared to 2MASS and hence the increased contamination from the very faint stars in the NWS images that are not deblended by the SExtractor algorithm.

2.3.5 Quality control

The photometric and seeing conditions can change significantly during observations. This implies that not all fields are observed under the same conditions. The FWHM of point sources was

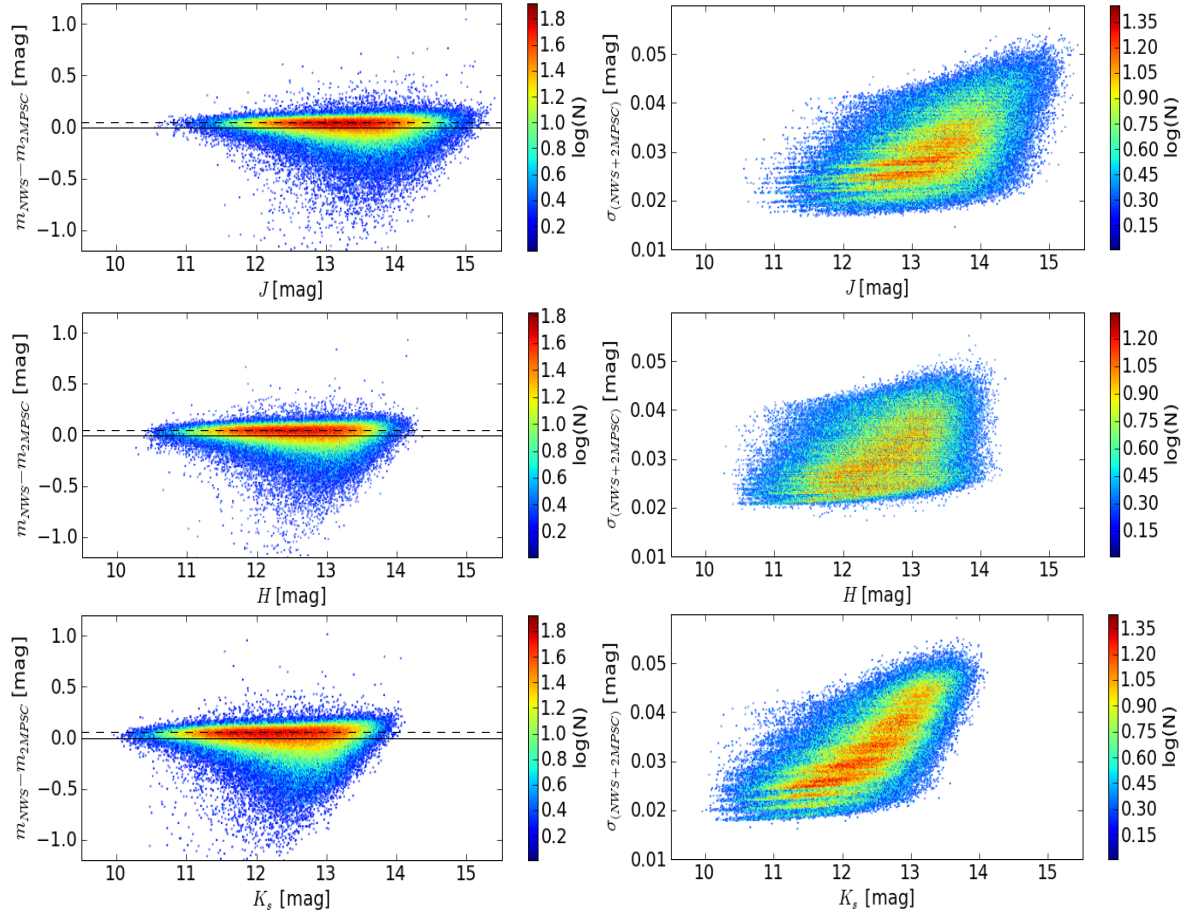


Figure 2.12: Photometric comparison for point sources in 2MASS, and NWS survey images. Left panel: the magnitude shift in the J , H and K_s bands. Systematic shifts of $0^{\text{m}}0452$ in the J band, $0^{\text{m}}0431$ in the H band and $0^{\text{m}}0561$ in the K_s band are shown on the plots as the horizontal dashed lines. Right panel: the combined magnitude error ($\sigma_{\text{NWS}} + \sigma_{\text{2MPSC}}$). The horizontal linear features that are seen on the combined error plots are an artifact of the 2MPSC accuracy being limited to $\pm 0^{\text{m}}001$.

therefore constantly checked to ensure that the seeing was always better than $\text{FWHM} \approx 2''.0$ (4.44 pixels). The photometric conditions were equally monitored and observations aborted when either the seeing or the weather conditions deteriorate. The final images therefore generally have good photometric and seeing conditions. Fields with bad image quality due to detector problems or image read-out failures were removed and marked for re-observation.

The quality of the final calibrated images was measured. Only fields with good photometric conditions and seeing better than $2''.1$ were accepted for further analysis. I used the value of the magnitude zero point as a measure of the photometric conditions. All images with a ZP_λ within a value $< ZP_\lambda^L > \pm 2\sigma_\lambda^L$ were considered to be photometric. The values for $< ZP_\lambda^L >$, and $2\sigma_\lambda^L$ were derived from the fields observed in 2006 and 2007. All fields observed in those two years were checked visually to remove fields that showed poor image quality or seeing of $\text{FWHM} \geq 2''.1$. The mean ZP , $< ZP_\lambda^L >$, and standard deviation $2\sigma_\lambda^L$ for these fields was then used to check the photometric quality for the survey images. Images that did not meet these criteria were re-observed.

Table 2.7 and Fig. 2.13 shows the distribution of the seeing and magnitude zero point with their respective standard deviation (σ), and standard error SE for the final 2712 images in the NWS.

Table 2.7: Mean magnitude zero point $< ZP >$, and seeing for the final 2712 survey images.

Band	$< ZP >$ [mag]	σ [mag]	SE [mag]	Seeing ["]	σ ["]	SE ["]
<i>J</i>	20.857	0.065	0.001	1.49	0.27	0.01
<i>H</i>	21.040	0.063	0.001	1.45	0.25	0.00
<i>K_s</i>	20.260	0.066	0.001	1.38	0.21	0.00

The slight shift in the seeing distribution in the *J* and *H* band towards the right (see right panel of Fig. 2.13) compared to the *K_s* band is due to the relative sensitivity of both bands compared to the *K_s* band.

The mean magnitude zero points for the NWS images were found to be consistent with earlier values determined by Cluver (2009) in previous observations with the IRSF using an identical imaging setup. Even though the values for the NWS and those found by Cluver (2009) agree well within their respective error bars, it is apparent that all the NWS values are systematically fainter. This is illustrated in Figure 2.14, which shows the mean magnitude zero point for the NWS (circles) and the values from Cluver (2009) (diamonds).

This systematic shift is presumably due to the variation of the reflective power of the telescope. The time variation of the magnitude zero point and its correlation with reflective power of the telescope is analysed further in Appendix B.

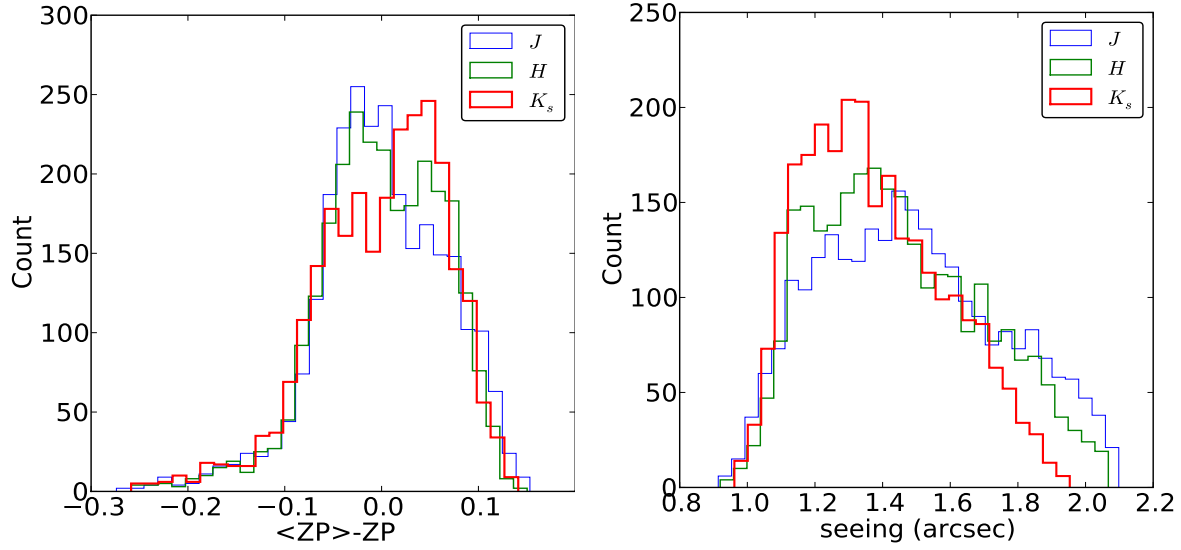


Figure 2.13: Histograms of $\langle ZP \rangle$ (left) and seeing (right) for all 2712 survey images.

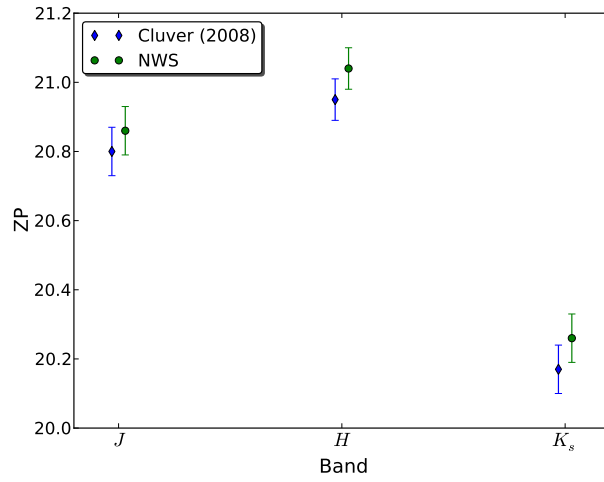


Figure 2.14: Mean magnitude zero point for the three NIR bands J , H , K_s for the NWS images (circles), and values calculated by Cluver (2009) (diamonds). The values are comparable within their respective error bars but the NWS values are systematically fainter.

2.3.6 Internal photometric comparison

To check the internal consistency of the calibrated images, I used stars that were present on the overlapping borders of adjacent fields. Strips of constant RA randomly distributed over the survey region were checked for stars common to more than one field. Hundreds of stars in each field overlap with neighbouring fields. To keep their numbers to a reasonable size, but still have a statistically sound sample, stars with a SExtractor stellarity index ≥ 0.98 that are neither flagged as saturated nor affected by the edge of the field in any of the three bands were considered for the investigation. Sources were considered to be identical if they lie within a radius of $0''.4$ of each other in all three bands. The number of analysed pairs was $N = 27087$ in 267 fields.

The magnitude comparison was achieved by calculating $\Delta m_\lambda = m_\lambda - m_{\lambda(SUR)}$, where m_λ is the source magnitude in one field, and $m_{\lambda(SUR)}$ its magnitude in a surrounding field. For the magnitude comparison, I used selected sub-sets from the total sample of $N = 27087$ correlated pairs. Stars were selected such to have reliable photometry in all J , H and K_s bands, i.e. not to have zero or negative $(J - H)$, $(J - K_s)$ colours, and to not be flagged by SExtractor as unreliable.

In Figure 2.15 (left panel) the distribution in Δm_λ is shown as a function of the source magnitude. Table 2.8 lists the absolute median $|\Delta \widetilde{m}_\lambda|$, mean $\langle \Delta m_\lambda \rangle$, standard deviation σ , and standard error SE . Only the absolute values are given here, as the direction of the shift is not relevant.

Table 2.8: Internal consistency, using multiply detected stars in overlapping fields.

Band	$ \Delta \widetilde{m}_\lambda $ [mag]	$ \langle \Delta m_\lambda \rangle $ [mag]	σ [mag]	SE [mag]	N
J	0.005	0.018	0.122	0.001	15080
H	0.004	0.001	0.074	0.001	15166
K_s	0.005	0.010	0.098	0.001	15099

The larger scatter for the fainter stars can be attributed to the increase in combined magnitude errors σ_λ for the fainter stars (see the right panel of Fig. 2.15). This comparison should give an upper limit to the uncertainties given that stars close to the edge of the field are expected to have the magnitudes with the least uncertainty due to the decrease in the signal-to-noise ratio at the edges of the field.

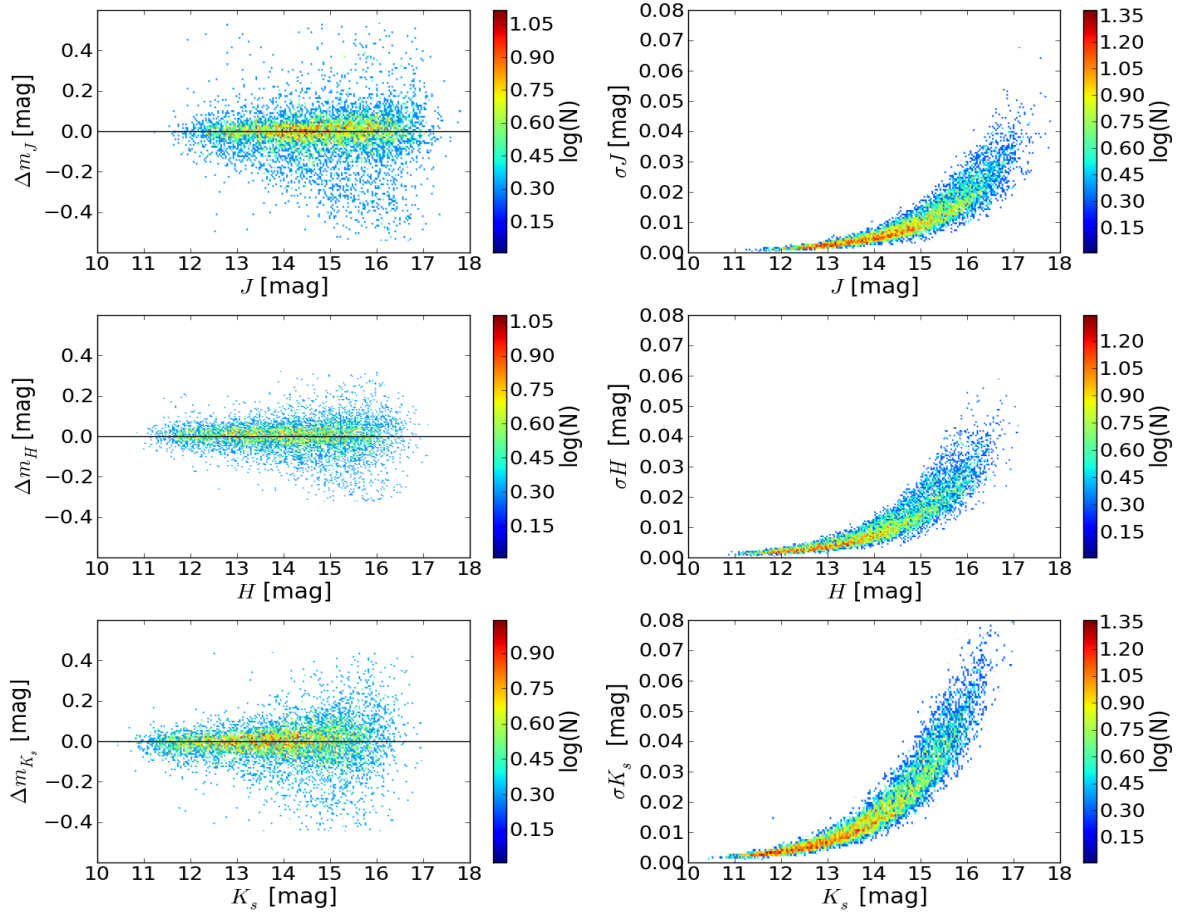


Figure 2.15: Internal magnitude consistency for stars multiply observed on adjacent fields. Left: magnitude comparison for J (top), H (middle) and K_s (bottom); right: combined error.

3

The galaxy catalogue

This chapter presents the steps, procedures and algorithms that were undertaken to identify, parametrize and catalogue galaxies on the NWS images. The reliability of the star-subtraction procedure that was used to remove light contamination from the detected galaxies is discussed in Sect 3.1.3. Particular emphasis is given in Sect. 3.2 to the description of the various derived parameters.

The final catalogue of 4630 galaxies is introduced in Sect 3.3. This is followed by an analysis of the quality of these parameter 3.3.2. Galaxies in this catalogue had a position reliability of $\Delta\text{RA}=0.009 \pm 0.202$ arcsec and $\Delta\text{Dec}=0.003 \pm 0.202$ arcsec. While they showed an isophotal magnitude reliability of $J_{iso} = 0.012 \pm 0.009$ mag.

A photometric and astrometric comparison between galaxies in the final catalogue and their counterparts in the 2MASX is given in Sect 3.3.2.

3.1 Galaxy cataloguing

The task of producing catalogues from survey images requires the identification, classification, and extraction of parameters for the sources in the images. For large surveys, where the sheer volume of data prohibits individual measurements of the parameters, this process has to be automated.

Several attempts have been made in this regard, for example FOCAS (Jarvis & Tyson, 1981), COSMOS (Beard, MacGillivray & Thanisch, 1990) and SExtractor (Bertin & Arnouts, 1996). These procedures implement different algorithms for identifying, deblending overlapping objects

and segregating fluxes of the different sources. The classification of objects into point sources (stars) or extended sources (galaxies) is achieved by looking at object parameters like Point Spread Function (PSF), light profiles and colour. Different algorithms and implementations use different sets of parameters.

I have adopted a method that utilizes SExtractor to classify sources as stars or galaxies. SExtractor (Bertin & Arnouts, 1996; Bertin, 1996) uses neural network algorithms (Wasserman, 1989; Beale & Jackson, 1990; Lahav, 1994) for this discrimination. The neural network algorithms assume that source parameters like the PSF, ellipticity, colour and others form a vector space in which stars and galaxies show different projections. The efficiency of neural network algorithms improves with training on different sets of galaxies and stars iteratively, refining the recognition pattern.

For observations at high Galactic latitude ($|b| \geq 30^\circ$), it is fairly straightforward to identify and classify objects as they are relatively isolated from neighbouring sources. The closer the field is to the Galactic Plane, the more complicated the process of deblending neighbouring sources from each other becomes especially for very faint blended sources. There the reliability of the automated algorithms degenerates (see Fig. 3.1, reproduced from Beard, MacGillivray & Thanisch 1990), leaving the identification/classification by eye the best choice. The plot shows the success rate as a function of Galactic latitude and stellar density for the automated identification of galaxies using the COSMOS (MacGillivray & Stobie, 1984) automation with and without a crowded field algorithm. COSMOS is a plate measuring machine/algorithm for identifying, classifying and extracting information of stellar and galaxian objects on photographic plates (Beard, MacGillivray & Thanisch, 1990). The crowded field algorithm was introduced to improve its performance in crowded fields (see discussion in Beard, MacGillivray & Thanisch 1990). On the abscissa they plot the stellar density around the object that was identified (lower axis) which they then correlate as a function of Galactic latitude (top axis). On the ordinate they plotted the success rate of the COSMOS algorithm to detect galaxies in crowded fields. It is obvious from the plot that the success rate for the COSMOS algorithm is $\gtrsim 90\%$ with and without the COSMOS crowded field algorithm for regions with an object density $\lesssim 30/\text{arcmin}^2$, i.e for Galactic latitudes $|b| \geq 30^\circ$. But it starts to fall rapidly for lower Galactic latitudes and higher stellar densities even when applying the COSMOS crowded field algorithm.

3.1.1 Galaxy identification

For the Norma Wall survey, I used a set of parameters extracted by SExtractor to semi-automate the process of galaxy identification.

In this process, SExtractor was first run on each J , H , K_s image, to produce a list of all the detected sources in each image (stars+galaxies). SExtractor reports an object's classification with the parameter "stellarity index". This parameter takes values between 0 and 1. For 1 the object is a clear point source, while 0 indicates an extended object. The reliability of the

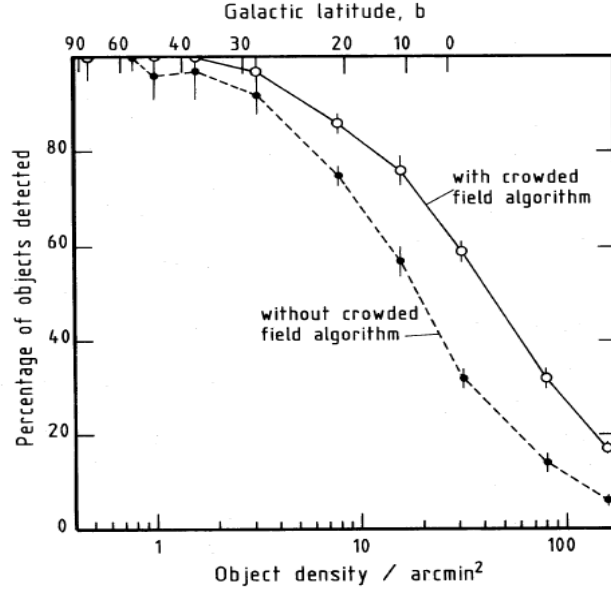


Figure 3.1: Simulating the performance of star/galaxy separation by COSMOS in the B band as a function of object density and Galactic latitude. Figure taken from Beard, MacGillivray & Thanisch (1990).

stellarity index decreases for fainter sources and in crowded fields.

Based on this list, I classify sources as galaxies if they have a stellarity index $SI \leq 0.1$, are brighter than $m_J < 18^m.5$ with a radius $R_J > 2''.3$ in the J band, and are detected in at least the J and H band. An object was also classified as a galaxy if it was only detected in the J band, has a stellarity index $SI \leq 0.1$ but was brighter than $m_J < 14^m.5$ and larger than $R_J > 4''.5$. The J band was chosen to be the preferred band because I noticed during the development time of the galaxy identification algorithm that SExtractor finds more potential sources/galaxies in this band than in the H and K_s bands. A similar deduction was made by Kraan-Korteweg & Lahav (2000) and Schröder et al. (2007) (see their figure, reproduced here in Fig. 3.2). The plot shows the performance of the NIR DENIS bands (left) and the 2MASS bands (right) as compared to the optical B band as a function of Galactic extinction A_B . Both plots shows that the NIR bands is better than the optical B band in regions of increased extinction with the J band better in the extinction range $A_B \lesssim 12^m.0$ for DENIS J band and $A_B \lesssim 4^m.0$ for the 2MASS. The K_s band performed better for extinction levels of $A_B \gtrsim 12^m.0$ for DENIS and $A_B \gtrsim 4^m.0$ for 2MASS.

The survey images were inspected visually by displaying a colour composite in DS9¹. SAOImage DS9 is an astronomical imaging and data visualization application. Galaxy candidates were

¹This research has made use of SAOImage DS9, developed by Smithsonian Astrophysical Observatory.

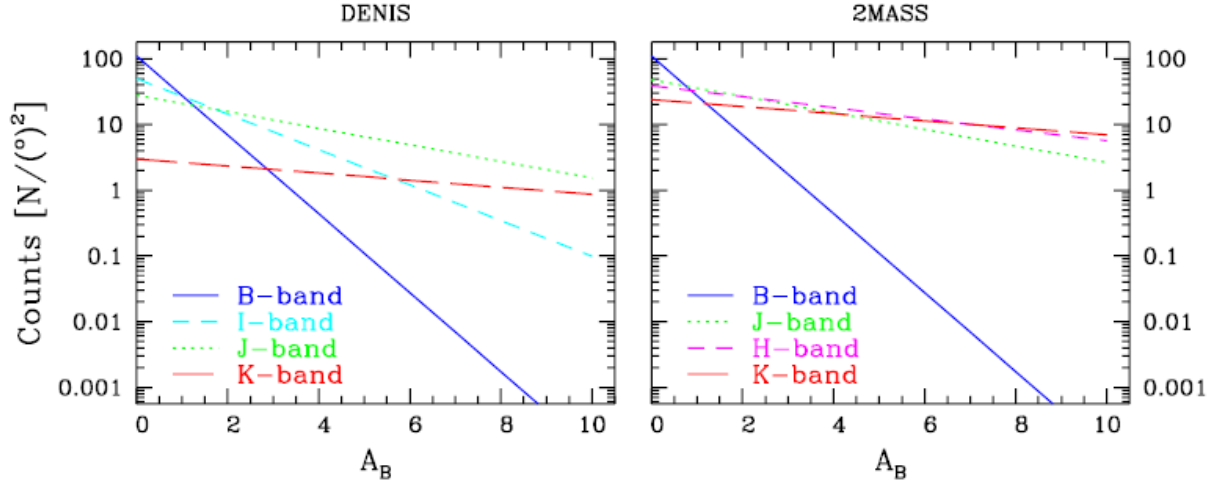


Figure 3.2: Galaxy counts for DENIS (left) and 2MASS (right) survey bands (plots are taken from Kraan-Korteweg & Lahav 2000).

assessed on their colour (they are redder than stellar sources in the images), light distribution, extent, bulge and disk features. Misidentified objects were removed, and missed galaxies added to the galaxy list.

The lists of galaxies compiled by me, were checked independently by our collaborators, Prof. Ken-Ichi Wakamatsu and Dr. Takahiro Nagayama, to confirm the entries in the list. They also examined all the images, and galaxies that went missing in the first check were added. This minimizes the subjective bias in the process of galaxy finding.

The pre-processing of the images with the galaxy identification code before the visual inspection is estimated to have reduced the overall time by 50-60% compared if galaxies were identified only visually.

A preliminary list of 5327 galaxies with their position, magnitude and size was produced. This list was later used for proper photometry and astrometry of the galaxies. In the following sections I will describe how these parameters were determined.

3.1.2 Star-subtraction

To obtain reliable photometry for a galaxy in an image, all the flux belonging to that galaxy must be accounted for while contributions from other sources must be excluded. For sources that are detected far from the GP ($|b| \geq 30^\circ$), contamination to the source flux is minimal as the sources are generally isolated. However, close to the GP, the stellar density increases rapidly resulting in an increase in contamination from nearby or overlapping sources.

This is illustrated by Fig. 3.3 from Jarrett et al. (2000a) who studied this effect for 2MASS.

The plot displays the stellar density on the abscissa and the Galactic latitude $|b|$ on the ordinate (left axis) for two regions along the GP at $\ell = 30^\circ$ and $\ell = 130^\circ$. They also plot the increase in the sky background due to confusion by the surrounding stellar density (right axis). The definition for the confusion noise is given in Jarrett et al. (2000a). The plot (the hashed area) shows a tight correlation between the increase in confusion noise and the increase in stellar density.

In the right panel of Fig. 3.3, I plot the Galactic latitude $|b|$ on the abscissa, the stellar density on the ordinate (left axis), and the mean distance between sources (prox) on the (right axis). Data for this plot are taken from the 2MASX. The plots shows the strong tie between the decrease in distance between sources and the increase in stellar density. Objects at low Galactic latitudes are closer to each other than those at higher Galactic latitude as a direct result of the increase in the stellar density close to the GP.

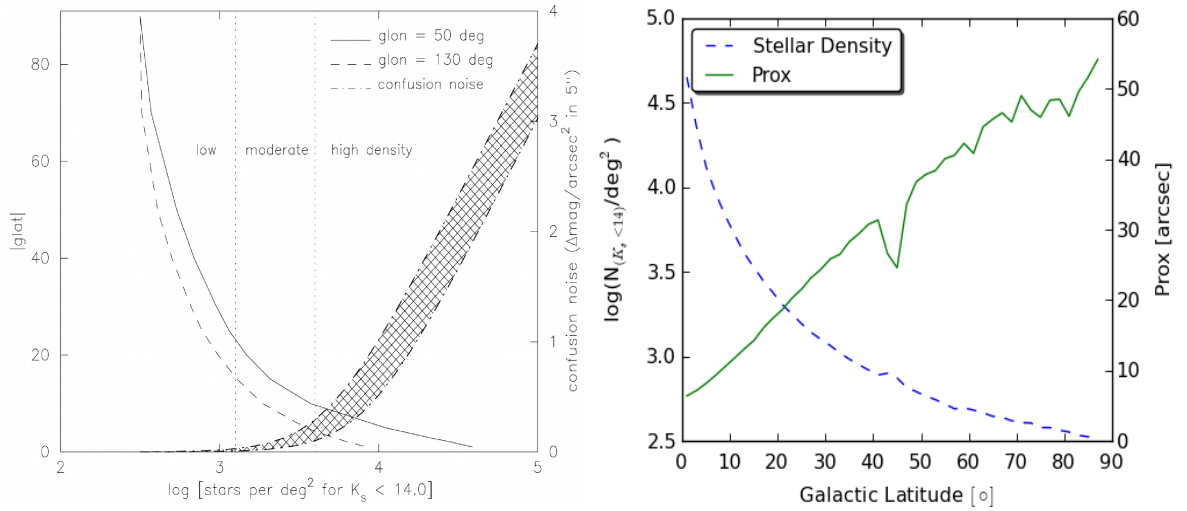


Figure 3.3: Left: variation in stellar density and stellar confusion with Galactic latitude (Jarrett et al., 2000a). Right: distance to nearest neighbour (prox) derived from the PSC (for stars of $14^m0 < m_J < 14^m1$) and stellar density as a function of Galactic latitude overlaid.

The increase in stellar density affects galaxy photometry two-fold. Firstly, through the light from nearby or overlapping sources as they blend with the galaxy. This makes it difficult for SExtractor to fully recover and isolate the flux of the galaxy of interest. Secondly, light from stars in the field raises the sky background level and hence the background noise, making it more difficult to detect the faint low surface-brightness galaxies. This increase in the sky background noise also results in galaxies appearing smaller than they really are.

Figure 3.4 shows a simulation for the effect of star crowding on galaxies. The top left panel shows the central region of the Hydra cluster (Abell 1060) centered at $\ell = 269^\circ63$ and $b = +26^\circ51$. The right panel shows the Hydra field overlaid with a crowded field observed at

$\ell = 309^\circ 5$, $b = +1^\circ 78$. The stellar density in the field is $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.64$. The sky-noise in the original images was $\text{rms}_J = 2.05$ ADU, $\text{rms}_H = 4.03$ ADU and $\text{rms}_{K_s} = 5.69$ ADU, while it is $\text{rms}_J = 6.28$ ADU, $\text{rms}_H = 15.47$ ADU and $\text{rms}_{K_s} = 13.04$ ADU in the star crowded field. Galaxies identified on both images are marked with the yellow circles. Both the Hydra and the crowded field were observed by our collaborator Dr. Nagayama using the IRSF/SIRIUS. Figure 3.5 displays a zoom-in of galaxies that are found both in the original Hydra image and the artificially star crowded image.

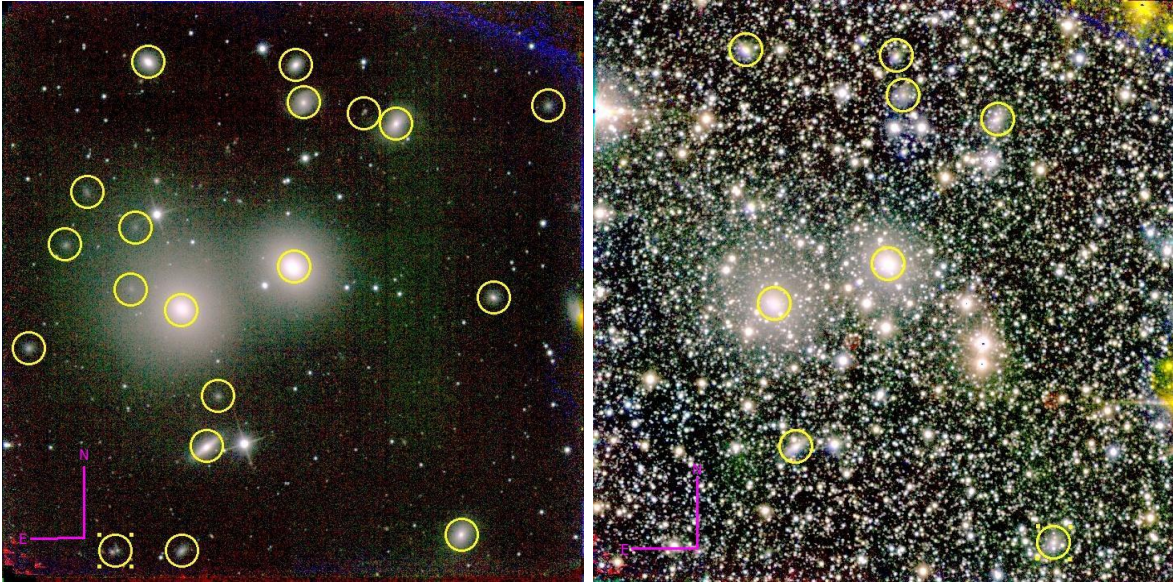


Figure 3.4: Left: The central region of the Hydra cluster (Abell 1060) at $\ell = 269^\circ 61$ and $b = +26^\circ 47$. Right: The image of the simulated field. The change in galaxies colours in the simulated field is an artifact of the overlay of the two images, which is due to the difference in the sky background and extinction levels between the fields. The images are $\approx 7'.8 \times 7'.8$

When comparing galaxies on the Hydra field with their counterparts on the artificially crowded field, it is apparent that galaxy size diminishes due to the increase in the stellar density. Some of the intrinsically small and faint galaxies are completely lost in the crowded field (the Hydra image and the simulated image will be used again in Sect. 3.1.3 to assess the performance of the star-subtraction procedure).

Because of the nature of our deep ZOA survey the stellar density unfortunately is very high. This is evident from Fig. 3.6 which shows the stellar density contour map in the survey region calculated from the NWS images.

Galaxy photometry derived from crowded fields is heavily contaminated by other sources. This holds unless images are treated to remove stellar sources from the images before galaxy photometry is performed. The term star-subtraction is used in the following for the algorithm



Figure 3.5: A zoom-in to galaxies that were found in both the Hydra and the simulated fields. The image size is $\approx 1'.75 \times 1'.75$.

and code I use to remove stars from the images. The star-subtraction algorithm and code were developed by my collaborator Dr. Nagayama.

The procedure progresses in two steps: the first creates an average PSF for point sources in the field, it then uses this PSF to remove stars in the neighbourhood of the detected galaxies. The following sections will give more details about the star-subtraction process including a qualitative assessment of the process.

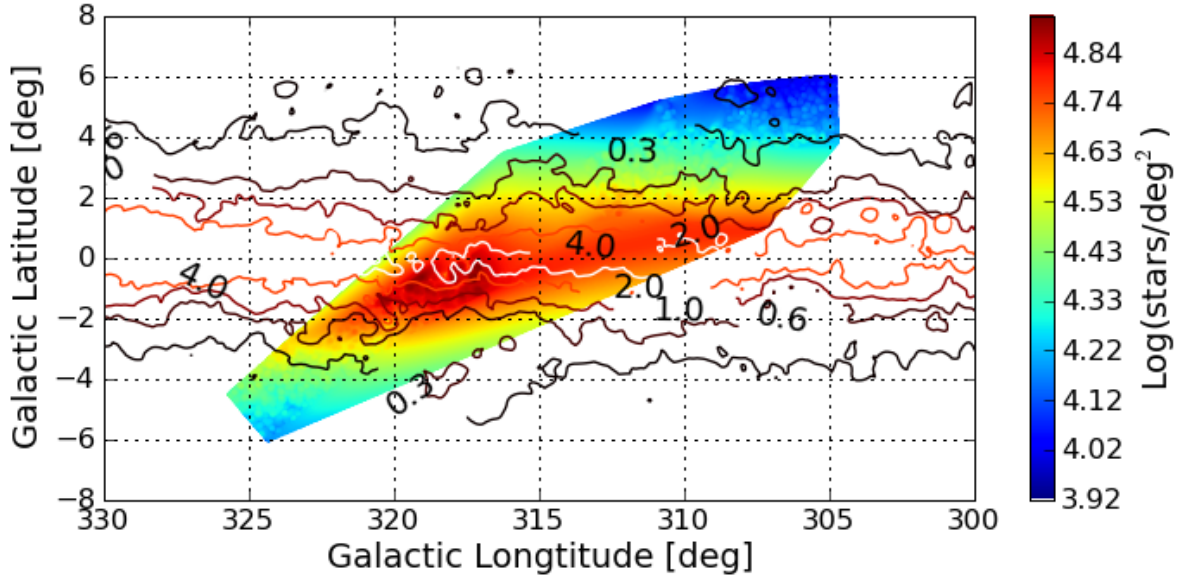


Figure 3.6: Distribution of stellar density $\log(N_{(K_s < 14)}/\text{deg}^2)$ for the Norma Wall survey region calculated from the NWS images. Superimposed are contours of constant Galactic extinction $A_{K_s} = 0^m3, 0^m6, 1^m0, 2^m0$ and 4^m0 . The stellar density in the region $|b| \lesssim 1^\circ$ as the stellar density in this region might be affected by the increased dust extinction in the region. Furthermore, for regions where we do not have data points (region not covered by the NWS survey footprint) the values shown in the plot are extrapolation from neighboring points.

Average PSF

Point sources are characterized by their Gaussian-shaped light profile or PSF. While only the amplitude of the PSF depends on the source, the shape only depends on the instrument that was used for observation. The shape of the PSF is sensitive to variations in the seeing conditions, which may result in a distortion of the Gaussian symmetry. The PSF for saturated stars deviates significantly from the Gaussian profile. Hence, the PSF varies over the image. Using a selected set of point sources distributed over the whole image, an average PSF model can be built for stars in that image. To do this, the following algorithm was devised:

1. A maximum of 50 stars are selected such that they are unsaturated and with no sources closer than ($\leq 1''$) that may distort their PSF. While it seems preferable to use a larger exclusion radius than the currently implemented radius using a larger radius would result in a very small number of stars that could be modeled for their PSF. The exclusion radius of ($\leq 1''$) was found to result in a good number of stars for PSF modeling.
2. With this set of stars, an initial PSF is created. It is used to remove all the stars from the

original image, except for the PSF model stars.

3. The set of selected stars are again modeled with a new PSF for the star-subtracted image. This process minimises contamination to the PSF from other sources and results in an improved PSF model.
4. The updated PSF is again used to remove stars from the original image, leaving only the set of model stars. The selected stars in the new star-subtracted image are once more modeled for the creation of a final PSF.
5. The final PSF is written to a fits-file.

The final model PSF is then used to remove all the stars superimposed on the galaxy's image.

Star subtraction

To efficiently remove a star blended with or superimposed on a galaxy, while minimally distorting the galaxy's light profile and hence its magnitude, the following method was used:

1. Create a model for the galaxy using the *ellipse* and *bmodel* **IRAF** procedures; subtract the galaxy model from the image and produce a temporary galaxy subtracted image.
2. Use the galaxy subtracted image to obtain photometry for point sources within a box of pre-defined size around the galaxy. This photometry based on the average PSF is then used to remove stars from the original image. This results in a new image with stars removed on and around the galaxy.
3. Steps 1 and 2 are iterated five times. Each iteration leads to an improved galaxy model, and hence a more accurate photometry for the stars in the galaxy-subtracted image. These stars are again removed from the original image.

The above process requires extensive computing time. Therefore only a square of 200 pixels around galaxies with a radius of $R \geq 9''.0$, and 150 pixels for galaxies with a radius $R < 9''.0$ is cleaned. The effect of the number of iterations is not significant when comparing images side-by-side, but is noticeable when blinking the galaxy images on a screen. Because of that I will not display the various iterations. As an example Fig. 3.7 displays the original crowded image together with the star-subtracted image. This field is the same as in Fig. 3.4.

3.1.3 Star-subtraction performance

This section provides an assessment of the performance of the star-subtraction process based on the simulated Hydra cluster images by Nagayama. Figure 3.8 shows a zoom-in of the galaxies



Figure 3.7: Top left the central part of the Hydra cluster with a crowded field superimposed on it see Fig. 3.4. The same field after being processed with the star-subtraction process. Images are $\approx 7'.8 \times 7'.8$

that were found both in the original Hydra image and the artificially star crowded image. The third panel displays the galaxies after they were processed with the star-subtraction algorithm.

It is evident from these images that the algorithm manages to clean the stars from the galaxies fairly well. However, the cleaned galaxies appear smaller than the original galaxies. This is attributed to the increase in the sky background noise due to the stellar density in the field (see also the discussion in Jarrett et al. 2000a). The star-subtracted images also reveal that the star-subtraction algorithm does not remove saturated stars effectively. This is not unexpected as saturated stars are not well described by a symmetric Gaussian PSF. Another artifact is noted for galaxies **828** and **945**, namely the ring of dots around the core of these galaxies. These are due to false detections by the star-subtraction algorithm for regions around the very bright cores of luminous galaxies. It happens when bright galaxies are modeled for subtraction during the procedure. The residual flux of the galaxy-subtracted image is misidentified as point sources and subsequently removed. This affects only the very bright galaxies (brighter than $J_{Kron} < 12^m0$; $\approx 0.9\%$ of the galaxies in our catalogue).

In the following I present a comparison of the Kron photometry (Kron magnitude is a measure of the total magnitude, it can account for 94% of the total flux (Kron, 1980; Bertin & Arnouts, 1996; Jarrett et al., 2003); see Sect. 3.2) determined from the original Hydra image and the star-subtracted Hydra image. This comparison must be interpreted qualitatively. A quantitative

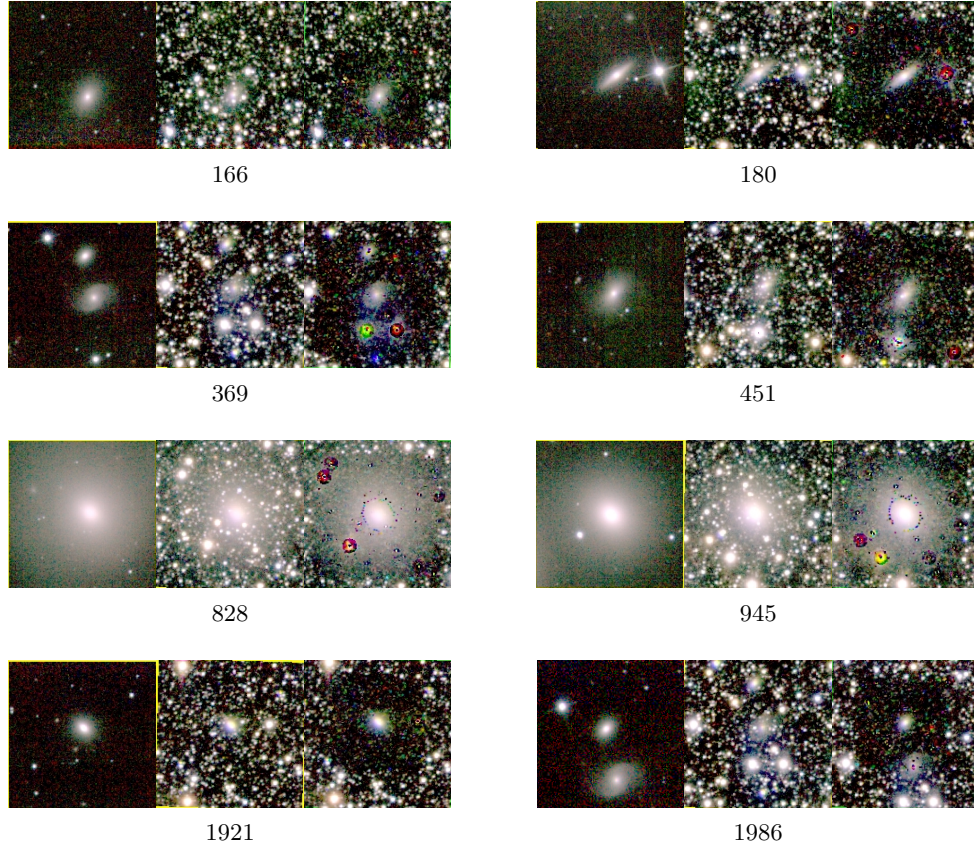


Figure 3.8: A zoom-in for galaxies detected in both the original Hydra image and the simulated image. Galaxies after being processed with the star-subtraction process are also shown. Left panel galaxies from original Hydra image. Middle panel galaxies simulated for star crowding. Right panel galaxies after being processed by the star-subtraction. The cutouts are $\approx 1'.75 \times 1'.75$.

comparison is difficult because the performance of the algorithm varies with size, brightness and inclination of the galaxy as well as the sky background noise and the stellar density in which it resides. The performance of the star-subtraction algorithm also depends on the photometric conditions and seeing for the field. Table 3.1 and Fig. 3.9 shows such a comparison between the original Hydra images and the star-subtracted images.

Table 3.1 lists the Kron magnitudes of the galaxies in the original Hydra image, Δm_λ (as the difference between the galaxy magnitude (Kron) in the original image and its magnitude in the star-subtracted image). The table also lists the flags (see Sect.3.2 and Bertin & Arnouts (1996); Bertin (1996)) as reported by SExtractor for the galaxies in both images, the left column is derived from the original image while the right column is from the simulated image. Figure 3.9 displays a plot of Δm_λ in the three bands J , H and K_s on the ordinate versus the Kron

The galaxy catalogue

magnitude in the J band (abscissa).

Table 3.1: Comparison of the Kron magnitudes of the galaxies measured in the original Hydra image and the simulated star crowded image.

Label	J	Δm_J	flags		H	Δm_H	flags		K_s	Δm_{K_s}	flags	
	[mag]	[mag]	org.	sim.	[mag]	[mag]	org.	sim.	[mag]	[mag]	org.	sim.
166	12.70	-0.249	3	3	11.94	-0.283	17	3	11.83	-0.261	3	3
180	12.22	-0.115	3	2	11.55	-0.163	3	2	11.33	-0.135	3	2
369	13.05	0.116	0	3	12.37	-0.122	0	3	12.26	-0.244	3	2
451	12.47	-2.192	3	23	11.79	-0.547	3	3	11.60	-0.945	2	3
828	10.08	-0.594	2	3	9.34	-0.200	2	3	9.12	-0.191	2	2
945	10.31	-0.449	3	3	9.57	-0.440	3	3	9.37	-0.386	2	3
1921	12.22	-0.045	2	0	11.50	-0.241	2	2	11.31	-0.121	2	0
1986	13.34	-0.023	0	2	12.58	-0.079	2	2	12.41	-0.185	2	2

The negative values of Δm_λ indicate that the galaxy is brighter in the original Hydra image. For the galaxy labels refer to Fig. 3.8. For the meaning of the above quoted flags see Sect.3.2 and also Bertin & Arnouts (1996); Bertin (1996).

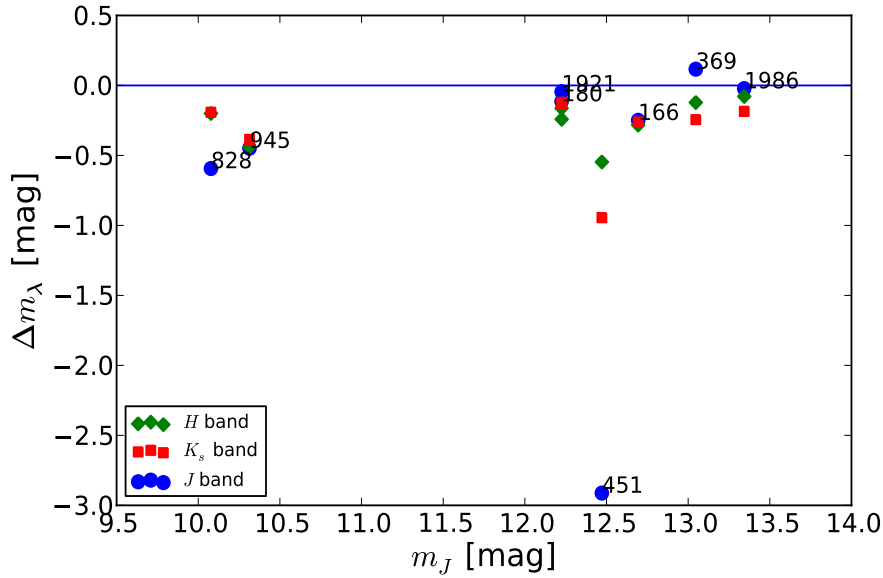


Figure 3.9: Comparison of Kron magnitude for galaxies in the original Hydra image and the simulated crowded image. The labels refer to galaxy identification as given in Fig. 3.8

The majority of the galaxies have a negative Δm_λ , i.e. they are brighter in the original Hydra image compared to their counterparts in the simulated image. This can be explained by the increase in sky-background, hence sky-noise, in the crowded fields causing galaxies to look smaller and fainter. Notable that the brightest ($J < 12$ mag) and hence the largest galaxies such as **828**, **945** show the larger deviations. This is because spatially extended galaxies are usually more contaminated by neighbouring sources than small galaxies.

The large offset of $\approx 0^m.5$ seen in the magnitudes for the galaxies **828**, **945** was investigated further. Looking at the star-subtracted images for these galaxies we could see that these galaxies had blended saturated stars (see Fig. 3.10), these stars were not properly removed by the star-subtraction algorithm.

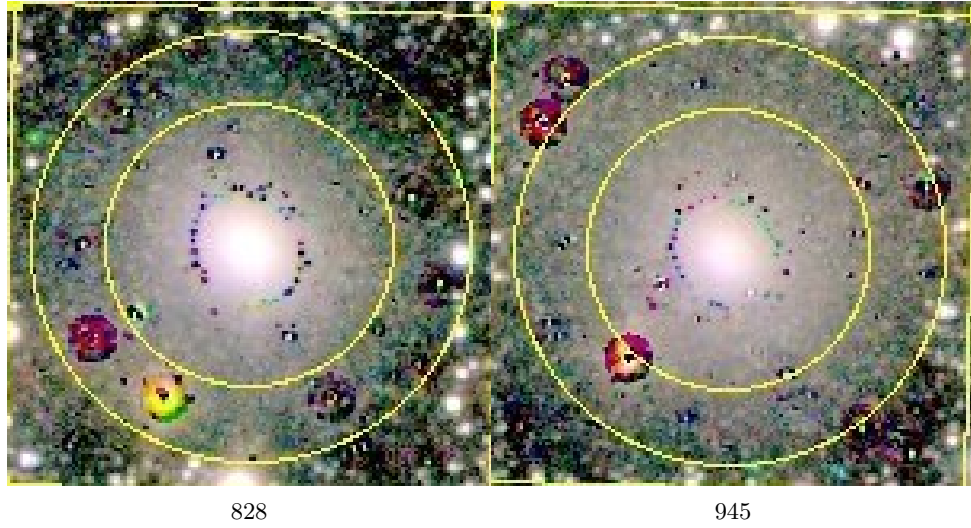


Figure 3.10: The two galaxies **828**, **945** having large magnitude offsets of $\approx 0^m.5$ between their original magnitudes and the star-subtracted magnitudes. Apertures of $R_A = 31''$ and $R_B = 47''$ are marked on the galaxy images. The cutouts are $\approx 1'.75 \times 1'.75$.

The effect of these stars on the offset seen for the two galaxies was gauged using two constant apertures of $R_A = 31''$ and $R_B = 47''$, these apertures are marked on Fig. 3.10. The magnitudes within $R_A = 31''$ were found to have an offset of $\approx 0^m.13$ in the three bands for the two galaxies **828**, **945**. These offsets jumped to $\approx 0^m.45$ for the magnitudes within the $R_B = 47''$ apertures. This analysis shows that the large offsets in the Kron magnitudes for galaxies **828**, **945** are due to the saturated stars blended with the original galaxies.

The above discussion represents an extreme case as only few of the NWS fields lie at such a high stellar density of $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.64$. The majority (83.7%) of the NWS images have a stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) < 4.64$ (See Fig. 3.11). Even in this extreme case, the photometry for galaxies with $J > 12$ mag is well reproduced ($|\Delta m| \leq 0^m.1$ for galaxies not

flagged by SExtractor as having unreliable photometry). In the whole survey area there are only 2 galaxies with $J < 12$ mag that are found in a region with $\log(N_{(K_s < 14)}/\text{deg}^2) > 4.60$. Figure 3.11 shows the distribution of the $\log(N_{(K_s < 14)}/\text{deg}^2)$ for images in the NWS (see also Fig. 3.20 which displays the distribution of galaxy count as a function of the stellar density).

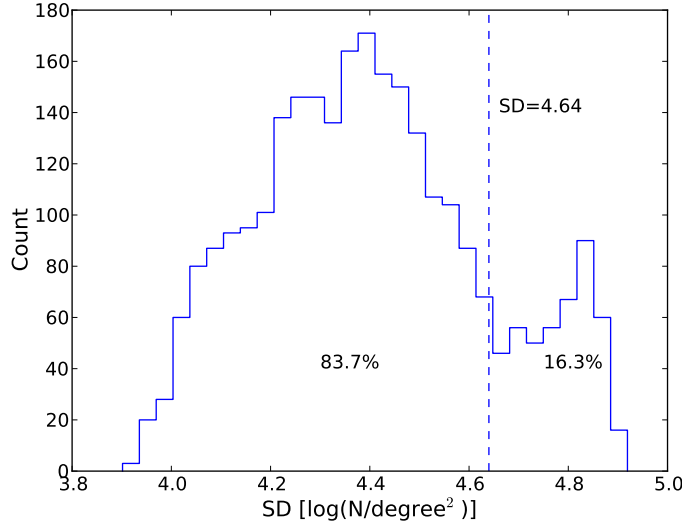


Figure 3.11: The distribution of $\log(N_{(K_s < 14)}/\text{deg}^2)$ for the NWS images. The vertical dashed line represents the stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.64$ in the artificially crowded image. The majority (83.7%) of the NWS images have a stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) < 4.64$.

To independently gauge the effect of the increase in the sky-noise on the resulting Kron magnitude for galaxies, I artificially added sky-noise to the original Hydra images using the **IRAF** *mknoise* procedure. Starting from the original J , H and K_s Hydra images, four new sets of images were created. The first set had a sky-noise of $\text{rms}_J = 3.74$ ADU in the J band, $\text{rms}_H = 4.94$ ADU in the H and $\text{rms}_{K_s} = 6.42$ ADU in the K_s . The values for the other sets are increasingly higher (see Table 3.2).

The original Hydra image and the four images with the increased sky-noise are shown in Fig. 3.12. It is evident from the images that galaxies in the fields with higher sky-noise appear smaller than their counterparts in the original image. It is also clear that some of the faint galaxies are now almost invisible because of the increase in the sky-noise.

This is quantified in Fig 3.13 where I plot the magnitude difference Δm_λ on the ordinate versus the Kron magnitude in the J band (abscissa). The magnitude difference Δm_λ is defined as the Kron magnitude in the original Hydra image minus the Kron magnitude for the same galaxy in the artificially increased sky-noise images. To keep the plot simple, I only show the magnitude difference in the J band. The two other bands (H and K_s) show very similar trends.

3.2 Catalogue parameters

Table 3.2: The table list the sky-noise for the original Hydra image, the artificially added sky-noise fields. For comparison the sky-noise for the simulated crowded field is given (last row).

Set	rms _{<i>J</i>} [ADU]	rms _{<i>H</i>} [ADU]	rms _{<i>K_s</i>} [ADU]
Original	2.05	4.03	5.69
1st	3.74	4.94	6.42
2nd	4.93	6.07	7.30
3rd	10.21	10.84	11.57
4th	12.38	12.92	13.54
Artificially crowded	6.28	15.47	13.04

The *J* band differences between the original image and the simulated crowded image are also displayed (yellow stars). Note that there are eight galaxies that were used to compare the effect of star crowding, while there were 11 used for the sky-noise comparison. This is because galaxies fainter than $m_J = 14^m0$ were not recovered in the star crowded-image. This decrease of the number of detected galaxies from 11 in the original Hydra image to 8 in the simulated crowded image gives a first indication of the effect of the increase of stellar density on the survey completeness limit.

This qualitative assessment of the influence of the sky-noise on the derived Kron magnitudes confirms our previous argument that magnitudes derived from the images with a high sky-noise are always fainter as compared to those in the images with a lower sky-noise and the fainter galaxies are the most affected.

3.2 Catalogue parameters

The galaxy parameters derived for the final galaxy catalogue range from astrometric to geometric and photometric. The astrometric parameters are the galaxy position in both Equatorial (J2000) coordinates and Galactic coordinates. The catalogued galaxy coordinates are derived from the *J* band image. In the case where a galaxy was not detected in the *J* band but is an unambiguous galaxy candidate in either the *H* or the *K_s* band, the position was obtained from either one of these bands.

The derived photometric parameters are the Kron magnitude (Kron, 1980) as a measure of the galaxy total magnitude. The magnitudes within a radius of 1'', 3'', 5'', 7'' and 10'' are also given. I also list the isophotal magnitude and central surface brightness. The photometric parameters are given for all three observed bands.

The geometric parameters that are included in the catalogue are the effective, Kron and isophotal radii, as well as ellipticity in the three bands, and the position angle in the *K_s* band.

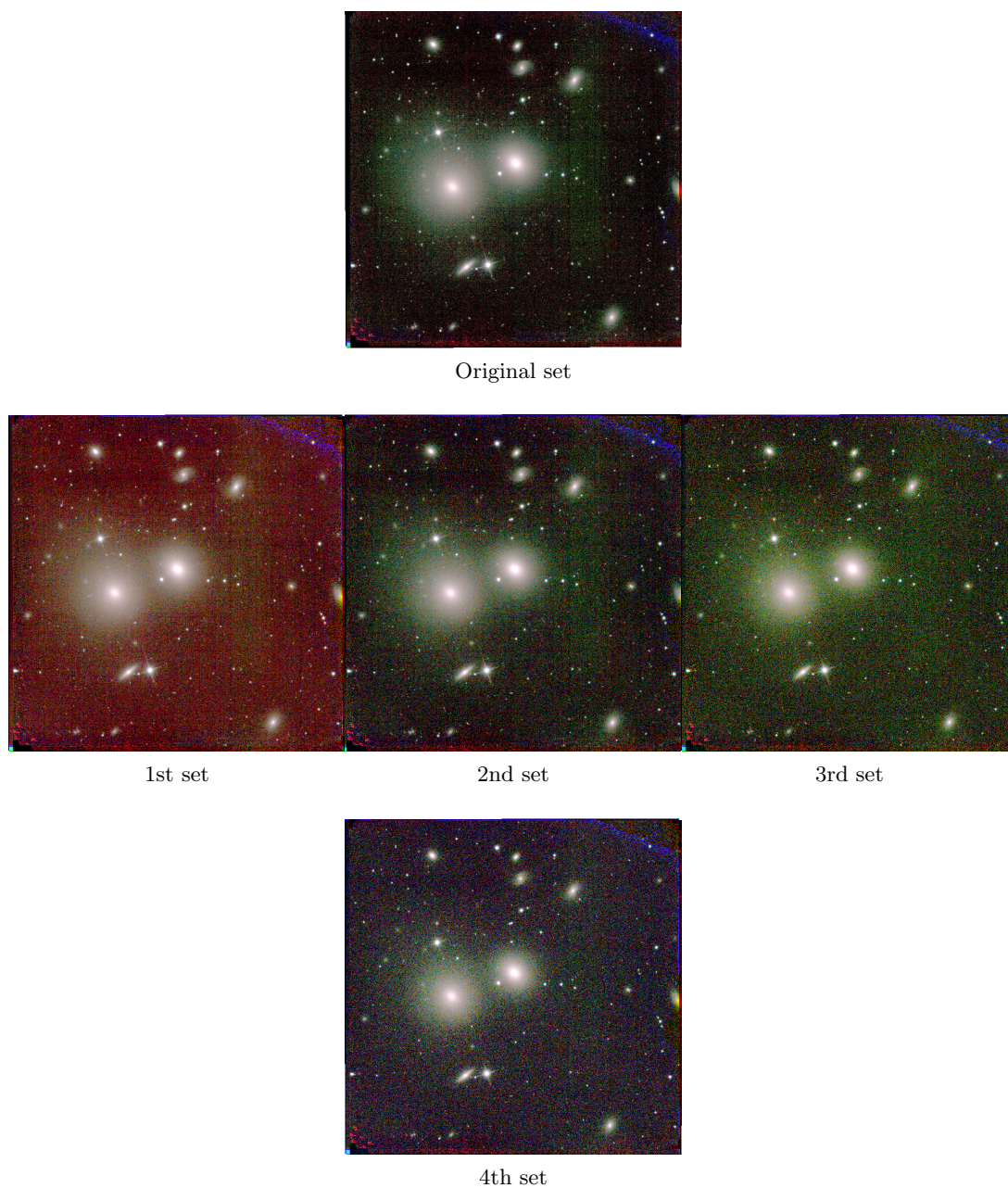


Figure 3.12: Top panel: the original Hydra image. Lower panels: the simulated images with added sky-noise in order of increasing sky-noise. Images are $\approx 7'.8 \times 7'.8$.

A crude classification of the galaxy's morphological type is also given. I only differentiate galaxies into early or late type. A complete list of all the parameters that are listed in the final catalogue is given below.

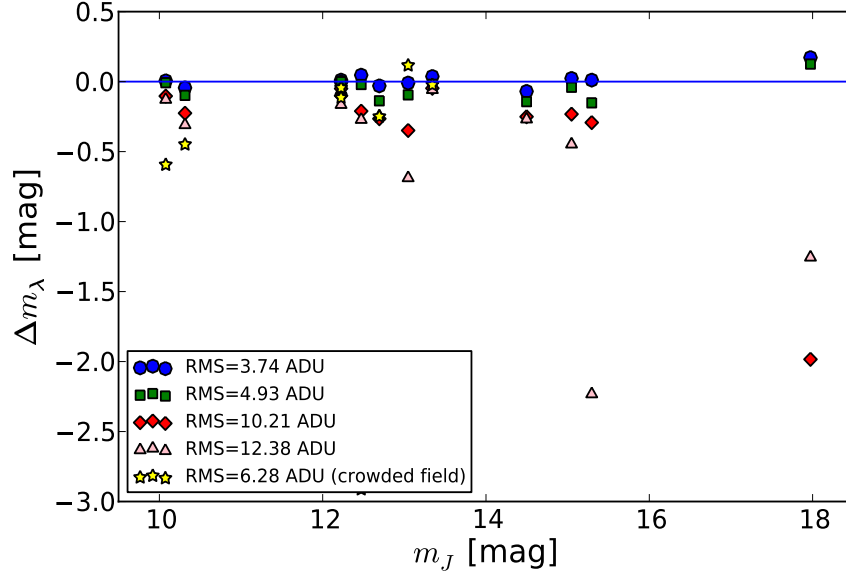


Figure 3.13: The effect of sky-noise on the galaxy magnitudes.

- ***Column 1:** A running label.
- ***Column 2:** Designation.
- ***Columns 3 & 4:** RA and Dec (J2000).
- ***Columns 5 & 6:** Galactic longitude and latitude.
- ***Column 7:** Galactic reddening along the line of sight (Schlegel et al., 1998).
- Column 8:** Stellar density for stars brighter than 14^m0 in the K_s band.
- Column 9:** Half light radius (arcsec) (J band)
- Column 10:** Kron radius (arcsec) (J band).
- Column 11:** Kron magnitude (J band).
- ***Column 12:** J_{21} isophotal radius (arcsec).
- ***Column 13:** J_{21} isophotal magnitude.
- ***Column 14:** J_{21} isophotal magnitude error.
- Column 15:** Error of the Kron magnitude (J band).
- Column 16:** 1'' aperture magnitude (J band).
- Column 17:** 3'' aperture magnitude (J band).
- Column 18:** 5'' aperture magnitude (J band).
- Column 19:** 7'' aperture magnitude (J band).
- Column 20:** 10'' aperture magnitude (J band).
- Column 21:** Error of the 1'' aperture magnitude (J band).
- Column 22:** Error of the 3'' aperture magnitude (J band).

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- Column 23:** Error of the 5'' aperture magnitude (J band).
Column 24: Error of the 7'' aperture magnitude (J band).
Column 25: Error of the 10'' aperture magnitude (J band).
Column 26: Half light radius (arcsec) (H band).
Column 27: Kron radius(arcsec) (H band).
Column 28: Kron magnitude (H band).
***Column 29:** $H_{20.6}$ isophotal radius (arcsec).
***Column 30:** $H_{20.6}$ isophotal magnitude.
***Column 31:** $H_{20.6}$ isophotal magnitude error.
Column 32: Error of the Kron magnitude (H band).
Column 33: 1'' aperture magnitude (H band).
Column 34: 3'' aperture magnitude (H band).
Column 35: 5'' aperture magnitude (H band).
Column 36: 7'' aperture magnitude (H band).
Column 37: 10'' aperture magnitude (H band).
Column 38: Error of the 1'' aperture magnitude (H band).
Column 39: Error of the 3'' aperture magnitude (H band).
Column 40: Error of the 5'' aperture magnitude (H band).
Column 41: Error of the 7'' aperture magnitude (H band).
Column 42: Error of the 10'' aperture magnitude (H band).
Column 43: Half light radius in K_s band (arcsec).
Column 44: Kron radius (arcsec) (K_s band).
Column 45: Kron magnitude in (K_s band).
***Column 46:** K_{s20} isophotal radius (arcsec).
***Column 47:** K_{s20} isophotal magnitude.
***Column 48:** K_{s20} isophotal magnitude error.
Column 49: Error of the Kron magnitude (K_s band).
Column 50: 1'' aperture magnitude (K_s band).
Column 51: 3'' aperture magnitude (K_s band).
Column 52: 5'' aperture magnitude (K_s band).
Column 53: 7'' aperture magnitude (K_s band).
Column 54: 10'' aperture magnitude (K_s band).
Column 55: Error of the 1'' aperture magnitude (K_s band).
Column 56: Error of the 3'' aperture magnitude (K_s band).
Column 57: Error of the 5'' aperture magnitude (K_s band).
Column 58: Error of the 7'' aperture magnitude (K_s band).
Column 59: Error of the 10'' aperture magnitude (K_s band).
Column 60: Position angle (K_s band).
Column 61: Ellipticity (K_s band).

Column 62: Magnitude flag (J band).

Column 63: Magnitude flag (H band).

Column 64: Magnitude flag (K_s band).

Column 65: Galaxy morphology.

The full catalogue is only available in an electronic form. In appendix A, I list the parameters marked with $\star$ for the 100 brightest galaxies.

A code was written by me to run SExtractor on the NWS images in the three bands using the pre-compiled galaxy list (see Sect. 3.1.1) based on the previously identified galaxies to catalogue all the parameters as derived from SExtractor. The code compiles a galaxy list for each field which is then combined into a single catalogue for the galaxies on all the survey images.

Another script was used to calculate the isophotal magnitudes and radii for the galaxies in each field. This code also compiles an output for each field, which is then combined into a catalogue.

A combined catalogue is produced by merging the previous two catalogues. This catalogue was then searched for duplicate galaxies identified in adjoining fields. Only one entry from multiple entries was kept in the final catalogue. The retained entry was the one with the better magnitudes errors.

Astrometry

The position of a source was defined as the first order moment (X, Y) of the source light profile defined in Eqns. 3.1, 3.2.

$$X = \bar{x} = \frac{\sum_{i \in S} I_i x_i}{\sum_{i \in S} I_i} \quad (3.1)$$

$$Y = \bar{y} = \frac{\sum_{i \in S} I_i y_i}{\sum_{i \in S} I_i}, \quad (3.2)$$

where i is a pixel of the source S , and I_i the flux at (x_i, y_i) in the (x, y) image coordinate system.

Internally SExtractor uses the image coordinates to manipulate and calculate the different parameters. The reported geometric and astrometric parameters in the World Coordinate format (J2000), are calculated by SExtractor. It uses the astrometric solution in the image fits-header to transform the sources coordinates to the World coordinates.

The **position-angle** (θ) is the angle between the semi-major axis and the image *NAXIS1* axis (image-axis), as illustrated in Fig. 3.14.

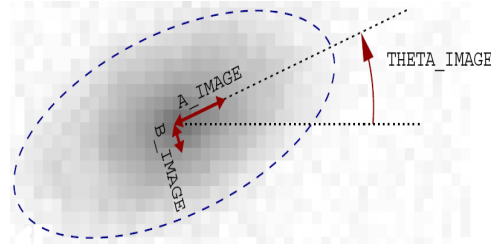


Figure 3.14: SExtractor elliptical parameters

The position angle listed in the catalogue is oriented east of north.

The ellipticity (ϵ) is defined as

$$\epsilon = 1 - \frac{b}{a}, \quad (3.3)$$

where a and b are the semi-major and minor axes respectively (Bertin, 1996; Holwerda, 1999).

Photometry

The NWS catalogue lists three types of photometry, Kron magnitudes as a measure of the total flux, constant radius aperture magnitudes and isophotal magnitudes. In the following I give definitions of the different photometric outputs that I determined.

Fixed-aperture magnitude: This is illustrated in Fig. 3.15. It estimates the flux above the sky background within a constant circular aperture. The diameter of the aperture can be set in the SExtractor parameter file. This photometry is minimally affected by contamination from neighbouring source if the radius is tight enough to encompass only the source. But it is becomes severely contaminated if it is wide to include other neighbouring sources. The small apertures are generally used for calculating galaxy colours to minimize contamination.

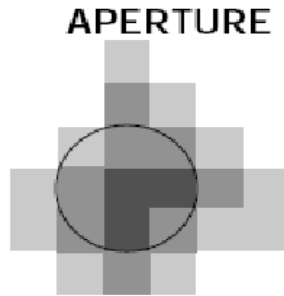


Figure 3.15: Constant aperture photometry.

Kron magnitude: The Kron magnitude (Kron, 1980; Bertin & Arnouts, 1996) is a measure of the total magnitude of a galaxy. To calculate the Kron photometry, an elliptical aperture with an axis ratio ϵ and position angle θ is used. ϵ and θ are derived from the second order moments. The elliptical aperture corresponds roughly to the twice the isophotal radii. The isophotal radius is defined by SExtractor as the radius of the isophote with a surface brightness magnitude equivalent to the detection threshold set in SExtractor. Within this aperture the first moment r_1 is computed as,

$$r_1 = \frac{\sum rI(r)}{\sum I(r)}.$$

For galaxy profiles that are convolved with Gaussian seeing, a constant fraction of the flux lies within the circular aperture radius kr_1 , independent of magnitude. This picture remains unchanged if we consider an ellipse with principal axes ϵkr_1 and kr_1/ϵ . Using a value of $k = 2.5$ the Kron magnitude can account for 94% of the total flux (Jarrett et al., 2003).

Isophotal radii and magnitudes: The isophotal radius R_μ is defined as the radius to the isophote at the surface brightness μ . The isophotal radii in the NWS catalogue are derived for a surface brightness $\mu_J = 21.0$ mag/arcsec² in the J band, $\mu_H = 20.6$ mag/arcsec² in the H and $\mu_{K_s} = 20.0$ mag/arcsec² in the K_s bands. These surface brightness magnitudes correspond roughly to 1σ noise above the NIR sky-background (Jarrett et al., 2003). The isophotal magnitude m_μ is defined as the integrated magnitude within the respective radius.

Isophotal magnitudes for galaxies in the NWS were computed with a script written by me using the **IRAF** *ellipse* procedure. The script creates the surface brightness profile and the isophotal magnitudes for each galaxy in the three bands. From the surface brightness profiles, the isophotal radii R_{21} , $R_{20.6}$ and R_{20} are determined and hence from the integrated light profiles the magnitudes within that radii R are found.

As an example Fig. 3.16 shows the surface brightness profile (left column) and the integrated isophotal magnitude profile (right column) for all the three bands J , H and K_s of a galaxy centred at $\ell = 308^\circ 54$, $b = +5^\circ 40$. It has a K_s band isophotal magnitude of $K_{s(iso)} = 11^m 53$. This galaxy is found in a region with an obscuration of $A_{K_s} = 0^m 31$ and a stellar density of $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.01$. In Table A.1 which lists parameters for the 100 brightest galaxies in the NWS this galaxy has an ID (NWSC98) and a designation 13323706-5701211. A postage stamp image for this galaxy is shown in the top panel of Fig. 3.16.

The vertical lines indicate the isophotal radii (solid), and the Kron radii (dashed). The horizontal lines in the panels of the left column indicate μ_J , μ_H and μ_{K_s} . Meanwhile the horizontal lines in the panel in the right column indicate the integrated isophotal magnitude (solid) and the Kron magnitude (dashed).

Mean central surface brightness: The NIR mean central surface brightness is a useful parameter. It can be used to classify galaxies into early or late-type galaxies (Jarrett, 2000).

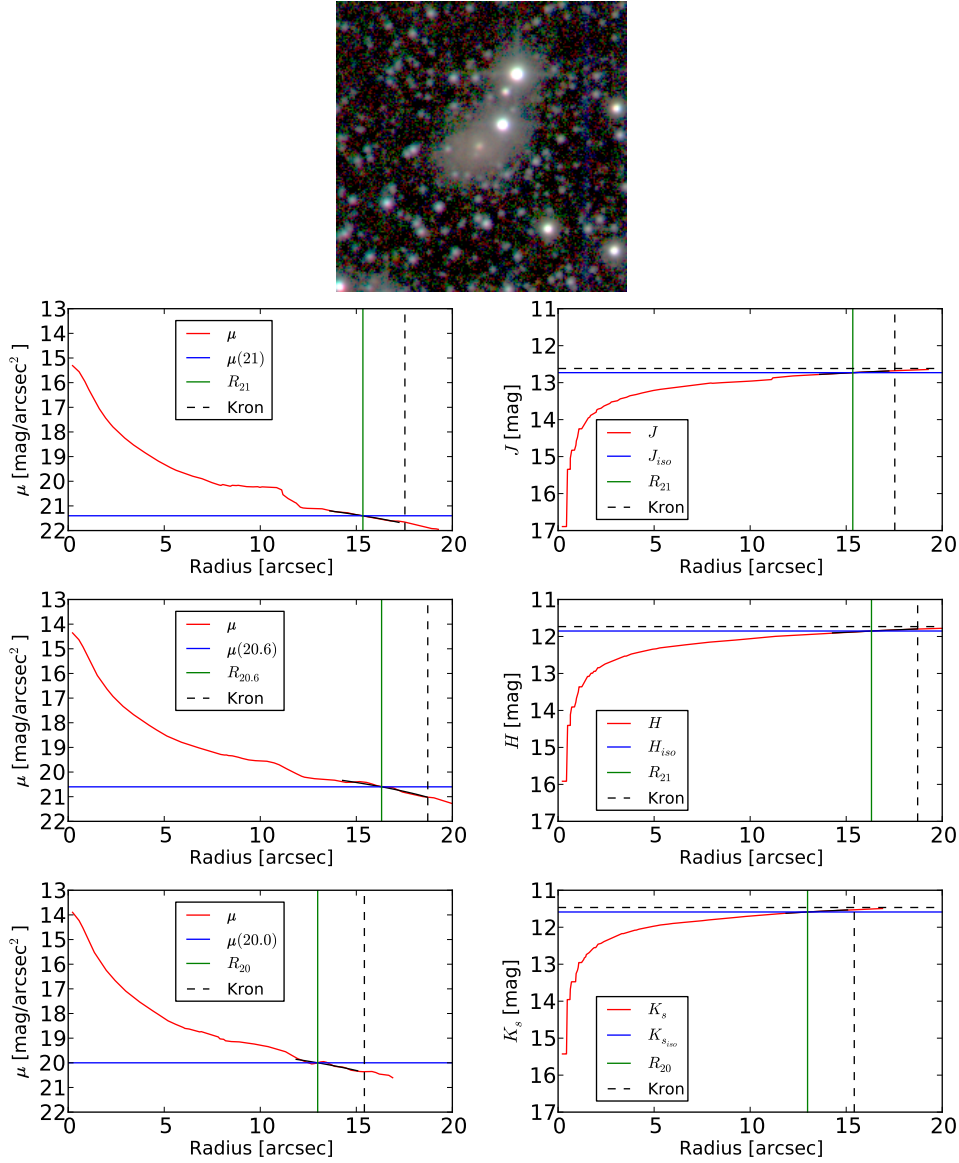


Figure 3.16: Isophotal radii and magnitudes for a galaxy centred at $\ell = 308^\circ 54$, $b = +5^\circ 40$ and a magnitude of $K_{s(iso)} = 11^m 53$. The top panel displays a postage stamp colour image for this galaxy. The left panel shows the surface brightness profile for the J band (top), H band (middle) and K_s band (bottom). The right panel shows the integrated isophotal magnitude profile for the galaxy as a function of radius. Indicated on the plot are the isophotal radius and magnitude, and the Kron radius and magnitude in the respective bands.

The central surface brightness has also proved to be an important tool in correcting isophotal magnitudes for Galactic dust obscuration (see chapter 4 for further details).

The central surface brightness μ is here defined as the magnitude of the mean flux within a radius of $R \leq 3''$. The $R \leq 3''$ radius was because the majority of our galaxies have a radius $\geq 3''$, and the seeing in our images is always below $\text{FWHM} \leq 2''.1$.

The mean central surface brightness is calculated as,

$$\mu'_\lambda = m_\lambda(3'') + 2.5 \log(3.0^2 * \pi), \quad (3.4)$$

where $m_\lambda(3'')$ is the magnitude within the constant radius aperture $R = 3''$.

Additional parameters

Flags: SExtractor reports the additional information about sources with the output parameter FLAGS. Flags that are reported by SExtractor are combinations of the following basic ones (Bertin & Arnouts 1996; Bertin 1996; Holwerda 1999):

1 $\equiv$ The object has neighbours, bright and close enough to significantly bias the Kron magnitude, or bad pixels (more than 10% of the integrated area is affected).

2 $\equiv$ The object was originally blended with another one.

8 $\equiv$ The object is truncated (too close to an image boundary)

16 $\equiv$ Object's aperture data are incomplete or corrupted.

32 $\equiv$ Object's isophotal data are incomplete or corrupted.

An object flagged as **26** means that it has all the following flags **2**, **8** and **16**.

Galaxy Morphology (internal use): Galaxies in the NWS catalogue are classified into early or late-type galaxies. This morphology is used internally to correct the galaxy magnitudes for extinction. The morphological discrimination was based on a statistical analysis for galaxies in the 2MASS Large Galaxy Atlas (LGA) by Jarrett et al. (2003) who correlated the morphological types of galaxies with the NIR central surface brightness. In their analysis they found that the central surface brightness for early-type galaxies is always brighter than for late-type galaxies. Their result is reproduced in Fig. 3.17. In this figure they plotted the mean central surface brightness μ_λ for the galaxies in the LGA versus their morphological type. For the purpose of this analysis they adopted the numerical T₂ “type” classification of de Vaucouleurs (1959). Elliptical and lenticular galaxies were assigned the type 0; normal spirals as Sa=1, Sab=2, Sb=3, etc., ending with dwarfs, Magellanic types and Irregulars Sm/Im=9 and 10. In the plot I marked with the vertical line the separation I adopted to distinguish into early and spiral types. The horizontal lines indicate the surface brightness values that separate two morphological types. These surface brightness values are $\mu_J = 17.27 \text{ mag/arcsec}^2$ in the J band, $\mu_H = 16.49 \text{ mag/arcsec}^2$ in H and $\mu_{K_s} = 16.17 \text{ mag/arcsec}^2$ in the K_s band.

To apply these criteria I used the extinction-corrected central surface brightness μ_λ^0 defined

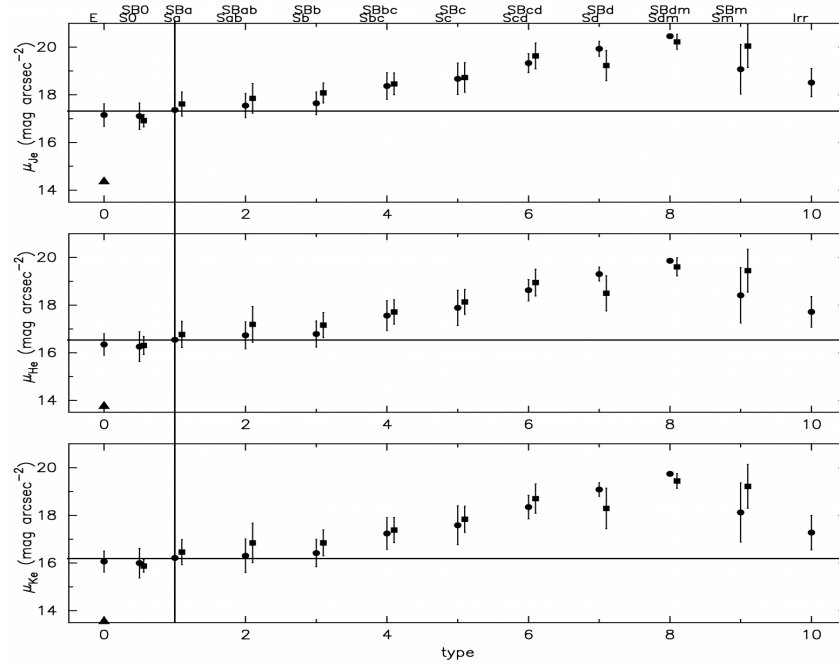


Figure 3.17: Correlation between central surface brightness and morphological types for galaxies in the LGA. The two points for each galaxy type referees to the barred and un-barred galaxies. The figure is reproduced from Jarrett et al. (2003).

as,

$$\mu_{\lambda}^0 = \mu'_{\lambda} - A_{\lambda}, \quad (3.5)$$

In this equation A_{λ} is the Galactic obscuration, and μ'_{λ} is the observed central surface brightness. The classification was achieved by comparing the values of μ_{λ}^0 with the values of μ_{λ} listed above and flagging the galaxy in each band as early-type (0) or late-type (1). The final morphological type was decided according to a total additive flag count of the three bands. A flag sum of either 0 or 1 indicate that the galaxy is an early-type and was flagged so in all three bands or in any two bands. Equally a galaxy flagged as 2 or 3 is a late-type and was flagged so in any two bands or all three bands.

3.3 The Norma Wall Survey Catalogue (NWSC)

The galaxy search in the Norma Wall survey region resulted in the identification of 5327 galaxies of which 946 were multiply observed in the overlapping regions between the fields. Excluding those galaxies, the “Norma Wall Survey Catalogue (NWSC)” contains 4360 galaxies of which 4175 (95.7%) were detected by SExtractor simultaneously in all three bands. The remaining

3.3 The Norma Wall Survey Catalogue (NWSC)

(4.3%) of the galaxies were detected in at least one band but not more than two. Galaxies in the catalogue range in size between $1''.6 \leq R_{K_s} \leq 81''.1$ and magnitude $9^m.09 \leq m_{K_s} \leq 18^m.84$. The quoted values correspond to the Kron radii and magnitudes in the K_s band. Only 237 galaxies (5.4% of the galaxies) were previously catalogued in the 2MASX.

Figure 3.18 shows the distribution of the galaxies in the NWSC (blue dots). The 2MASX galaxies in this region (green dots) are also shown. The galaxy clusters Norma, CIZA J1324.7-5736, Cen-Crux and PKS 1343-601 are marked on the map by the magenta circles. Contours of constant extinction at $A_{K_s} = 0^m.1, 0^m.2, 0^m.3, 1^m.0, 2^m.0, 3^m.0$ are also shown. The tight correlation between the decrease in the galaxy numbers and the increase in the extinction levels is evident on the map. The $2^\circ \times 2^\circ$ gray box, centred on $\ell \approx 317^\circ.1$, and $b \approx -1^\circ.0$, was surveyed by the IRAC, and MIPS *Spitzer* instruments (Jarrett et al., 2007b).

To assess the relation between the detected galaxy numbers and stellar density, I superimpose in Fig. 3.19 the galaxy distribution on the stellar density $\log(N_{(K_s < 14)}/\text{deg}^2)$ contours. The extinction contour at $A_{K_s} = 1^m.0$ is displayed with the brown contour line. A contour of stellar density at $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ is plotted by the dashed dark gray line. Note that in the stellar density contours in the regions outside the survey area are extrapolations from the region within the survey area due to the lack of stellar density information in these regions.

From this map it is obvious that the regions of increased stellar density have the lower number of galaxies. In fact it is this dual effect of increased stellar density and dust obscuration that affects the galaxy distribution. The majority of the galaxies (97.8%) were found in the region with extinction $A_{K_s} \leq 1^m.0$ and $\log(N_{(K_s < 14)}/\text{deg}^2) \leq 4.71$. A strong link between extinction and stellar density along the Galactic Plane is evident when comparing extinction contours at $A_{K_s} \leq 1^m.0$ and $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ roughly outline the same region in Fig. 3.19.

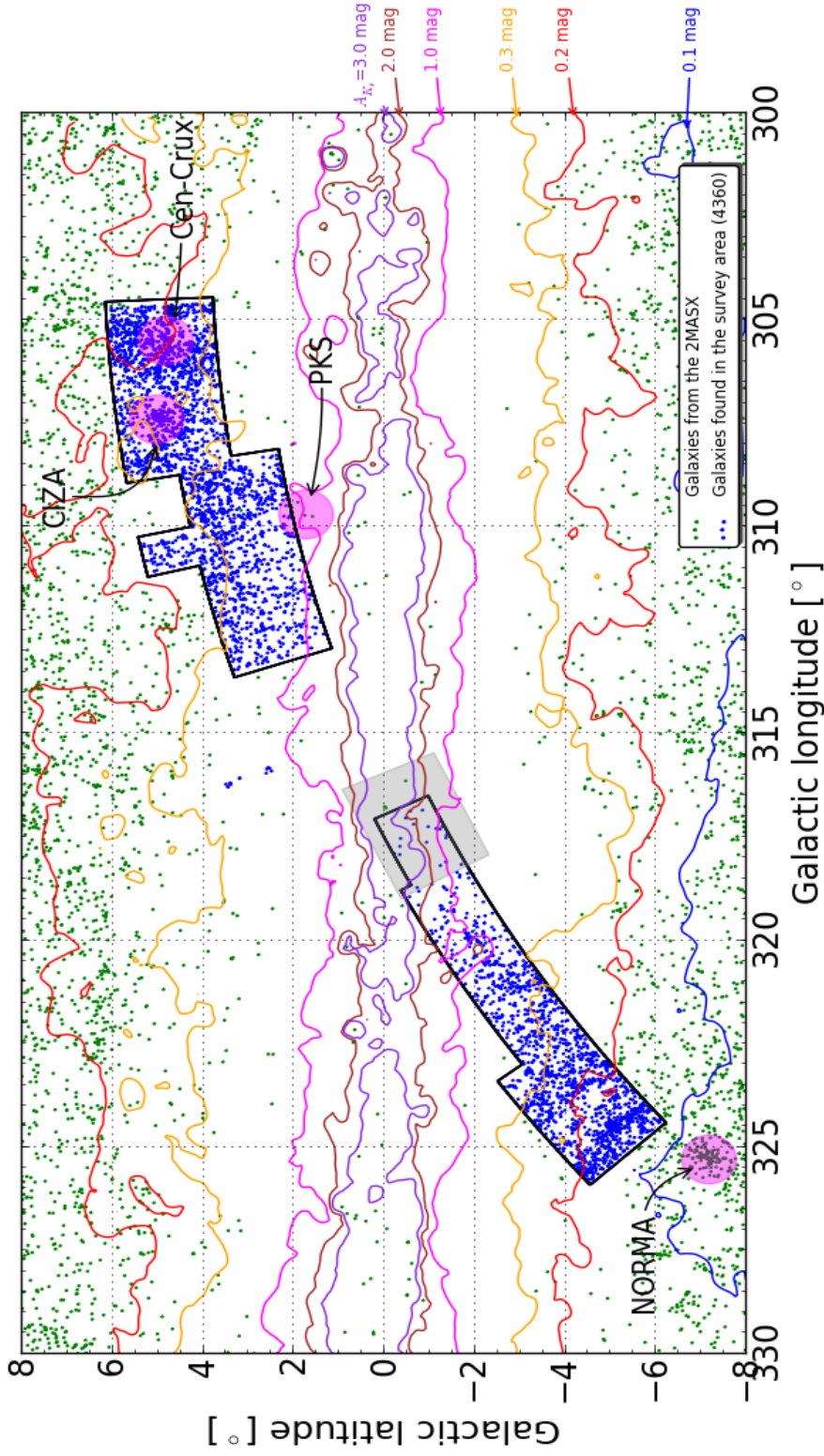


Figure 3.18: Distribution of the 4360 galaxies in the NWSC (blue dots). The green dots are galaxies from the 2MASX. The large magenta circles mark the centers of the Norma ($\ell = 324^\circ.3$, $b = -7^\circ.2$), PKS 1343-601 ($\ell = 309^\circ.7$, $b = +1^\circ.7$), ClZA 1324.7-5736 ($\ell = 307^\circ.4$, $b = +5^\circ.0$) and Cen-Crux clusters ($\ell = 305^\circ.5$, $b = +4^\circ.8$). Contours of constant extinction at $A_{K_s} = 0^m1, 0^m2, 0^m3, 1^m0, 2^m0$ and 3^m0 are indicated. The solid black line marks the survey footprint. The $2^\circ \times 2^\circ$ gray box, centred on $\ell \approx 317^\circ.1$, and $b \approx -1^\circ.0$, was surveyed by the IRAC, and MIPS *Spitzer* instruments (Jarrett et al., 2007b).

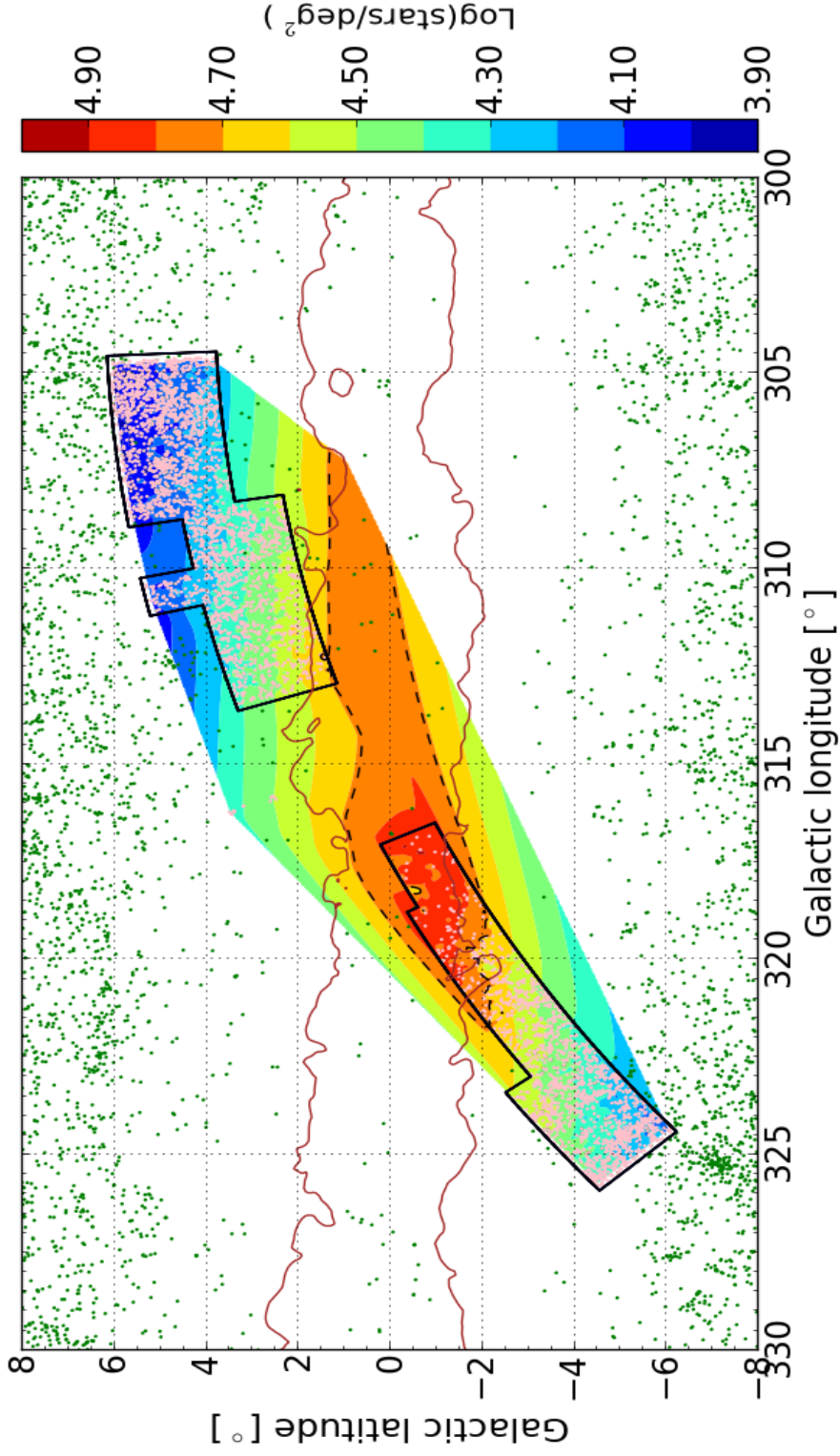


Figure 3.19: Distribution of the 4360 galaxies in the NWSC (magenta dots). The green dots are 2MASX galaxies. Stellar density is marked by the shaded areas. The extinction at $A_{K_s} \leq 1^m0$ (brown line) and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ (dark dashed gray line) delimit the area where most (97.8%) of the galaxies lie. The stellar density contours in the region outside the survey area are extrapolations from the region within the survey area outlined with the black line.

The histograms in Fig. 3.20 display the galaxy number count as a function of extinction A_{K_s} (left panel) and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2)$ (right panel). The extinction levels at $A_{K_s} \leq 1^m0$ and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ which delimit the regions where 97.8% of the galaxies lie are marked on their respective histograms.

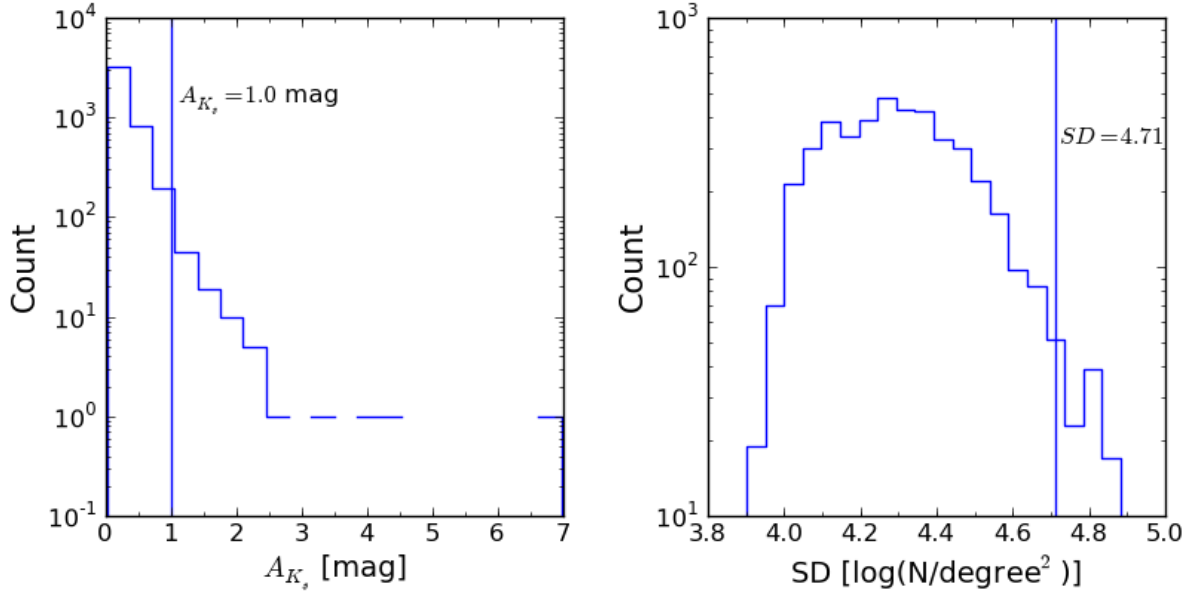


Figure 3.20: Galaxy distribution as a function of Galactic obscuration A_{K_s} (left panel) and stellar density (right panel). Extinction at $A_{K_s} \leq 1^m0$ and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ below 97.8% of the galaxies lie are marked on their respective histograms

3.3.1 Internal consistency of galaxy parameters

A number of galaxies (946) were observed on more than one image and can be recovered on up to four separate observations. These were hence parametrized multiple times. These galaxies are located in the overlapping regions of fields. After identification they were removed, retaining only one entry per galaxy. These galaxies were used to quantify the internal astrometric and photometric accuracy of the catalogued galaxies.

To search for such galaxies, I assumed that galaxies within a radius of $R \leq 1''.14$ of each other are the same. This radius corresponds to $\sim 10\sigma$ the astrometric accuracy for the point sources in the NWS images (see Sect. 2.3.4). 1061 galaxy coincidences were matched to 946 individual galaxies. A visual inspection of a random set of these pairs confirmed their matches.

Astrometry

All 1061 matched pairs were used for the astrometric check. Figure 3.21 displays the position offsets, ΔRA and ΔDec , defined as the difference between the galaxy positions of the matched pairs. The galaxy positions show an insignificant offset in RA of $\Delta\text{RA} = 0''.009$ with a standard

deviation $\sigma = 0''.202$, and of $\Delta\text{Dec} = 0''.003$ in declination with a standard deviation $\sigma = 0''.202$. The dispersion in RA and Dec is much smaller than the imposed correlation radius $R \leq 1''.14$. This is a good indicator that almost all the multiple entries of a galaxy in the catalogue were identified. This compares with the astrometric accuracy of 2MASX galaxies observed in multiple tiles which has an offset of (-0.010 ± 0.390) arcsec and (-0.002 ± 0.390) arcsec in RA and Dec respectively. The smaller dispersion in Δ RA and Dec in the NWS compared to the 2MASS is due to the improved spatial resolution of the SIRIUS camera. Figure 3.21 displays Δ RA on the abscissa and Δ Dec on the ordinate.

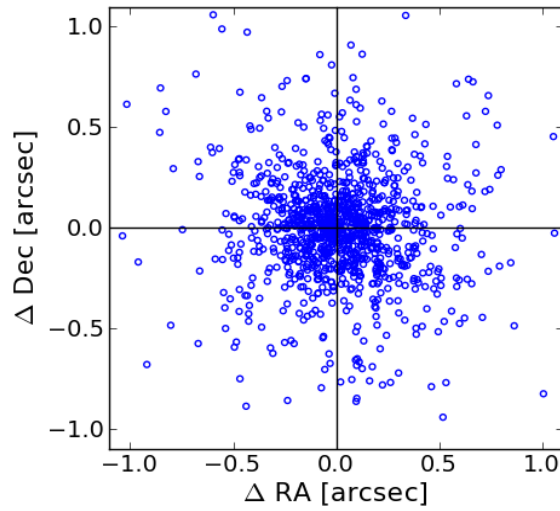


Figure 3.21: Internal astrometric accuracy for the NWS catalogue. The internal accuracy was estimated using galaxies identified in adjacent fields.

Photometry

To estimate the photometric accuracy of the catalogue, I compared the Kron, isophotal, $3''$ and $5''$ magnitudes for the matched pairs. All these galaxies are located close to the borders of the fields. They therefore have a lower signal-to-noise ratio compared to galaxies closer to the center of the field. Galaxies close to field edges may also suffer from incomplete apertures which will render their photometry less accurate. For this reason only a selected sub-set of the matched galaxies was used for the photometric comparison. Different criteria were applied to select the galaxy sets that were used for the respective photometric tests. An example of such criteria: galaxies are required to have a Kron radius larger than $3''$ and have consistent $J-H$ and $J-K_s$ colours for the $3''$ photometry check. The colour consistency was imposed on all galaxies in the different sets. The Kron radii criteria were varied according to the photometric test.

The comparison was achieved by calculating the magnitude difference, Δm , between the galaxy magnitudes of the corresponding galaxies pairs. The left panel of Fig. 3.22 shows the

offsets for the Kron magnitudes while the right panel displays the offsets for the isophotal magnitudes. Figure 3.23 shows the same for the 3'' and 5'' constant aperture magnitudes in the left and right panels respectively. The horizontal colour bands are the 1σ dispersion around the mean shift.

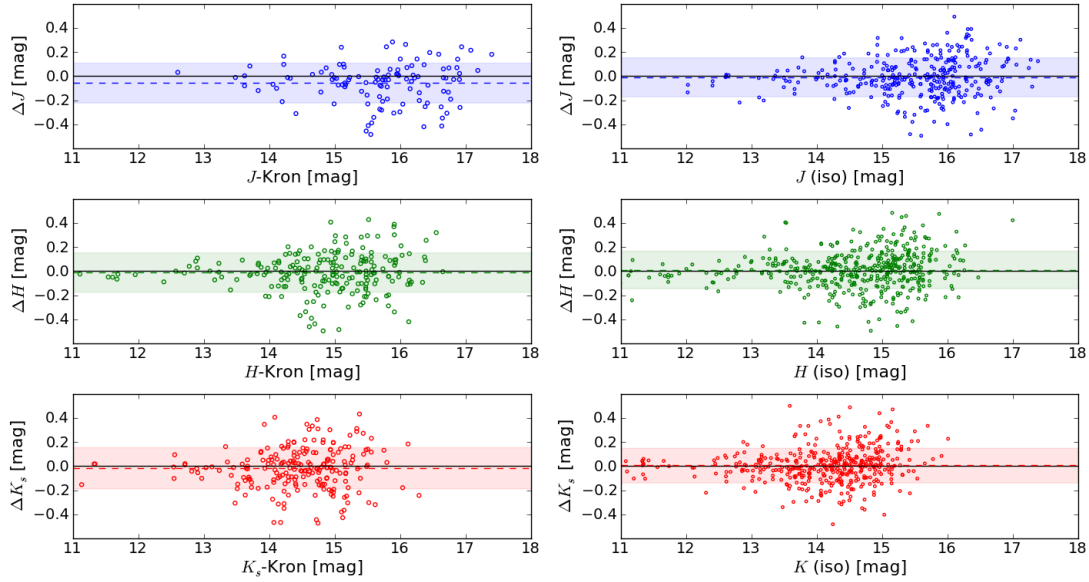


Figure 3.22: Photometric accuracy of the NWS catalogue. Left panel: the Kron magnitude offset, right panel: isophotal magnitude difference for matched pairs.

The accompanying Tables 3.3 - 3.5 list the absolute median offset, mean offset, standard deviation σ , standard error SE and the number of pairs N used in each comparison. Both the median and mean values for the magnitude shift are quoted. This allows a better insight into the distribution given that the mean value is biased towards extreme outliers which is not the case for the median. The plots and tables suggest that the Kron magnitudes show the larger dispersion compared to the isophotal and constant aperture photometry. This is expected because the Kron photometry is an estimate of the total magnitude which is most affected by the star-subtraction process. The J band shows the largest dispersion. This must be due to the fact that the J band goes to fainter magnitudes compared to the other two bands.

3.3 The Norma Wall Survey Catalogue (NWSC)

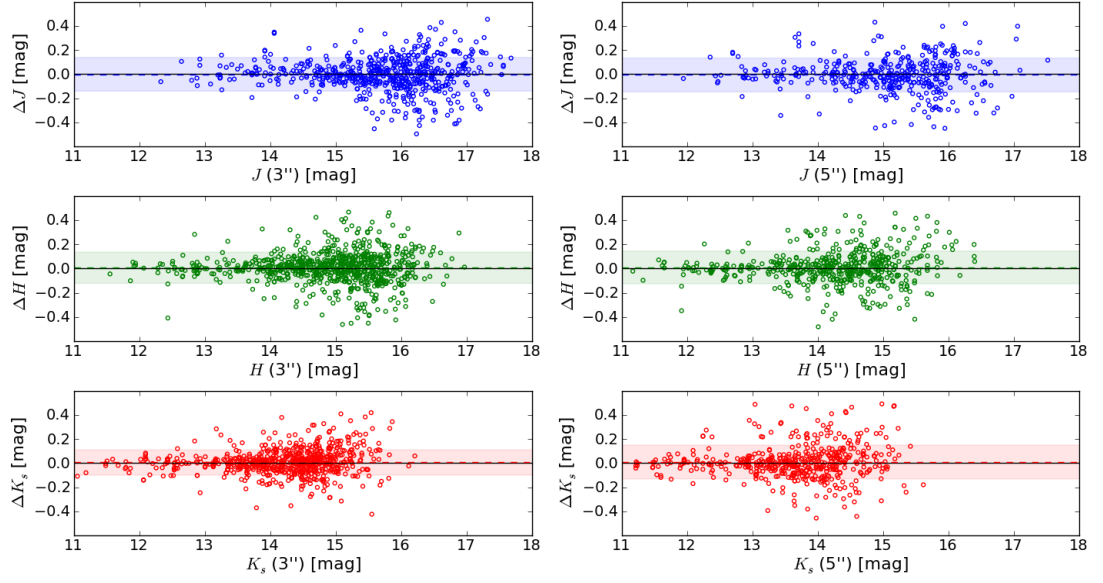


Figure 3.23: Photometric accuracy of the NWS catalogue for the 3'' (left panel) and 5'' (right panel) constant aperture magnitudes.

Table 3.3: J band magnitude accuracy.

Aperture	$ \tilde{\Delta} $	$ \langle \Delta \rangle $	σ	SE	N
	[mag]	[mag]	[mag]	[mag]	
3''	0.001	0.002	0.139	0.006	598
5''	0.009	0.008	0.140	0.007	398
ISO	0.012	0.011	0.161	0.009	330
KRON	0.028	0.058	0.165	0.016	112

Table 3.4: H band magnitude accuracy.

Aperture	$ \tilde{\Delta} $	$ \langle \Delta \rangle $	σ	SE	N
	[mag]	[mag]	[mag]	[mag]	
3''	0.008	0.006	0.129	0.005	783
5''	0.004	0.009	0.134	0.006	521
ISO	0.003	0.009	0.156	0.007	449
KRON	0.014	0.013	0.163	0.011	204

Table 3.5: K_s band magnitude accuracy.

Aperture	$ \tilde{\Delta} $ [mag]	$ \langle \Delta \rangle $ [mag]	σ [mag]	SE [mag]	N
3''	0.004	0.011	0.105	0.004	678
5''	0.002	0.009	0.140	0.006	487
ISO	0.006	0.003	0.143	0.007	430
KRON	0.013	0.019	0.171	0.012	210

The magnitude accuracy listed in Tables 3.3 - 3.5 are the maximum expected uncertainty in the galaxy photometry as it is estimated from a sample of galaxies that has the least signal-to-noise ratio and is most affected by the fields borders.

3.3.2 Comparison to the 2MASX

In this section, I compare the astrometric and photometric properties of the NWSC galaxies that have counterparts in 2MASX. To cross-identify galaxies in the two catalogues I assumed that any two entries in the the catalogues that lie within a radius of $R \leq 1''.14$ are the same object. The relatively small correlation radius seems sufficient as the NWS images were astrometrically calibrated using 2MASS. Using this radius criterion, 237 galaxies could be cross-correlated between the two catalogues. The majority of the 2MASX galaxies within our survey region have counterparts in the NWSC, but only a few of the 2MASX galaxies (29) did not correlate with any in the NWSC. On closer examination it was found that 16 of these galaxies are misidentified as galaxies in 2MASS. They were found to be faint stars that are not well resolved in 2MASS. The list of the misidentified objects is given in Table 3.6 with their Galactic latitude, longitude and 2MASS designations. The remaining 13 2MASS galaxies showed an offset in the 2MASX positions due to unresolved sources blended with the galaxy image that influenced the galaxy position. The list of these galaxies is given in Table 3.7, again with Galactic latitude, longitude and 2MASS designations.

3.3 The Norma Wall Survey Catalogue (NWSC)

Table 3.6: Misidentified galaxies in 2MASX.

$\ell[^\circ]$	$b[^\circ]$	Designation
324.768	-5.699	J16033562-6009011
322.599	-3.849	J15404508-6005144
321.709	-3.540	J15360225-5944487
305.715	4.242	J13124275-5830529
305.500	4.572	J13104691-5801220
310.384	4.654	J13465925-5724413
305.499	4.708	J13104807-5804010
305.376	4.888	J13094664-5753480
307.815	5.039	J13274469-5729173
307.628	5.044	J13262218-5730322
307.810	5.050	J13274196-5728413
305.177	5.491	J13075968-5718291
306.783	5.511	J13194517-5708549
305.045	5.581	J13065923-5713382
307.532	5.592	J13250777-5658423
304.868	5.988	J13053141-5649504

Table 3.7: Galaxies in 2MASX with offset positions.

$\ell[^\circ]$	$b[^\circ]$	Designation
324.595	-5.736	J16024527-6017302
324.383	-5.623	J16005230-6020456
325.137	-4.784	J16005865-5913139
306.795	3.836	J13211651-5848424
307.089	4.192	J13231070-5825251
307.438	4.727	J13251666-5750543
307.161	4.728	J13231301-5752581
307.402	4.790	J13245728-5747272
305.623	4.934	J13113584-5749580
305.210	5.339	J13081875-5727300
305.990	5.524	J13135684-5712500
306.716	5.592	J13191214-5704309
306.504	5.627	J13173777-5703459

All the 237 matched galaxies were used for the astrometric comparison. The NWS catalogue has an offset of $\Delta\text{RA} = -0''.01$ with a dispersion of $\sigma = 0''.42$ and $\Delta\text{Dec} = 0''.11$ with $\sigma = 0''.39$ with respect to 2MASX. The individual NWS and 2MASX astrometric errors given in Sect. 3.3.1 predict a combined error of $\sigma = 0''.43$ in both RA and Dec. This is compatible with the dispersion found above between the NWS and 2MASX astrometry. Figure 3.24 displays the distribution of ΔRA on the abscissa and ΔDec on the ordinate.

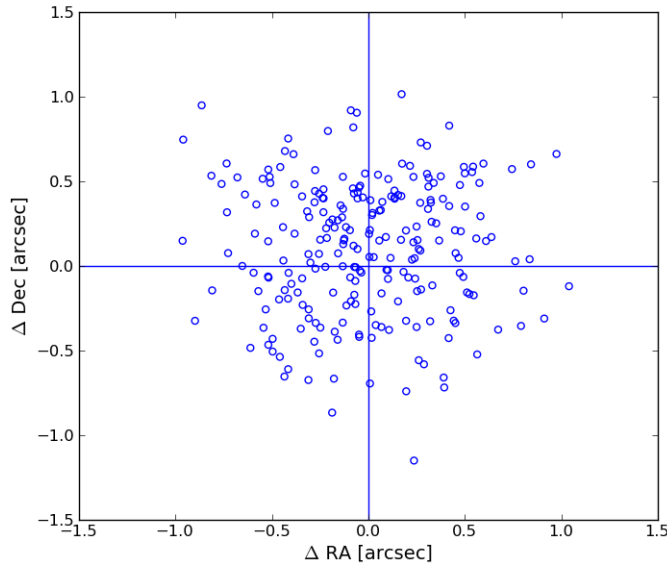


Figure 3.24: Astrometric comparison of all 237 galaxies in common with 2MASX.

I next assess the photometric quality based on a subset of galaxies. Galaxies were selected to have a reliable photometry and to not be flagged by SExtractor as unreliable. The comparison was made for the $5''$ constant aperture magnitude in all three bands. A comparison for the Kron and isophotal magnitudes was only made for the K_s band. The J and H bands were not compared to 2MASX as there are no available colour terms to transform the 2MASX magnitudes to the SIRIUS magnitudes. This is due to the difference in isophotes and Kron radii used for the respective derivations. The galaxy magnitudes are compared by determining the magnitude shift Δm ,

$$\Delta m = m_{NWS} - m_{2MASX},$$

where m_{NWS} is the magnitude in the SIRIUS magnitude system and m_{2MASX} is the galaxy magnitude in 2MASX corrected for the difference in filters (see Eqn. 2.5). Figure 3.25 illustrates the magnitude difference Δm for the $5''$ aperture, while Table 3.8 lists the mean Δm in the three bands, the standard deviation, standard error and the number of galaxies used in the comparison.

3.3 The Norma Wall Survey Catalogue (NWSC)

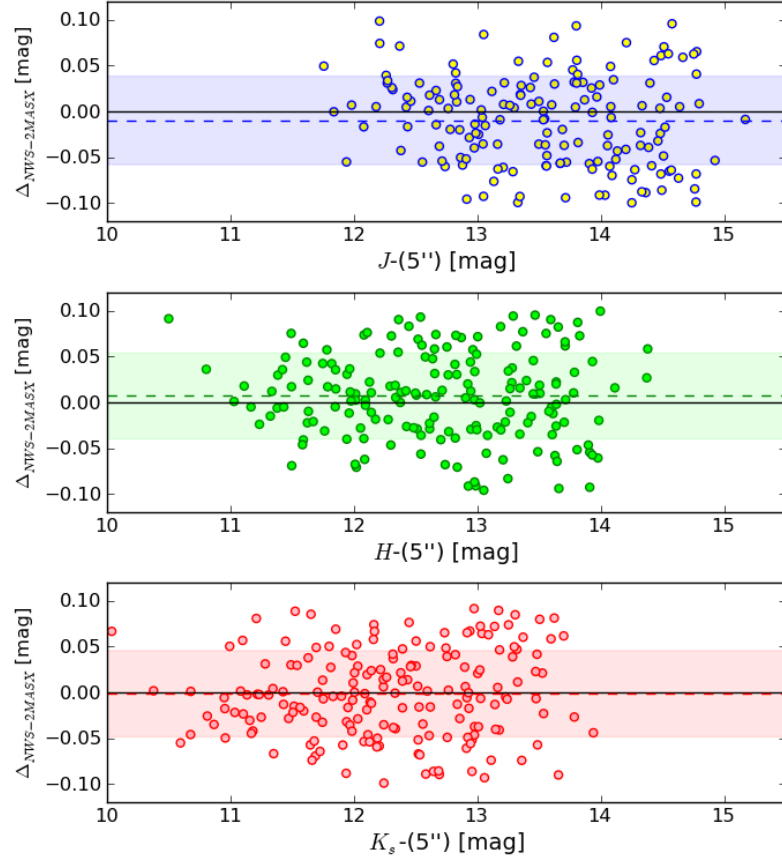


Figure 3.25: The difference in the 5'' constant aperture magnitude between NWS and the 2MASX catalogue. Top: J band, middle: H band in and bottom: K_s band. The horizontal coloured strips indicate the 1σ dispersion around the mean.

Table 3.8: The 5'' constant aperture magnitude difference between the NWS and the 2MASX catalogue.

Band	$\bar{\Delta m}$	$\langle \Delta m \rangle$	σ	SE	N
J	-0.007	-0.010	0.048	0.004	163
H	+0.009	+0.007	0.047	0.004	178
K_s	-0.003	-0.002	0.047	0.004	183

Figure 3.26 shows the magnitude offset for the K_s band isophotal magnitude (top panel), and Kron magnitude (bottom panel), while Table 3.9 lists the median, mean offsets, standard deviation, standard error, and the number of pairs used in the comparison.

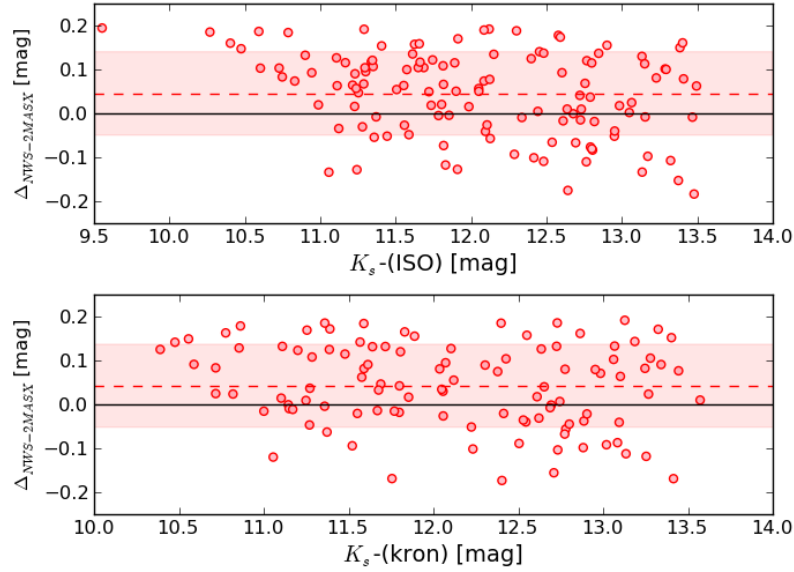


Figure 3.26: Comparison of the isophotal and Kron magnitudes between the NWS and 2MASX catalogue. Top: isophotal magnitudes comparison. Bottom: the Kron magnitude. The horizontal coloured strip indicate the 1σ dispersion around the mean.

Table 3.9: Comparison of the isophotal and Kron K_s band magnitude of the NWS and 2MASX galaxies.

Photo	$\tilde{\Delta m}$	$\langle \Delta m \rangle$	σ	SE	N
ISO	0.063	0.045	0.095	0.006	125
Kron	0.044	0.043	0.094	0.004	108

Not unexpectedly the magnitude offsets find the $5''$ magnitudes to have the least offset and dispersion relative to 2MASX compared to the isophotal and Kron magnitudes. The above analysis also indicates that the 2MASX isophotal and Kron magnitudes are brighter than the NWS magnitudes. This was expected because of the improved resolution of the NWS images that allow for a more detailed star-subtraction of the faint stars from the galaxies. Furthermore the comparison with 2MASX clearly show that almost all the bright galaxies $K_s(ISO < 11^m0)$ are brighter in 2MASX than in the NWS. This is also anticipated as brighter galaxies are expected to be more contaminated from the neighbouring source as they are spatially larger than the fainter galaxies.

To complement the above discussion I list in Table 3.10 the mean and median magnitude offset between the J and H NWS isophotal magnitudes and the 2MASS magnitudes. The table

3.3 The Norma Wall Survey Catalogue (NWSC)

also lists the standard deviation, standard deviation error and the number of galaxy pairs that were used for the comparison. The values listed in this table should be read with caution as no colour corrections were applied for transformation between the two IRSF and 2MASS magnitude system.

Table 3.10: Isophotal magnitude comparison with 2MASX for the J and H bands.

Band	Δm	$\langle \Delta m \rangle$	σ	SE	N
J	-0.039	-0.029	0.098	0.004	112
H	+0.072	+0.051	0.101	0.007	122

4

Isophotal parameters corrections and Galactic extinction

Galaxies in the NWS are strongly affected by dust extinction. Obscured galaxies look smaller and fainter than they intrinsically are. In this chapter I investigate the effect of extinction on galaxies observed in the NIR J , H and K_s bands. For this study I sampled 64 galaxies from the 2MASS LGA (Jarrett et al., 2003). This study has led to the description of two independent methods to correct isophotal magnitudes and radii for the obscuration effect. The first method uses the central surface brightness of galaxies to optimise the corrections, while the second method gives an average correction. The second method is more useful when the central surface brightness for a galaxy is not available. Results in sections 4.1 - 4.3 have been published¹ in the Monthly Notices of the Royal Astronomical Society (MNRAS) of which I was first author.

The Schlegel dust maps are widely used to estimate the extinction along a line-of-sight to extragalactic sources. Due to the decreased number of galaxies in the ZOA the Schlegel maps are not properly calibrated in the ZOA. Here I also investigate the reliability of the dust maps in the NWS area. I note that the Schlegel maps overestimate extinction by $\approx 29\%$ in the survey area.

¹Riad, I. F., Kraan-Korteweg, R. C., & Woudt, P. A. 2010, MNRAS, 401, 924

4.1 Isophotal parameters corrections

Galaxies observed through foreground extinction suffer size reduction and dimming due to their obscuration by the veil of dust in the Milky Way. The degree of obscuration is wavelength dependent, decreasing the longer wavelengths. The effect of dust extinction on point-like objects, stars, is linearly related to extinction. If, for example, the observed magnitude of a star is $K_s = 6^m0$ and it suffers an extinction of $A_{K_s} = 1^m5$, its intrinsic magnitude will be $K_s^\circ = 4^m5$. Constant aperture magnitudes of galaxies are similar to stars in that their extinction corrections are linear with extinction, i.e.

$$m_\lambda^\circ = m_\lambda - A_\lambda, \quad (4.1)$$

where m_λ° is the extinction-corrected magnitude, m_λ the observed magnitude and A_λ the extinction in a passband.

Galaxies are extended objects, hence they suffer further dimming in their total, Kron and isophotal magnitude due to the loss of their fainter outer regions in the sky background. An obscured galaxy appears smaller and fainter in the sky than it really is. Corrections for this extra dimming are non-linear as was shown by Fisher & Tully (1981); Hauschildt (1987) and Cameron (1990) in the optical. Extinction corrections for total, Kron and isophotal magnitudes can be summarized as,

$$m_\lambda^\circ = m_\lambda - A_\lambda - E_\lambda, \quad (4.2)$$

where again m_λ° is the extinction-corrected magnitude, m_λ the observed magnitude, A_λ the extinction in a passband and E_λ is the non-linear extinction term. This term is different for the different types of magnitudes, i.e total, Kron or isophotal. Nagayama et al. (2004) derived corrections to the K_s band isophotal magnitudes. Their extinction-correction study was initiated to correct the isophotal magnitudes for galaxies observed in the vicinity of the giant radio galaxy PKS 1343-601 centred at $(\ell, b) = (309^\circ7, 1^\circ7)$. From their study they showed that the isophotal magnitude correction can be approximated by a linear relation for extinction levels $A_{K_s} \lesssim 1^m0$. Their work also showed that the different morphological types of galaxies are affected differently by extinction. Galaxies that have an exponential light profile bulge (late type) need larger corrections than those with a de Vaucouleurs profile (early type), or those with a bulge+disk light profile. To study this in further details, I simulated extinction in the J , H and K_s bands on 64 (unobscured) galaxies from the LGA (Jarrett et al., 2003). It is difficult to define a reliable total radius and magnitude for a galaxy (Jarrett et al., 2003), but more straightforward to work with isophotal radii and magnitudes out to a given radius. For this reason I only consider corrections to isophotal radii and the flux within that respective radius (see Sect. 3.2 for the definition of isophotal magnitudes and radii). In this thesis, the Kron magnitudes are only corrected with the linear term in Eqn. 4.2; the non-linear term E_λ is neglected.

Two methods are proposed for the extinction correction of isophotal magnitudes. The first is optimised to provide the most accurate correction and the second provides a convenient statisti-

cal correction that works adequately in lower extinction regions. The optimised correction utilizes the galaxy surface brightness, either the disk central surface brightness, μ_0 (mag/arcsec²), or the combined disk plus bulge central surface brightness μ_c (mag/arcsec²).

As the majority of our galaxies were found in regions with an extinction $A_{J,H,K_s} \lesssim 3^m0$ (see Table. 5.1) I limited the extinction simulation to $A_{J,H,K_s} \leq 3^m0$. For the purpose of estimating the foreground extinction of galaxies in the NWSC, I used the general extinction law given in Sect. 1.1.1.

In the following sections, I derive NIR corrections to isophotal magnitudes and radii for galaxies obscured by the Milky Way.

4.2 Data and method

I selected 64 galaxies from the LGA to simulate the effect of extinction on isophotal radii and magnitudes for galaxies observed in the NIR. Galaxies were selected in such a way that they are minimally affected by contamination from neighbouring sources and give a fair representation of all morphological types. The sample includes 25 elliptical and lenticular (**E/S0**) and 39 spiral (**S**) galaxies. Half of the galaxies in the spiral galaxy sample are barred with some of them having ring features. The selected galaxies cover a wide range in galaxy size and brightness. The apparent radii range between $r_{20} = 34'' - 1614''$ where r_{20} is the isophotal radius at the surface brightness level $\mu_K = 20$ mag/arcsec². The apparent isophotal magnitude range covered by our sample is $K_{20} = 1^m04 - 10^m77$, where K_{20} is the integrated magnitude within r_{20} . The galaxies in our sample suffer minimal obscuration ranging between $A_{K_s} = 0^m01 - 0^m07$ (see last column in Table 4.1). The list of selected galaxies is given in Table 4.1. This table lists the most common name of the galaxy, followed by the morphological type, r_{20} , K_{20} , inclination (b/a) and position angle (PA) in the K_s band. All the data are taken from Jarrett et al. (2003). In the table I also give the disk central surface brightness μ_0 (Freeman, 1970) and the central surface brightness μ_c in the K_s band. The last column lists the mean extinction A_{K_s} derived from the Schlegel et al. (1998) reddening maps and Eqn. 1.2. The surface brightness profiles for the galaxies are taken from the LGA¹ (given in tabular format).

¹The surface brightness profiles for galaxies in the LGA are found at <http://irsa.ipac.caltech.edu/applications/2MASS/LGA/>

Isophotal parameters corrections and Galactic extinction

Table 4.1: Galaxy sample used for the study of extinction effects on the observed NIR isophotal parameters. The table lists the morphological type, r_{20} , K_{20} , (b/a) and PA; the values are taken from the LGA (Jarrett et al., 2003). The table also lists the K_s band μ_0 and μ_c . Extinction in the K_s band is also listed. Galaxies marked with $\star$ are those showing a deviating correction trend, explained in the next section.

No.	Galaxy	Morphology	r_{20} [arcsec]	K_{20} [mag]	b/a	PA [°]	μ_0 [mag arcsec ⁻²]	μ_c [mag arcsec ⁻²]	A_{K_s} [mag]
1	NGC4697	E6	123.8	6.502	0.63	+67.5	16.10	12.88	0.011
2	M86	S03/E3	151.4	6.283	0.67	-55.0	16.37	13.21	0.011
3	M60	E2	146.6	5.825	0.81	-72.5	15.83	13.06	0.010
4	M59	E5	109.0	6.866	0.65	-15.0	16.11	12.67	0.012
5	M84	E1	115.0	6.347	0.92	-57.5	16.12	12.93	0.015
6	M105	E1	108.0	6.362	0.85	+67.5	15.92	12.65	0.009
7	NGC584	E4	88.8	7.445	0.62	+62.5	16.18	13.05	0.015
8	NGC720	E5	90.5	7.396	0.55	-40.0	16.14	13.63	0.006
9	NGC1395	E2	93.7	7.024	0.82	-87.5	16.10	13.29	0.008
10	NGC1407	E0	100.2	6.855	0.95	+60.0	16.25	13.62	0.025
11	NGC4365	E3	113.0	6.800	0.74	+45.0	16.32	13.36	0.008
12	NGC4473	E5	93.7	7.269	0.54	-85.0	15.96	12.89	0.010
13	NGC4494	E1-2	91.1	7.145	0.87	-07.5	16.15	13.04	0.009
14	NGC4589	E2	69.5	7.915	0.75	+92.5	16.27	13.67	0.010
15	NGC1377	S0	35.0	9.892	0.56	-86.5	16.15	15.43	0.010
16	NGC2310	S0	91.5	8.565	0.24	+47.0	15.97	14.99	0.039
17	NGC3630	S0	42.2	8.911	0.45	+37.0	15.70	13.46	0.016
18	NGC3966	S0	61.5	9.077	0.24	-72.5	15.75	14.63	0.011
19	NGC3115	S0	164.6	5.937	0.39	+45.0	15.74	12.27	0.017
20	NGC4636	E/S0;1	134.8	6.628	0.84	-37.5	16.36	13.82	0.010
21	NGC1340	E5	86.0	7.546	0.62	-17.5	16.01	13.58	0.007
22	M49	E2/S0(2)	179.2	5.506	0.81	-17.5	16.11	12.98	0.008
23	M32	cE2	147.4	5.139	0.87	+15.0	14.96	11.11	0.023
24	M87	E+0-1;pec;Sy	136.0	5.904	0.86	+27.5	16.05	13.64	0.008
25	NGC855	E	41.6	10.161	0.50	+67.0	16.71	15.97	0.026
26	NGC4244*	SA(s)cd	157.0	8.110	0.30	+45.5	17.49	16.82	0.008
27	NGC55*	SB(s)m	273.5	6.562	0.30	-67.0	17.12	17.03	0.005
28	NGC1073*	SB(rs)c	57.7	9.690	0.72	+42.5	18.70	16.99	0.014
29	NGC247*	SAB(s)d	141.7	8.180	0.55	+01.5	18.21	17.01	0.007
30	NGC24*	SA(s)c	83.0	9.215	0.28	+43.5	16.97	17.03	0.007
31	M33*	SA(s)cd	499.9	5.38	0.80	+50.5	17.71	14.10	0.015

Table A.1: (Continued)

No.	Galaxy	Morphology	r_{20} [arcsec]	K_{20} [mag]	b/a	PA [°]	μ_0 [mag/arcsec ²]	μ_c [mag/arcsec ²]	A_{K_s} [mag]
32	NGC4569	SAB(rs)ab;Sy	165.1	7.686	0.40	−15.0	16.35	12.83	0.017
33	NGC4216	SAB(s)b	217.6	6.587	0.80	+109.5	15.76	12.97	0.012
34	M100	SAB(s)bc;LINER	150.8	6.810	0.73	−72.5	17.28	13.97	0.010
35	M106	SAB(s)b;LINER	263.9	5.598	0.49	−20.0	15.98	13.39	0.006
36	M51a	SA(s)bc	197.5	5.601	0.68	+57.5	16.38	13.57	0.013
37	M109	SAB(rs)bc;LINER	142.6	7.139	0.56	+38.0	17.17	14.02	0.010
38	NGC908	SA(s)c	128.9	7.365	0.55	+87.5	16.41	14.54	0.009
39	NGC488	SA(r)b	107.8	7.133	0.81	+05.0	16.45	13.81	0.011
40	NGC4826	SA(rs)ab;Sy2	214.8	5.396	0.57	−70.0	15.24	12.38	0.015
41	NGC4594	SA(s)a;Sy1.9	201.7	5.009	0.54	+87.5	16.35	11.87	0.019
42	NGC474	SA(s)0	46.1	8.815	0.99	+45.0	16.42	14.05	0.013
43	NGC1532	SB(s)b;pec;sp	143.6	6.861	0.30	+35.0	15.92	13.84	0.006
44	NGC7090	SBc?;sp	136.4	8.404	0.26	−48.0	17.13	13.65	0.008
45	NGC2442	SAB(s)bc;pec	126.4	7.071	0.87	+27.5	17.04	13.61	0.074
46	M51b	SB0;pec	124.2	6.402	0.99	+27.5	15.77	12.33	0.013
47	NGC1808	SAB(s)bc;Sy2	131.1	6.732	0.42	−37.0	15.78	12.77	0.011
48	NGC5005	SAB(rs)bc;Sy2	130.8	6.501	0.42	+67.5	15.25	12.84	0.005
49	M88	SA(rs)b	155.4	6.334	0.44	−40.0	15.56	13.24	0.014
50	NGC4527	SAB(s)bc	141.0	7.021	0.34	+69.5	15.60	12.89	0.008
51	M63	SA(rs)bc	204.2	5.728	0.58	−82.5	15.76	12.71	0.006
52	M98	SA(s)ab,HII	172.8	7.012	0.34	+69.5	16.54	13.38	0.013
53	NGC47	SB(rs)bc	33.8	9.988	0.55	+85.5	17.12	15.49	0.004
54	NGC210	SA(s)b	54.1	8.515	0.52	−07.5	15.85	14.21	0.008
55	NGC628	SA(s)c	125.3	7.187	0.86	+87.5	17.53	15.47	0.026
56	NGC772	SA(s)b	105.2	7.440	0.80	−45.0	16.64	14.08	0.027
57	NGC1187	SB(r)c	86.1	8.315	0.55	+52.5	17.18	14.28	0.008
58	NGC522	Sc	68.9	9.389	0.14	+33.0	15.45	15.67	0.032
59	NGC891	SA(s)b	225.4	5.994	0.24	+25.0	15.11	14.55	0.024
60	M31	SA(s)b	1614.0	1.038	0.56	+45.0	14.81	11.50	0.023
61	NGC5746	SAB(rs)b?;sp	162.2	6.927	0.26	−10.0	15.10	14.08	0.015
62	M94	SA(r)ab	172.3	5.169	0.79	+85.0	15.50	11.70	0.007
63	NGC1300	SB(s)bc	131.8	7.896	0.48	−79.0	17.63	14.26	0.011
64	M65	SAB(rs)a	211.6	6.113	0.32	−08.5	14.95	13.312	0.009

The method I implement here to simulate the effect of extinction on galaxies follows closely

the precepts of work done by Cameron (1990) in the B -band.

4.2.1 Simulating extinction

The simulation of the effect of Galactic extinction on the apparent properties of a galaxy was achieved by the inward displacement of the limiting isophote along the surface brightness profile. The limiting isophote was shifted in non-uniform steps along the galaxy light profile with each step being equivalent to a certain extinction level in the investigated band. This is illustrated with Fig. 4.1. The left panel shows the effect of extinction on the surface brightness profile of the spiral galaxy M88 in the K_s band. The panel indicates increasing levels of extinction at $A_{K_s} = 0^m0, 0^m7, 1^m4, 1^m7, 1^m9, 2^m2, 2^m6$ and $A_{K_s} = 3^m0$ applied to the galaxy. The extinction levels are represented as horizontal lines on the plots. For each of the horizontal lines, the part of the profile lying below the line represents the obscured part of the galaxy while the part above is what remains visible at a given extinction. The intercept of the line with the ordinate gives the apparent limiting isophote, while the intercept of the light profile on the abscissa shows the size of the obscured galaxy that remains visible. The projection of the point of intercept of the line representing $A_{K_s} = 0^m0$ with the light profile on the abscissa gives the intrinsic radius R° . The additional dimming caused by the loss of the faint outer region is demonstrated by the integrated isophotal magnitude profile m_{iso} shown in Fig. 4.1 (right panel).

The reduced radii and magnitudes were calculated for each step and compared to the original values. The quantities calculated as a function of extinction were $f(R)$ and Δm_{iso} , defined as,

$$\begin{aligned} f(R) &= \frac{R^\circ}{R}, \\ \Delta m_{iso} &= m_{iso} - m_{iso}^\circ, \end{aligned}$$

where m_{iso}° , m_{iso} , R° and R are the intrinsic and absorbed magnitudes and radii respectively. The different values of $f(R)$ and Δm_{iso} corresponding to the simulated extinction values were then calculated, and fitted to the empirical relations following the formalism given by Cameron (1990):

$$f(R) = 10^{a \cdot (A_\lambda)^b}, \quad (4.3)$$

$$\Delta m_{iso} = F \cdot (A_\lambda)^v, \quad (4.4)$$

where F , v , a and b are the fitting parameters, and A_λ the extinction. This parameter fitting was done for all galaxies in our sample. It was performed separately for all three J , H and K_s bands.

The resulting corrections show very comparable trends in the three bands, due to the similarity of the light profiles of the galaxy in the three bands. To demonstrate the effectiveness of our procedure I therefore reduce the discussion to the results of the K_s band only. Figure 4.2

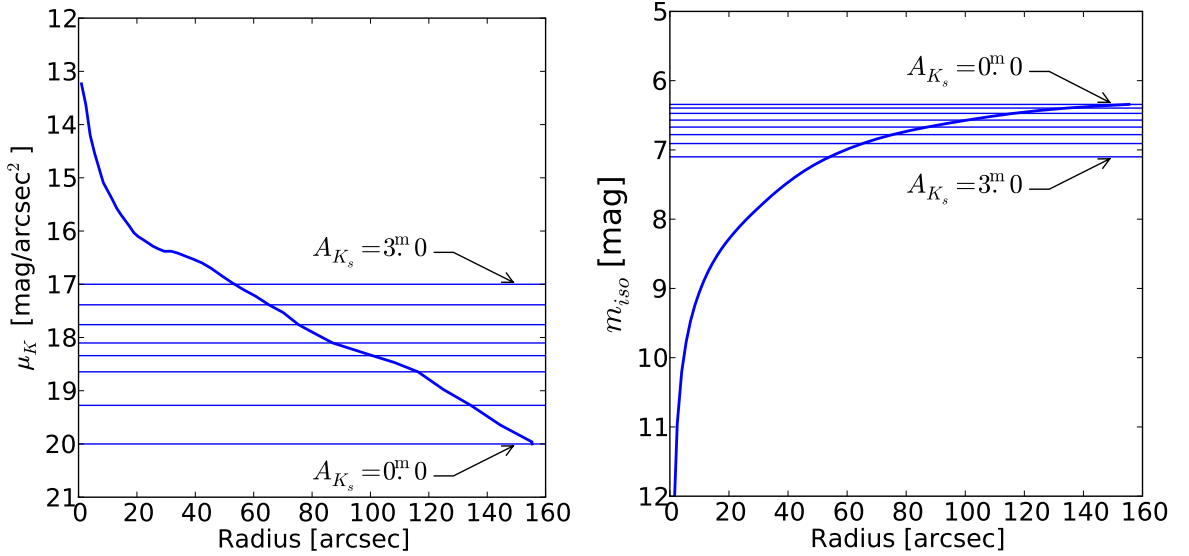


Figure 4.1: The effect of extinction on the spiral galaxy M88. Left panel: surface brightness profile for M88 in the K_s band, with various levels of the simulated extinction in the range $A_{K_s} = 0^m0$ to 3^m0 . Right panel: integrated isophotal magnitude m_{iso} with extinction with the same levels of the simulated extinction.

displays the calculated values of $f(R)$ and Δm_{iso} as a function of A_{K_s} , with their fitted relations for the galaxy M88 in the K_s band. The ability of Eqns. 4.3 and 4.4 to fit the simulated data varies among the galaxies. Some galaxies show tighter fits compared to M88, while others show more dispersion. The variation in the quality of the fitting is expected due to the different structures imprinted on the surface brightness profile of the galaxies.

4.2.2 Variation among galaxies (optimised corrections)

In Fig. 4.3 I show the magnitudes and radii corrections for all the **E/S0** (top) and **S** galaxies (bottom). The curves in the plots clearly show that the Cameron (1990) relations in their present form can not fully account for the variation among the galaxies in the two respective groups.

I investigated the origin of these discrepancies by looking at trends with e.g. inclination, central surface brightness μ_c and the disk central surface brightness μ_0 extrapolated from the fainter outer disk. No significant trend was found between the corrections and the variation among galaxies inclinations. Most probably a much larger sample than the current one is needed to investigate the correlation. A clear correlation between μ_0 and μ_c with the corrections was noticed, however. It was noted that galaxies with a low central surface brightness, $\mu_c \geq 17.0$ mag/arcsec² in the K_s band, and low surface brightness galaxies in general require larger

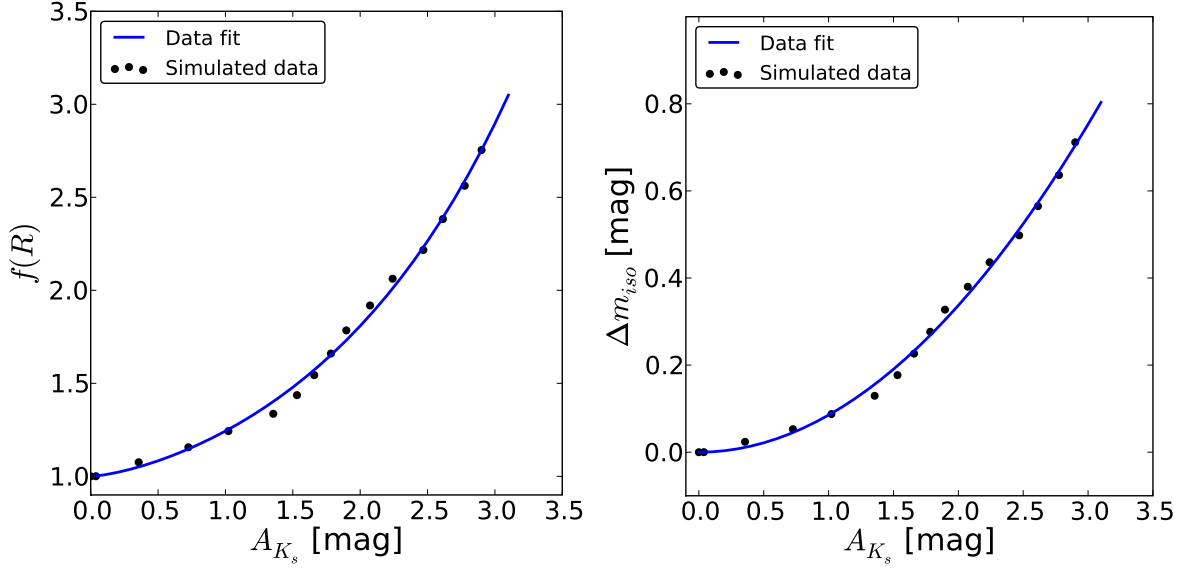


Figure 4.2: The calculated $f(R)$ (left) and Δm_{iso} (right), with their fitted corrections for the spiral galaxy M88 in the K_s band.

corrections. This is expected as those galaxies become obscured much more quickly. Galaxies that required larger corrections in our sample are M33, NGC24, NGC247, NGC1073, NGC55, NGC4244; they are labeled in Fig. 4.3. Even though the corrections were found to depend on μ_c , it was in fact found that μ_0 shows the better correlation with the corrections.

In this section I describe the method to optimise the corrections using either μ_0 or μ_c . Optimising the corrections using μ_0 gives tighter estimates to the corrections than using μ_c . On the other hand, optimizing the corrections using μ_c is convenient since it is easily measured and is typically found in large catalogues including 2MASX. A further point to note is that the NIR μ_c can be used to roughly classify the galaxies as early or late-type galaxies (Jarrett, 2000). In Sect. 2.3 I derive a more general correction which can be applied when neither μ_0 nor μ_c is available but the galaxy morphology.

Optimised correction based on μ_0

It was realized that the derived quantity, μ_0 , defined as the disk central surface brightness extrapolated from the fainter outer regions of the galaxy correlates well with the deviation among the galaxies. The definition of μ_0 corresponds to the disk central surface brightness for spirals as defined by Freeman (1970). The better correlation of the corrections with μ_0 rather than μ_c is expected since it is the fainter outer regions of the galaxy that suffer most from

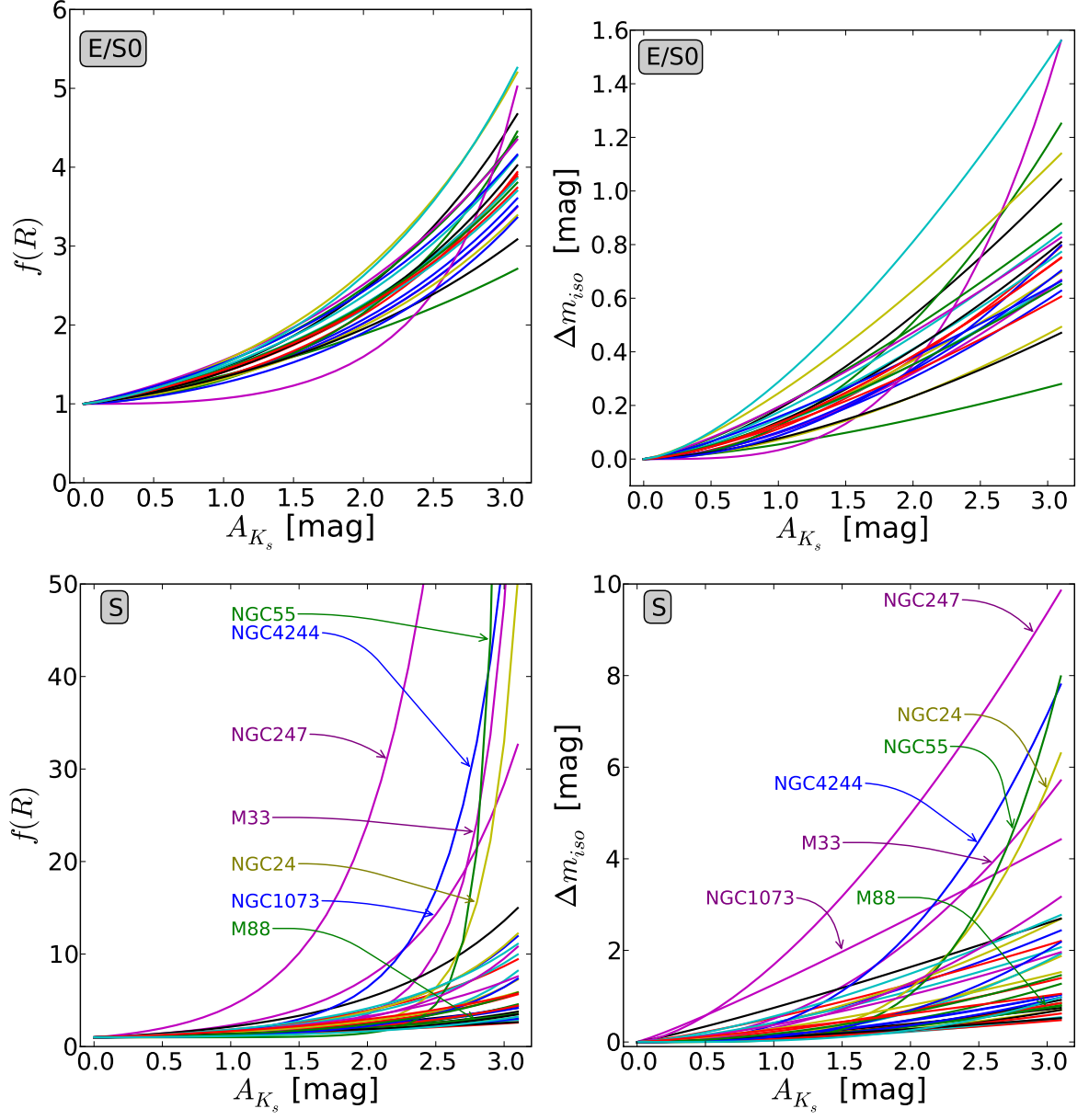


Figure 4.3: Simulated corrections $f(R)$ and Δm_{iso} . **E/S0** top panel, **S** bottom panel.

extinction. To accommodate μ_0 into the corrections, Eqns. 4.3 and 4.4 are re-written as,

$$f(R, \mu_0) = 10^{a(\mu_0) \cdot (A_\lambda)^{b(\mu_0)}}, \quad (4.5)$$

$$\Delta m_{iso}(\mu_0) = F(\mu_0) \cdot (A_\lambda)^{v(\mu_0)}, \quad (4.6)$$

with

$$\begin{aligned} a(\mu_0) &= a_o \exp(\mu_0 \cdot a_1), \\ b(\mu_0) &= b_o \exp(\mu_0 \cdot b_1), \\ F(\mu_0) &= F_o \exp(\mu_0 \cdot F_1), \\ v(\mu_0) &= v_o \exp(\mu_0 \cdot v_1). \end{aligned} \quad (4.7)$$

Using the parameter products ($a \times b$) and ($F \times v$) for each galaxy, and analyzing how they vary with μ_0 , I derived the parameters ($a_o, b_o, F_o, v_o, a_1, b_1, F_1$, and v_1). These values are listed in Table 4.2. For each galaxy, the value of μ_0 was found from a linear fitting to the disk part of the light profile of the galaxy with $\mu_\lambda \gtrsim 17.0$ mag/arcsec². The intercept of the straight line fitted to the disk part of the light profile with the surface brightness axis was then μ_0 . The disk part of the light profile was identified by visual inspection.

The goodness of $f(R, \mu_0)$ and Δm_{iso} in describing the correction curves for the different galaxies accurately was found to be very sensitive to the value of μ_0 . This shows the importance of having an accurate light profile of the galaxies, and hence μ_0 , to be able to use the μ_0 optimised correction.

Optimised correction based on μ_c

To optimise the extinction corrections using the central surface brightness μ_c , I used the same methodology as for the μ_0 optimization. To incorporate μ_c in the corrections I re-wrote Eqns. 4.3 and 4.4 as,

$$f(R, \mu_c) = 10^{a(\mu_c) \cdot (A_\lambda)^{b(\mu_c)}}, \quad (4.8)$$

$$\Delta m_{iso}(\mu_c) = F(\mu_c) \cdot (A_\lambda)^{v(\mu_c)}, \quad (4.9)$$

with

$$\begin{aligned} a(\mu_c) &= a_o \exp(\mu_c \cdot a_1), \\ b(\mu_c) &= b_o \exp(\mu_c \cdot b_1), \\ F(\mu_c) &= F_o \exp(\mu_c \cdot F_1), \\ v(\mu_c) &= v_o \exp(\mu_c \cdot v_1). \end{aligned} \quad (4.10)$$

Again I determine the products ($a \times b$) and ($F \times v$) and how they vary with μ_c and hence derived the parameters ($a_o, b_o, F_o, v_o, a_1, b_1, F_1$, and v_1). The values of these parameters are given in Table 4.3.

Table 4.2: Parameters a_o , b_o , F_o , v_o , a_1 , b_1 , F_1 , and v_1 for the μ_0 optimization Eqn. 4.7.

Galaxy	Param.	J	H	K_s
E/S0	a_o	0.0005	$5.2(e^{-06})$	0.0002
	a_1	0.3301	0.6248	0.3993
	b_o	0.3659	15.9697	1.9398
	b_1	0.0704	-0.1589	-0.0289
	F_o	$2.8(e^{-11})$	$1.5(e^{-11})$	$6.7(e^{-11})$
	F_1	1.3090	1.3912	1.3309
	v_o	8.1329	236.9696	18.9573
	v_1	-0.0979	-0.3075	-0.1561
S	a_o	$3.3(e^{-06})$	$3.9(e^{-06})$	0.0001
	a_1	0.6093	0.6203	0.4406
	b_o	9.7884	7.0789	2.6909
	b_1	-0.1116	-0.095	-0.0395
	F_o	$8.1(e^{-11})$	$1.4(e^{-10})$	$2.4(e^{-7})$
	F_1	1.2277	1.2443	0.8365
	v_o	201.5666	56.9891	17.5403
	v_1	-0.2693	-0.2055	-0.1415

To quantify the performance of the two optimization corrections, I computed the difference between the corrections as given by the simulated data and by the optimised corrections using both the parametrization $f(R, \mu_0)$, $\Delta m_{iso}(\mu_0)$ and using $f(R, \mu_c)$, $\Delta m_{iso}(\mu_c)$. The comparison was made for all galaxies in the K_s band in the extinction range $A_{K_s} = 0^m0 - 3^m0$. A summary of the comparisons is listed in Table 4.4, and displayed in Fig. 4.4 for the μ_0 optimization and Table 4.5, Fig. 4.5 for the μ_c optimization.

The error bars in Figs. 4.4 and 4.5 and the plots that follow are the standard deviation error SE .

The plots and tables show that the accuracy of the corrections are extinction dependent, showing smaller deviations and less dispersion at low levels of extinction. It is also evident that spiral galaxies show larger deviations and more dispersion than elliptical and lenticular galaxies. The relatively larger errors for the spiral galaxies can be attributed to the structural features like spiral arms, bars traced by their light profiles. The comparison also shows that the corrections parametrized using the disk central surface brightness show less systematic shifts and tighter dispersion than the corrections using the central surface brightness optimisation. The better performance of μ_c in describing the corrections results from the fact that it is the outer galaxy disk that suffers more obscuration.

Table 4.3: Parameters a_o , b_o , F_o , v_o , a_1 , b_1 , F_1 , and v_1 for the μ_c optimization Eqn. 4.10.

Galaxy	Param.	J	H	K_s
E/S0	a_o	0.1279	0.0547	0.1598
	a_1	0.0063	0.0707	-0.0061
	b_o	0.8397	1.3805	0.7292
	b_1	0.0248	-0.0115	0.0381
	F_o	0.0073	0.0034	0.0151
	F_1	0.1889	0.2574	0.1632
	v_o	1.4504	2.1299	0.8602
	v_1	0.0046	-0.0253	0.0420
S	a_o	0.0068	0.0095	0.0157
	a_1	0.1953	0.1824	0.1641
	b_o	2.7721	2.5213	1.3653
	b_1	-0.0455	-0.0397	0.0009
	F_o	0.0003	0.0007	0.0012
	F_1	0.4136	0.3833	0.3751
	v_o	6.4910	4.6215	2.3296
	v_1	-0.0866	-0.0674	-0.0267

 Table 4.4: Comparison between simulated corrections and μ_0 optimised corrections at the extinction levels $A_{K_s} = 0^m5, 1^m0, 2^m0$ and 3^m0 .

Galaxy	Param.	0^m5	SE	1^m0	SE	2^m0	SE	3^m0	SE
E/S0	$f(R)$	0.0012	0.0071	0.0017	0.0130	0.0087	0.0236	0.0424	0.0433
E/S0	Δm_{iso}	0.0004	0.0022	0.0002	0.0035	0.0050	0.0091	0.0218	0.0280
S	$f(R)$	0.0042	0.0104	0.0071	0.0248	0.0748	0.1476	0.7993	1.1632
S	Δm_{iso}	-0.0016	0.0069	-0.0090	0.0156	-0.0070	0.0457	0.0479	0.1042

The μ_0 optimised corrections were calculated using Eqns. 4.5, 4.6. The value of μ_0 for each galaxy was found by performing a linear regression to fainter outer region of the galaxy light profile with $\mu_\lambda \gtrsim 17.0$ mag/arcsec² and measuring its intercept with the ordinate.

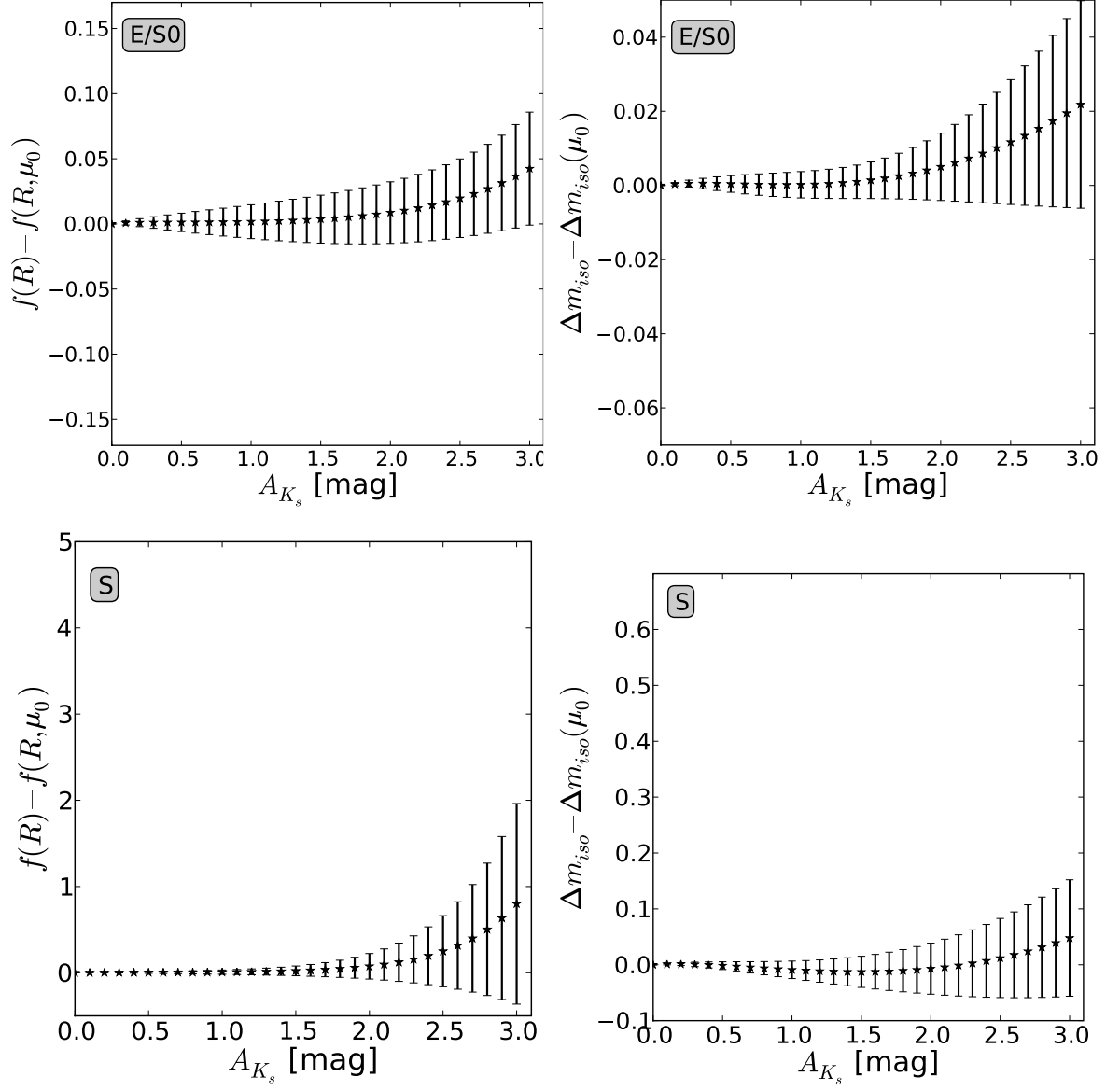


Figure 4.4: Comparison between simulated corrections and m_0 optimised corrections derived using $f(R, \mu_0)$ and $\Delta m_{iso}(R, \mu_0)$, top: **E/S0**, bottom: **S** galaxies.

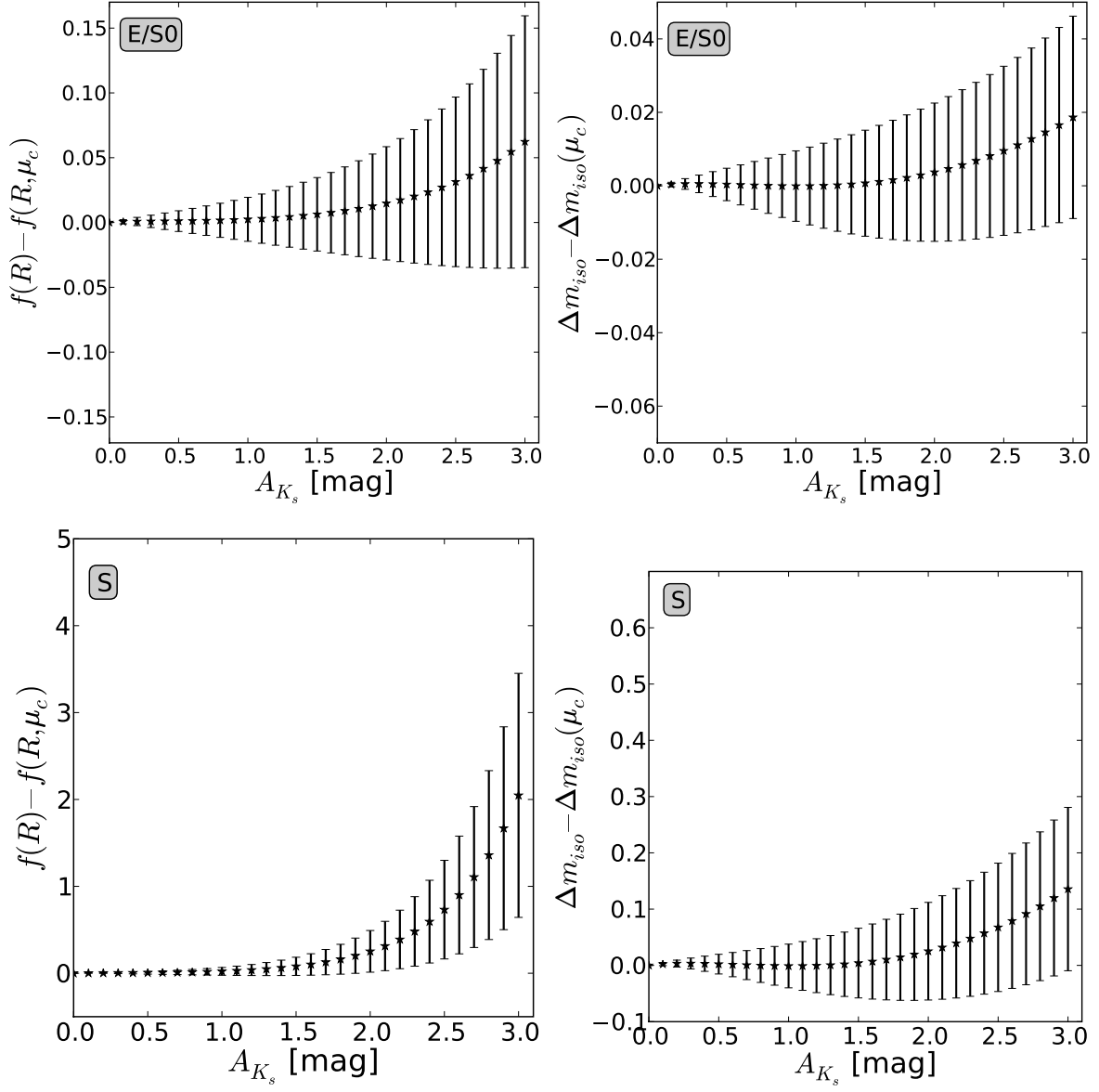


Figure 4.5: Comparison between simulated corrections and the μ_c optimised corrections derived using $f(R, \mu_c)$ and $\Delta m_{iso}(R, \mu_c)$, top: **E/S0**, bottom: **S** galaxies.

Table 4.5: Comparison between simulated corrections and μ_c optimised corrections at the extinction levels $A_{K_s} = 0^m5, 1^m0, 2^m0$ and 3^m0 .

Galaxy	Param.	0^m5	SE	1^m0	SE	2^m0	SE	3^m0	SDE
E/S0	$f(R)$	0.0010	0.0080	0.0025	0.0170	0.0148	0.0437	0.0623	0.0972
E/S0	Δm_{iso}	0.0004	0.0044	0.0000	0.0096	0.0037	0.0188	0.0186	0.0276
S	$f(R)$	0.0057	0.0157	0.0215	0.0449	0.2520	0.2398	2.0472	1.4042
S	Δm_{iso}	0.0022	0.0175	-0.0011	0.0388	0.0252	0.0868	0.1356	0.1451

The μ_c optimised corrections were calculated using Eqns. 4.8, 4.9.

It is also worth noting that $\approx 91\%$, 97% and 99% of the galaxies in the J , H and K_s bands in our ZOA survey are in regions with an extinction $A_{J,H,K_s} \lesssim 1^m0$ where the corrections show very little dispersion.

4.2.3 Average behaviour (average correction)

The application of the optimised method to estimate the obscuration corrections for galaxies requires the knowledge of the value of μ_0 and hence the galaxy light profile. In many cases that information is not available, or hard to obtain, like trying to correct isophotal radii or magnitudes for galaxies in a galaxy catalogue such as the 2MASX. For such cases an average correction independent of the galaxy light profile is required. In this section I derive such an average correction. A comparison between the application of the optimised and average corrections is given later in Sect. 4.3.

All elliptical galaxies and the majority of the spiral galaxies (85% of the spirals) show comparable trends (see Fig. 4.3), while only a few galaxies (M33, NGC24, NGC247, NGC1073, NGC55, NGC4244, marked on the plots) deviate from the average behaviour. To produce an average correction for each galaxy family **E/S0** or **S**, I excluded the strongly deviating galaxies. For the ones showing a similar behaviour (25 **E/S0** and 33 **S** galaxies) the simulated corrections were binned, resulting in an average correction curve for each family in each of the three bands. These average curves for the J , H and K_s bands are displayed in Fig. 4.6. For comparison, the B -band corrections are displayed as well. The latter are taken from Cameron (1990).

As expected, the error bars grow with increasing extinction. The error bars in Fig. 4.6 are biased with our selection of only those galaxies that show comparable extinction-corrections. Obviously including the strongly deviating galaxies the error bars would have been larger. Given that the majority of the galaxies follow the general behaviour, it would be unreasonable to include those outliers for the correction. It is also obvious from Fig. 4.6 that the correction curves are similar to those given by Cameron for the B band, especially the shorter J and H bands. The average correction curves were then fitted with Eqns. 4.3, 4.4. The respective fitting parameters are given in Table 4.6.

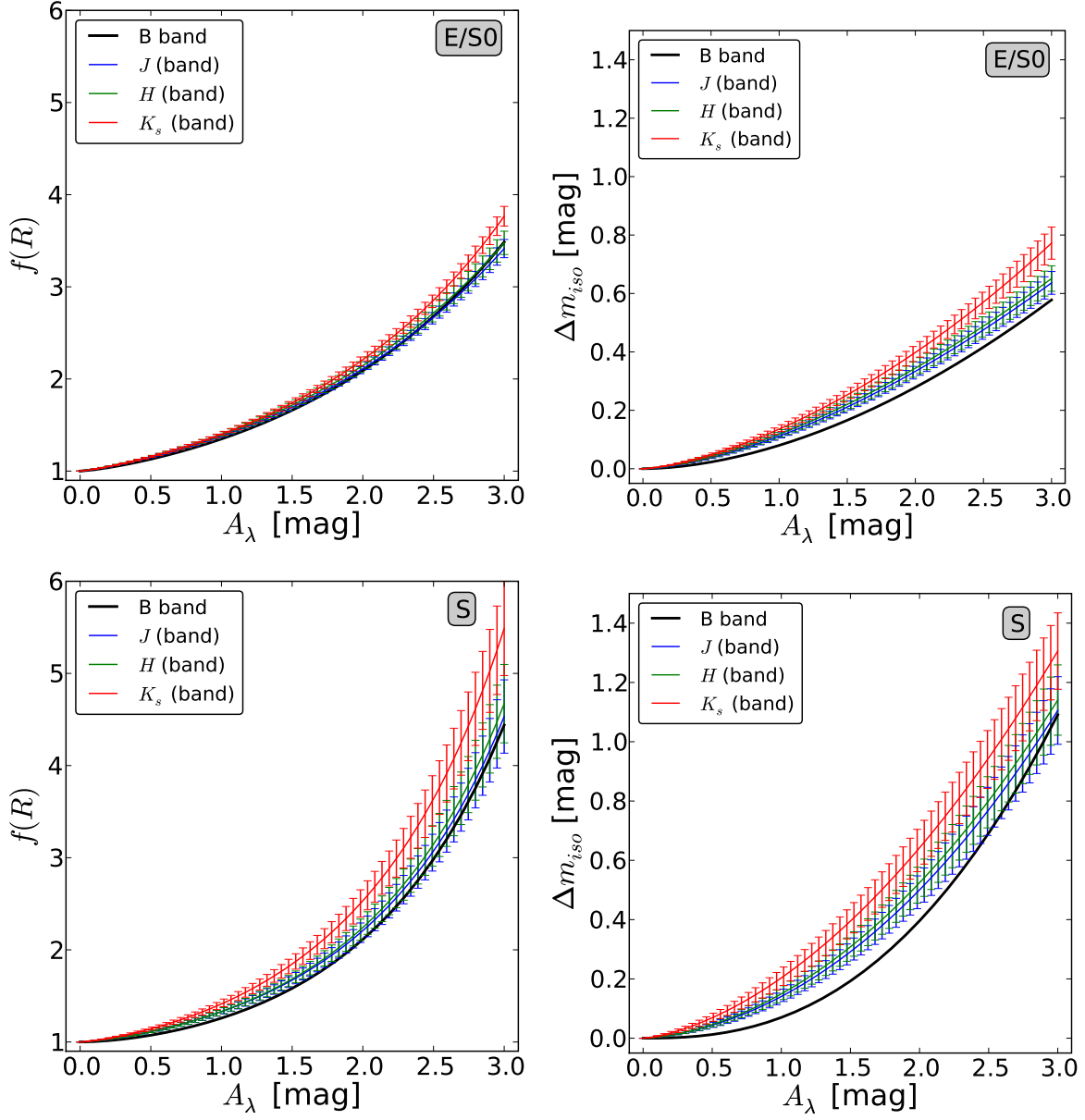


Figure 4.6: Average correction curves for the 25 **E/S0** (top), and 33 **S** galaxies (bottom) representing the average correction in each respective galaxy class, for the bands J , H , K_s and B band.

Table 4.6: Average fitting parameters a , b , F , and v for **E/S0** and **S** galaxies.

Galaxy	Param.	J	H	K_s
E/S0	a	0.1393 ± 0.0001	0.1438 ± 0.0001	0.1445 ± 0.0003
	b	1.2212 ± 0.0005	1.2056 ± 0.0004	1.2555 ± 0.0018
	F	0.1111 ± 0.0001	0.1175 ± 0.0002	0.1328 ± 0.0005
	v	1.5872 ± 0.0008	1.5559 ± 0.0019	1.5950 ± 0.0041
S	a	0.1169 ± 0.0007	0.1185 ± 0.0006	0.1453 ± 0.0005
	b	1.5650 ± 0.0056	1.5718 ± 0.0047	1.4778 ± 0.0032
	F	0.1346 ± 0.0008	0.1442 ± 0.0007	0.1982 ± 0.0009
	v	1.9080 ± 0.0064	1.8755 ± 0.0053	1.7093 ± 0.0049

Table 4.7: Comparison between simulated corrections and the average corrections at extinction levels $A_{K_s} = 0^m5, 1^m0, 2^m0$ and 3^m0 .

Galaxy	Param.	0^m5	SE	1^m0	SE	2^m0	SE	3^m0	SDE
E/S0	$f(R)$	0.0085	0.0081	0.0108	0.0170	0.0000	0.0450	-0.0457	0.1089
E/S0	Δm_{iso}	0.0425	0.0046	0.0045	0.0108	-0.0020	0.0266	-0.0126	0.0501
S	$f(R)$	0.0348	0.0177	0.0913	0.0530	0.4994	0.2961	2.9797	1.6339
S	Δm_{iso}	0.0406	0.0212	0.0920	0.0502	0.2365	0.1236	0.4594	0.2188

Average corrections were calculated using Eqns. 4.3, 4.4, and the parameters in Table 4.6.

To gain more insight on the variation of the average correction among the galaxies, I calculated the difference between the simulated corrections and the average corrections for each galaxy at $A_{K_s} = 1^m0$. The average correction was calculated using Eqns. 4.3, 4.4 and the parameters in Table 4.6. In Fig. 4.7, I plot these differences against the value of μ_0 for the galaxy in the K_s band. I find that **E/S0** galaxies with $\mu_0 \geq 16.2$ mag/arcsec² and **S** galaxies with $\mu_0 \geq 16.6$ mag/arcsec² are generally underestimated by the average correction, while brighter galaxies are overestimated by the correction.

To assess the accuracy of the average correction as a function of extinction, I made a comparison between the simulated corrections and those derived from the average correction in the extinction range $A_{K_s} = 0^m0 - 3^m0$. The results are plotted in Fig. 4.8. A summary is given in Table 4.7, where I list the mean difference between the simulated data and the average correction value at the extinction levels $A_{K_s} = 0^m5, 1^m0, 2^m0$ and 3^m0 , as well as their scatter.

Similar to the optimised corrections, the average correction method performs better for lower levels of extinction. Comparing Figs. 4.4, 4.5 and 4.8, Tables 4.4, 4.5 and 4.7, I note that the

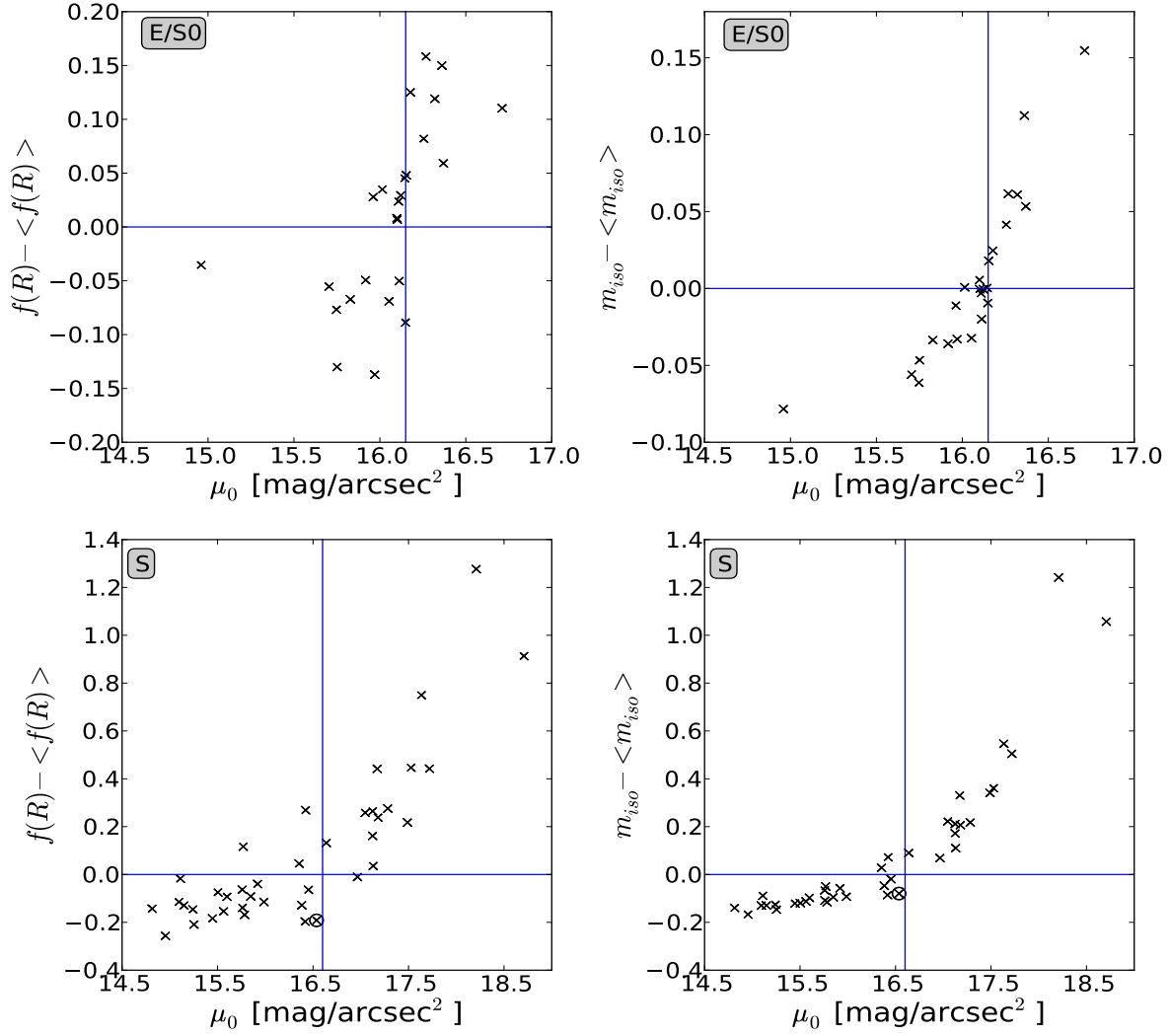


Figure 4.7: Difference between simulated corrections and average correction for an extinction value of $A_{K_s} = 1.0$. Top: **E/S0**, radius correction left panel, magnitude correction right panel. Bottom: **S**, radius correction left panel, magnitude correction right panel. The values for the galaxy M88 are indicated on the spiral panels with the symbol $\otimes$.

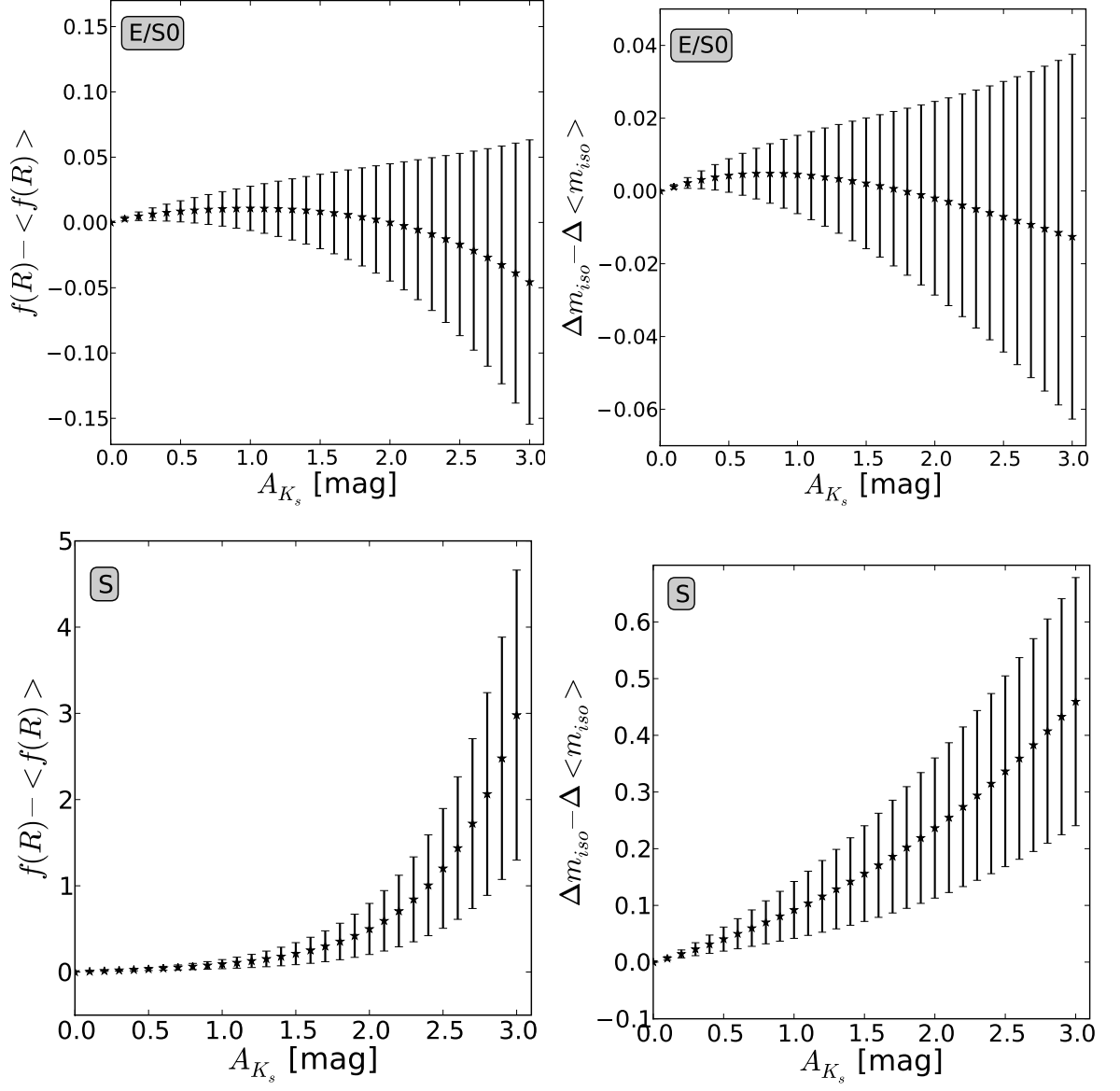


Figure 4.8: Comparison between simulated corrections and average corrections.

optimised corrections are more accurate than the average correction method.

4.3 Corrections reliability

To assess the accuracy of the average and the μ_0 -optimised method, I considered their comparison with the simulated corrections, see Figs. 4.4 and 4.8 and Tables 4.4 and 4.7. For spiral galaxies, estimating the magnitude corrections based on the μ_0 optimization, $\Delta m_{iso}(\mu_0)$ shows a systematic shift $\Delta = -0^m01$ with a $SE = 0^m0$ for an obscuration level of $A_{K_s} = 0^m5$. The average correction shows a $\Delta = 0^m04$ with $SE = 0^m02$ at that same level of extinction. At $A_{K_s} = 1^m0$, $\Delta m_{iso}(\mu_0)$ has a systematic shift of $\Delta = -0^m01$ and a $SE = 0^m02$, while the average correction has a $\Delta = 0^m09$ with a $SE = 0^m05$. Radius corrections for spiral galaxies revealed a similar trend for the two methods (see Tables 4.4 and 4.7). The comparisons for the elliptical galaxies are also given in Tables 4.4 and 4.7.

Figures 4.4, 4.8 and Tables 4.4, 4.7 give the comparison between the optimised and average corrections as compared to the simulated corrections for the extinction values $A_{K_s} = 0^m5$, 1^m0 , 2^m0 and 3^m0 . They clearly emphasize that the μ_0 optimised correction is more accurate compared to the average correction method. But the average correction remains more useful when applying the corrections to galaxy parameters from a galaxy catalogue.

The μ_c optimised correction shows larger shifts and more dispersion than the μ_0 optimised correction, but smaller shifts and tighter dispersion compared to the average correction.

In the following, I discuss some average correction values for magnitudes and radii of obscured galaxies. The average correction estimates a 0^m13 correction to the isophotal magnitude of elliptical galaxies at $A_{K_s} = 1^m0$. This magnitude correction is an addition to the $A_{K_s} = 1^m0$ correction. The magnitude correction shows a systematic shift of $\Delta = 0^m01$ with a $SE = 0^m01$ at $A_{K_s} = 1^m0$. As a function of radius, ellipticals are estimated to be 28.3% smaller in radius at $A_{K_s} = 1^m0$, when using the average correction. The radius correction shows a $\Delta = 0.6\%$ and $SE = 0.9\%$ at the same extinction level (see Table 4.8).

The isophotal magnitudes of spiral galaxies at $A_{K_s} = 1^m0$ are expected to be 0^m20 brighter when applying the average correction. They show a systematic shift of $\Delta = 0^m09$ with a $SE = 0^m05$ at $A_{K_s} = 1^m0$. The average corrections predict that spiral galaxies appear 28.4% smaller at $A_{K_s} = 1^m0$. The corrections show a systematic shift of $\Delta = 4.4\%$ with a $SE = 2.6\%$ at the same obscuration level (see Table 4.8). The table also lists the expected magnitudes and radii corrections at the extinction levels $A_{K_s} = 0^m5$, 1^m0 and 2^m0 respectively, it also includes the systematic shifts and the SE . The magnitude values listed in Table 4.8 give the additional dimming, the galaxy size reduction, the systematic shift when using the average correction and their respective SD . The positive systematic shifts indicate that the average correction under-estimates the obscuration corrections.

It is worth mentioning that these corrections agree well with values derived independently by Nagayama et al. (2004) for galaxies in the K_s band obscured by $A_{K_s} \lesssim 1^m0$. In their

4.4 Galactic extinction and the Schlegel reddening maps

Table 4.8: Average magnitudes and radii corrections at $A_{K_s} = 0^m5, 1^m0, 2^m0, 3^m0$.

	0 ^m 5			1 ^m 0			2 ^m 0			3 ^m 0		
[mag]	Δm_{iso}	Δ	SE	Δm_{iso}	Δ	SE	Δm_{iso}	Δ	SE	Δm_{iso}	Δ	SE
E/S0	0.044	0.004	0.005	0.133	0.005	0.011	0.401	-0.002	0.027	0.766	-0.013	0.050
S	0.061	0.041	0.021	0.198	0.092	0.050	0.648	0.236	0.124	1.296	0.459	0.219
[%]	$f(R)$	Δ	SE	$f(R)$	Δ	SE	$f(R)$	Δ	SE	$f(R)$	Δ	SE
E/S0	13.0	0.7	0.6	28.3	0.6	0.9	54.8	0.0	0.9	73.3	-0.3	0.8
S	11.3	2.7	1.4	28.4	4.4	2.6	60.6	6.5	4.1	81.7	6.5	4.3

The table lists the extra dimming and the radii reduction as estimated by the average corrections. It also lists the systematic shift Δ for comparing the simulated correction and the average correction with the respective SE . The positive systematic shifts indicate that the average correction under estimate the extinction correction.

work they estimated the extra dimming to elliptical galaxies to be $\Delta m_{iso} = 0^m15$ compared to $\Delta m_{iso} = 0^m13$ as expected by my average correction. For spiral galaxies they estimated the correction to be $\Delta m_{iso} = 0^m18$ which agrees well with our expected correction of $\Delta m_{iso} = 0^m20$. Compared to the Nagayama et al. (2004) corrections, our results are useful for higher extinction levels in the three NIR bands J , H and K_s i.e $A_{J,H,K_s} \leq 3^m0$.

Since the central surface brightness μ_c for galaxies in the NWS is listed in the final catalogue, and they give better estimates for the non-linear extinction correction term I used this method to correct the NWSC galaxies for extinction.

Extinction corrections derived in this chapter will be invaluable for NIR galaxy surveys aimed at revealing Large Scale Structures in the ZOA. It will also be applicable to other galaxy surveys e.g. 2MASX or prospective ESO galaxy surveys e.g. VISTA Kilo-Degree Infrared Galaxy Survey (VIKING¹) using the VISTA telescope.

4.4 Galactic extinction and the Schlegel reddening maps

The Schlegel dust maps (Schlegel et al., 1998) are widely used to estimate reddening along the line-of-sight to extragalactic sources. Adapting an appropriate extinction law (for example Cardelli, Clayton & Mathis 1989) the absorption can be calculated as a function of wavelength. Extinction in the NIR bands J , H and K_s is related to reddening via,

$$\begin{aligned}
 A_J &= 0.863 E(B - V), \\
 A_H &= 0.570 E(B - V), \\
 A_{K_s} &= 0.368 E(B - V).
 \end{aligned}
 \tag{4.11}$$

¹<http://www.eso.org/sci/observing/policies/PublicSurveys/sciencePublicSurveys.html>

According to Eqn. 4.11 the obscured NIR galaxies colours, $(J - H)$, $(H - K_s)$ and $(J - K_s)$ are related to $E(B - V)$ as follows,

$$\begin{aligned}(J - H) &= (J - H)^\circ + 0.293 E(B - V), \\(H - K_s) &= (H - K_s)^\circ + 0.202 E(B - V), \\(J - K_s) &= (J - K_s)^\circ + 0.495 E(B - V),\end{aligned}\tag{4.12}$$

where $(J - H)^\circ$, $(H - K_s)^\circ$ and $(J - K_s)^\circ$ are the extinction-corrected colours.

The Schlegel maps are not properly calibrated at low Galactic latitudes $|b| < 5^\circ$ because of contamination from unresolved Galactic and extragalactic sources in the DIRBE maps. A number of studies have indicated that the Schlegel maps overestimate extinction at these low Galactic latitudes. For example, Nagayama et al. (2004), using colour excess of giant stars in the region around PKS 1343-601, found that extinction in their survey region is overestimated by 33% when extrapolating the Schlegel maps to these latitudes. For the same region, but using the NIR galaxy colours, $(I - J)$, $(J - K_s)$, $(I - K_s)$, Schröder et al. (2007) concluded that extinction is overestimated by 13% in this region. In the work by van Driel et al. (2009), using 2MASS NIR colours for a sample of galaxies in the northern ZOA, it was found that reddening derived from Schlegel maps is 14% higher for galaxies seen through dust column densities of $0^m18 < A_{K_s} < 0^m54$, and 31% higher for galaxies obscured by $0^m54 < A_{K_s} < 0^m99$.

The above discussion can be summarized as follows: the Schlegel maps overestimate the extinction in the region $|b| < 5^\circ$. The degree of overestimation appears to be extinction-dependent.

To verify this with the NWS galaxies, I plot in Fig 4.9 the extinction-corrected galaxy colours as a function of $E(B - V)$. The dashed lines are a linear regression for colours as a function of reddening. Galaxy colours that are displayed in the figure were calculated from the $3''$ constant radius aperture. For reference I plot, as horizontal lines, the mean intrinsic galaxy colours $(J - H)^\circ = 0^m73$, $(H - K_s)^\circ = 0^m27$, and $(J - K_s)^\circ = 1^m0$ derived by Jarrett et al. (2003) for the 2MASX galaxies.

A linear regression for the colours as a function of extinction predict the following colours, $(J - H)^\circ = 0^m70$, $(H - K_s)^\circ = 0^m48$, and $(J - K_s)^\circ = 1^m18$ for galaxies in the NWS. It is worth noting here that the NWS galaxy colours were calculated using the $3''$ constant aperture magnitudes while those for 2MASS were derived using the 2MASS $5''$ constant aperture magnitudes. The shift between the NIR colours derived by Jarrett et al. (2003) and the colours found for the NWS galaxies is expected to be due to the fact of using different aperture magnitudes for calculating the galaxy colours in 2MASS and the NWS survey. Not correcting the NWS colours for redshift reddening is another reason for the NWS galaxy colours to look redder than their 2MASS counterparts. Galaxies that are further away are redder than nearby galaxies. The $(J - H)^\circ$ colour shows the smallest shift. This is not surprising Jarrett (2004), already showed that $(J - H)$ is the least affected by k-corrections compared to the other two NIR colours.

An aside on k-corrections:

k-corrections gives the magnitude transformation from a Hubble flow to a stationary moving

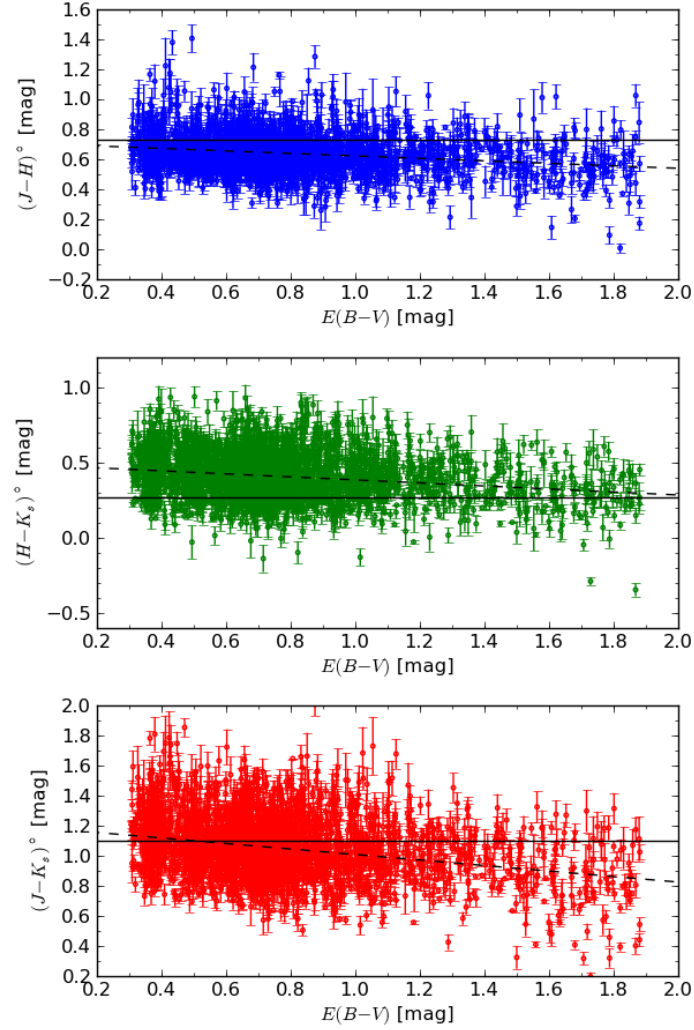


Figure 4.9: Extinction corrected galaxy colours as a function of extinction. The top panel shows $(J - H)^\circ$, the middle $(H - K_s)^\circ$ and bottom $(J - K_s)^\circ$. The dashed line is a linear regression through the plotted data. Only galaxies with $A_{K_s} < 0.7$ are shown on these plots.

frame. To de-redden a galaxy using the k-correction, the galaxy's redshift is required. Glass (1999) has shown that galaxy colours can be de-reddened using the following relation;

$$\begin{aligned}(J - H)^{\circ,k} &= (J - H)^{\circ} - 0.5z \\ (H - K_s)^{\circ,k} &= (H - K_s)^{\circ} - 3.5z \\ (J - K_s)^{\circ,k} &= (J - K_s)^{\circ} - 4.0z.\end{aligned}\tag{4.13}$$

This makes the $(J - H)$ colour the preferred choice over the other two colours for deriving corrections for the Schlegel reddening values.

The analysis here was limited to galaxies in regions with an extinction $A_{K_s} < 0^m7$, 94% of the galaxies in the NWS catalogue lie in such regions. The remaining 6% were excluded from the analysis as they were scarce and widely dispersed. I only considered a subset of galaxies from the NWS catalogue. Galaxies were selected to have reliable photometry in all three bands and a radius above $R > 3''$. The radius limit was imposed as to limit contamination to the aperture magnitudes for galaxies with a radius $R < 3''$. Outlier galaxies were also excluded from the analysis.

The method used here was previously applied by Schröder et al. (2007) to estimate corrections to the Schlegel maps in the region around PKS 1343-601. Here I briefly summarize the method. Equation 4.12 can be written for a generic colour C as,

$$C^{\circ} = aE(B - V) + b.\tag{4.14}$$

Where C° is the extinction-corrected colour, a , and b are the fitting parameters. The reddening equation for a colour C is given by,

$$C = C^{\circ} + E(C)E(B - V),\tag{4.15}$$

where $E(C)$ is the colour excess for C . Equivalently the true extinction-corrected colour $\widetilde{C}^{\circ}$ can be written as a function of the true reddening $\widetilde{E}(B - V)$ as,

$$\widetilde{C}^{\circ} = C - E(C)\widetilde{E}(B - V).\tag{4.16}$$

Combining Eqns. 4.14 - 4.16, and assuming that $E(B - V)$ scales as $E(B - V) = f\widetilde{E}(B - V)$, where f is the reddening scale factor we get,

$$\widetilde{C}^{\circ} = b + (a + (1 - f)E(C))E(B - V).\tag{4.17}$$

For extinction-corrected colours to be independent of extinction the term $(a + (1 - f)E(C))$ must vanish. Hence we get,

$$f = 1 + \frac{a}{E(C)}.\tag{4.18}$$

Performing a linear regression for the $(J - H)^{\circ}$ colours as a function of $E(B - V)$, Eqn. 4.14 can be written as,

$$C^{\circ} = (-0.85 \pm 0.01)E(B - V) + (0.70 \pm 0.01).\tag{4.19}$$

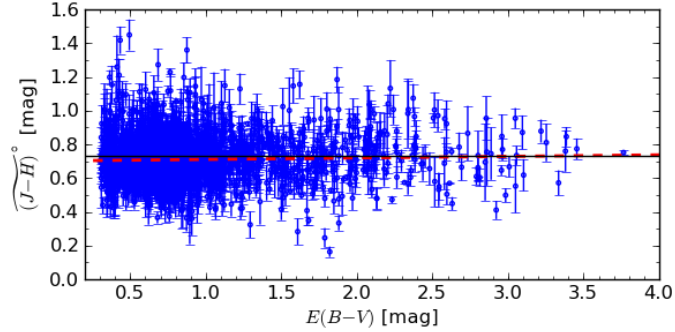


Figure 4.10: $(\widetilde{J-H})^\circ$ as a function of Galactic reddening. The red dashed line is a linear regression for $(\widetilde{J-H})^\circ$ as a function of $E(B-V)$ for galaxies with $E(B-V) < 4.0$. The solid horizontal line is $(J-H)^\circ = 0.73$.

For the $(J-H)$ colour, the colour excess $E(J-H) = 0.293$. Using this inputs, and Eqn. 4.18 the scale factor f was calculated to be $f = 0.71 \pm 0.02$.

This analysis shows that the Schlegel reddening maps overestimate extinction across the NWS area by 29%. This result is comparable to previous efforts by Nagayama et al. (2004); Schröder et al. (2007); van Driel et al. (2009). Nagayama et al. (2004), and Schröder et al. (2007) found that extinction around PKS 1343-601 is 33% and 14% overestimated respectively. van Driel et al. (2009) estimated the shift by 14% higher for galaxies obscured by $0.18 < A_{K_s} < 0.54$, and 31% for galaxies obscured by $0.54 < A_{K_s} < 0.99$.

Figure 4.10 shows the extinction corrected galaxy colours $(\widetilde{J-H})^\circ$ as a function $E(B-V)$ for galaxies in regions with galaxy reddening as high as $E(B-V) = 4.0$ ($A_{K_s} = 1.5$). Less than 1% of the galaxies in the NWS are in regions with extinction $A_{K_s} > 1.5$. These galaxies are sparsely distributed and hence are excluded from this plot. A linear regression to the data is shown with the red dashed line. The solid horizontal line is $(J-H)^\circ = 0.73$ (galaxy colour given by Jarrett et al. (2003)). Eventhough the corrections to the Schlegel reddening values is derived for values $E(B-V) < 2.0$ the plot in Fig. 4.10 shows that the correction is reliable to use for reddening as high as $E(B-V) = 4.0$. This is evident from the slight deviation between the fitted line (dashed) and the intrinsic galaxy colour (solid horizontal line) $(J-H)^\circ = 0.73$ for galaxy reddening $E(B-V) < 4.0$.

For the analysis of the large-scale structure described by the galaxies in the NWSC the Schlegel extinction values will be reduced by 29%.

5

The Norma Wall Survey Catalogue and Norma Wall

Our goal in this chapter is to describe and characterize the galaxy distribution uncovered by the Norma Wall Survey and how it is related to the large-scale structures in the region.

A first step toward this is to statistically quantify the observed parameters for the galaxies in the NWS area and to calculate the magnitude completeness limits for the NWS. The majority (99.2%) of the galaxies in the NWS are found in regions with dust obscuration $A_{K_s} < 1$ mag. Approximately 33.2 deg^2 (89%) of the survey area suffers a foreground extinction of $A_{K_s} < 1^m0$. Investigating the survey completeness limit as a function of extinction showed the galaxies in the NWS area are complete to $J_{(iso)}^\circ = 15^m6$, $H_{(iso)}^\circ = 15^m3$ and $K_{s(iso)}^\circ = 14^m8$ for galaxies suffering a foreground extinction less than $A_{J,H,K_s} < 1$ mag respectively.

The galaxy overdensity seen in the NWS footprint is studied in this chapter using galaxy number and density distributions. By comparing the galaxy density counts in the NWS to the mean density counts of 2MASX all-sky survey excluding the ZOA ($|b| < 10^\circ$), the NWS showed a clear galaxy density excess. Comparing this galaxy density excess to regions with known galaxy over/underdensities lying in the foreground, background or at the distance of the GA, here I assume that the GA is at the same distance of Norma cluster $cz = 4844 \text{ km s}^{-1}$ i.e. $z \approx 0.015$, the excess density in the NWS is found to be primarily due to galaxies at the GA distance. Apart from this general density enhancement no new hidden clusters at the GA distance are uncovered in the NWS area.

Investigating the survey area using galaxy density maps shows an overall homogeneous galaxy overdensity spread over the whole survey area. The density distribution in the two parts of the survey footprint that lie on the opposite sides of the GP are found to be quite similar. This

strongly suggested that the survey footprint maps a single large-scale structure that extends across the ZOA.

Over and above the identified homogeneous galaxy distribution five density peaks were further identified within the survey area. Two of these regions matched to the positions of the CIZA J1324.7-5736 and Cen-Crux clusters at the GA distance while the remaining three regions are expected to be due to structures more distant than the GA.

The excess galaxy density at the distance of the GA was identified from foreground and background galaxies using two methods. The first compares the density counts in the NWS to the mean 2MASX density counts while the second method uses photometric redshifts. Both suggest that the galaxy overdensity observed within the NWS area is due to galaxies at the GA distance. By deriving the luminosity function for galaxies in the NWS at the GA and hence the total flux due to these galaxies, the total mass in the Norma Wall is estimated to be $\approx 4.06 \times 10^{15} h^{-1} M_{\odot}$.

Beside using photometric redshifts for identifying the galaxy distribution at the GA distance, they were also used to study the overall galaxy distribution in the NWS area. This provided evidence for another large-scale structure that might lie behind the GA at $z \approx 0.1$.

5.1 The NWS catalogue statistics

To analyze the galaxy distribution in the NWS, I first characterize the observed galaxy parameters statistically. As a function of extinction, 90.6% of the galaxies are found in regions with $A_J \leq 1^m0$, while 97.1% and 99.2% of the galaxies are found in regions with $A_{H,K_s} \leq 1$ mag respectively. The histograms in Fig. 5.1 display the galaxy counts as a function of extinction for galaxies with $A_{(J,H,K_s)} \leq 3$ mag. Galaxy counts for galaxies with $A_{(J,H,K_s)} > 3$ mag are not shown in these histograms. Only $< 0.5\%$ of the galaxies in the survey area are found in regions with $A_{(J,H,K_s)} > 3$ mag. They are not expected to influence the distributions in Fig. 5.1.

The foreground extinction suffered by galaxies in the NWS area varies between $0^m19 < A_J < 11^m60$ with a mean $\bar{A}_J = 0^m55$ and median $\tilde{A}_J = 0^m45$ in the J band. In the H band galaxies suffer an obscuration between $0^m12 < A_H < 7^m66$ with a mean $\bar{A}_H = 0^m37$ and median $\tilde{A}_H = 0^m29$. In the K_s band the extinction ranges from $0^m08 < A_{K_s} < 4^m95$, a mean $\bar{A}_{K_s} = 0^m24$ and a median $\tilde{A}_{K_s} = 0^m19$. The vertical lines on the histograms are the mean extinctions $\bar{A}_{J,H,K_s}$. Table 5.1 lists the number(percentage) of galaxies found at different extinction levels. Almost 90% of the galaxies are found in a region with foreground extinction $A_J = 0^m98$, $A_H = 0^m65$ and $A_{K_s} = 0^m42$.

In the following sections I will discuss the statistical distribution for selected number of the observed galaxy parameters with and without extinction corrections. The selected galaxy parameters are the central surface brightness, the Kron magnitudes, isophotal magnitudes and radii. These parameters are discussed here as they are important for deriving the survey completeness limits and the subsequent study of the large-scale structures in the survey area.

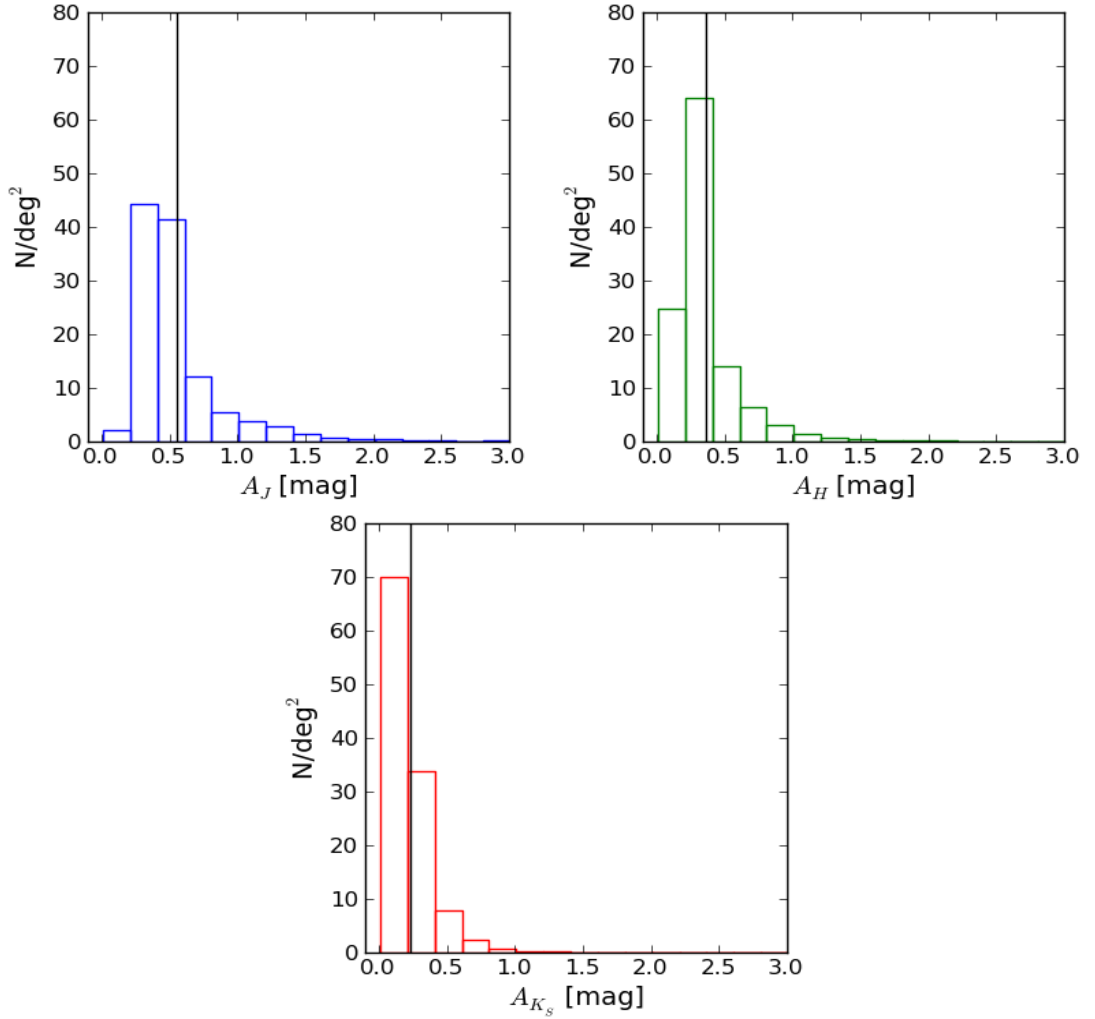


Figure 5.1: Histograms of the number of galaxies detected per square degree as a function of Galactic extinction A_{J,H,K_s} . Top left: J band, top right: H band and bottom: K_s band. Only the distribution of galaxies in regions with $A_{J,H,K_s} \leq 3$ mag are shown.

The central surface brightness (μ_c ; Sect. 3.2) has been found to be a good indicator for the galaxy morphological types (Jarrett, 2000; Jarrett et al., 2003). In Sect. 4.2.2 μ_c was also used to optimize the extinction corrections to the isophotal magnitudes and radii. Figure 5.2 displays the histograms for the $3''$ central surface brightness. The dashed histograms correspond to the observed central surface brightness while the extinction-corrected values are represented by the hatched histograms. μ_c is corrected for extinction using Eqn. 4.1. The mean values for the observed and extinction-corrected values are indicated in Fig. 5.2 by dashed and solid vertical lines respectively. Galaxies in the NWS have the following mean observed central surface

Table 5.1: Galaxy distribution as a function of extinction

Passband	$0^m0 < A_\lambda \leq 1^m0$	$1^m0 < A_\lambda \leq 2^m0$	$2^m0 < A_\lambda \leq 3^m0$	$A_\lambda > 3^m0$
	N([%])	N([%])	N([%])	N([%])
J	3952(90.63)	351(8.06)	38(0.88)	19(0.43)
H	4235(97.14)	106(2.42)	15(0.35)	4(0.09)
K_s	4325(99.20)	31(0.70)	2(0.05)	2(0.05)

brightness $\mu_c(J) = 19^m90$, $\mu_c(H) = 19^m00$ and $\mu_c(K_s) = 18^m40$. The obscured and extinction-corrected mean μ_c values are listed in Table 5.2.

The Kron magnitudes are listed in the NWS catalogue as a measure of the total galaxy magnitudes. Figure 5.3 shows the distribution for the observed (dashed histograms) and extinction-corrected (hatched histograms) Kron magnitudes. Kron magnitudes are corrected for extinction using Eqn. 4.1, i.e. only applying the linear extinction-correction. The nonlinear extinction corrections are not applied for the Kron magnitudes as they are not straightforward to derive (see discussion in Chapter 4). The mean observed and extinction-corrected Kron magnitudes are indicated in Fig. 5.3 with the dashed and solid lines respectively. The galaxies listed in the NWS catalogue have the following mean observed Kron magnitudes $J_{(Kron)} = 15^m99$, $H_{(Kron)} = 15^m10$ and $K_{s(Kron)} = 14^m53$. The mean observed and extinction-corrected Kron magnitudes are listed in Table 5.2.

Even though isophotal magnitudes are not a direct measure of a galaxy's total luminosity, they are reliable measures of the luminosity of the galaxies. Contrary to the Kron magnitudes, extinction corrections for isophotal magnitudes are more straightforward to define (see discussion in Chapter 4). For this reason isophotal magnitudes are favoured in this chapter for studying the galaxy distribution in the NWS. The isophotal magnitudes distribution are displayed in Fig. 5.4 while the isophotal radii distributions are shown in Fig. 5.5. Again the dashed histograms are representative of the observed parameters and the hatched histograms of the extinction-corrected parameters. Isophotal magnitudes and radii were corrected for extinction using the μ_c -optimized corrections defined by Eqns. 4.2, 4.9 and 4.8. The mean observed and extinction-corrected isophotal parameters are indicated in the plots by the dashed and solid lines respectively. The observed galaxies in the NWS area have a mean observed isophotal magnitudes $J_{(iso)} = 16^m03$, $H_{(iso)} = 15^m15$ and $K_{s(iso)} = 14^m55$. The mean observed and extinction-corrected values are listed in Table 5.2. To complement Table 5.2 I also list in Table 5.3 the median values for the observed and extinction-corrected central surface brightness, Kron and Isophotal magnitudes and Isophotal radii.

Table 5.2: Mean observed and extinction-corrected galaxy parameters.

param		J	J°	H	H°	K_s	K_s°
μ_c	[mag]	19.90	19.35	19.00	18.63	18.40	18.17
Kron	[mag]	15.99	15.44	15.10	14.73	14.53	14.29
ISO	[mag]	16.03	15.12	15.15	14.58	14.55	14.30
Radii	[arcsec]	5.35	7.57	5.55	6.33	4.93	5.48

Table 5.3: Median observed and extinction-corrected galaxy parameters.

param		J	J°	H	H°	K_s	K_s°
μ_c	[mag]	20.02	19.47	19.14	18.78	18.53	18.30
Kron	[mag]	16.16	15.61	15.30	14.93	14.72	14.48
ISO	[mag]	16.24	15.30	15.39	14.81	14.78	14.41
Radii	[arcsec]	3.75	3.34	3.75	4.60	3.58	4.00

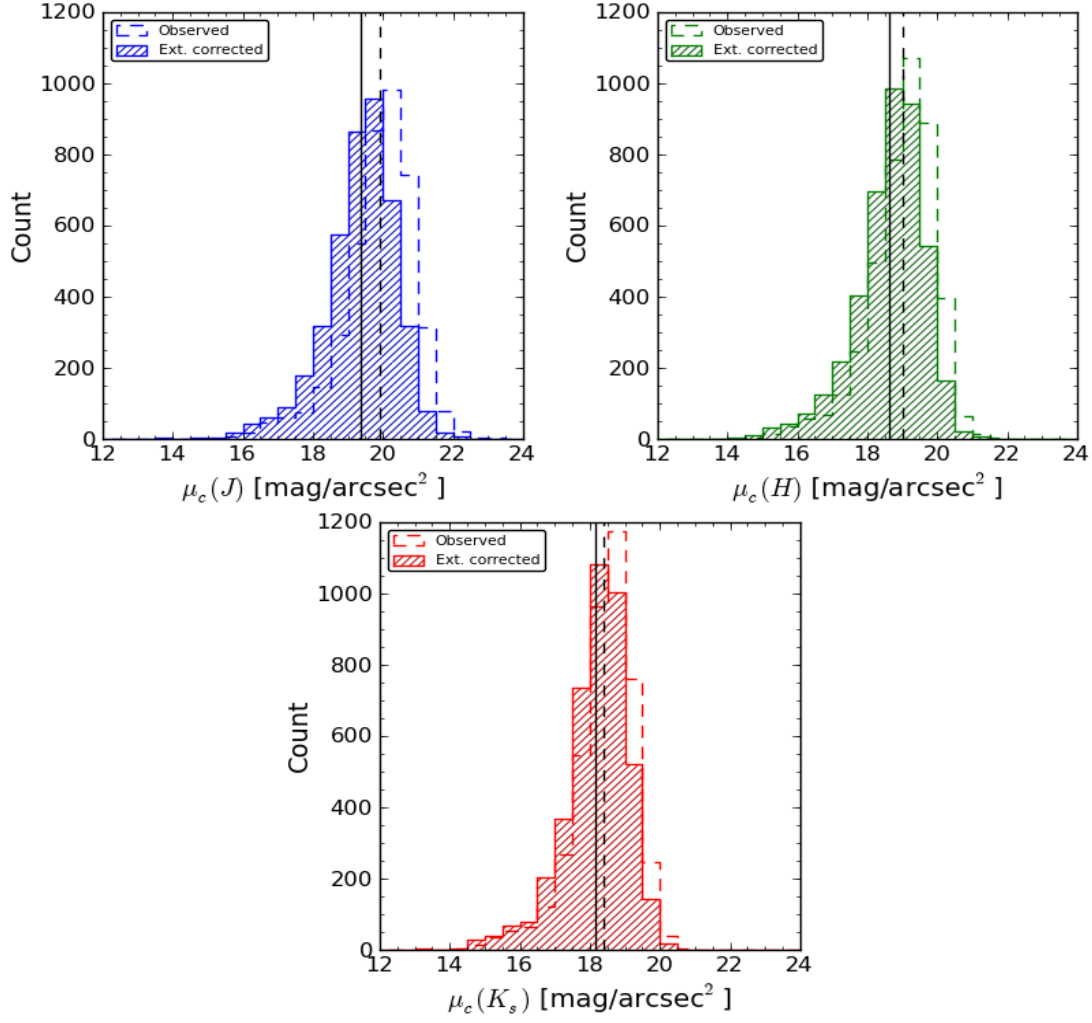


Figure 5.2: Central surface brightness distribution for the NWS catalogue. The shaded histograms are for the extinction-corrected central surface brightness and the open histograms are the observed values. Left: J band, middle: H band and right: K_s band.

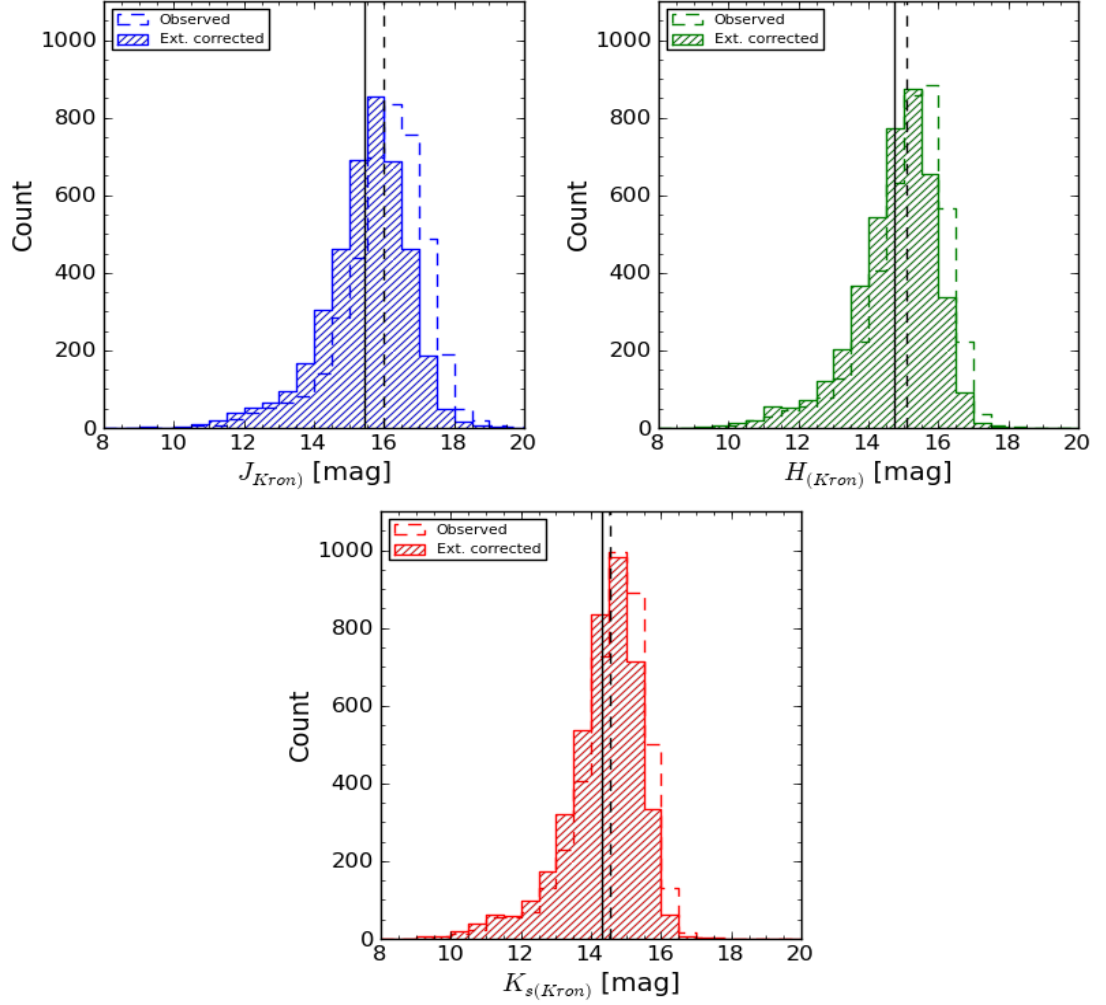


Figure 5.3: Kron magnitude distribution for the NWS catalogue. The shaded histograms are for the extinction-corrected Kron magnitude and the open histograms are the observed magnitudes. Top left: J band, top right: H band and bottom: K_s band.

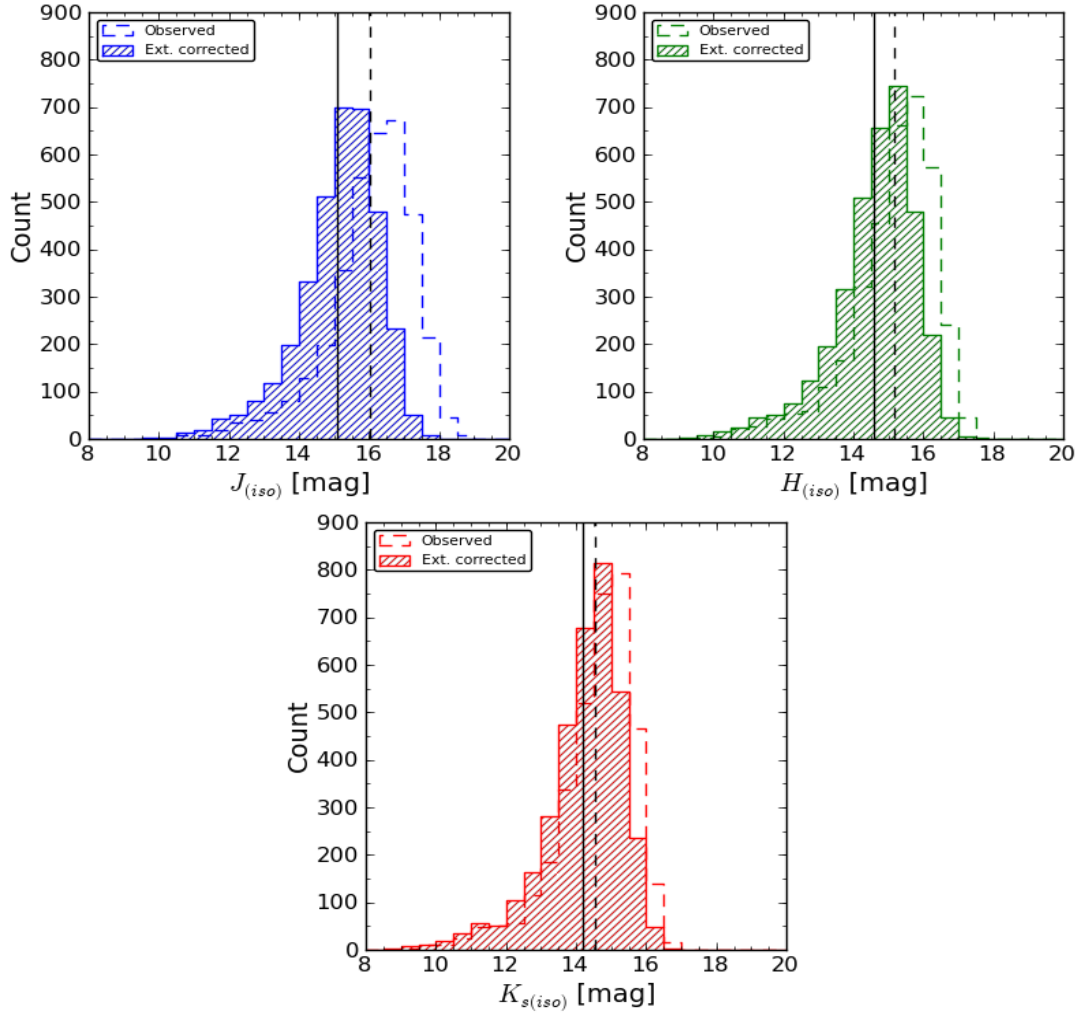


Figure 5.4: Isophotal magnitude distribution for the NWS catalogue. The shaded histograms are for the extinction-corrected isophotal magnitude. Top left: J band, top right: H band and bottom: K_s band.

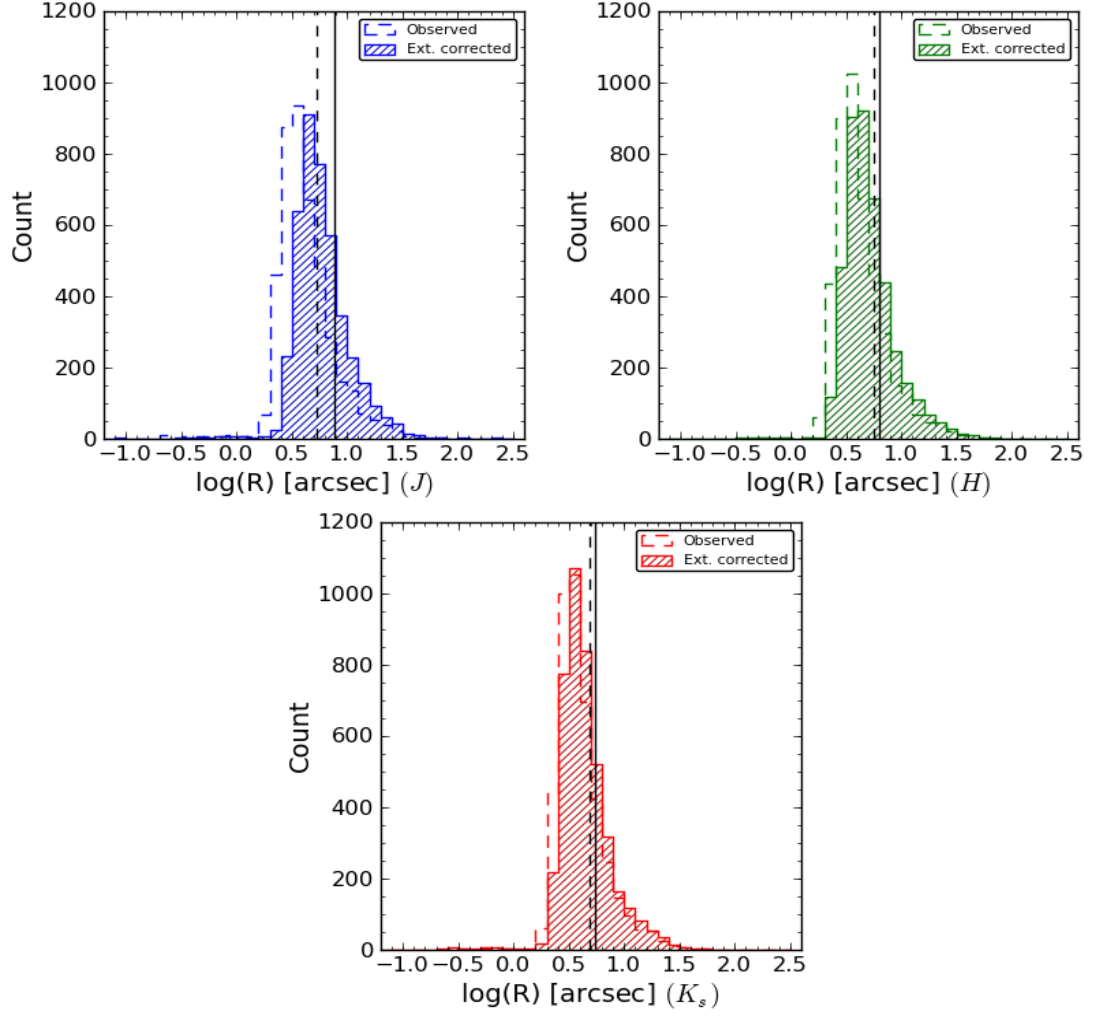


Figure 5.5: Isophotal radii distribution for the NWS catalogue. The shaded histograms are for the extinction-corrected radii. Top left: J band, top right: H band and bottom: K_s band.

As was mentioned earlier, the mean central surface brightness (μ_c) is used to identify galaxies as early or late-type (Sect. 3.2) and hence for correcting their observed isophotal parameters using the μ_c -optimized extinction corrections (Sect. 4.2.2). Equation 3.4 indicates that μ_c is a function of the aperture size used for its calculation. This has the consequence that μ_c is brighter for increasingly smaller apertures. This is expected as small apertures sample more of the luminous galaxy core than the larger apertures do. According to Jarrett (2000) and Jarrett et al. (2003), early-type galaxies are always brighter ($\mu_c(K_s) < 16^m.7$) than late-type galaxies (Sect. 3.2). For example, using 3'' aperture magnitude only 4.4% of the galaxies are identified as early-type, while 19.0% of the galaxies are classified as early-type when using the 1'' aperture magnitudes.

According to the discussions in Sect. 4.2.2 and Eqns. 4.2, 4.8, 4.9 galaxies with a faint central surface brightness get larger μ_c -optimized extinction corrections for their isophotal magnitude compared to galaxies with a brighter central core. To investigate the effect of the variation in μ_c as a function of aperture size on the extinction corrections, the galaxy classification and extinction-correction are repeated using both the 3'' magnitude and the 1'' central surface brightness magnitudes. Based on these differently determined galaxy morphologies the isophotal magnitudes are independently corrected for extinction. The distribution for the extinction-corrected isophotal magnitudes is compared in Fig 5.6. In these plots the shaded histograms correspond to the magnitudes corrected with the 3'' μ_c , while the dashed histograms correspond to the 1'' μ_c -corrected magnitudes. The mean extinction-corrected isophotal magnitudes are marked on the histograms with the dashed vertical line for the 1'' corrections and the solid line for the 3'' corrections.

The mean 3'' extinction-corrected J° , H° and K_s° isophotal magnitudes are $0^m.17$, $0^m.07$ and $0^m.05$ brighter than the respective 1'' extinction-corrected isophotal magnitudes. The larger extinction corrections for the 3'' central surface brightness are expected as it was mentioned in Sect. 4.2.2 that galaxies with a low central surface brightness require larger extinction corrections compared to galaxies with a higher central surface brightness. The histograms in Fig. 5.6 shows that extinction corrections are not very sensitive to the size of the aperture used for calculating μ_c . The larger corrections in the J band compared to the H and K_s results from the fact that extinction in J band is higher than in the other two bands (see Fig. 5.1).

Galaxies in the NWS area have a mean isophotal radius of $\langle R \rangle = 5''.35$ the J band, $\langle R \rangle = 5''.55$ in the H band and $\langle R \rangle = 4''.93$ in the K_s band. The 3'' is favoured over the 1'' aperture to apply the extinction corrections because it is large enough compared to the mean isophotal radii of the galaxies to sample most of the light in the galaxy, yet not so large to be contaminated by light from the neighbourhood of the galaxy. Furthermore the 1'' magnitudes aperture are expected to be strongly affected by the average seeing in the survey images which was found to be FWHM = $1''.38$ in the K_s band (see Table 2.7).

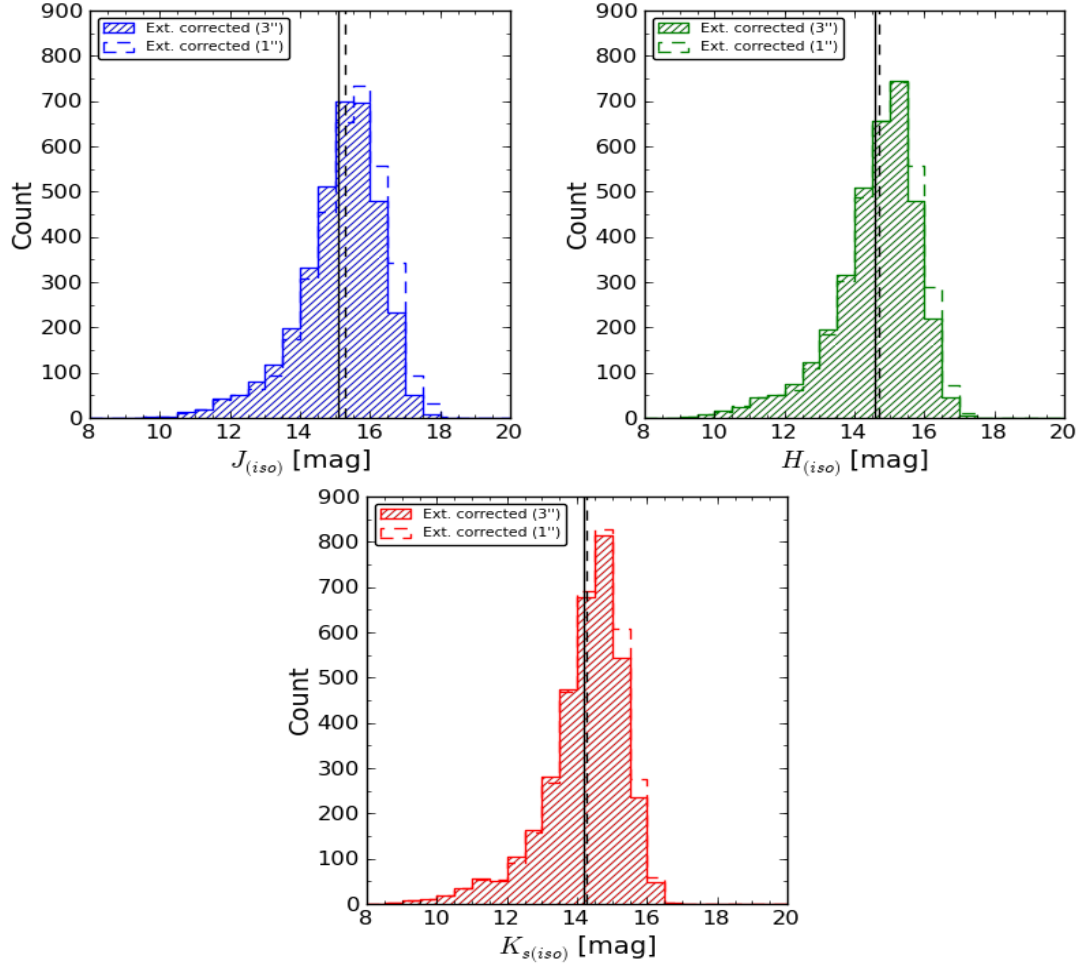


Figure 5.6: Extinction-corrected isophotal magnitudes for the NWS catalogue. The shaded histograms are for the extinction-corrected isophotal magnitude using the 3'' mean central surface brightness and the dashed are for the 1'' central surface brightness. Top left: J° band, top right: H° band and bottom: K_s° band.

5.2 Magnitude completeness limits

Before studying the galaxy distribution and the large-scale structure in the NWS area it is important to first investigate the survey magnitude completeness limit. Because of the strongly varying extinction in the survey region, the completeness limits of the survey area are investigated as a function of extinction. Isophotal magnitudes have well-defined extinction corrections compared to the Kron magnitudes. For this reason the completeness limits for galaxies identified in the NWS area are determined as a function of isophotal magnitudes only.

To do this, I display in Fig. 5.7 the histograms for the logarithm of the cumulative galaxy count, $\log N$. The left hand panel shows $\log N$ as a function of the observed isophotal magnitudes and the right panel displays $\log N$ as a function of the extinction-corrected magnitudes. In these plots, galaxies at different extinction intervals are plotted independently.

The completeness limits were derived from the cumulative galaxy counts by visually inspecting the knee in these histograms. The cumulative galaxy counts are expected to increase linearly as a function of magnitude. Where these counts start deviating from the linear increasing trend (the knee), signals incompleteness. The completeness magnitude is defined here as the magnitude where the $\log N$ distribution flattens. Using this definition and the histograms in Fig. 5.7 the NWS catalogue is found to be complete to $J_{(iso)} = 16^m6$, $H_{(iso)} = 15^m8$ and $K_{s(iso)} = 15^m4$. These magnitudes are the completeness limits for the observed isophotal magnitudes. Cluver (2009) found very similar values of $J_{(iso)} = 16^m4$, $H_{(iso)} = 15^m8$ and $K_{s(iso)} = 15^m4$ for galaxies found in her survey area in the Vela region centred on $\ell = 262^\circ48$, $b = -1^\circ64$. The survey by Cluver (2009) was also carried out with the IRSF/SIRIUS, i.e. the same telescope and instrument as the NWS, and with the same exposure time as the NWS.

The cumulative curves as a function of extinction-corrected magnitudes (right panel of Fig. 5.7) are clearly extinction dependent. Galaxies in regions with extinction $A_\lambda \leq 1^m0$ are found to be complete to $J_{(iso)}^\circ = 15^m6$, $H_{(iso)}^\circ = 15^m3$ and $K_{s(iso)}^\circ = 14^m8$. Galaxies in regions with $1^m0 < A_\lambda \leq 2^m0$ are complete to $J_{(iso)}^\circ = 14^m2$, $H_{(iso)}^\circ = 13^m2$ and $K_{s(iso)}^\circ = 12^m2$. As there are so few galaxies in regions with $A_\lambda > 2^m0$ this extinction range is not investigated further for completeness. Table 5.4 gives a summary of the NWS completeness limits as a function of the observed isophotal magnitudes and the extinction-corrected magnitudes.

Table 5.4: The NWS completeness limits.

	$J_{(iso)}$ [mag]	$H_{(iso)}$ [mag]	$K_{s(iso)}$ [mag]
observed	16.6	15.8	15.4
extinction-corrected ($A_\lambda \leq 1^m0$)	15.6	15.3	14.8
extinction-corrected ($1^m0 \leq A_\lambda \leq 2^m0$)	14.2	13.2	12.2

Both Galactic extinction and star-crowding increases significantly towards the GP. As discussed earlier, the completeness limits for NIR surveys are due to the combined effects of both the dust obscuration and star-crowding. This is seen in Fig. 5.8, in this map I show the distribution of NWS galaxies (magenta dots), 2MASX galaxies (green dots), stellar-density $\log(N_{(K_s < 14)}/\text{deg}^2)$ (coloured contours). The stellar density contours shown in this map are created from the stellar density derived from the NWS images. The contours in the region outside the survey area are extrapolations from the region within the survey area (outlined with the black line). The stellar density contour at $\log(N_{(K_s < 14)}/\text{deg}^2)=4.71$ (dashed) and the extinction contour at $A_{K_s} = 1^m0$ (solid brown) where 97.8% of the galaxies lie below are both marked on

the map.

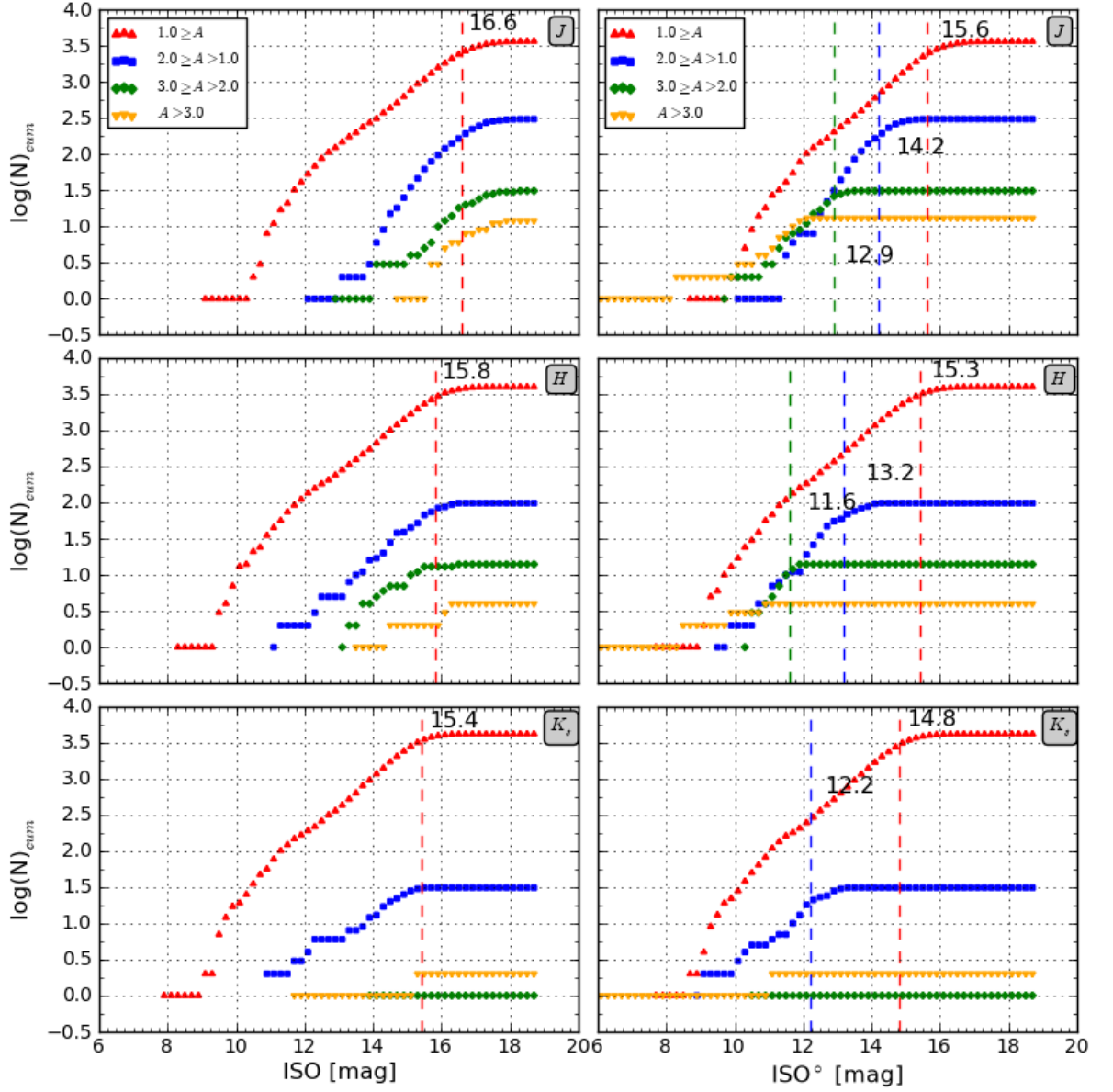


Figure 5.7: Magnitude completeness limits. The left column shows the completeness limit for the observed isophotal magnitudes, while the right column shows the extinction-corrected isophotal magnitudes. The top row is for the J band, the middle H and the bottom the K_s band.

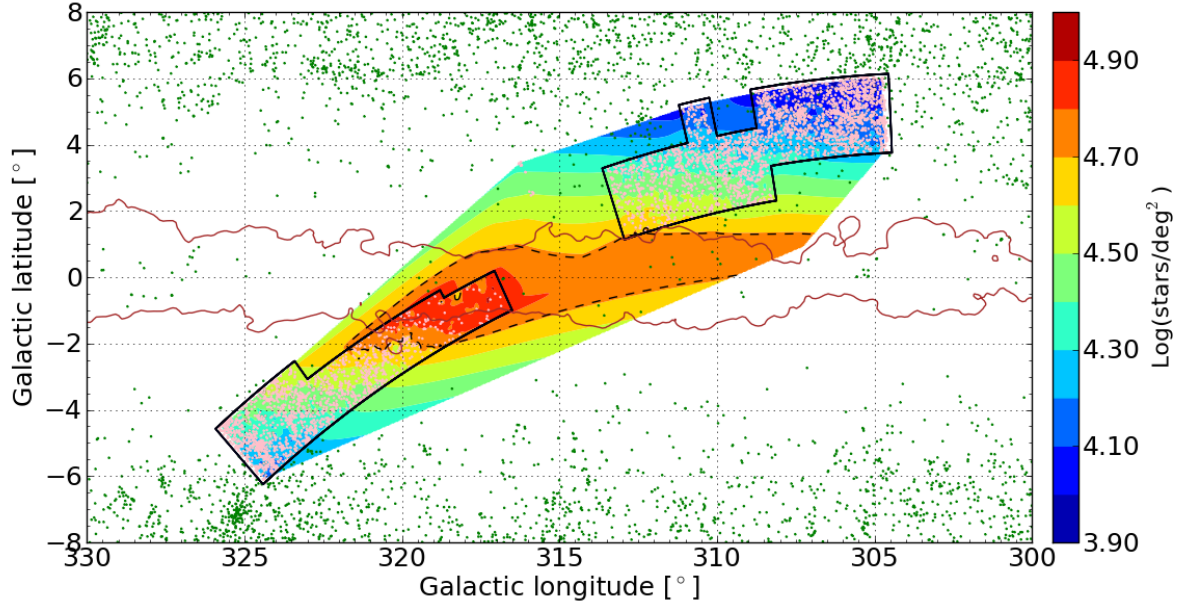


Figure 5.8: Distribution of the NWS galaxies (magenta dots). The green dots are 2MASX galaxies. Stellar density is marked with the filled contours. Extinction at $A_{K_s} = 1.0$ (brown line) and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2) = 4.71$ (dark dashed gray line) below which 97.8% of the galaxies lie. The stellar-density contours shown in this map are created from the stellar-density derived from the NWS images. The contours in the region outside the survey area are extrapolations from the region within the survey area (outlined with the black line).

A strong correlation between the dust obscuration and the Galactic extinction is evident. Approximately 33.2 deg^2 (89%) of the survey area is found in regions with an extinction $A_{K_s} \leq 1.0$ and $\log(N_{(K_s < 14)}/\text{deg}^2) \leq 4.71$. The majority (97.8%) of the galaxies observed in the NWS are found in this 33.2 deg^2 . This area includes the whole survey area in the top part of the survey footprint above the GP and the lower part of the footprint below $b \lesssim -2^\circ$. This discussion leads to the conclusion that the NWS catalogue is complete to $K_{s(iso)}^\circ = 14^m8$ for 89% of the survey area for extinction levels and stellar densities below $A_{K_s} \leq 1.0$ and $\log(N_{(K_s < 14)}/\text{deg}^2) \leq 4.71$ respectively.

Galaxy Number counts

Galaxy number counts per square degree per magnitude, $\log(N \text{ deg}^{-2} \text{ mag}^{-1})$, can also be used to assess the completeness limits of galaxy surveys. Figure 5.9 displays $\log(N \text{ deg}^{-2} \text{ mag}^{-1})$ for the J , H and K_s bands. Galaxy magnitudes are grouped in bins of 0^m5 . The plain histograms are for the observed magnitudes counts and the hashed histograms are based on the extinction-

corrected counts.

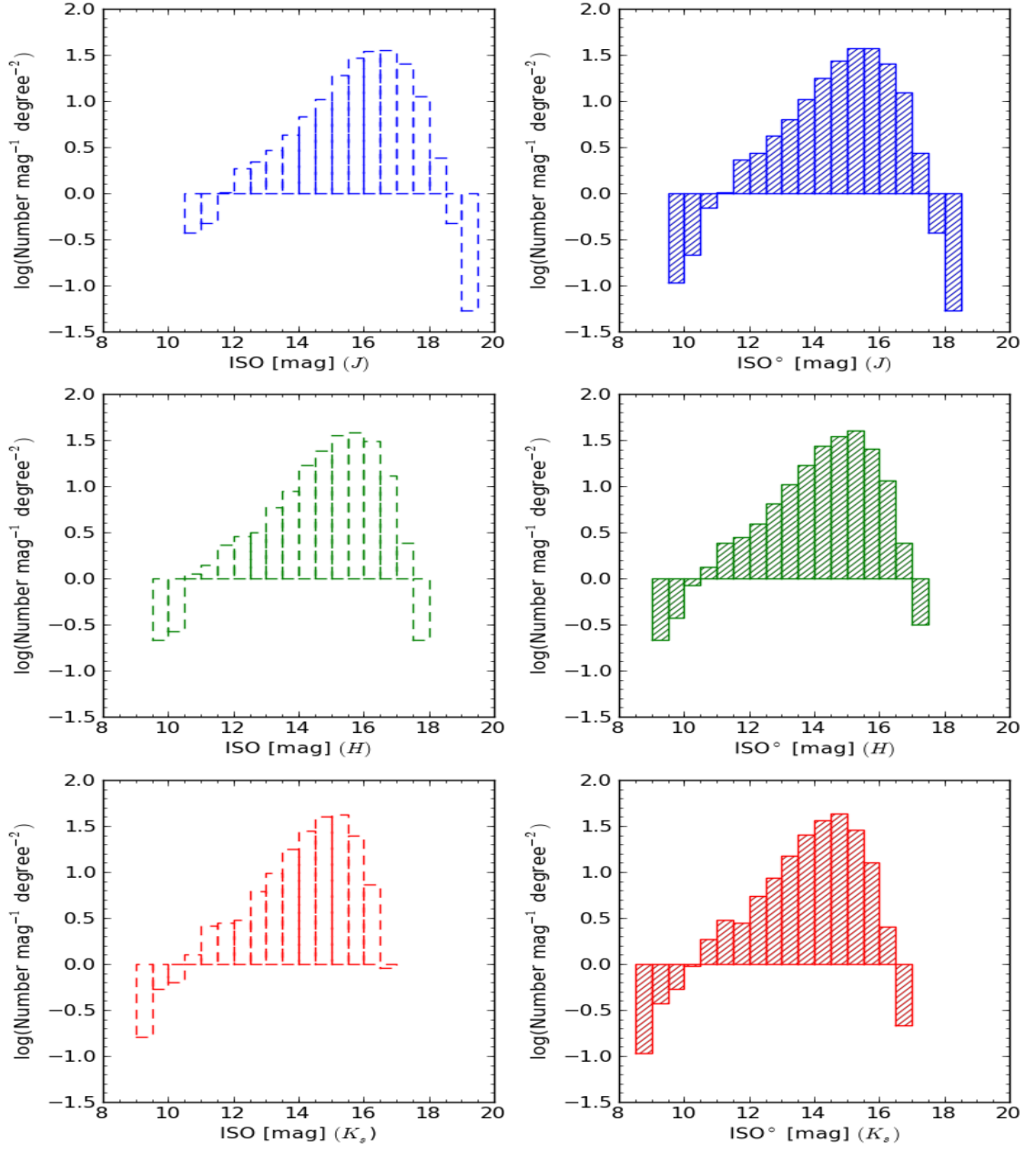


Figure 5.9: The NWS catalogue galaxy number density. The plots show the number density defined as $\log(N \text{ mag}^{-1} \text{ deg}^{-2})$. The isophotal magnitudes are grouped in bins of $0^{\text{m}}.5$. Top: *J* band, middle: *H* band and bottom: *K_s* band. The plain histograms are for the observed magnitudes counts and the hashed histograms are based on the extinction-corrected counts.

Figure 5.9 shows that these density counts peak in the magnitude ranges $15^m0 \leq J_{(iso)}^\circ \leq 16^m0$, $15^m0 \leq H_{(iso)}^\circ \leq 15^m5$ and $14^m5 \leq K_{s(iso)}^\circ \leq 15^m0$. On these histograms number counts for galaxies fainter than $J_{(iso)}^\circ \leq 16^m0$, $H_{(iso)}^\circ \leq 15^m5$ and $K_{s(iso)}^\circ \leq 15^m0$ fall off very rapidly, again a sign for incompleteness. The positions of the peak counts (see 5.9) suggests completeness limits of $J_{(iso)}^\circ = 15^m5$, $H_{(iso)}^\circ = 15^m3$ and $K_{s(iso)}^\circ = 14^m8$. The quoted magnitude completeness limits are the mid-point values approximated to one significant figure for the peak density counts of the extinction corrected isophotal magnitudes shown in the right panel of Fig. 5.9. These values are in agreement with those estimated from the cumulative density counts.

The number density counts are also useful to identify overdensities in a survey area. By comparing the counts in a survey area to counts from other regions with known counts, the over and underdensities of galaxies within the survey can be gauged. Figure 5.10 shows the distribution for the NWS number counts (lime circles), $\log(N \text{ deg}^{-2} \text{ mag}^{-1})$, as a function of the extinction-corrected K_s band isophotal magnitude. For comparison I also display with the open circles, the mean density counts for 2MASX all-sky survey excluding the ZOA ($|b| < 10^\circ$). 2MASX is known to be complete to $K_s = 13^m5$ for galaxies outside the ZOA (Skrutskie et al., 2006). Figure 5.10 marks the NWS and 2MASX completeness limits with the solid and dashed vertical lines, respectively.

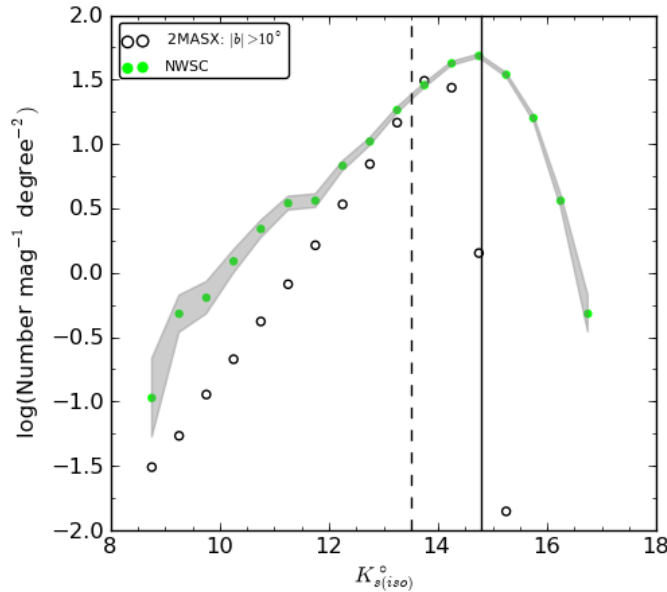


Figure 5.10: The NWS density counts (lime circles), the 2MASX mean density counts (open circles). The completeness limits for the NWS ($K_{s(iso)} = 14^m8$) and 2MASX ($K_{s(iso)} = 13^m5$) are represented by the solid and dashed vertical lines respectively.

The comparison between the two number counts in Fig. 5.10 suggests an overdensity in the

NWS compared to the mean 2MASX counts. This density enhancement is clearly evident in the magnitude range $8^{\text{m}}5 \leq K_{s(\text{iso})}^{\circ} < 13^{\text{m}}5$ and strongest in the range $9^{\text{m}}0 \leq K_{s(\text{iso})}^{\circ} < 11^{\text{m}}5$. As I will demonstrate later the origin of this overdensity is a homogeneous galaxy distribution at the GA distance.

5.3 The distribution of galaxies in the Norma Wall

In this section I investigate the galaxy density distribution in the NWS and the overdensity suggested in Fig. 5.10. Before analysing the galaxy distribution uncovered by the Norma Wall Survey and its connection to the other large-scale structures that are found in the same region I will first review the large-scale structures in the following section.

5.3.1 Large-scale structures in the Great Attractor region

Many large-scale structures are known to reside in the vicinity of the Norma Wall such as the nearby Centaurus Wall (Fairall, Woudt & Kraan-Korteweg, 1998), the Hydra Wall (Fairall, Woudt & Kraan-Korteweg, 1998) and the more distant Shapley Supercluster (Shapley, 1930; Scaramella et al., 1989). Figure 5.11 displays the large-scale structures in the GA region displayed in four different redshift slices, $2000 < v < 4000 \text{ km s}^{-1}$, $4000 < v < 7000 \text{ km s}^{-1}$, $6000 < v < 11000 \text{ km s}^{-1}$ and $11000 < v < 18000 \text{ km s}^{-1}$. These redshift slices are optimized such that the different large-scale structures in the GA region are most pronounced in at least one slice. Note that the galaxies' positions and redshifts are taken from the Hyperleda¹ galaxy database .

In the redshift slice $2000 < v < 4000 \text{ km s}^{-1}$ (panel 1 of Fig. 5.11) the Centaurus cluster (Abell 3526) centred at $\ell = 302^{\circ}41$, $b = +21^{\circ}56$, $cz = 3418 \text{ km s}^{-1}$, the Hydra cluster at $\ell = 269^{\circ}63$, $b = +26^{\circ}51$, $cz = 3777 \text{ km s}^{-1}$ and the Antlia cluster at $\ell = 272^{\circ}95$, $b = +19^{\circ}19$, $cz = 2797 \text{ km s}^{-1}$ are the most prominent clusters. The Centaurus Wall (Fairall, Woudt & Kraan-Korteweg, 1998) extends from the Centaurus cluster and downwards through the GP and including the region $\ell \approx 327^{\circ}$, $b = -7^{\circ}$ i.e. very close to the position of the Norma cluster. Even though the Centaurus Wall seems to pass through the position of the Norma Wall, dynamical analysis of galaxies in both walls reveals that the Centaurus Wall lies in the foreground of the Norma Wall Radburn-Smith et al. (2006). The two walls are separated by $\approx 2000 \text{ km s}^{-1}$ in redshift space. Another wall-like structure in this redshift slice is the Hydra Wall (Fairall, Woudt & Kraan-Korteweg, 1998) extending from the Centaurus cluster towards the Hydra and Antlia clusters. The Hydra-Antlia filament (Kraan-Korteweg & Woudt, 1999) extends from the Hydra cluster to the Antlia cluster then crosses the GP at $\ell = 278^{\circ}$ ending in a group of galaxies at $\ell = 280^{\circ}$, $b = -8^{\circ}$.

¹<http://leda.univ-lyon1.fr/intro.html>

In the redshift slice $4000 < v < 7000 \text{ km s}^{-1}$ (panel 2 of Fig. 5.11) the strongest features are due to the following clusters: Pavo II centred at $\ell = 332^\circ$, $b = -24^\circ$, $v = 4200 \text{ km s}^{-1}$ (Lucey & Carter, 1988), Norma at $\ell = 324.3^\circ$, $b = -7.2^\circ$, $v = 4848 \text{ km s}^{-1}$ (Kraan-Korteweg et al., 1996), Abell S0639 centered at $\ell = 281^\circ$, $b = 11^\circ$, $v = 6194 \text{ km s}^{-1}$ (Stein, 1997), the CIZA J1324.7-5736 cluster $\ell = 307.4^\circ$, $b = +5.0^\circ$, $v = 5700 \text{ km s}^{-1}$ (Ebeling, Mullis & Tully, 2002; Kocevski et al., 2007) and the Cen-Crux $\ell = 305.5^\circ$, $b = +4.8^\circ$, $v = 6214 \text{ km s}^{-1}$ cluster (Woudt & Kraan-Korteweg, 2001). These clusters outline the Norma Wall in the $4000 < v < 7000 \text{ km s}^{-1}$ redshift slice.

In the redshift slice $6000 < v < 11000 \text{ km s}^{-1}$ (panel 3) no particular structures stand out.

The Shapley Supercluster centred at $\ell = 312^\circ$, $b = +31^\circ$, $cz = 14500 \text{ km s}^{-1}$ is the most prominent feature in the redshift range $11000 < v < 18000 \text{ km s}^{-1}$ (panel 4 of Fig. 5.11). In this redshift range four other rich clusters are known to exist: CIZA J1638.2-6420 (the Triangulum Australis cluster; McHardy et al. 1981) at $\ell = 324.5^\circ$, $b = -11.6^\circ$, $cz = 15060 \text{ km s}^{-1}$, CIZA J1653.0-5943 (the Ara cluster; Woudt 1998) at $\ell = 329.3^\circ$, $b = -9.9^\circ$, $cz = 14634 \text{ km s}^{-1}$, CIZA J1514.6-4558 centred at $\ell = 327.3^\circ$, $b = +10.0^\circ$, $cz = 16715 \text{ km s}^{-1}$ and CIZA J14104.4-4246 at $\ell = 318.0^\circ$, $b = +17.8^\circ$, $cz = 15574 \text{ km s}^{-1}$ (Ebeling, Mullis & Tully, 2002; Kocevski et al., 2007). The CIZA J1638.2-6420 and CIZA J1653.0-5943 clusters lie right behind the Norma cluster in the redshift space. Radburn-Smith et al. (2006) estimated Virial masses of $5.7 \pm 0.6 \times 10^{15} h^{-1} M_\odot$ for Triangulum Australis, $2.0 \pm 0.3 \times 10^{15} h^{-1} M_\odot$ for Ara, $1.2 \pm 0.1 \times 10^{15} h^{-1} M_\odot$ for CIZA J1514.6-4558 and $1.1 \pm 0.1 \times 10^{15} h^{-1} M_\odot$ for CIZA J14104.4-4246.

The Triangulum Australis and Ara clusters are separated by only $\sim 13.7 \text{ Mpc}$ and both lie approximately in the same plane as the CIZA J1514.6-4558 and CIZA J14104.4-4246. The cluster Abell 3558, the core of the Shapley Supercluster lies only 38 Mpc from CIZA J14104.4-4246. These clusters may well form an extension to the Shapley Supercluster with a possible connection between the two clusters CIZA J1514.6-5736 and CIZA J1653.0-5943 through a wall-like structure. These wall-like structures are outlined in Fig. 4 of Radburn-Smith et al. (2006).

It is important to note here that the plotted galaxy distribution within the ZOA ($|b| < 10^\circ$) apparently seems to be highly inhomogeneous compared to the other part outside the ZOA with only few galaxy clumps scarcely distributed. This is an artifact of the dedicated observations within the ZOA undertaken for only regions of interest to the study of the GA and not homogeneous surveys as it is the case for regions outside the ZOA.

5.3 The distribution of galaxies in the Norma Wall

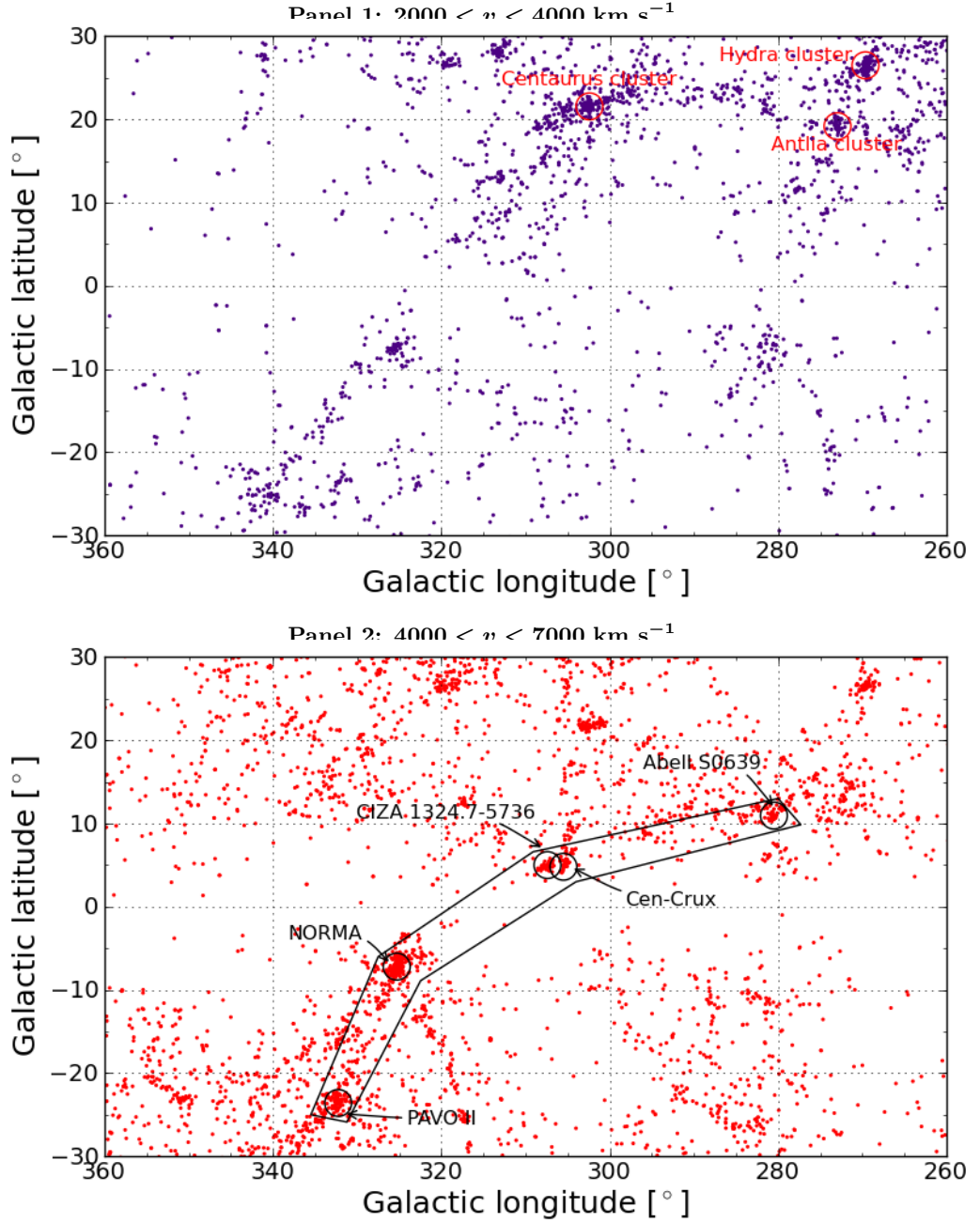


Figure 5.11: Panel 1: galaxies in the redshift slice $2000 < v < 4000 \text{ km s}^{-1}$. In this redshift slice the Centaurus cluster (ℓ, b, cz)=($302^\circ.41, 21^\circ.56, 3418 \text{ km s}^{-1}$), the Hydra cluster ($269^\circ.63, +26^\circ.51, 3777 \text{ km s}^{-1}$) and the Antlia cluster ($272^\circ.95, +19^\circ.19, 2797 \text{ km s}^{-1}$) are marked. The Hydra Antlia and Centaurus Walls are prominent in this panel. Panel 2: galaxies in the redshift slice $4000 < v < 7000 \text{ km s}^{-1}$. The Norma Wall is outlined with the black line is the strongest feature in this redshift slice. The clusters Pavo II at ($332^\circ, -24^\circ, 4200 \text{ km s}^{-1}$), Norma at ($324^\circ.3, -7^\circ.2, 4848 \text{ km s}^{-1}$), Abell S0639 ($281^\circ, 11^\circ, 6194 \text{ km s}^{-1}$), CIZA J1324.7-5736 ($307^\circ.4, +5^\circ.0, 5700 \text{ km s}^{-1}$) and Cen-Crux ($305^\circ.5^\circ, +4^\circ.8, 6214 \text{ km s}^{-1}$) are marked on this redshift slice.

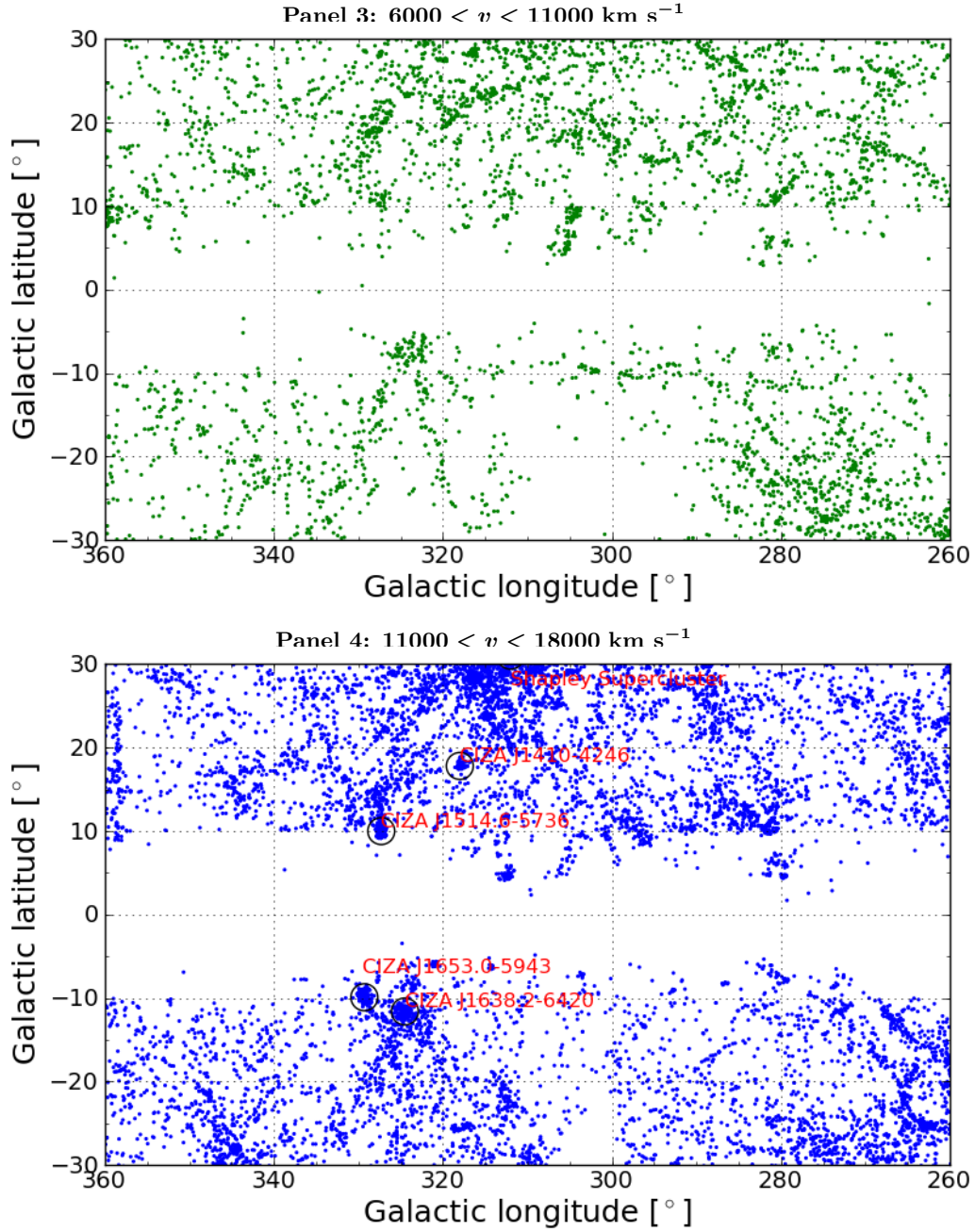


Figure 5.11: Panel 3: galaxies in the redshift slice $6000 < v < 11000 \text{ km s}^{-1}$. No large-scale structures are apparent in this panel. Panel 4: galaxies in the redshift slice $11000 < v < 18000 \text{ km s}^{-1}$. The Shapley overdensity is the dominant structure in the $11000 < v < 18000 \text{ km s}^{-1}$ redshift slice. The marker for the Shapley Supercluster lies outside the borders of panel 4. In this redshift slice the clusters CIZA J1638.2-6420 (ℓ, b, cz)=($324^{\circ}5, -11^{\circ}6$), CIZA J1653.0-5943 ($329^{\circ}3, -9^{\circ}9$), CIZA J1514.6-4558 ($327^{\circ}3, +10^{\circ}0$) and CIZA J1410.4-4246 ($318^{\circ}0, +17^{\circ}8$) are marked.

5.3.2 Large-scale structures in the NWS area

Following the summary of the known large-scale structures in and around the GA region I will now discuss the structures that can be identified in the Norma Wall Survey. For this purpose I start with inspecting the galaxy density contour maps.

Figure 5.12 shows the density contours for galaxies brighter than $K_{s(iso)}^\circ = 14^m8$. This magnitude is the completeness limit for galaxies in our survey for a foreground obscuration of $A_{K_s} \leq 1$ mag. The extinction $A_{K_s} = 1$ mag is marked on this map with the brown contour line. Recall that $\approx 98\%$ of the survey area has an extinction $A_{K_s} < 1$ mag.

The galaxy distribution observed in the NWS area has a mean density of $\log(N/\text{deg}^2) = 1.74 \pm 0.33$ for galaxies brighter than $K_{s(iso)}^\circ = 14^m8$. The distribution in Fig. 5.12 shows a decrease in density towards the GP especially in the lower section of the survey footprint where the extinction is above $A_{K_s} \gtrsim 1$ mag and the stellar density is higher than $\log(N_{(K_s < 14)} / \text{deg}^2) \geq 4.71$.

The CIZA J1324.7-5736 cluster is the densest region in the survey area with a mean galaxy density of $\log(N/\text{deg}^2) = 2.33$. Beside the regions where the CIZA J1324.7-5736 and Cen-Crux clusters lie, I identified five other areas with higher density counts compared to the mean of the survey area. These regions are characterized by peak densities above $\log(N/\text{deg}^2) = 2.4$ which correspond to $\approx 2\sigma$ above the mean density counts in the survey area. These regions will be further investigated later in the chapter. Region 4, centred at $\ell = 319^\circ94$, $b = -1^\circ92$, is also identified as a candidate region of an excess density even though it has a lower peak density than $\log(N/\text{deg}^2) = 2.4$ compared to the other five regions. This region lies close to a region with high levels of extinction $A_{K_s} > 1$ mag. It would be worthwhile to investigate this further as it might be an overdensity obscured by the high extinction in the region. The Galactic longitude, latitude, mean density, and average extinction for all of these high density areas are listed in Table 5.5. The mean density is for galaxies brighter than $K_{s(iso)}^\circ \leq 14^m8$ within an area of $35' \times 35'$ around the centre of these regions.

Table 5.5: High density regions identified in Fig. 5.12.

Label	ℓ [°]	b [°]	$\log(N/\text{deg}^2)$	A_{K_s} [mag]	Notes
1	307.39	+4.97	2.33	0.27	CIZA J1324.7-5736
2	306.21	+4.97	2.18	0.22	
3	213.31	+4.80	2.10	0.17	Cen-Crux
4	319.94	-1.92	1.85	0.85	
5	323.23	-3.69	2.07	0.28	
6	324.46	-5.04	2.20	0.20	
7	324.30	-5.39	2.20	0.14	

To gauge whether the overdensities marked in Fig. 5.12 and listed in Table 5.5 are due

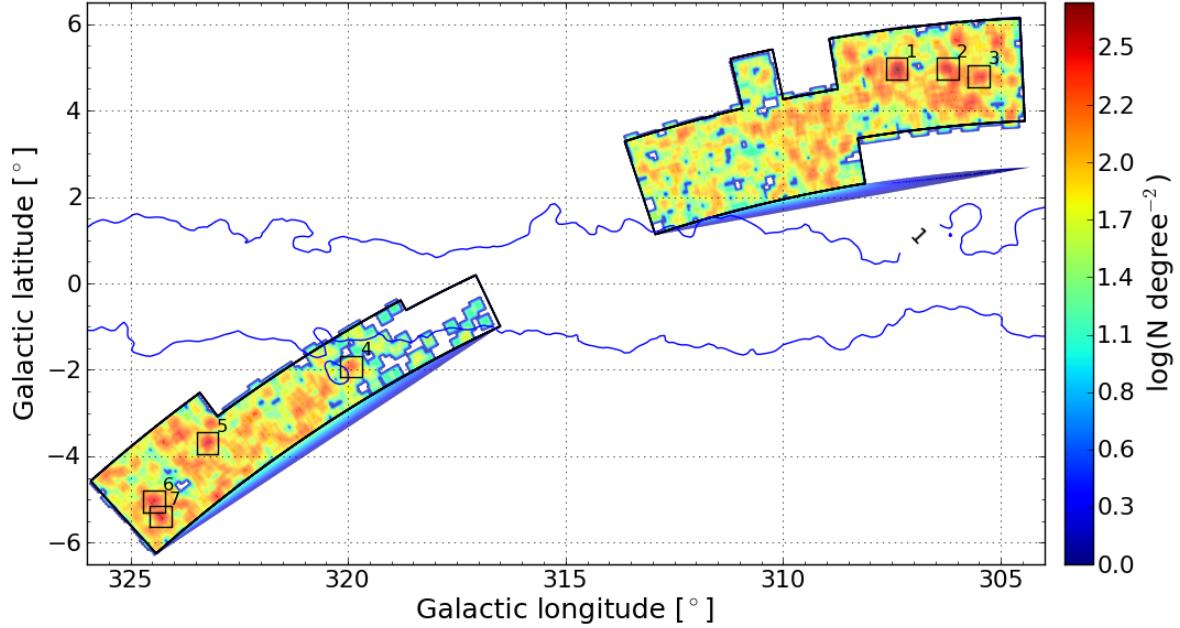


Figure 5.12: Galaxy density contours for galaxies brighter than $K_{s(iso)}^o \leq 14^m8$. Six regions with a peak density $\log(N/\text{deg}^2) > 2.4$ are marked with the $35' \times 35'$ boxes. A seventh region with $\log(N/\text{deg}^2) < 2.4$ is also marked.

to nearby structures or more distant ones, the distribution is subdivided in two magnitude intervals, $K_{s(iso)}^o < 13^m5$ (top panel in Fig. 5.13) and $13^m5 \leq K_{s(iso)}^o \leq 14^m8$ (lower panel). The $K_{s(iso)}^o < 13^m5$ magnitude limit is the completeness limit of 2MASX away from the ZOA (Jarrett et al., 2000a) while the $K_{s(iso)}^o < 14^m8$ is the completeness of the NWS.

Excluding the region of the survey area defined by $A_{K_s} > 1$ mag, the distribution in the top panel of Fig. 5.13 has a mean density of $\log(N/\text{deg}^2) = 1.43$ for galaxies brighter than $K_{s(iso)}^o < 13^m5$. In comparison, the mean density for 2MASX all-sky survey excluding the band $|b| < 10^\circ$ is $\log(N/\text{deg}^2) = 1.15$, i.e. the NWS is a factor of 1.9 more dense than the mean 2MASX counts.

The density enhancements in regions 1, 3 and 4 are more pronounced in the magnitude range $K_{s(iso)}^o < 13^m5$ compared to other parts of the survey area. Meanwhile the overdensities 2, 5, 6 and 7 are strongest in the magnitude range $13^m5 \geq K_{s(iso)}^o \geq 14^m8$. This suggests that the density enhancements in regions 1, 3 and 4 are due to nearby galaxies, while those in regions 2, 5, 6 and 7 are likely due to galaxies that are further away.

To study the seven regions listed in Table 5.13 in more detail I will use the magnitude distribution for galaxies found within these regions. By further comparing these distributions to the magnitude distribution for galaxies in the CIZA J1324.7-5736 cluster we can assess if these

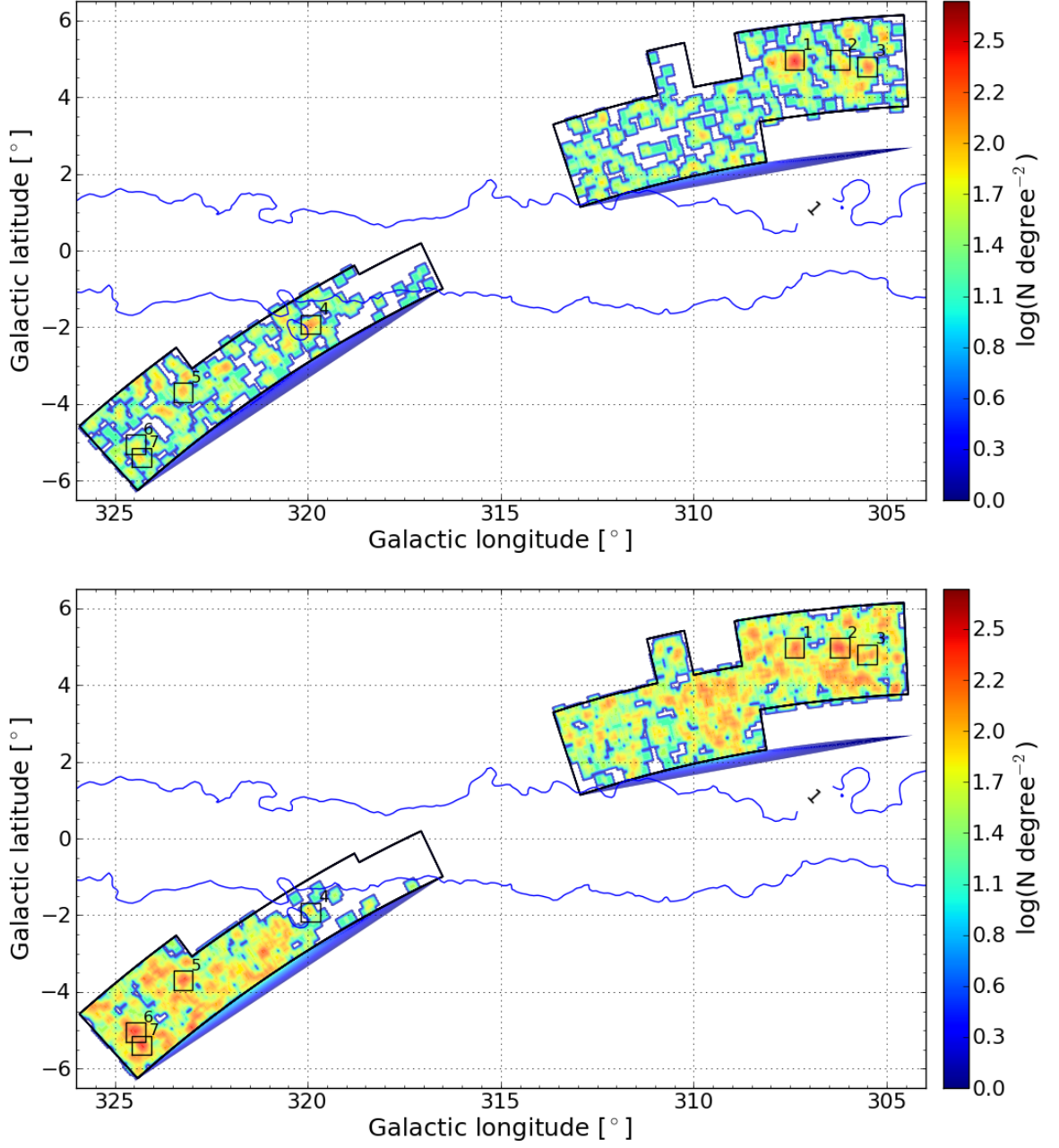


Figure 5.13: Galaxy density counts in two magnitude slices. Top panel: the distribution for galaxies complete to $K_{s(iso)}^o < 13^m5$. Lower panel: density contours for galaxies in the magnitude range $13^m5 \leq K_{s(iso)}^o \leq 14^m8$.

overdensities are caused by galaxies at the GA distance.

Figure 5.14 displays the magnitude histograms for galaxies within an area $35' \times 35'$ centred around each of the regions listed in Table 5.5. For comparison I also repeat the distribution for region 1 (the nearby CIZA J1324.7-5736 cluster) in all other histograms. Histograms in panels 1 and 3 correspond to regions where the CIZA J1324.7-5736 and Cen-Crux clusters respectively reside.

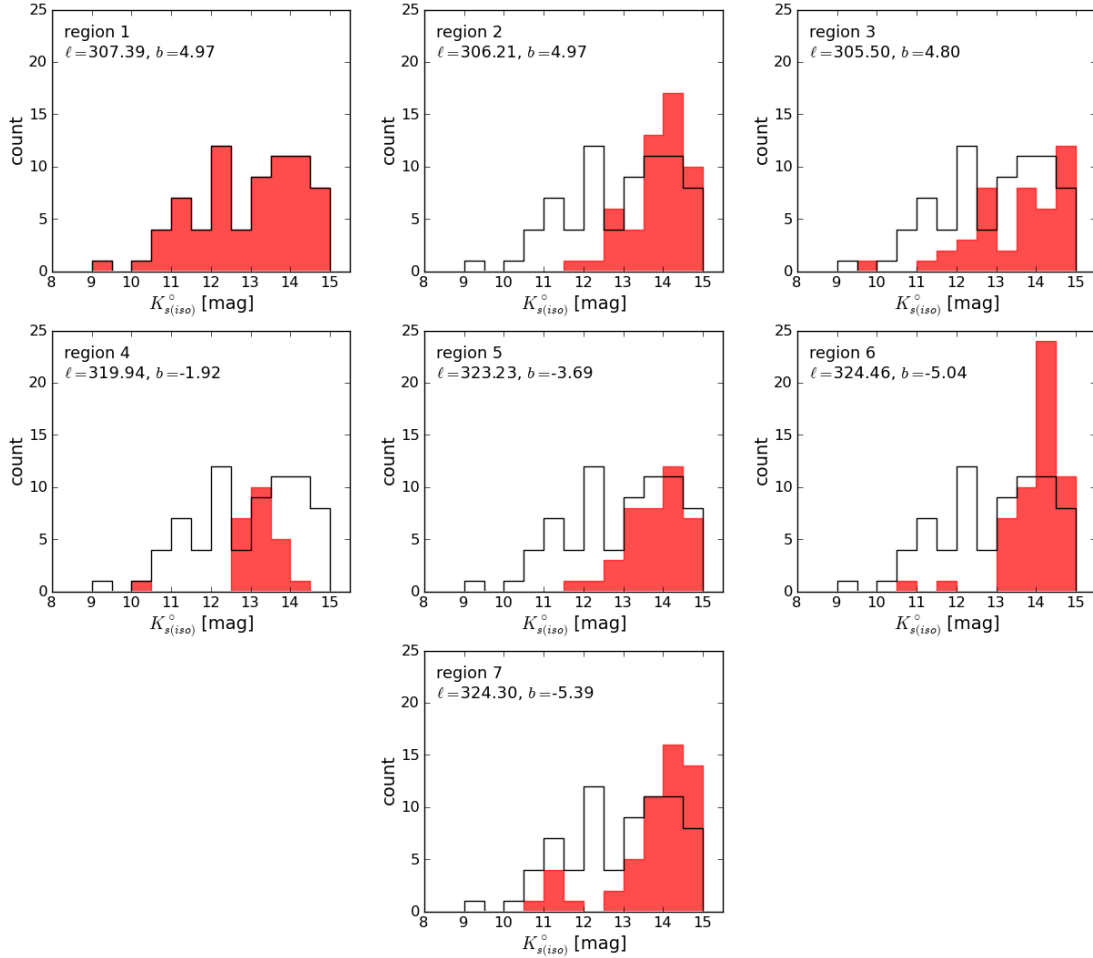


Figure 5.14: Magnitude counts for candidate regions of magnitude enhancement for the 7 regions listed in Table 5.5 (red bins). The magnitude counts for region 1 (CIZA J1324.7-5736 cluster) are overlaid over each histogram for comparison.

The histogram for region 1 represents the galaxy distribution around the CIZA J1324.7-5736 cluster which is at a redshift of $cz = 5696 \text{ km s}^{-1}$, i.e. at the distance of the GA. This makes the magnitude distribution in this region an indicator for CIZA J1324.7-5736 like clusters that are

at the GA distance. Region 2 is $\sim 1^\circ 17'$ from the CIZA J1324.7-5736 cluster and $\sim 0^\circ 72'$ from the Cen-Crux cluster. The region has a peak in the magnitude range $13^m 5 \leq K_{s(iso)}^\circ \leq 14^m 8$ indicating that the overdensity in this region is due to galaxies lying further than the GA. The galaxy distribution for the Cen-Crux cluster, also a member of the Norma Wall, is displayed with the histogram for region 3. Regions 4 and 5 both do not show any relevant density peaks due to nearby galaxies but they show signs of a moderate density enhancement due to galaxies beyond the GA. Region 6 and 7, only separated by $\sim 0^\circ 38'$, show density peaks in the range $13^m 5 \leq K_{s(iso)}^\circ \leq 14^m 8$. The observed galaxy distribution in both regions can be explained by galaxies more distant than the GA. The two regions 6 and 7 are $\sim 7^\circ$ away from the Triangulum Australis cluster (CIZA J1638.2-6420) at $\ell = 324^\circ 5'$, $b = -11^\circ 6'$, $cz = 15060 \text{ km s}^{-1}$ and the Ara cluster (CIZA J1653.0-5943) at $\ell = 329^\circ 3'$, $b = -9^\circ 9'$, $cz = 14634 \text{ km s}^{-1}$. It would be interesting to know whether these regions are also at the distance of the Triangulum Australis and Ara clusters and hence at the distance of the Shapley Supercluster.

To conclude this section I argue that there is no evidence of any additional rich clusters similar to CIZA J1324.7-5736 in the NWS survey area below extinction levels of $A_{K_s} \leq 1 \text{ mag}$. The overdensities in regions 2, 6 and 7 might be due to galaxies that are more distant than the GA. Although no further rich clusters similar to CIZA J1324.7-5736 are found in the survey area, the region is twice as dense as the mean 2MASX all sky counts for the common magnitude limit $K_{s(iso)}^\circ < 13^m 5$. The regions marked in Fig. 5.12 will be further investigated as a function of photometric redshift in Sect. 5.6.

5.4 The density enhancement in the NWS

The discussion in the previous section revealed no signs of previously unknown galaxy clusters hidden in the NWS area. However, the mean density in the survey area is found to be approximately twice that of the mean 2MASX all sky density counts excluding the ZOA ($|b| < 10^\circ$), hence suggesting a density enhancement caused by the whole survey area. To gauge the overdensity observed in the NWS area I will compare the galaxy density counts in the NWS to mean density counts (2MASX mean counts and Glazebrook et al. 1995), a region of moderate overdensity at the Vela region (HIZOA J0836-43) and clusters counts (Norma and CIZA J1324.7-5736).

Figure 5.15 (top-left panel) compares the NWS density to the 2MASX mean density defined by 2MASX all sky distribution excluding the ZOA. The error bars are indicated for the NWS counts by the shaded regions. This panel also includes the galaxy counts by Glazebrook et al. (1995) for a 552 arcmin^2 field complete down $K \leq 17^m 3$. The vertical lines (solid) at $K_{s(iso)}^\circ = 14^m 8$ and (dashed) at $K_{s(iso)}^\circ = 13^m 5$ mark the completeness limits for the NWS and 2MASX respectively (those lines are shown in all subsequent panels). The difference between the 2MASX mean counts and the Glazebrook et al. (1995) counts can be understood as being due to the different magnitude systems used by 2MASX and Glazebrook et al. (1995). While

the 2MASX magnitudes are also K_s band isophotal magnitudes, the analysis by Glazebrook et al. (1995) is based on $4''$ aperture magnitudes. The 2MASX counts are therefore shifted towards the brighter end compared to counts given by Glazebrook et al. (1995).

For a further independent assessment of the overdensity in the NWS, the top-right panel of Fig. 5.15 compares the NWS counts to counts for a 2.24° area around the starburst supermassive HI galaxy HIZOA J0836-43. The starburst galaxy HIZOA J0836-43 lies in the Vela region at $\ell = 262^\circ.48$, $b = -1^\circ.64$, $cz = 10689 \text{ km s}^{-1}$ (Meyer et al., 2004). This region was observed by Cluver (2009) in the NIR bands J , H , K_s using the IRSF/SIRIUS with identical imaging parameters and exposure time to the NWS. The counts reproduced here for the HIZOA J0836-43 are courtesy of Michelle Cluver. According to Cluver (2009), this region appears to be overdense in low luminosity galaxies only, distinctly different from galaxy clusters, filamentary structures and low density (field) regions. The NWS counts have an increase number counts in the bright end of the distribution with tight error bars compared to the Vela region counts where only one data point is available for galaxies brighter than $K_{s(iso)} < 10^m$ located at $K_{s(iso)} = 8.25^m$. It is also important to note that the data point at $K_{s(iso)} = 8.25^m$ has very low statistics. However at the faint end an increase in the number counts is seen in Vela compared to the NWS counts. This excess was already noticed and discussed by Cluver (2009).

Comparing the density counts in the NWS to cluster counts helps our understanding of the observed overdensity in the Norma Wall Survey area. The lower-middle panel of Fig. 5.15 compares the NWS density counts to the Norma and CIZA J1324.7-5736 clusters. Counts for the Norma cluster were produced from the catalogue compiled by Skelton et al. (2009) from independent observations carried out with the IRSF/SIRIUS for a $0^\circ.75 \times 0^\circ.75$ area centred on the Norma cluster. Counts for the CIZA J1324.7-5736 cluster are extracted from the NWS catalogue for an area $0^\circ.75 \times 0^\circ.75$ centred on the cluster. For comparison the 2MASX field counts are also displayed.

Figure 5.15 confirms the overall density enhancement in the NWS area compared to the mean 2MASX counts but are much lower than the cluster counts associated with Norma or CIZA J1324.7-5736. The NWS density distribution is also significantly different than the counts in the Vela region.

The NWS enhancement is due to two components, the overall galaxy distribution in the survey area plus the two clusters CIZA J1324.7-5736 and Cen-Crux. To gauge the strength of each of these two components I plot as before in Fig. 5.16 the density distribution for all galaxies in the survey area (lime circles) as before and also the distribution but excluding two $0^\circ.75 \times 0^\circ.75$ regions centred around the two known clusters (blue circles).

The two distributions displayed in Fig. 5.16 are very comparable to each other; with the distribution for the survey area excluding the cluster counts (blue circles) is slightly less than the counts for the whole survey area (lime circles). This analysis herewith finds that the overdensity is primarily due to the overall galaxy distribution in the survey area and not the CIZA J1324.7-5736 and Cen-Crux clusters. The contribution of the two clusters is mostly seen in the magnitude

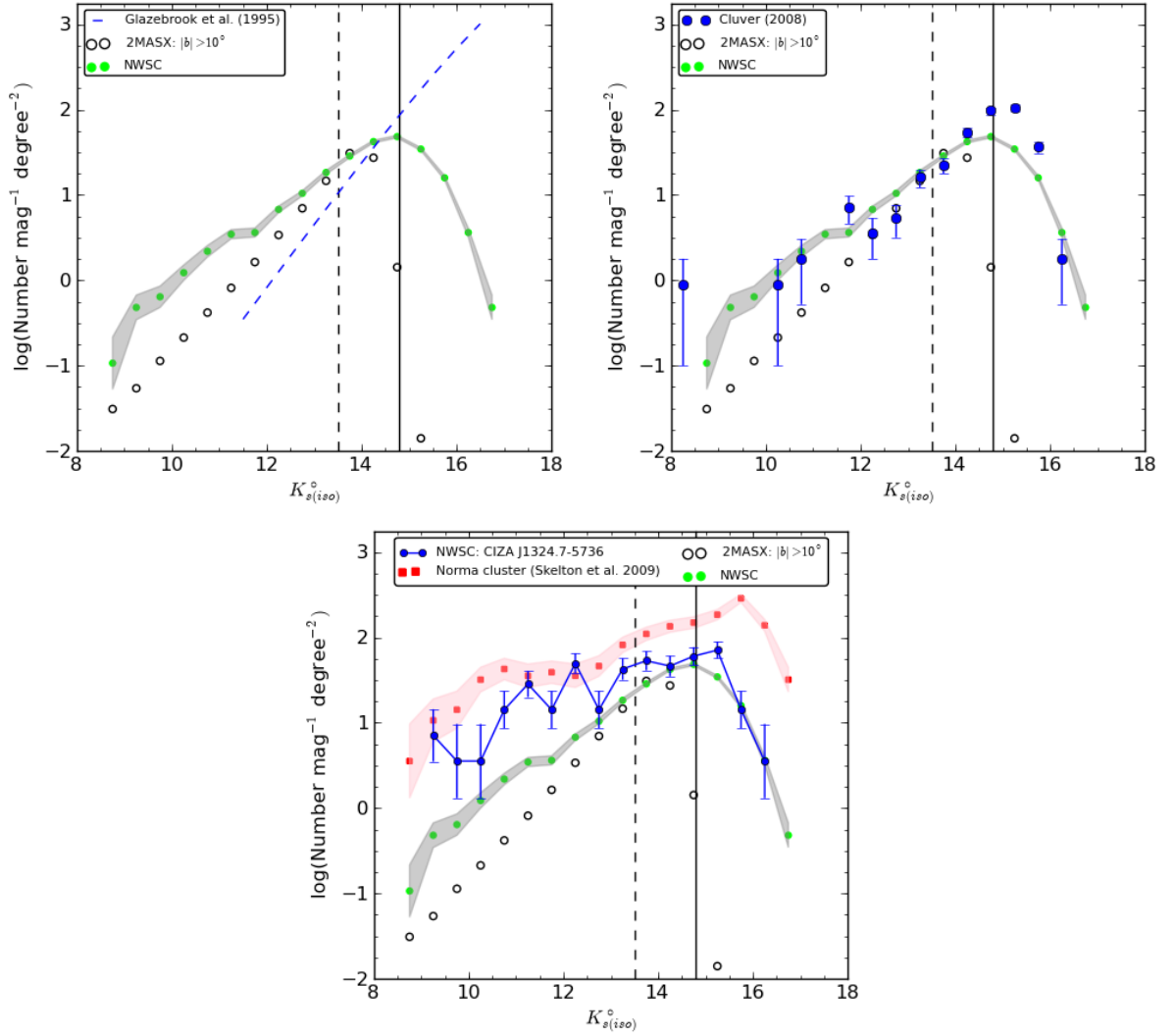


Figure 5.15: Galaxy counts comparison. Top-left: the NWS counts (lime circle), mean 2MASX counts (open circle) and Glazebrook et al. (1995) field counts (dashed line). Top-right the HIZOA J0836-43 counts (blue circles) and 2MASX mean counts (open circle). Lower-middle: the NWS counts (lime circle), the 2MASS mean counts (open circle), the Norma cluster counts (red squares) taken from Skelton et al. (2009) and the CIZA J1324.7-5736 cluster counts (blue circles) extracted form the NWS counts.

range $10^m5 \leq K_{s(ISO)} \leq 12^m0$. The NWS still shows increased counts in this magnitude range even when both the CIZA J1324.7-5736 and Cen-Crux clusters are excluded. To analyze the density distribution further, the survey area is subdivided into five non-overlapping regions A,

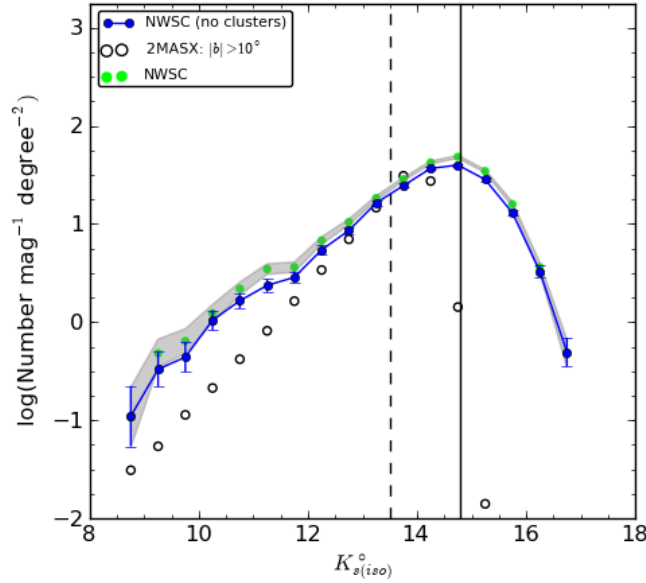


Figure 5.16: A comparison between the density enhancement due to all galaxies in the survey area (lime circles) and for galaxies excluding those within two 0.75×0.75 regions centred on the CIZA J1324.7-5736 and Cen-Crux clusters.

B, C, D and E (see Fig. 5.17) with areas of 6.3, 5.6, 4.3, 11.7 and 9.6 deg^2 respectively. Regions A, B, C, D do not contain any known clusters, while E hosts both the CIZA J1324.7-5736 and Cen-Crux clusters. Regions A, B, C, D and E have mean densities of 51.20, 43.24, 13.75, 41.51 and 40.73 galaxies/ deg^2 respectively. Figure 5.18 displays the galaxy distribution for the whole survey area, the 2MASX mean density counts and the distribution of the five region.

The density counts in region C are significantly lower than in the other four regions and the whole survey area. The lower counts in region C are not unexpected given that the region is severely affected by the high levels of dust obscuration $A_{K_s} > 1$ mag and star crowding $\log(N/\text{deg}^2) > 4.8$. The density counts in regions A, B, D, E are very similar and comparable to those of the whole survey area. The slightly higher density in region A compared to the other regions may well be due to two density peaks identified in regions 6 and 7 (see Fig. 5.13 and Table 5.5) that might lie at a higher redshift than the GA. This indicates that the overall enhancement in the NWS area is not due to individual structures that reside within the survey footprint but to an overall galaxy density enhancement. Furthermore, the similarity in the distribution of the regions in the lower branch of the survey footprint (A and B) to those in the upper branch (D and E) provides an indicator that the NWS survey maps a continuous structure on the two opposite sides of the GP.

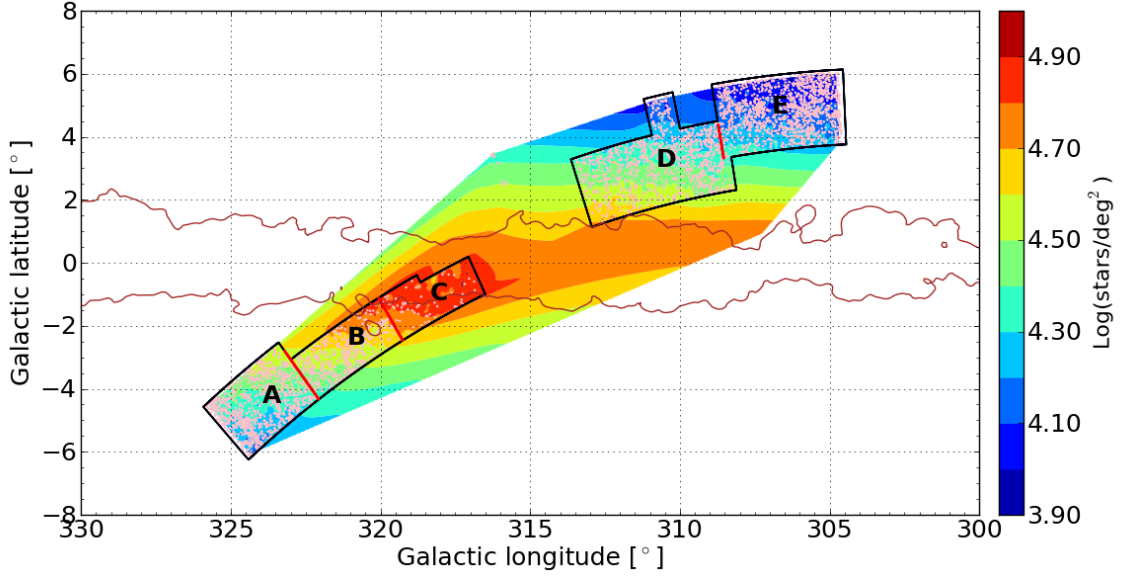


Figure 5.17: The survey area footprint subdivided into five non-overlapping regions A, B, C, D and E which have areas of 6.3, 5.6, 4.3, 11.7 and 9.6 deg² respectively. The extinction of $A_{K_s} = 1^m0$ is marked by the brown contour line. Filled colour contours are for the stellar density. The stellar density countours are derived from star counts in the NWS images. The stellar density contours outside the survey footprint are extrapolations from the values within the survey area.

5.4.1 NWS galaxy counts comparison with different regions on the sky

To obtain a better understanding of the density enhancement observed in the NWS and whether this overdensity is caused by galaxies in the Norma Wall, which we expect to be the case, I selected nine ($3^\circ \times 3^\circ$) regions distributed over the 2MASX sky distribution for comparison. These regions were visually identified in the 2MASX redshift slices of Jarrett (2004) and represent regions in walls, in the vicinity of clusters that are prominent at either the distance of the Norma Wall or in the foreground/background of the Norma Wall. Some of these regions are also selected such they lie along the Norma Wall.

Table 5.6 lists the central positions for the nine selected regions and their galaxy number density as calculated from the 2MASS extended source catalogue for galaxies that are brighter than $K_{s(iso)} \leq 13^m5$. These regions have a mean density in the range 18.2 galaxies/deg². and 41.67 galaxies/deg². In comparison the mean density in the NWS area is ≈ 26.9 galaxies/deg². for galaxies brighter than $K_{s(iso)}^\circ \leq 13^m5$.

Figure 5.19 outlines the nine regions in the all-sky 2MASX redshift distribution map. Figure 5.20 then displays these regions on the redshift slices: $0.0 < z < 0.01$, $0.01 < z < 0.02$,

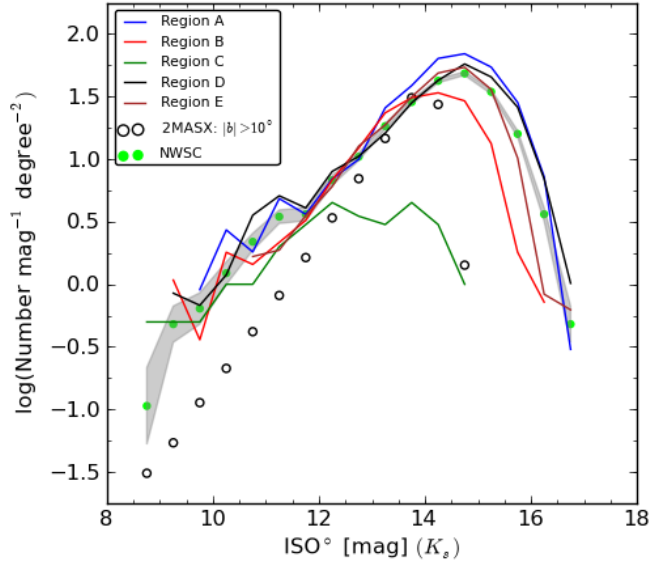


Figure 5.18: Galaxy density distribution for the five regions A, B, C, D and E.

$0.02 < z < 0.03$, $0.03 < z < 0.04$ and $0.04 < z < 0.05$. The redshift maps are complete for galaxies that are brighter than $K_{s(iso)} = 12$ mag. The redshifts used in these maps are either spectroscopic when available or photometric otherwise. Approximately 65% of redshifts in these maps are photometric. The redshift maps are reproduced from T. Jarrett's "Large Scale Structure" web page¹. In these maps I also outline the Norma Wall (white contour) and the NWS footprint (red contour).

The nine regions are selected for their following features:

Region I: The region is ~ 5.4 from the Virgo cluster ($\ell = 279^\circ.7$, $b = +74^\circ.5$, $z = 0.0036$). The enhancement in this region is clearly seen in the redshift slice $0.0 < z < 0.01$. This overdensity is in the foreground of the Norma Wall. Comparing the galaxy distribution in this region to that in the NWS area will help us to assess the contribution of galaxies at this redshift to the overdensity seen in the NWS.

Region II: As it can be seen on panel 2 of Fig. 5.20 this area has an overdensity in the redshift slice $0.01 < z < 0.02$. It is anticipated that this galaxy distribution will match well with the overdensity in the NWS as it is expected that the NWS overdensity is caused by a large-scale structure in the redshift range $0.01 < z < 0.02$.

Region III: This region is part of the Norma Wall connecting the CIZA J1324.7-5736 cluster to Abell S0639. This region does not show a significant galaxy enhancement at the GA distance when looking at the 2MASX redshift slice $0.01 < z < 0.02$.

¹<http://spider.ipac.caltech.edu/staff/jarrett/lss/index.html>

Region IV: This region is $\sim 0.2^\circ$ away from the Pavo II cluster. It has a density enhancement at the GA distance which is influenced by the nearby Pavo II cluster. I expect this region to show higher density counts than the Norma Wall Survey area in the magnitude range ($9^m0 \leq K_{s(iso)} \leq 12^m0$) i.e. where the NWS overdensity is strongest because of its proximity to the Pavo II cluster.

Region V: It is the closest region to the Norma Cluster at $\sim 2.3^\circ$ from the cluster. The region is clearly overdense at the GA distance as it is located in the filamentary structure that connects the Norma and Pavo II clusters.

Region VI: This region has an overdensity that is seen in the redshift slice $0.02 < z < 0.03$ i.e. in the background of the Norma Wall. Assuming that the overdensity in the NWS is due to galaxies at the GA distance, the galaxy distribution in this region will be lower in galaxy counts in the magnitude range $9^m0 \leq K_{s(iso)} \leq 12^m0$ where the NWS density enhancement is prominent.

Region VII: This region shows a density enhancement in the redshift slice $0.03 < z < 0.04$. Also similar to region VI, the galaxy density in the magnitude range $9^m0 \leq K_{s(iso)} \leq 12^m0$ is expected to also be lower than the NWS counts.

Region VIII: This region has an its most prominent overdensity in the redshift range $0.01 < z < 0.02$ in addition to a contribution from an overdensity in the redshift range $0.03 < z < 0.04$. This region is selected this way to assess if the density enhancement in the NWS is due to galaxies at the GA in addition to other structures that are farther away.

Region IX: This region lies within 2.9° of Abell 3558 ($\ell = 312^\circ$, $b = +31^\circ$, $z = 0.048$) the central cluster of the Shapley supercluster. It has its density enhancement at the redshift range $0.04 < z < 0.05$. A galaxy overdensity at this redshift distance will have less density counts than the NWS in the magnitude range $9^m0 \leq K_{s(iso)} \leq 12^m0$ while it will have excess counts for the fainter magnitudes.

Table 5.6: The 2MASX comparison regions. All regions are ($3^\circ \times 3^\circ$).

Field	$\ell[^\circ]$	$b[^\circ]$	Density [$\log(N/\square^\circ)$]	z
I	290.0	+70.0	1.29	$0.0 < z < 0.01$
II	303.3	+50.0	1.40	$0.01 < z < 0.02$
III	291.5	+08.7	1.42	$0.01 < z < 0.02$
IV	332.4	-23.4	1.36	$0.01 < z < 0.02$
V	326.5	-09.3	1.40	$0.01 < z < 0.02$
VI	165.0	-44.0	1.26	$0.02 < z < 0.03$
VII	62.3	+44.0	1.56	$0.03 < z < 0.04$
VIII	319.0	+27.3	1.37	$0.03 < z < 0.04$
IX	310.0	2+09.5	1.62	$0.04 < z < 0.05$

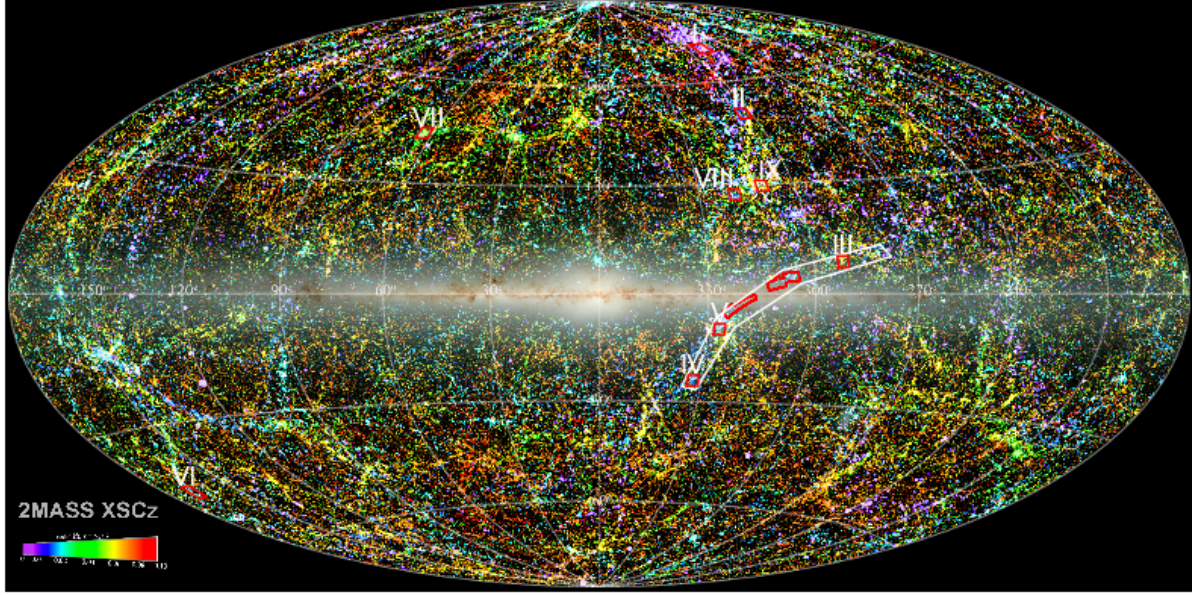


Figure 5.19: Selected 2MASX regions projected on the 2MASX redshift map. Galaxies are colour coded according to their redshift with the bluer galaxies being closer than the redder galaxies.

To compare the nine regions listed in Table 5.6, I plot in the nine panels of Fig. 5.21 the mean density counts for these regions (blue circles) as a function of apparent magnitudes and the NWS mean density counts (green circles). Regions that are closer than the GA their density distributions are labeled with the pink square while regions at the GA distance are marked with the blue squares. Region further away than the GA are marked with the red squares. In addition to these two distributions, I also display the 2MASX mean density counts excluding the ZOA.

Analysing the overdensity in this substantiate quite strongly that the observed overdensity in the NWS is primarily due to galaxies found at the GA distance. This conclusion is directly evident from the comparison of the NWS counts to the counts in the nine selected region.

The distribution in panel 1 of Fig. 5.21 represents an overdensity in the foreground of the GA ($0.00 < z < 0.01$). The deficiency in galaxy counts compared to the NWS counts for galaxies in the magnitude range $11^m0 \leq K_{s(iso)} \leq 12^m0$ is expected assuming that the density enhancement in the NWS is due to galaxies at the GA distance. The similarity in the galaxy counts for the brighter galaxies $11^m0 \leq K_{s(iso)}$ is a further evidence that the excess density in the NWS area is due to galaxies in the background of the density in region I.

The analysis of the galaxy distribution in the four regions II, III, IV and V and their comparison to the NWS gives the strongest proof that the overdensity observed in the NWS is due to a structure that is part of the Norma Wall. All these four regions have density enhancement

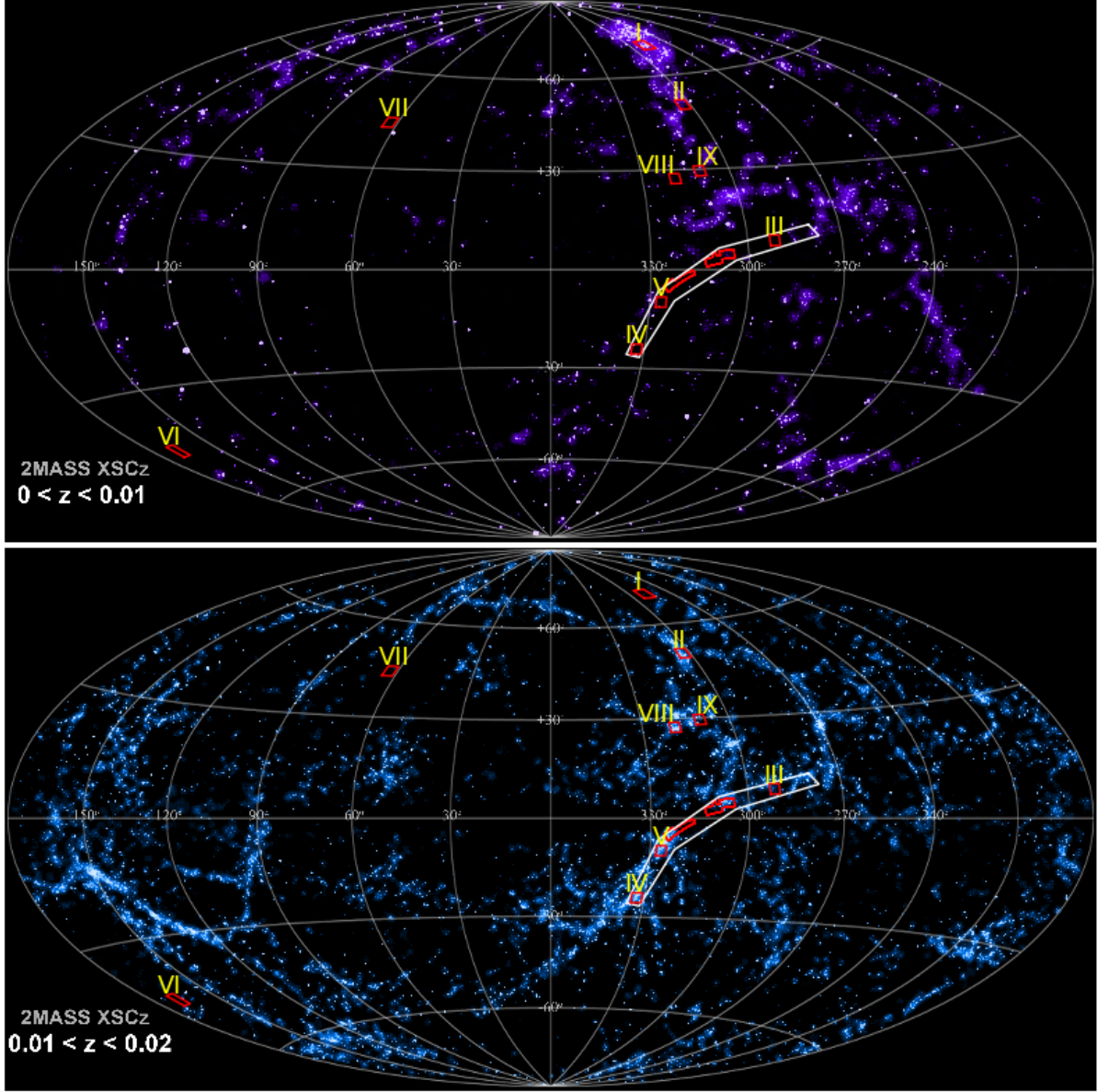


Figure 5.20: Nine ($3^\circ \times 3^\circ$) regions selected for density comparisons with the NWS counts. The regions are shown in different redshift slices. Top panel: $0 < z < 0.01$ redshift slice. Lower panel: $0.01 < z < 0.02$ redshift slice. The redshift slices are from T. Jarrett "Large Scale Structure" web page.

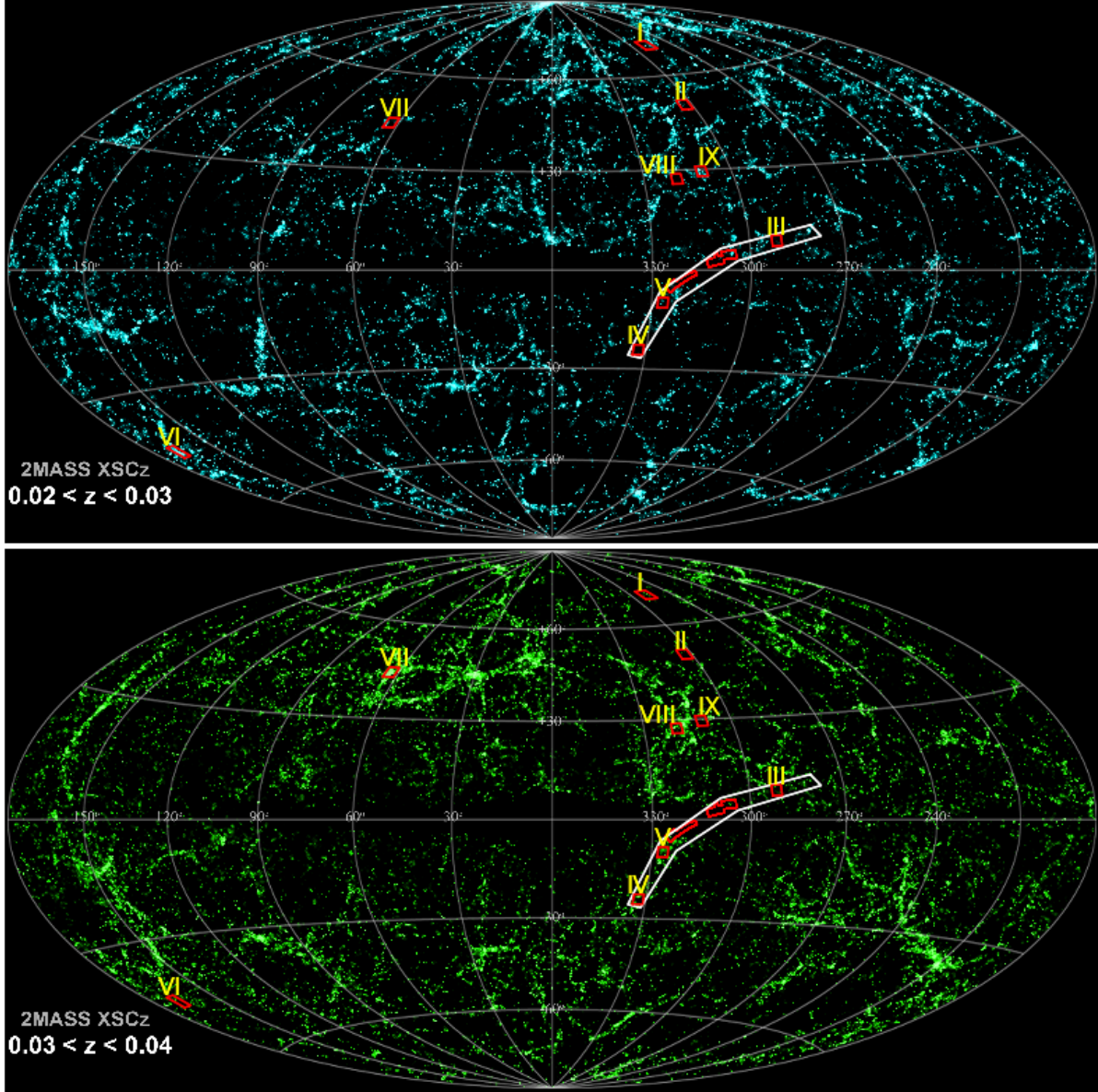


Figure 5.20: Nine ($3^\circ \times 3^\circ$) regions selected for density comparisons with the NWS counts. Top panel: $0.02 < z < 0.03$ redshift slice. Lower panel: $0.03 < z < 0.04$ redshift slice.

in the redshift range $0.00 < z < 0.01$ i.e. at the distance of the GA. The panels 2, 4 and 5 show a good match between the galaxy distribution in these panels and the distribution in the NWS, especially in the magnitude range $9^m0 \leq K_{s(iso)} \leq 12^m0$ again supporting the preposition that the density enhancement in the NWS is due to galaxies in the redshift range $0.00 < z < 0.01$. The higher counts seen in panel 4 compared to the NWS counts are caused by the proximity of

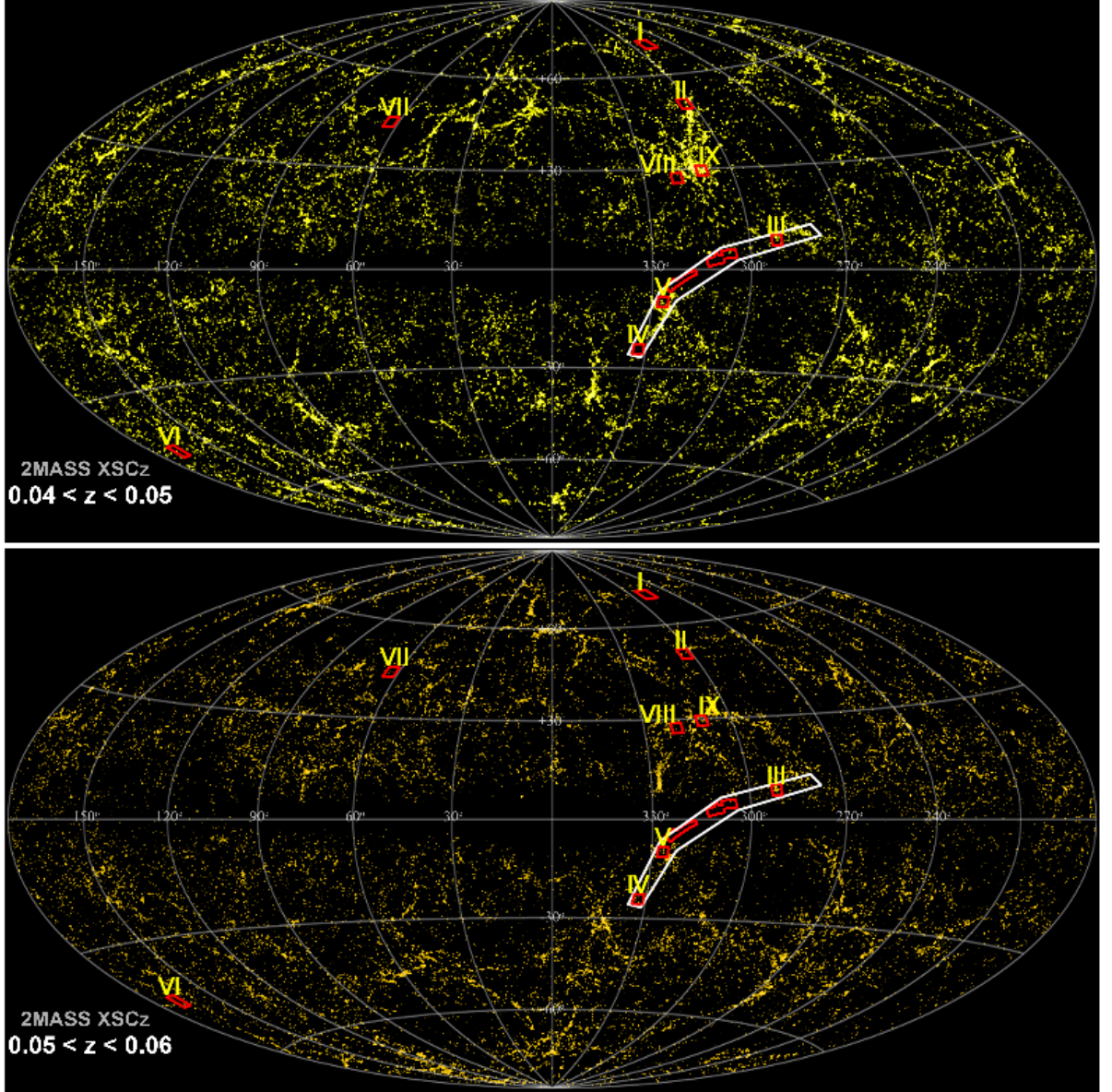


Figure 5.20: Nine ($3^\circ \times 3^\circ$) regions selected for density comparisons with the NWS counts. Top panel: $0.03 < z < 0.04$ redshift slice. Lower panel: $0.04 < z < 0.05$ redshift slice.

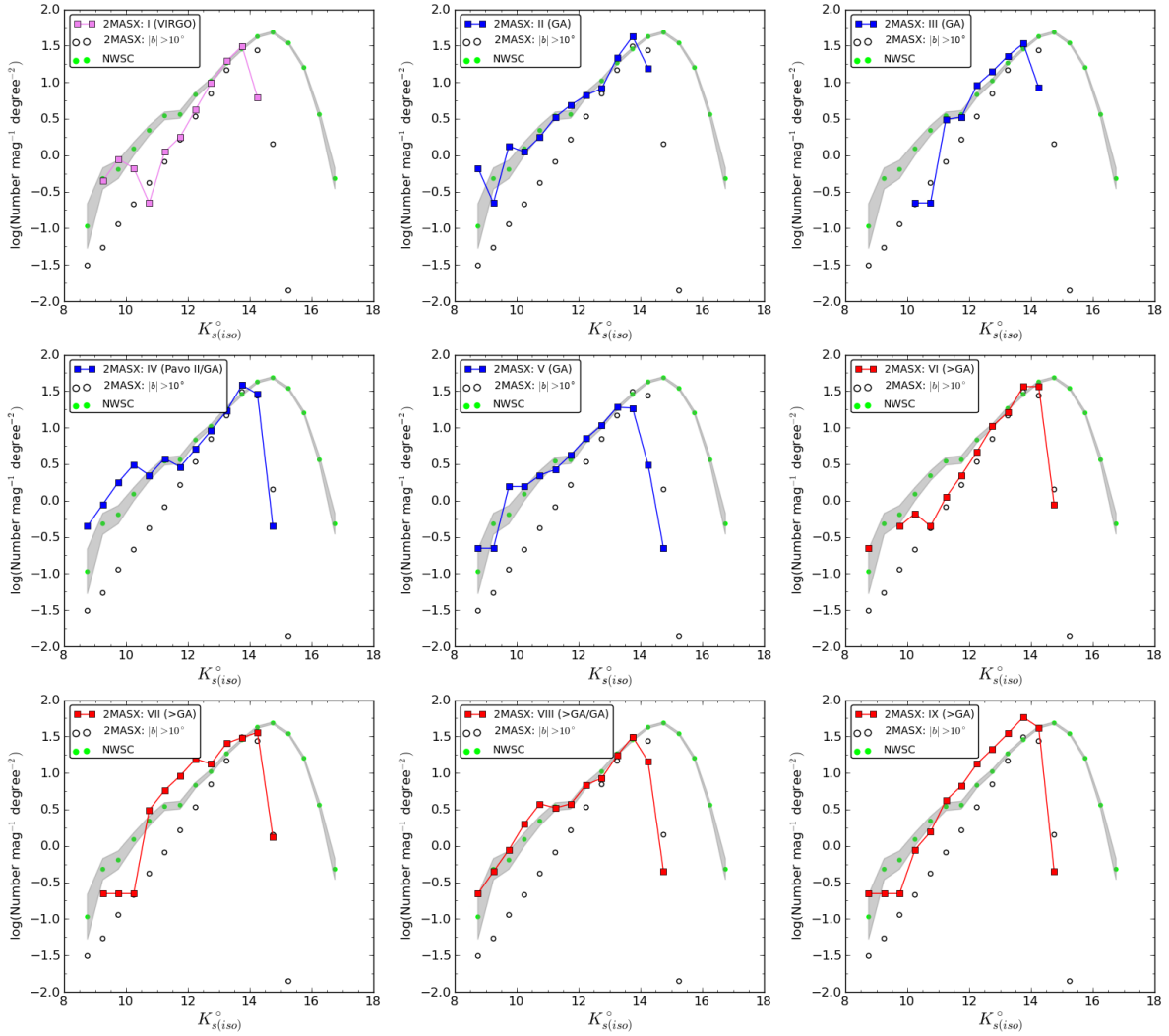


Figure 5.21: Galaxy density counts for the nine 2MASX selected regions. The NWS density counts (solid circles) are also shown in every panel with the 2MASX field counts (open circles).

this region to the Pavo II cluster. Even though the distribution in panel 3 is for a region of the Norma Wall that connects the CIZA J1324.7-5736 cluster to Abell S0639, the distribution in this region runs short of galaxies compared to the NWS. Looking more closely into this region we can see from panel 2 of Fig. 5.20 that this region is actually devoid of galaxies in the GA.

The distributions in Fig. 5.21 reveal that beside regions II, IV and V region VIII also shows a similar behaviour as the NWS distribution. As mentioned before this region has a major contribution from galaxies in the redshift range $0.01 < z < 0.02$ plus another density enhancement from galaxies in the redshift slice $0.03 < z < 0.04$. The good comparison between the NWS counts and the counts in this region can hence be explained as due to galaxies at

the GA distance while the bump in the distribution at $10^m5 \leq K_{s(iso)} \leq 11^m0$ is due to the additional density enhancement found in the background of the GA ($0.03 < z < 0.04$).

The galaxy distributions for regions VI, VII and IX are all for density enhancements at redshifts higher than $z > 0.03$, i.e. they are all further away than the GA. The distributions in these three regions have lower density counts in the magnitude range $9^m0 \leq K_{s(iso)} \leq 12^m0$ i.e. where the NWS overdensity is most prominent. This also strongly indicate that galaxy distributions farther than the GA can not explain the observed overdensity in the NWS area.

The relatively good correspondence of the NWS density counts with regions that have overdensities at the GA distance i.e. II, IV, V, and VIII supports the notion that the NWS density enhancement is mainly due to galaxies at the GA distance. The comparison of the NWS density counts with regions IV and V which are part of the Norma Wall indicates that the survey area has a comparable density to the other parts of the Norma Wall. This assessment will allow an estimate of the total mass of the Norma Wall assuming that the whole wall is homogeneous in galaxy distribution (see Sect. 5.4).

5.5 Photometric redshifts

Ideally, it would be very usefull to have redshifts for galaxies in the NWS area to map these galaxies in 3-dimensions. Unfortunately as the NWS lies deep in the ZOA where dust obscuration and star crowding are extreme, the process of determining redshifts for galaxies in the ZOA using optical observations is very difficult. In fact inquiring the NASA/IPAC Extragalactic Database¹ (NED) resulted in identifying only 128 galaxies with redshifts, i.e. $\approx 97.1\%$ of the galaxies in the NWS area do not have redshifts, almost all of which are at the lower extinction levels.

For the purpose of analysing our galaxy distribution using a distance indicator we supplemented the list of galaxies in the NWS with photometric redshifts. Even though photometric redshifts are not very accurate they have the benefit that they can be calculated from galaxies apparent magnitudes. A method that was first developed by Kochanek et al. (2003) and then improved and implemented by T. H. Jarrett¹ uses the 2MASS NIR J , H and K_s magnitudes to estimate redshifts (photometric redshifts). The typical uncertainty in photometric redshifts is ($\approx 30 - 40\%$).

Photometric redshifts for galaxies in the NWS were kindly derived by T. H. Jarrett for 3936 ($\approx 90\%$ of the galaxies in the NWS catalogue). The remaining 10% did not have enough photometric information to enable the derivation of photometric redshifts. The photometric redshift procedure is based on two fundamental assumptions: that galaxies have the same absolute lu-

¹This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

¹Infrared Processing and Analysis Center, Spitzer Science Center, Jet Propulsion Laboratory, California Institute of Technology

minosity in the K_s band and that their NIR colours $(J - H)^\circ$ and $(H - K_s)^\circ$ are affected by cosmic reddening (k-correction). Galaxy colours were calculated using the $5''$ constant aperture magnitudes.

In the following sections I will use the derived photometric redshifts to first study the galaxy distribution at the GA and how this distribution relates to the overall galaxy overdensity seen in the NWS. I will also use photometric redshifts to further study the seven overdense regions previously discussed in Sect. 5.3.2. But to begin it is important to have at first a good understanding of the reliability of the photometric redshifts derived for the heavily obscured galaxies in our survey area. The high levels of dust extinction in the NWS survey area are expected to introduce large uncertainties in the calculations of photometric redshifts. This is done in the next section.

5.5.1 NWS photometric redshifts reliability

To assess the accuracy of the photometric redshifts, I cross-correlated 128 galaxies in the NWS catalogue to their counterparts with spectroscopic redshifts in NED. Figure 5.22 displays the distribution of the 128 galaxies in the NWS area with spectroscopic redshifts. Galaxies on the map are colour-coded according to their spectroscopic redshifts. The red dots are galaxies in the redshift range $4000 < cz < 7000 \text{ km s}^{-1}$, i.e. at the GA distance, while galaxies marked in green are in the foreground of the GA and those in blue are in the background of the GA.

The majority (78.1%) of the galaxies in this map lie at the GA distance. Only 5.4% of the galaxies are in the foreground of the GA ($4000 < cz \text{ km s}^{-1}$) and 16.4% are in the background with $cz > 7000 \text{ km s}^{-1}$. Most of the galaxies with spectroscopic redshifts at the GA are located in the CIZA J1324.7-5736 and Cen-Crux clusters.

The top panel of Fig. 5.23 shows the photometric redshift (z_{phot}) on the ordinate and the spectroscopic redshift (z_{spec}) on the abscissa, the red dashed line is the line of equality. The lower panel displays the redshift offset $\Delta = z_{phot} - z_{spec}$ as a function of z_{spec} .

Most of the galaxies in Fig. 5.23 have photometric redshifts that are comparable to the spectroscopic redshifts with a median offset of $\Delta = 0.001$ and a standard deviation of $\sigma = 0.02$. Only few galaxies show a significant offset $\Delta > 0.05$. There are no galaxies that have a match in the NED for a photometric redshift $z_{phot} \geq 0.12$. This emphasizes the difficulty in deriving spectroscopic redshifts for apparently faint and distant galaxies in the ZOA. The lack of galaxies with redshift $z > 0.12$ makes it impossible to assess the accuracy of photometric redshifts in this redshift regime. The typically large uncertainties ($\approx 30 - 40\%$) in photometric redshifts causes higher velocity dispersions compared to their distributions in spectroscopic redshift space. This results in photometric redshift distributions being considerably broader than the respective spectroscopic redshift and subsequently more washed-out large-scale structures.

To illustrate this broadening effect in the distribution of the photometric redshifts I compare the galaxy distribution for the 128 galaxies as a function of photometric and spectroscopic

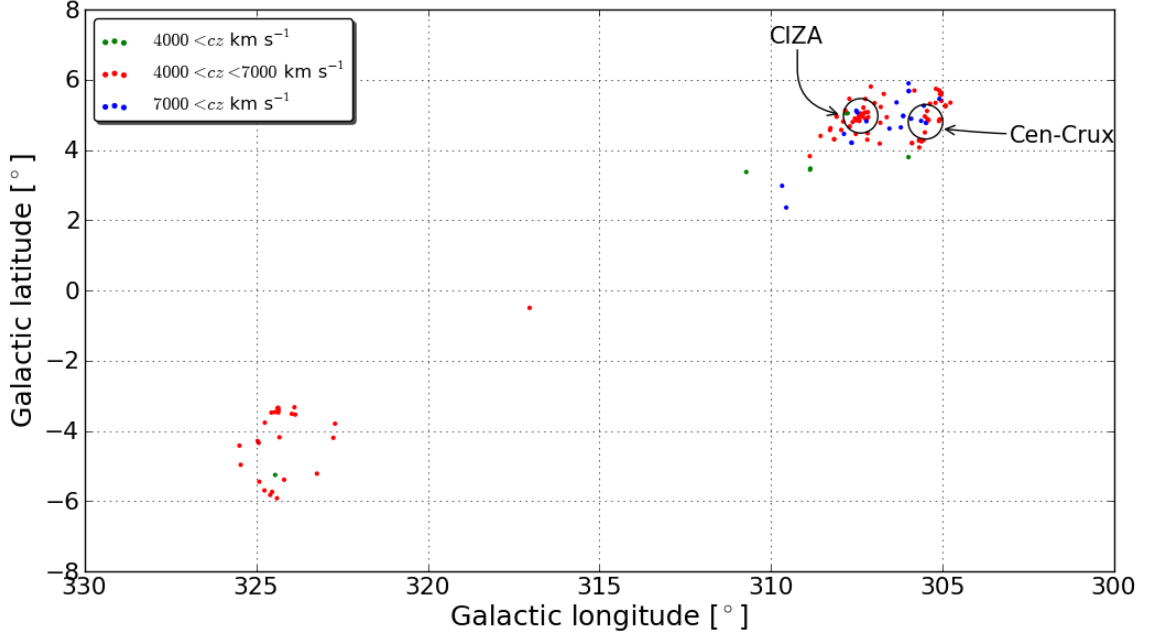


Figure 5.22: Spatial distribution of the 128 galaxies with spectroscopic redshifts. Green dots are galaxies with $cz < 4000 \text{ km s}^{-1}$, red dots are galaxies with $4000 < cz < 7000 \text{ km s}^{-1}$ and blue dots galaxies with $7000 \text{ km s}^{-1} < cz$.

redshifts. The top panel of Fig. 5.24 shows the redshift histogram for galaxies brighter than $K_{s(iso)} = 12^m75$ (this magnitude cut is imposed for later comparisons as discussed in later in this section) with both spectroscopic and photometric redshifts. Only galaxies brighter than $K_{s(iso)} = 12^m75$ were plotted to emphasize more the nearby galaxy distribution than the more distant one. The hashed histogram is for the spectroscopic redshifts while the open histogram is for the photometric redshifts. The two later panels subdivide the sample in left with no galaxy clusters (CIZA J1324.7-5736 and Cen-Crux) and right with only the CIZA J1324.7-5736 cluster. Galaxy counts used in these two panels are for galaxies brighter than $K_{s(iso)} = 12^m75$ within a $45' \times 45'$ area centred at the CIZA J1324.7-5736 and Cen-Crux clusters.

For the sake of completeness it is also useful to compare the redshift distributions in the three panels of Fig. 5.24 to a mean field galaxy distribution as a function of redshift. This comparison assists in identifying regions in redshift space with excess galaxy counts. To derive the field distribution as a function of redshift I used the field luminosity function (luminosity function is a probability distribution for galaxies as a function of absolute magnitude) derived by Jones et al. (2006) for the 6-degree Field Galaxy Survey (6dFGS) (Jones et al., 2004, 2005). The 6dF Galaxy Survey is a near-infrared-selected redshift and peculiar velocity survey that is complete to the 2MASX total extrapolated magnitude limits of $(J, H, K_s) = (13^m75, 13^m00,$

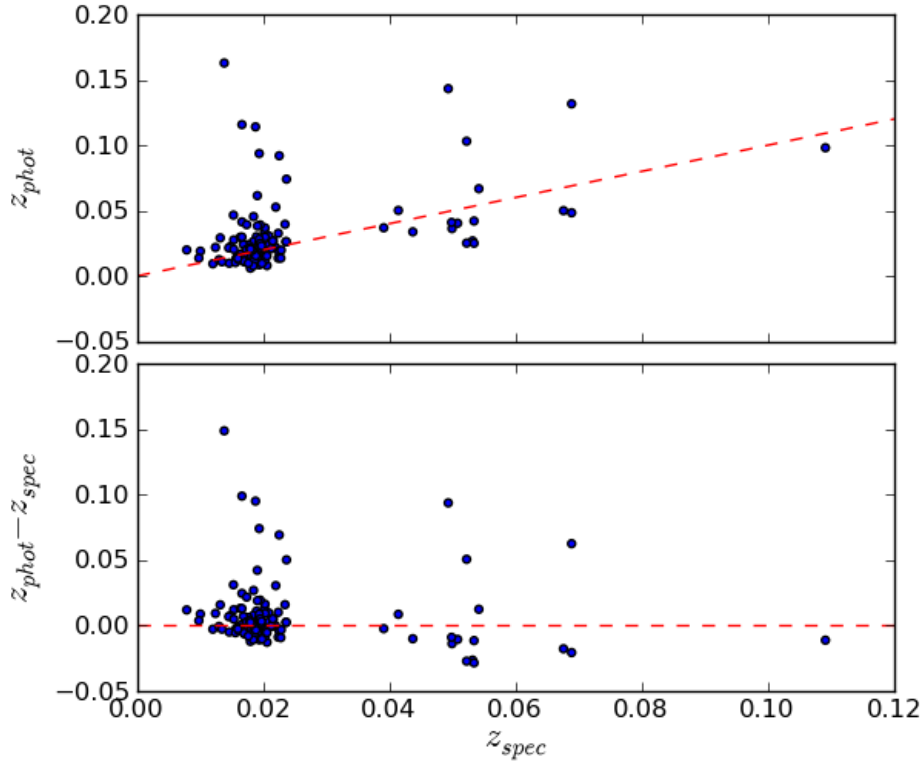


Figure 5.23: Photometric and spectroscopic comparison for 128 galaxies in the NWS catalogue that had spectroscopic redshift in NED. Top panel: photometric redshift on the ordinate and spectroscopic on the abscissa, the red dashed line is the line of equality. Lower panel: redshift offset $\Delta = z_{phot} - z_{spec}$ as a function of the z_{spec} .

12^m75) over 83% of the southern sky ($|b| > 10^\circ$). For each of the distributions displayed in Fig. 5.24 the field counts are normalized to the total number counts in the respective galaxy distributions.

The three panels of Fig. 5.24 show that the photometric redshifts histograms are always broader than their respective spectroscopic redshifts. We also note that the photometric redshift histograms are skewed towards higher redshifts. This suggests that galaxies' distances derived from photometric redshifts are on average larger than when using spectroscopic redshifts. Even though photometric redshifts are less accurate than their spectroscopic redshift counterparts they are still reliable enough to be used for identifying structures that are well separated in the redshift space.

With these biases in photometric redshifts, they are used in the following sections to study the galaxy overdensity recovered by the NWS. The photometric redshifts will also be used to further study the seven regions with excess density (Sect. 5.3.2).

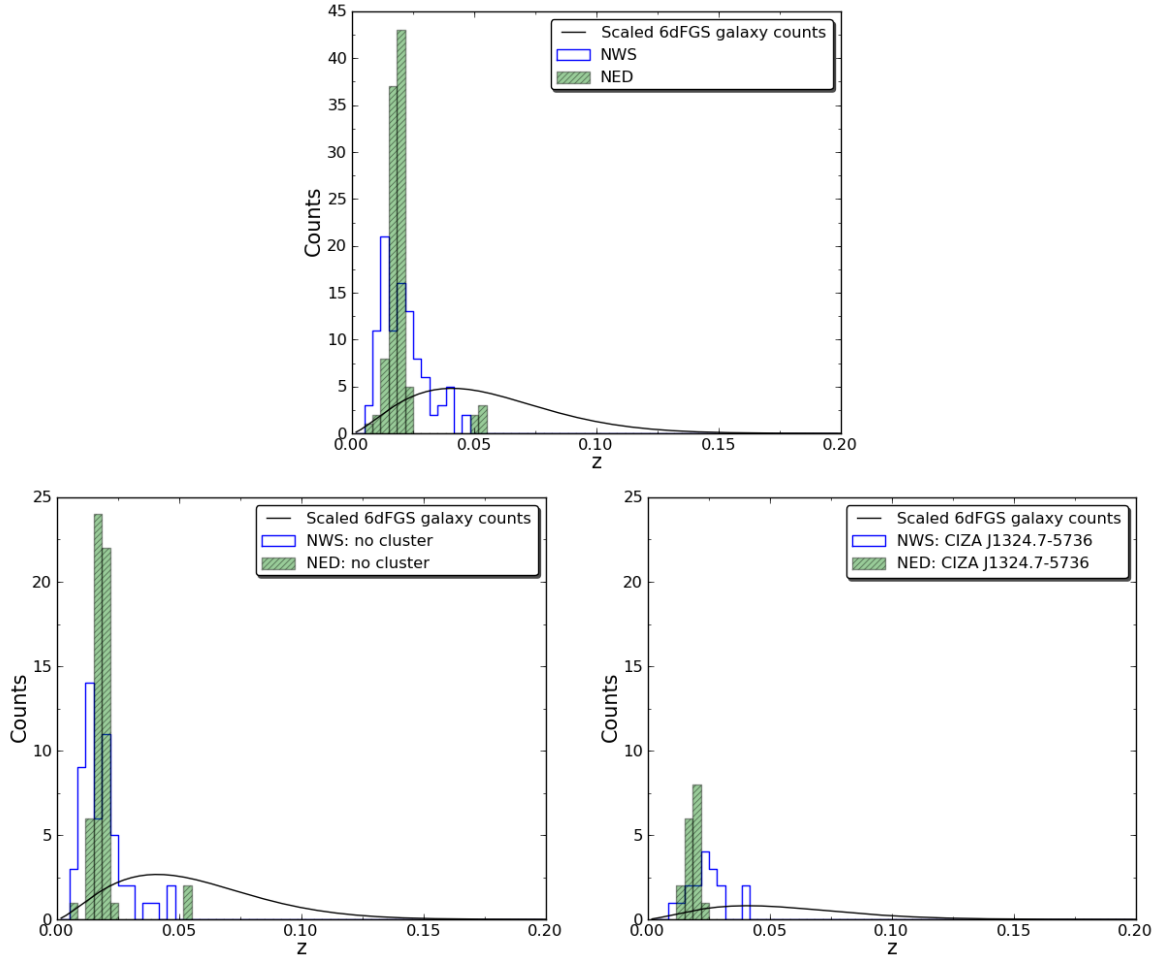


Figure 5.24: Redshift distributions for galaxies with spectroscopic redshifts. Top: galaxies brighter than $K_{s(iso)} = 12^m.75$ with spectroscopic and photometric redshifts. Left bottom: histograms for galaxies excluding those within a $45' \times 45'$ area centred at the CIZA J1324.7-5736 and Cen-Crux clusters. Right bottom: distribution for galaxies within $45' \times 45'$ area centred at the CIZA J1324.7-5736 cluster. The smooth distribution is the field counts derived using the 6dFGS luminosity function. In each case the derived field counts are normalized to the total number counts in the respective galaxy distributions.

5.5.2 The NWS galaxy distribution in photometric redshift space

As discussed before in previous sections the NWS shows an overdensity compared to the 2MASX mean density counts. This overdensity was found to be due to the overall galaxy distribution in the Norma Wall Survey area and not related to individual clusters within the area (Sect.

5.4). Investigating the origin of this overdensity by comparing it to other regions in the 2MASX skies centred at different redshifts (Sect. 5.4.1) resulted in the conclusion that the observed overdensity in the NWS is due to a galaxy distribution at the GA distance.

In this section I will use the photometric redshifts for galaxies in the NWS to independently assess the origin of this overdensity and whether it can be explained by galaxies that form part of the Norma Wall. For this purpose I display in Figure 5.25 the histogram of the NWS galaxies brighter than $K_{s(iso)} < 12^m.75$ as a function of redshift. Only galaxies brighter than $K_{s(iso)} < 12^m.75$ are used in this histogram to better enhance the nearby structures. In this figure I also plot the normalized field counts as a function of redshift calculated using the 6dFGS luminosity function derived by Jones et al. (2006). It is worth reminding here again the the magnitude $K_{s(iso)} = 12^m.75$ is also the limiting magnitude for the galaxies used for deriving the 6dFGS luminosity function (Jones et al., 2004, 2005). The field distribution is given here as a reference for what an average galaxy distribution would look like as a function of redshift.

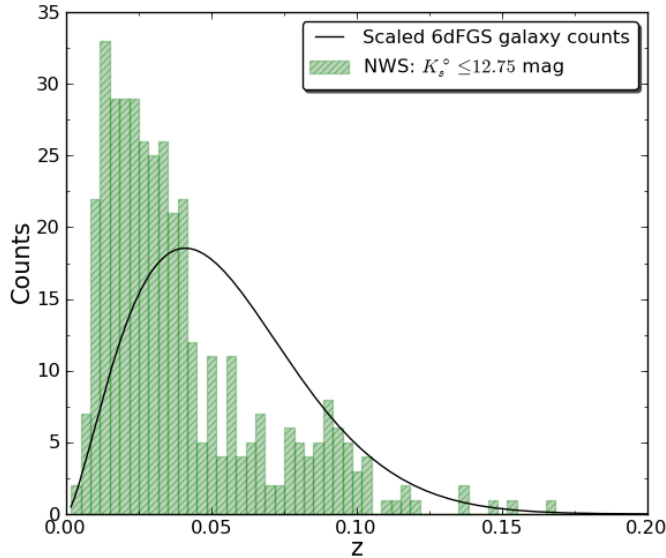


Figure 5.25: Photometric redshift histogram for galaxies brighter than $K_{s(iso)} = 12^m.75$ and the 6dFGS field density scaled for the NWS counts in the shown histogram.

The distribution in Fig. 5.25 shows broad excess compared to the 6dFGS field counts in the photometric redshift range $0.005 < z_{phot} < 0.04$ or $1500 < cz_{phot} < 12000 \text{ km s}^{-1}$. This excess galaxy counts are well within the Norma Wall redshift range $3000 \lesssim cz \lesssim 8000 \text{ km s}^{-1}$ assuming that photometric redshift distributions are always broader than their respective spectroscopic redshifts. This adds further evidence in support of the overdensity in the NWS area being caused by galaxies at the GA distance.

Another feature of interest in the distribution in Fig. 5.25 is the galaxy counts around

$z_{phot} \sim 0.09$. Even though the counts in the histogram are not higher than the field counts at the same redshift, the distribution around $z_{phot} \sim 0.09$ can be a sign of a distant large-scale structure. The histogram in this figure was limited to galaxies brighter than $K_{s(iso)} = 12^m.75$ to emphasize the nearby structures. The distribution around $z_{phot} \sim 0.09$ may well be due to the regions 2, 6 and 7 of high density that are prominent in panel 2 of Fig. 5.13. The magnitude histograms in Fig. 5.14 also supports this possibility. In the next section I will investigate the photometric redshift distribution for galaxies in the seven regions with excess galaxy counts over and above the mean NWS counts (Sect. 5.3.2).

5.6 The overdense regions as a function of photometric redshift

Studying the galaxy distributions in the overdense seven regions as a function of apparent magnitude resulted in the conclusion that regions 1 and 3 are due to the CIZA J1324.7-5736 and Cen-Crux clusters and three other regions (2, 6 and 7) are likely to be due to structures more distant than the GA.

I will now look at the photometric redshifts of the galaxies in these regions. The central positions for these seven regions is listed in Table 5.5 in addition to their respective galaxy densities. For the purpose of investigating these regions using photometric redshifts I display in Fig. 5.26 their galaxy counts as a function of photometric redshifts for galaxies brighter than $K_{s(iso)}^\circ \leq 14^m.8$ within an area of $35' \times 35'$ centred on the central positions of these regions. On each panel the histogram of the CIZA J1324.7-5736 cluster region (region 1) is overlaid.

In panel 1 of Fig. 5.26, the CIZA J1324.7-5736 cluster has the strongest peak. Two other peaks are also seen in this panel at $z_{phot} \sim 0.1$ and $z_{phot} \sim 0.055$. The peak at $z_{phot} \sim 0.1$ is indicative of an overdensity that lies behind the GA at this redshift. Meanwhile the peak at $z_{phot} \sim 0.055$ can be caused by the large uncertainty and broadening in the photometric redshifts distribution. I expect this peak to be due to the CIZA J1324.7-5736 cluster and not to a more distant overdensity.

Panel 3 shows a peak at $z_{phot} \sim 0.025$ due to the Cen-Crux cluster. No other peaks are seen in this panel. As expected the galaxy counts for the Cen-Crux cluster are significantly lower than those for the CIZA J1324.7-5736.

Panels 2, 6 and 7 have strong peaks at $z_{phot} \sim 0.1$ which also indicate the presence of an overdensity at this redshift. This is in support of the result in Sect. 5.3.2 that the excess counts in these regions are due to galaxies further than the GA. Regions 6 and 7 are only $0^\circ.38$ apart and might form part of the same structure. Region 2 is $\sim 1^\circ.17$ away from region 1 where again a peak at $z_{phot} \sim 0.1$ is found. This suggests that there might be an extended overdensity at $z_{phot} \sim 0.1$ which lies behind the CIZA J1324.7-5736 cluster.

Region 5 also has a moderate peak also at $z_{phot} \sim 0.1$. The strong peaks at $z_{phot} \sim 0.1$ in regions 2, 6 and 7 and moderate one in region 1 behind the CIZA J1324.7-5736 cluster and in region 5 both also at $z_{phot} \sim 0.1$ is a sign for a possible large-scale structure at $z_{phot} \sim 0.1$.

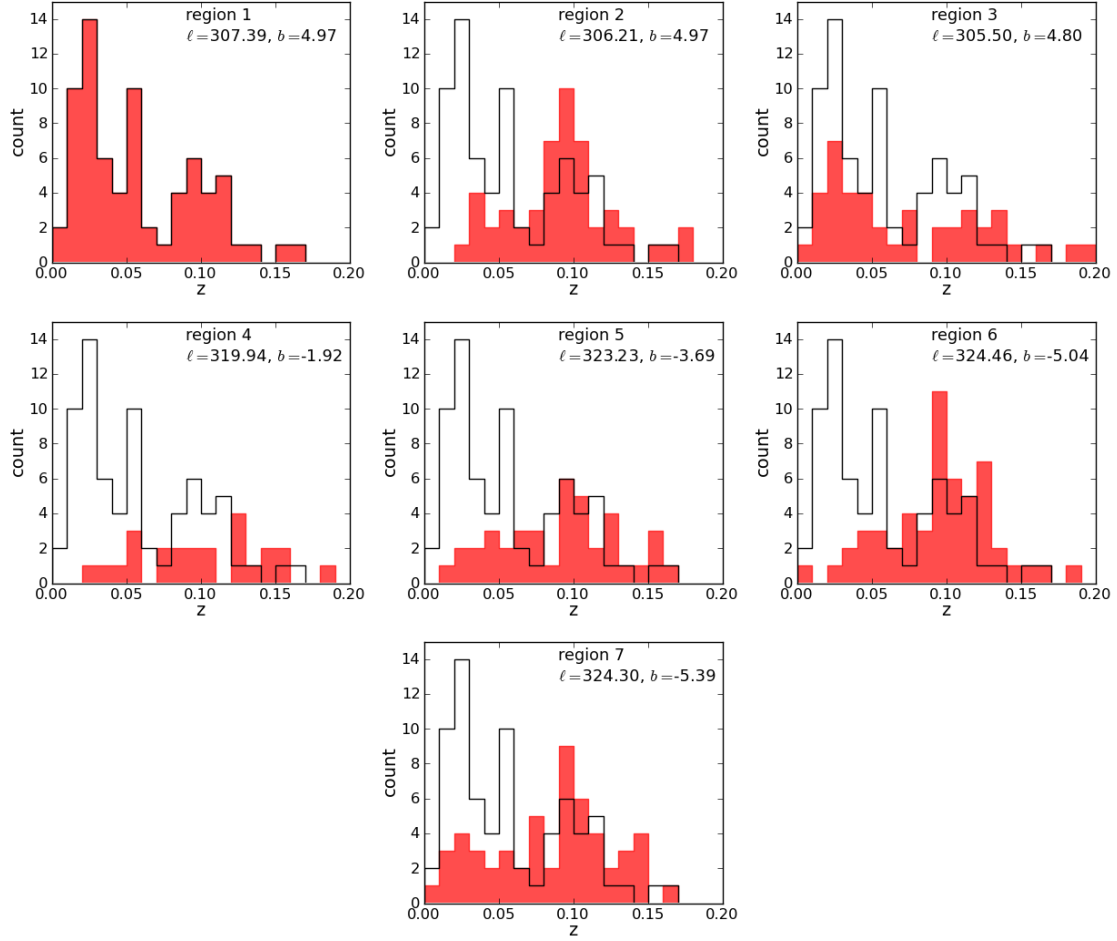


Figure 5.26: Photometric redshift distribution for regions listed in Table 5.5 (red bins). The histogram (open) for region 1 (CIZA J1324.7-5736 cluster) is overlaid in all panels for comparison.

Unfortunately because of the large uncertainties in the photometric redshifts, this structure can not be further investigated with photometric data, but instead requires deep spectroscopy to detect the redshifted spectral features.

Panel 4 does not show any sign for an overdensity. To summarize this discussion, no region with excess counts over and above the mean galaxy counts in the NWS area are seen at the GA distance i.e. no galaxy clusters within the NWS footprint are newly discovered. On the other hand we see compelling evidence for galaxy clusters or even large-scale structures that might lie in the background of the Norma Wall at $z_{phot} \sim 0.1$.

5.7 The NWS density enhancement

From the discussions in the previous sections the following picture about the galaxy overdensity in the NWS and how it is related to the Norma Wall has emerged. The NWS area is a part of the Norma Wall with a homogeneous galaxy distribution over and above the mean 2MASX galaxy counts. The galaxy distribution in the NWS area is similar to distributions in the other parts of the Norma Wall.

In this section I will quantify the observed overdensity at the GA distance. A first step towards this goal is to distinguish the galaxy density at the GA distance from foreground and background galaxy distributions. For this purpose I used two independent methods. The first uses the mean 2MASX all sky galaxy density counts excluding the ZOA. The mean 2MASX counts are interpreted as the density distribution for an average field where all signatures of clusters, galaxy groups, wall-structures, filaments and voids wash out leaving a mean distribution. In this method the difference between the NWS counts and the 2MASX mean counts (the NWS and 2MASX counts are shown in top-left panel of Fig. 5.15) are considered as the number of excess galaxies at the GA distance. In the second method I use the galaxies' photometric redshifts. Based on the discussions in Sect. 5.5.2, all galaxies with photometric redshifts $0.005 < z_{phot} < 0.04$ can be considered members of the GA. This is displayed in top-left panel of Fig. 5.27 where it shows the excess density counts $\log(N \text{ mag}^{-1} \text{ deg}^{-2})$ (blue boxes) due to galaxies at the GA distance found using the first method. The top-right panel shows the excess counts (red boxes) due to galaxies at the GA distance in the redshift range $0.005 < z_{phot} < 0.04$. For reference, the all-area NWS density counts (lime dots) and 2MASX mean density counts (open circles) are displayed in the two top panels of Fig. 5.27. It is worth mentioning here that the galaxy counts used here are for galaxies in regions A, B, D and E (see Sect. 5.4 and Fig. 5.17), i.e. only galaxies in the 33.2 deg^2 area of the survey footprint where extinction is lower than $A_{K_s} \leq 1^m0$ and stellar density $\log(N_{(K_s < 14)}/\text{deg}^2)=4.71$.

The lower panel of Fig. 5.27 shows the excess counts due to the two methods. The shaded regions around the density counts are the counts error bands.

The two distributions in the Lower panel of Fig. 5.27 agree remarkably well within their respective error bars. This gives further evidence that the observed overdensity forms part of the Norma Wall. The good agreement between the two methods used for identifying the galaxy overdensity encourages us to use them both to further quantify the Norma Wall Survey overdensity. In the next section I will use two methods independently to derive the luminosity function for the overdensity and hence calculate the total light flux due to them.

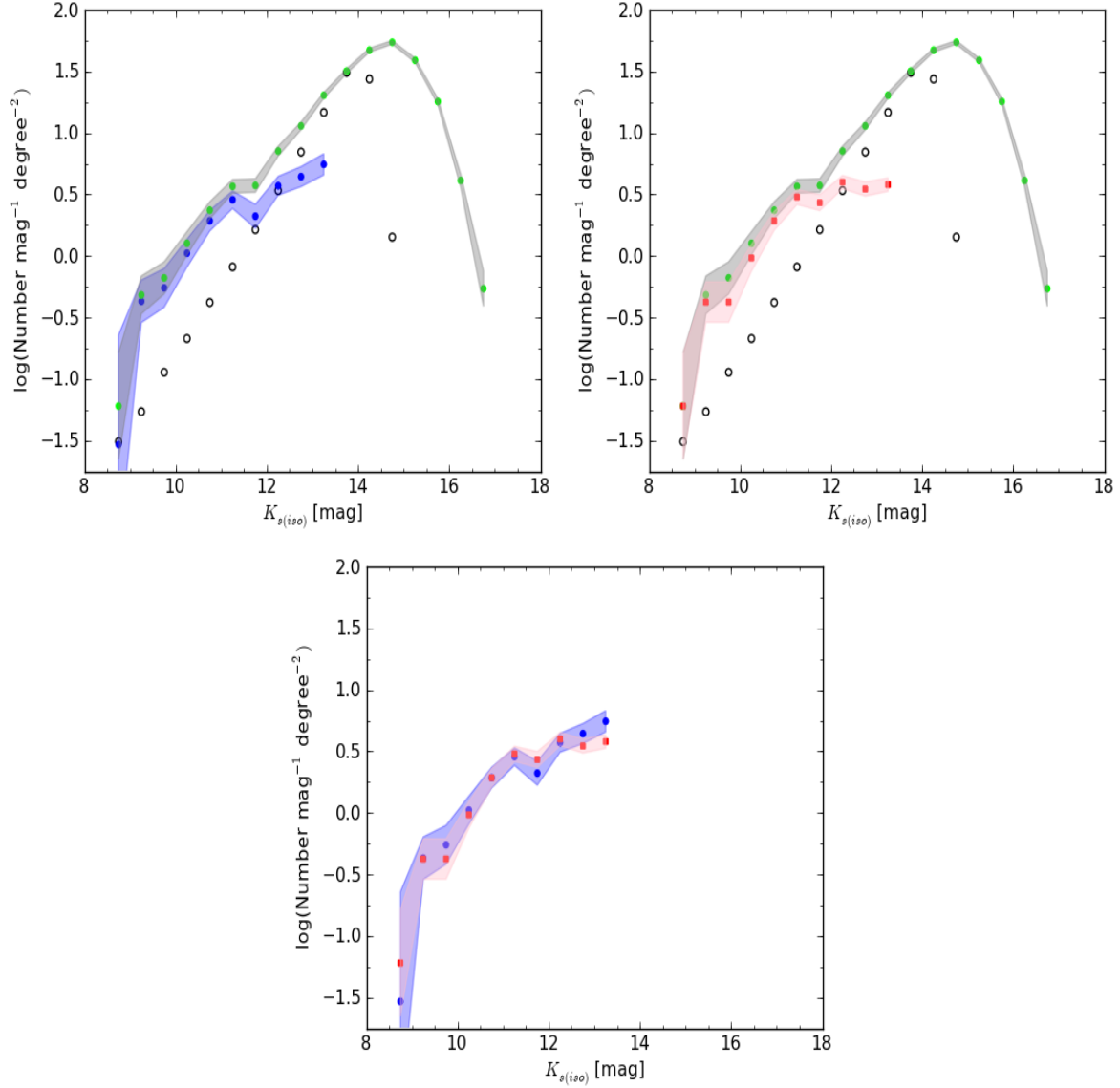


Figure 5.27: Galaxy overdensity counts. Top-left panel: The NWS counts (lime circles), the mean 2MASX density counts (open circles) and the difference between the two, i.e. the excess density counts (blue circles). Top-right panel: The all survey area NWS counts (lime circles), the mean 2MASX density counts (open circles) and the density counts for galaxies in the redshift range $0.005 < z_{\text{phot}} < 0.04$. Lower panel: The excess density counts (blue circles) calculated as the difference between the NWS counts and the 2MASS mean counts and the density counts for galaxies in the redshift range $0.005 < z_{\text{phot}} < 0.04$.

5.8 Galaxy count and the Luminosity Function

Determining the total flux for galaxies that make up the observed overdensity in panel 3 of Fig. 5.27 will only account for the luminosity due to galaxies that are brighter than the magnitude completeness limit of the survey. To account for the missing luminosity as a result of the galaxies being fainter than the magnitude completeness limit, it is customary to derive the Luminosity Function (LF) (Schechter, 1976) for the observed galaxy distribution. As mentioned before, the LF is a probability distribution of absolute magnitudes for galaxies. An analytic form for the LF was given by Schechter (1976). As a function of absolute magnitude (M) the Schechter function is written as,

$$\phi(M)dM = \phi^* 10^{0.4(\alpha+1)(M^*-M)} e^{-10^{0.4(M^*-M)}}. \quad (5.1)$$

In terms of the galaxy luminosity (L) it is,

$$\phi(L)dL = \frac{\phi^*}{L^*} \left(\frac{L}{L^*} \right)^\alpha e^{-(\frac{L}{L^*})} dL, \quad (5.2)$$

where M^* and L^* are the characteristic magnitude and luminosity respectively (“knee of the curve”). Galaxies brighter than M^* are described by a logarithmic density distribution while the fainter galaxies are better described using a power law.

α is the slope of faint-end and ϕ^* the normalisation factor. The absolute magnitude M is related to the apparent magnitude via the distance module:

$$M = m^0 - 5 \log \left(\frac{v}{H_0} \right) - 25 - k(z), \quad (5.3)$$

where m^0 is the extinction-corrected apparent magnitude, H_0 the Hubble constant (a value of $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ is adopted throughout), v the Hubble recession velocity and $k(z)$ the k-correction. The K_s band k-correction is defined according to Worthey (1994) as,

$$k(z) = -6.0 \log(1 + z). \quad (5.4)$$

The total luminosity for a galaxy distribution characterized by Eqn. 5.2 is,

$$\int_0^\infty L \phi(L) dL = L^* \phi^* \Gamma(\alpha + 2), \quad (5.5)$$

where Γ is the Gamma function.

To convert apparent magnitudes of galaxies to absolute magnitudes the excess galaxies in the two distributions in lower panel of Fig. 5.27 are assumed to be at the distance of the Norma cluster i.e. a mean of $z = 0.016$ (4844 km s^{-1}). The resulting luminosity functions due to the overdensity is displayed in Fig. 5.28. The left panel of this figure shows the density counts $\log(N \text{ mag}^{-1} \text{ Mpc}^{-2})$ as a function of absolute magnitude for deduced by excluding foreground and background galaxy counts from the NWS counts based on the 2MASX mean density counts.

The right panel shows the density counts as a function of absolute magnitude for galaxies within a photometric redshift range $0.005 < z_{phot} < 0.04$. The shaded regions represent the density counts error bars. In both panels of Fig. 5.28, the fitted Schechter function to the distribution is indicated by the solid line. The dashed lines are the 1σ confidence band for the fitted Schechter functions.

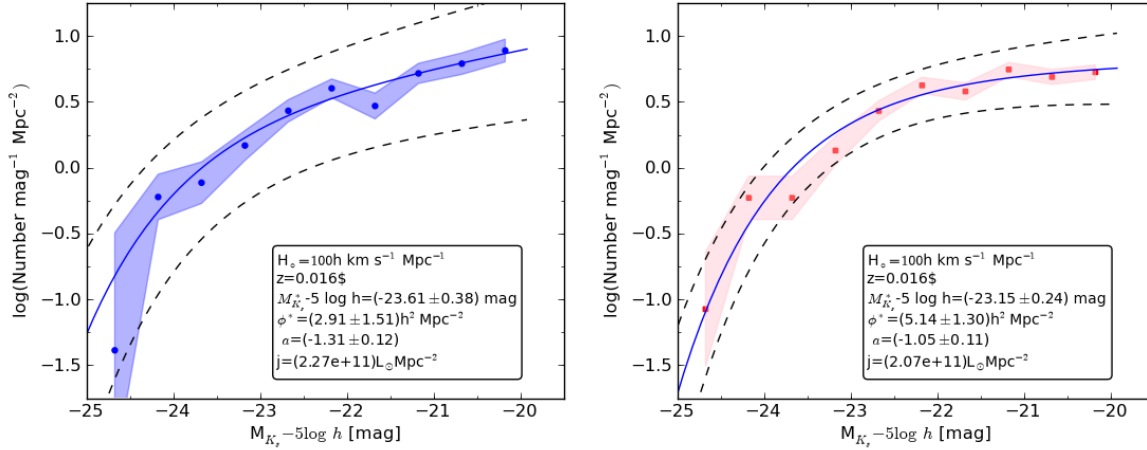


Figure 5.28: The LF for the galaxy overdensity. Left panel: Excess galaxy counts determined from the difference between the NWS counts and the 2MASX mean counts. Right panel: Density counts for galaxies in the redshift range $0.005 < z_{phot} < 0.04$. All galaxies in the overdensity are assumed to be at the distance of the Norma cluster $\langle z \rangle = 0.016$. The regarded survey area is 33.2 deg^2 . The fitted Schechter function is displayed on the plots with the solid line, while the dashed lines are the 1σ confidence band for the fitted Schechter functions.

The galaxy overdensity distribution in the left panel of Fig. 5.28, defined as the excess between the NWS density counts and the mean 2MASX density counts, is characterized by a Schechter function with the following parameters $M_{K_s}^* - 5 \log h = (-23.61 \pm 0.38) \text{ mag}$, $\phi^* = (2.93 \pm 1.51)h^2 \text{ Mpc}^{-2}$ and $\alpha = -1.30 \pm 0.12$. Using equation 5.5 to deduce the K_s band total luminosity density due to this distribution yields $j_{NWS} = 2.27 \times 10^{11} L_{\odot} \text{ Mpc}^{-2}$, where $L_{\odot}$ is the solar luminosity in the K_s band.

The distribution of galaxies in the redshift range $0.005 < z_{phot} < 0.04$ is characterized with the following Schechter parameters: $M_{K_s}^* - 5 \log h = (-23.15 \pm 0.24) \text{ mag}$, $\phi^* = (5.14 \pm 1.30)h^2 \text{ Mpc}^{-2}$ and $\alpha = -1.05 \pm 0.11$. The total luminosity density in this region is $j_{NWS} = 2.07 \times 10^{11} L_{\odot} \text{ Mpc}^{-2}$. This is $\approx 91\%$ the luminosity density calculated using the excess counts between the NWS density counts and the 2MASX mean counts. The two luminosity densities agree extremely well despite the quite significant difference in their respective faint-end slopes. This is not unexpected as most of contribution to the luminosity density comes from galaxies that

are ≈ 2 magnitudes brighter or fainter than the characteristic M^* galaxies for which the two distributions agree.

It is important to note here that this luminosity density estimate is for the part of the Norma Wall surveyed in the NWS that also hosts two clusters CIZA J1324.7-5736 and Cen-Crux.

5.9 The M^* galaxy

M^* is the characteristic magnitude for a LF fitted with a Schechter function. Galaxies brighter than M^* are described by a logarithmic density distribution while the fainter galaxies are better sampled with a power law. In the previous section I derived M^* magnitudes for the two galaxy distributions plotted in Fig. 5.28. The first distribution was selected to represent the galaxy overdensity at the GA distance with the galaxy counts corrected for foreground/background galaxies using 2MASX mean density counts. The second distribution also represents galaxies at the GA distance, but with galaxies selected according to their photometric redshifts. The first galaxy distribution had $M^* = -23.60 \pm 0.38$ mag while the second distribution had $M^* = -23.15 \pm 0.24$ mag. These M^* values are comparable to K_s band values from other authors. In Table 5.7, I list the K_s band values for M^* galaxies from different authors with their respective values of α . The faint end slopes (α) are also listed because of the degeneracy in the values of M^* and α of the Schechter function.

Table 5.7: Schechter parameters from different authors.

Reference	LF type	$M^* - 5 \log h$	α	Notes
Current work	overdensity	-23.61 ± 0.38	-1.31 ± 0.12	NWS-2MASX
Current work	overdensity	-23.15 ± 0.29	-1.05 ± 0.11	$0.005 < z < 0.04$
Jones et al. (2006)	field	-23.83 ± 0.03	-1.16 ± 0.04	
Kochanek et al. (2001)	field	-23.39 ± 0.03	-1.09 ± 0.05	
Cole et al. (2001)	field	-23.44 ± 0.03	-0.96 ± 0.05	
Skelton et al. (2009)	cluster	-24.61 ± 0.80	-1.26 ± 0.10	the Norma cluster

Jones et al. (2006); Kochanek et al. (2001); Cole et al. (2001) used the 2MASX K_s band magnitudes for deriving their field LF. While Skelton et al. (2009) used the IRSF/SIRIUS K_s band observations of the Norma cluster. No effort was made here to homogenize the M^* values due to the different authors.

From the listed values of M^* it is apparent that the here derived values are comparable to those for field distributions but fainter than for instance the Norma cluster. This is expected as the density of bright galaxies in clusters are higher than in fields and filaments.

The K_s band completeness limit of $K_{s(iso)}^o = 14^m8$ of the NWS translates to an absolute magnitude of $M_{K_s}^o = -18^m63$ at the distance of the GA ($v = 4844$ km s $^{-1}$). This indicates that

the NWS can probe galaxy distribution $\sim 5^m$ fainter than the characteristic M^* galaxies and ~ 2.5 magnitudes into the dwarf elliptical galaxies distributions found in the GA assuming that dwarf ellipticals have fluxes $0.1L^*$ (Sparke & Gallagher, 2000).

At the distance of the Shapley Supercluster (14500 km s^{-1}) the completeness limit corresponds to an absolute magnitude of $M_{K_s}^o = -21 \text{ mag}$ i.e. we can probe galaxy distribution 2.5 magnitudes deeper than M^* galaxies at this redshift. This discussion indicates that with current completeness limits we can identify clusters and other structures at both the GA and the Shapley Supercluster distance very well.

For structures at a redshift of $z = 0.1$ (30000 km s^{-1}), the NWS completeness limit is equivalent to an absolute magnitude $M_{K_s}^o = -22.58$ i.e only 1.0 magnitude fainter than the M^* galaxies in the NWS. Hence in our current survey we are able to only detect the bright galaxies in structures at this redshift.

5.9.1 Mass in the Norma Wall

Radburn-Smith et al. (2006) estimated the extent of the Norma Wall to be $\approx 100^\circ$ ($84.5h^{-1}\text{Mpc}$) across the sky. According to Colberg, Krughoff & Connolly (2005) and based on simulations of intercluster filaments, such a filament has a mean cross-sectional radius of $2h^{-1} \text{ Mpc}$. Based on this and the density estimates of such filaments by Colberg, Krughoff & Connolly (2005), Radburn-Smith et al. (2006) estimated the total mass in the Norma Wall to be $\approx 2.5 \times 10^{15}h^{-1} M_\odot$. This mass estimate does not include the mass due to the galaxy clusters. This section gives a crude estimate for the total mass due to the Norma Wall assuming it is a filamentary structure homogeneously filled with a galaxy distribution similar to the observed density in the NWS area.

The galaxy distributions in Fig. 5.16 and the subsequent discussion of the figure indicated that the density counts due to CIZA J1324.7-5736 and Cen-Crux clusters are not the major cause for the observed overdensity in the NWS. Galaxy clusters are known to have a higher density of bright galaxies compared to other structures like filaments for example. Hence, the total luminosity in a filamentary structure may well be influenced by the presence of clusters in the filament. To investigate this in Fig. 5.29 I display the galaxy distribution the two cases. First for all the overdense galaxies defined as the excess between the NWS counts and the 2MASX mean density counts (blue dots). Second the distribution for the excess galaxies excluding the counts due to two $\approx 0.36^\circ$ areas centred on the CIZA J1324.7-5736 and Cen-Crux clusters (green circles). The two distributions agree in their shape quite well with the NWS counts excluding the clusters showing lower density counts.

To account for the total luminosity due to the excess galaxies but excluding the galaxies in the CIZA J1324.7-5736 and Cen-Crux clusters, a Schechter function is fitted to the respective distribution. This Schechter function is characterized by the following parameters: $M_{K_s}^* - 5 \log h = (-23.49 \pm 0.38) \text{ mag}$, $\phi^* = (2.20 \pm 1.46)h^2 \text{ Mpc}^{-2}$ and $\alpha = -1.23 \pm 0.13$. The total

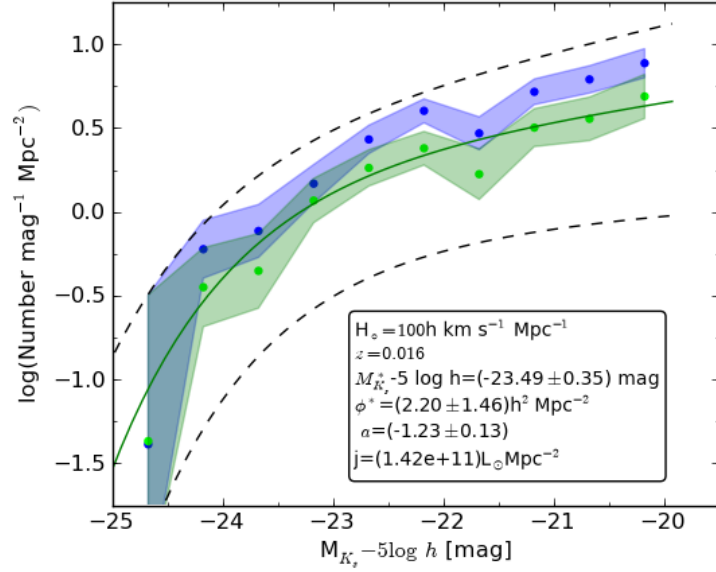


Figure 5.29: The blue dots are the density distribution for the observed overdensity in the NWS defined as the excess between the NWS counts density and the 2MASX mean density. The green circles represent the excess density counts excluding the CIZA J1324.7-5736 and Cen-Crux density counts. The Schechter function fitted to the excess distribution excluding the clusters is plotted with the green solid line.

luminosity due to the excess counts excluding the CIZA J1324.7-5736 and Cen-Crux clusters counts is $j = 1.42 \times 10^{11} L_{\odot} \text{ Mpc}^{-2}$. This is approximately 65% the density of the filament including the clusters.

Now assuming that the Norma Wall is a filamentary structure (a cylinder) of length $84.5h^{-1}$ Mpc, a cross-sectional radii of $2h^{-1}$ Mpc and a luminosity density of $j = 1.42 \times 10^{11} L_{\odot} \text{ Mpc}^{-2}$. Assuming a cylindrical shape for the filamentary structure constituting the Norma Wall is enough to give a crude estimate for the mass of the Norma Wall. A more precise estimate for the mass of the Norma Wall requires a more detailed knowledge of the topology of the Norma Wall which is beyond the scope of the current work. The total mass of such a structure is hence $\approx 2.5 \times 10^{15} h^{-1} M_{\odot}$. This is in excellent agreement with the mass estimate for the Norma Wall filament given by Radburn-Smith et al. (2006). To estimate the mass in the filament I assumed a mass-to-light ratio of $M/L = 53h M_{\odot}/L_{\odot}$. This mass-to-light ratio was adopted from Rines et al. (2004) for regions within $1\text{--}10 h^{-1}$ Mpc of a galaxy cluster. The Norma wall is a rich structure with a number of clusters known to reside along it. This makes the use of $M/L = 53h M_{\odot}/L_{\odot}$ a plausible assumption to estimate the mass within the Norma Wall.

The clusters Norma, Pavo II, CIZA J1324.7-5736, Cen-Crux and Abell S0639 contribute an

additional mass of $\approx 1.56 \times 10^{15} h^{-1} M_{\odot}$; Table 5.8 lists dynamical masses for clusters in the Norma Wall. This give a combined mass of $\approx 4.06 \times 10^{15} h^{-1} M_{\odot}$ in the filamentary structure and clusters of the Norma Wall. This mass is $\approx 15\%$ of the GA mass ($2.7 \times 10^{16} h^{-1} M_{\odot}$) as estimated by Lynden-Bell et al. (1988). The here derived mass favours previous discussions by Staveley-Smith et al. (2000) and Kocevski et al. (2007). Staveley-Smith et al. (2000) using HI observations by the Parkes telescope estimated a mass for the GA of $\sim 2 \times 10^{15} h^{-1} M_{\odot}$ from HI observations. Kocevski et al. (2007) using the CIZA catalogue also gave a very similar estimate for the GA mass using a census of rich X-ray clusters within the Norma Wall. The estimate by Kocevski et al. (2007) does not include the mass within the filamentary structure of the Wall. The current estimate for the mass of the Norma Wall ($\approx 4.06 \times 10^{15} h^{-1} M_{\odot}$) is also compatible with mass estimates by Bolejko & Hellaby (2008) for the GA. Bolejko & Hellaby (2008), using a non-linear relativistic model of the Shapley Concentration with the model constrained by observational data, they estimated the mass of the GA to be $4 - 6 \times 10^{15} h^{-1} M_{\odot}$. The above quoted mass estimates of the Norma Wall are summarized in Table 5.9.

Table 5.8: Masses for clusters contributing to the Norma Wall

Cluster	Mass [$\times 10^{15} h^{-1} M_{\odot}$]	Ref.
Norma	0.80	Woudt et al. 2008
CIZA J1324.7-5736/Cen-Crux	0.35	Radburn-Smith et al. 2006
Abell S0639	0.12	Radburn-Smith et al. 2006
Pavo II	0.29	Girardi et al. 1998

Table 5.9: The Norma Wall mass.

Ref.	Mass [$\times 10^{15} h^{-1} M_{\odot}$]
Current work	4.06
Lynden-Bell et al. (1988)	27
Staveley-Smith et al. (2000)	~ 2
Kocevski et al. (2007)	~ 2
Bolejko & Hellaby (2008)	4-6

6

Conclusion and future work

6.1 Conclusion

This thesis reports on the results obtained from the near-infrared imaging survey, the so called Norma Wall Survey (NWS). This survey was performed along most of the highly obscured and kistar-crowded region of the Norma Wall. Approximately 37.5° was systematically surveyed in the J , H and K_s bands with the IRSF telescope and the SIRIUS camera, requiring 2793 individual pointings. The survey images have a spatial resolution of 0.45 pixel/arcsec and an average seeing of FWHM= $1''.38$ in the K_s band. The galaxy search in the survey area resulted in identifying and cataloguing 4360 galaxies, of which 4123 (94.5%) have no counterparts in 2MASX. A multitude of galaxy parameters from astrometric to geometric and photometric were computed and are listed in the NWS catalogue. Galaxies listed in the catalogue have an astrometric reliability of $\sigma = 0''.202$ in both Right Ascension and Declination, and a K_s band isophotal magnitude reliability of $\sigma = 0^m.14$.

Galaxies in the NWS area suffer dimming and size reduction caused by dust obscuration in the Milky Way. I investigated the effect of dust obscuration on the J , H and K_s band observed isophotal magnitudes and radii. The study has led to the proposition of two methods to correct isophotal magnitudes and radii for dust obscuration. One method uses either the mean central surface brightness μ_c or the disk central surface brightness μ_0 to optimize the extinction correction. The other method gives a mean extinction correction for the galaxies depending on their classification as early or late-type galaxies only.

With regard to the extinction-corrected isophotal magnitudes, the NWS is found to be

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complete to $J_{(iso)}^\circ = 15^m6$, $H_{(iso)}^\circ = 15^m3$ and $K_{s(iso)}^\circ = 14^m8$ over $33.2 \square^\circ$ ($\sim 89\%$) of the survey area where dust obscuration and star crowding are less than $A_{K_s} < 1$ mag and $\log(N_{K_s < 14}/\text{deg}^2) < 4.71$ respectively.

The survey area was studied using galaxy density maps in two isophotal magnitudes slices $K_{s(iso)}^\circ \leq 13^m5$ and $13^m5 \leq K_{s(iso)}^\circ \leq 14^m8$. This led to the conclusion that no other galaxy clusters beside the CIZA J1324.7-5736 and Cen-Crux are found at the GA distance for regions with dust obscuration $A_{K_s} \leq 1$ mag and stellar density $\log(N_{K_s < 14}/\text{deg}^2) \leq 4.71$. Based on these density maps, three other regions are identified as having a higher mean galaxy overdensity than average. These regions, centred at $\ell = 306^\circ21$, $b = +4^\circ97$, $\ell = 324^\circ46$, $b = -5^\circ04$ and $\ell = 324^\circ30$, $b = -5^\circ39$, are all found to have a photometric redshift $z_{phot} \sim 0.1$, hence a signal of a large-scale structure that lies behind the Great Attractor.

Except for these local overdensities, the overall galaxy overdensity in the survey area was found to be quite homogeneous. A comparison of the galaxy density with other overdense regions at different redshifts indicate that this overdensity is consistent with a location at the GA distance. Analysing the observed galaxies in NWS as a function of photometric redshifts also suggest that the observed galaxy distribution to be due to galaxies at the GA distance. Using the calculated flux density due to the NWS area, the mass in the Norma Wall, including clusters and galaxies in its filamentary structure add up to $4.06 \times 10^{15} h^{-1} M_\odot$. While this is only 15% the mass of the GA estimated originally by Lynden-Bell et al. (1988), it is in agreement with independent more recent mass estimates by Staveley-Smith et al. (2000) using HI, Kocevski et al. (2007) using a census of rich X-ray clusters, and Bolejko & Hellaby (2008) using a non-linear relativistic model of the Shapley Concentration.

The completed Norma Wall Survey for the central part of the Norma Wall finds the mass in the Norma Wall is to be in the range of $\sim 4 - 8 \times 10^{15} h^{-1} M_\odot$. The upper limit for the GA mass is estimated assuming that two very massive clusters similar to the Norma cluster could be found in the gap ($|b| < 2^\circ$) in the NWS where the survey is incomplete and that the mass-to-light ratio is twice what is currently used in this thesis. Another parameter that might influence the mass estimate in the Norma Wall is the width of the filamentary structure of the Wall. Assuming the Norma Wall to be $3h^{-1}$ Mpc wide instead of $2h^{-1}$ Mpc would result in increasing the current estimate by $\sim 30\%$.

6.2 Future work

A better analysis of the NWS could be achieved if we had spectroscopic redshifts. Only 128 galaxies identified in the NWS area had previously measured redshifts. The majority of these galaxies are found at the GA distance $0.01 < z < 0.02$ and none of them had a redshift beyond $z \gtrsim 0.12$. For the uncovered galaxies photometric redshifts were derived for 3936 galaxies ($\approx 90\%$ of the galaxies in the NWS catalogue). The small number of galaxies with reliable photometry and the lack of galaxies with spectroscopic redshifts larger than $z \gtrsim 0.12$ has the

direct effect of rendering the photometric redshift metric poorly calibrated for galaxies within the ZOA and those at redshifts higher than $z = 0.12$. Having more reliable redshifts for galaxies at a wider range in velocities will improve our assessment of the 3-dimensions distribution and supply enough accurate redshifts to improve the reliability of the photometric redshift algorithm.

As a first step, this can be pursued with the Southern African Large Telescope (SALT), and its multi-object spectrograph, the Robert Stobie Spectrograph (RSS). SALT is a 10-meter telescope with a field-of-view $8' \times 8'$. A future upgrade of the RSS with a NIR arm will enable SALT to penetrate very deep into the thick layers of dust and have redshifts for severely obscured galaxies.

The galaxy distribution in the NWS area is complete to $K_{s(iso)}^0 = 14^m8$ for 33.2° , i.e. 89% of the survey area. This region is roughly defined by the Galactic latitude $b \lesssim 2^\circ$. This leaves a gap in the NWS galaxy distribution for this part of the Norma Wall.

It will be worthwhile to explore whether future NIR surveys can close this gap, and also allow an extension of the current NWS. Two ESO public surveys will be useful for closing the gap in the galaxy distribution in the region $b \lesssim 2^\circ$ and extend the current NWS. The “VISTA Variables in the Via Lactea (VVV)” surveys amongst others the region $-65^\circ < \ell < -10^\circ$, $-2^\circ < b < +2^\circ$ of the Galactic Plane in five infrared passbands ($0.9 - 2.5$) μm , including the three NIR J , H and K_s . The VVV survey will be complete for point sources to $J = 20^m6$, $H = 19^m0$ and $K_s = 20^m0$. Even though this survey is not optimal for a galaxy at the latitudes of $|b| < 2^\circ$ because of the high stellar density, it is still worth investigating. If successful galaxies identified within the VVV survey images will complement the galaxy distribution uncovered by the NWS in the region.

The other VISTA survey that will be of interest is the VISTA Hemisphere Survey (VHS). The VHS will image the entire 20000 square degrees of the southern sky, with the exception of the areas already covered by the VVV surveys, in J , H and K_s and is complete to the same magnitude limits as the VVV survey. This survey will help accurately estimate the width of the Norma Wall especially the region $|b| < 8^\circ$. Accurately defining the extent and borders of the overdense region of the Norma Wall would result in a better estimate of the mass within the Wall.

Another survey that will also help in closing the gap in the region $|b| < 2^\circ$ and also better estimate the width of the filamentary structure of the Norma Wall is the NASA Wide-field Infrared Survey Explorer (WISE) all-sky survey. WISE is currently mapping the entire extragalactic sky in four far-infrared wave bands 3.4 μm , 4.6 μm , 12.6 μm and 22 μm .

The VISTA surveys are more sensitive towards the early-type galaxy population, while on the other hand the WISE survey is sensitive for the late-type galaxies. This makes these surveys complementary to each other.

MeerKAT is well suited for acquiring redshifts for galaxies within the NWS area. MeerKAT is an 80 12-meter dishes telescope with a field-of-view of $\sim 1 \text{ deg}^2$ at the 21 cm wavelength. For example using a 30 dishes configuration for KAT a 200° ($312^\circ \leq \ell \leq 332^\circ$; $|b| \leq 5^\circ$) can be

Conclusion and future work

observed for galaxies with an HI content as low as $10^8 M_{\text{HI}}(M_{\odot})$ at the GA distance in 42 days using integration time of 2 hours/pointing (Kraan-Korteweg et al., 2008).

The Australian Square Kilometre Array Pathfinder ASKAP is another radio instrument that can efficiently supply redshifts for a good sample of the galaxies in the NWS. The Widefield ASKAP L-band Legacy All-Sky Blind survey (WALLABY) (Koribalski et al., 2009) will survey approximately 75% of the sky ($-90^{\circ} < Dec < +30^{\circ}$) in the redshift range of $-2000 < cz < 77000 \text{ km s}^{-1}$ and will detect galaxies with an HI content as low as $10^8 M_{\text{HI}}(M_{\odot})$.

The WALLABY survey and any survey with MeerKAT for the Norma Wall will complement the VISTA and WISE all-sky surveys to better map the galaxy distribution in the region $|b| < 2^{\circ}$.

Surveys from WALLABY or MeerKAT (Norma Wall) will result in enough redshifts to be cross-identified with galaxies in the NWS area with known photometric redshifts. This will significantly help improve the photometric redshift algorithm for galaxies within the ZOA. These redshifts are also useful to further investigate the large-scale structures in the GA area in 3-dimensions.



Catalogue and postage stamps

This section lists a sample of the parameters available in the NWS catalogue for the 100 brightest galaxies in the catalogue. Table A.1 lists:

Column 1: running ID number

Column 2: Designation (formed from the galaxy Right Ascension and Declination)

Column 3: Galactic longitude

Column 4: Galactic latitude

Columns 5, 7, 9: Isophotal radii (J , H , K_s)

Columns 6, 8, 10: Isophotal magnitudes (J , H , K_s)

Column 11: galaxy reddening $E(B - V)$ taken from the Schlegel maps

Galaxies in Table A.1 are sorted according to their K_s band isophotal magnitudes. Figure A.1 displays the postage-stamps for galaxies listed in Table A.1.

Table A.1: The 100 brightest galaxies in the NWSC. Galaxies are ordered in this table according to their K_s band isophotal magnitudes, from the brightest to the fainter.

ID	Designation	ℓ [°]	b [°]	R_{iso}^J ["]	J_{iso} [mag]	R_{iso}^H ["]	H_{iso} [mag]	R_{K_s} ["]	$K_{s(iso)}$ [mag]	$E(B-V)$ [mag]
00	13513862-5835155	310.724	3.370	33.53	10.512 ± 0.002	35.84	9.551 ± 0.002	34.24	9.065 ± 0.002	0.996
01	13140801-5832413	305.897	4.196	31.01	10.758 ± 0.003	40.88	9.662 ± 0.002	29.70	9.423 ± 0.002	0.795
02	13272379-5729229	307.768	5.044	29.41	11.077 ± 0.003	35.44	9.973 ± 0.002	28.25	9.497 ± 0.002	0.806
03	15380528-5947126	322.511	-3.409	23.72	10.895 ± 0.003	25.03	9.949 ± 0.002	24.35	9.532 ± 0.003	1.021
04	13140604-5832589	305.892	4.192	39.14	10.907 ± 0.003	37.59	10.012 ± 0.002	36.39	9.596 ± 0.003	0.796
05	13244650-5736326	307.402	4.973	27.37	11.020 ± 0.003	27.91	10.103 ± 0.002	27.26	9.695 ± 0.003	0.715
06	16033485-6008562	324.767	-5.697	26.03	10.818 ± 0.003	27.21	10.054 ± 0.002	23.82	9.778 ± 0.003	0.338
07	15471079-5904088	323.868	-3.538	50.89	11.362 ± 0.004	39.15	10.761 ± 0.004	46.20	9.789 ± 0.004	0.633
08	13103374-5800203	305.472	4.772	23.87	10.965 ± 0.003	25.35	10.108 ± 0.002	22.92	9.812 ± 0.003	0.484
09	16011282-5842436	325.495	-4.420	30.67	10.980 ± 0.004	30.04	10.158 ± 0.003	26.64	9.865 ± 0.003	0.566
10	15192404-6004187	320.416	-2.322	13.32	12.061 ± 0.006	15.19	11.125 ± 0.004	8.53	9.873 ± 0.004	2.613
11	15360297-5944488	322.327	-3.225	32.59	11.356 ± 0.005	25.02	10.500 ± 0.004	34.44	9.878 ± 0.004	0.975
12	15502514-5838388	324.461	-3.467	23.04	11.329 ± 0.004	25.20	10.503 ± 0.003	21.76	10.189 ± 0.004	0.619
13	13585700-5846011	311.602	2.964	-50.94	13.602 ± 0.004	28.96	10.565 ± 0.003	23.75	10.194 ± 0.004	1.038
14	13372456-5852218	308.855	3.469	35.60	11.433 ± 0.004	40.48	10.575 ± 0.003	31.15	10.212 ± 0.003	1.091
15	15530848-5916591	324.329	-4.184	21.06	11.334 ± 0.003	21.01	10.565 ± 0.002	19.69	10.231 ± 0.003	0.488
16	13373281-5854139	308.867	3.436	43.41	11.694 ± 0.005	33.19	10.799 ± 0.004	33.31	10.239 ± 0.004	1.092
17	13065974-5713286	305.046	5.583	20.97	11.342 ± 0.004	21.15	10.513 ± 0.002	17.70	10.255 ± 0.003	0.382
18	13183225-5832097	306.471	4.149	19.77	11.514 ± 0.004	8.00	11.012 ± 0.003	17.61	10.348 ± 0.003	0.769
19	15513888-6046285	323.236	-5.219	24.37	11.765 ± 0.004	26.21	10.800 ± 0.003	24.22	10.358 ± 0.003	0.446
20	15491421-5836350	324.363	-3.344	22.58	11.601 ± 0.004	43.68	10.572 ± 0.003	18.59	10.404 ± 0.004	0.673
21	15492920-5839535	324.353	-3.407	21.62	11.576 ± 0.004	22.70	10.762 ± 0.003	20.18	10.419 ± 0.004	0.661
22	13335813-5800301	308.558	4.398	26.18	11.644 ± 0.004	24.21	10.816 ± 0.003	21.53	10.454 ± 0.004	0.776
23	13115838-5831274	305.617	4.240	19.97	11.698 ± 0.004	20.53	10.846 ± 0.003	18.12	10.482 ± 0.004	0.733
24	13203726-5752418	306.817	4.773	24.24	11.876 ± 0.004	24.98	10.900 ± 0.003	24.19	10.537 ± 0.004	0.897

Table B.1: (Continued)

ID	Designation	ℓ [$^{\circ}$]	b [$^{\circ}$]	R_{iso}^J [$''$]	J_{iso} [mag]	R_{iso}^H [$''$]	H_{iso} [mag]	$R_{iso}^{K_s}$ [$''$]	$K_{s(iso)}$ [mag]	E(B-V)
25	15495235-5842563	324.361	-3.478	20.82	11.753 $\pm$ 0.005	22.58	10.97 $\pm$ 0.003	20.78	10.546 $\pm$ 0.004	0.632
26	15420517-5845034	323.541	-2.884	19.42	11.967 $\pm$ 0.006	21.22	10.967 $\pm$ 0.004	18.56	10.547 $\pm$ 0.005	1.252
27	15064059-5950013	319.173	-1.297	2.50	16.615 $\pm$ 0.068	3.16	13.288 $\pm$ 0.011	6.17	10.559 $\pm$ 0.003	3.260
28	15492471-5836053	324.386	-3.351	40.40	11.593 $\pm$ 0.005	22.24	10.983 $\pm$ 0.003	18.10	10.672 $\pm$ 0.004	0.678
29	13240146-5734208	307.307	5.022	13.43	12.013 $\pm$ 0.005	16.29	11.073 $\pm$ 0.003	15.10	10.685 $\pm$ 0.004	0.692
30	13050566-5728449	304.775	5.344	17.30	11.675 $\pm$ 0.004	17.39	10.927 $\pm$ 0.003	14.28	10.692 $\pm$ 0.004	0.386
31	15300829-5928096	321.876	-2.567	13.96	11.77 $\pm$ 0.004	28.12	10.992 $\pm$ 0.004	10.01	10.709 $\pm$ 0.006	1.534
32	15572698-5857199	324.965	-4.287	28.15	11.755 $\pm$ 0.004	17.59	11.037 $\pm$ 0.003	20.35	10.731 $\pm$ 0.004	0.508
33	13313326-5750049	308.269	4.621	22.71	11.981 $\pm$ 0.005	23.21	11.129 $\pm$ 0.003	21.87	10.745 $\pm$ 0.004	0.647
34	13333917-5747434	308.552	4.615	-25.07	16.318 $\pm$ 0.005	21.80	10.988 $\pm$ 0.004	12.84	10.798 $\pm$ 0.004	0.677
35	13081851-5727305	305.209	5.339	23.45	11.976 $\pm$ 0.005	22.58	11.127 $\pm$ 0.003	17.99	10.830 $\pm$ 0.005	0.397
36	13070256-5714296	305.052	5.566	72.36	11.368 $\pm$ 0.004	14.39	11.064 $\pm$ 0.003	13.09	10.836 $\pm$ 0.004	0.384
37	13263819-5705183	307.722	5.456	20.01	12.037 $\pm$ 0.006	19.74	11.228 $\pm$ 0.004	19.73	10.844 $\pm$ 0.005	0.877
38	16031531-6021265	324.598	-5.826	28.10	11.839 $\pm$ 0.005	38.75	11.107 $\pm$ 0.004	23.89	10.866 $\pm$ 0.005	0.346
39	13073639-5704260	305.139	5.729	-8.07	12.442 $\pm$ 0.005	34.60	11.761 $\pm$ 0.007	21.47	10.888 $\pm$ 0.004	0.349
40	13200915-5725562	306.805	5.223	15.62	12.271 $\pm$ 0.005	15.48	11.360 $\pm$ 0.003	15.93	10.931 $\pm$ 0.005	0.815
41	13123663-5827035	305.706	4.307	18.22	12.145 $\pm$ 0.005	19.31	11.310 $\pm$ 0.004	18.09	10.943 $\pm$ 0.005	0.705
42	14501857-6012498	317.189	-0.675	3.33	16.683 $\pm$ 0.066	9.03	13.26 $\pm$ 0.016	8.02	10.963 $\pm$ 0.005	5.938
43	13061291-5733215	304.921	5.259	25.72	11.943 $\pm$ 0.005	24.43	11.311 $\pm$ 0.004	22.34	10.968 $\pm$ 0.006	0.358
44	15472170-6014173	323.160	-4.470	26.55	12.006 $\pm$ 0.007	38.74	11.168 $\pm$ 0.005	27.02	10.977 $\pm$ 0.006	0.578
45	13252904-5727058	307.518	5.117	16.79	12.446 $\pm$ 0.005	19.22	11.389 $\pm$ 0.004	17.93	11.018 $\pm$ 0.005	0.876
46	13283692-5742186	307.900	4.807	22.70	12.179 $\pm$ 0.005	22.96	11.336 $\pm$ 0.003	19.34	11.033 $\pm$ 0.005	0.703
47	15592201-6001233	324.454	-5.256	13.89	12.189 $\pm$ 0.005	13.25	11.444 $\pm$ 0.004	15.40	11.041 $\pm$ 0.004	0.377
48	13380853-5845201	308.969	3.568	12.39	12.403 $\pm$ 0.006	12.65	11.446 $\pm$ 0.004	11.93	11.051 $\pm$ 0.005	0.997
49	13245479-5735402	307.422	4.985	13.82	12.348 $\pm$ 0.005	13.15	11.492 $\pm$ 0.003	13.55	11.056 $\pm$ 0.004	0.733
50	15385970-5950279	322.570	-3.520	18.83	12.299 $\pm$ 0.006	49.95	11.265 $\pm$ 0.005	19.06	11.067 $\pm$ 0.005	0.997

Table B.1: (Continued)

ID	Designation	ℓ [$^{\circ}$]	b [$^{\circ}$]	R_{iso}^J [$''$]	J_{iso} [mag]	R_{iso}^H [$''$]	H_{iso} [mag]	$R_{iso}^{K_s}$ [$''$]	$K_{s(iso)}$ [mag]	$E(B-V)$ [mag]
51	15393151-5934381	322.782	-3.348	20.30	12.539 $\pm$ 0.008	20.76	11.572 $\pm$ 0.006	20.87	11.082 $\pm$ 0.006	0.977
52	15582251-5917483	324.834	-4.624	16.26	12.271 $\pm$ 0.006	15.54	11.494 $\pm$ 0.005	14.88	11.110 $\pm$ 0.006	0.469
53	13105332-5758074	305.518	4.805	23.54	12.050 $\pm$ 0.005	27.19	11.254 $\pm$ 0.004	18.97	11.134 $\pm$ 0.006	0.471
54	15413126-5917376	323.155	-3.274	11.95	11.954 $\pm$ 0.004	11.93	11.006 $\pm$ 0.002	8.23	11.146 $\pm$ 0.004	1.061
55	15133394-6000399	319.828	-1.887	2.07	17.140 $\pm$ 0.09	3.99	13.857 $\pm$ 0.017	5.16	11.151 $\pm$ 0.004	2.548
56	13214629-5649225	307.095	5.803	20.67	12.200 $\pm$ 0.005	23.22	11.280 $\pm$ 0.003	9.45	11.152 $\pm$ 0.004	0.772
57	13093049-5728160	305.370	5.315	12.85	12.369 $\pm$ 0.006	23.01	11.530 $\pm$ 0.004	12.06	11.158 $\pm$ 0.005	0.456
58	13443629-5813103	309.903	3.931	18.65	12.296 $\pm$ 0.006	10.34	11.659 $\pm$ 0.004	13.66	11.169 $\pm$ 0.005	0.947
59	13274942-5724017	307.838	5.124	20.22	12.462 $\pm$ 0.006	21.28	11.532 $\pm$ 0.004	17.26	11.172 $\pm$ 0.005	0.822
60	13235262-5723200	307.310	5.207	25.59	12.365 $\pm$ 0.006	23.74	11.606 $\pm$ 0.004	28.78	11.174 $\pm$ 0.006	0.801
61	15573339-5901084	324.935	-4.344	13.88	12.192 $\pm$ 0.006	14.72	11.452 $\pm$ 0.004	11.77	11.182 $\pm$ 0.005	0.519
62	13150985-5856120	305.995	3.794	24.72	12.416 $\pm$ 0.007	24.18	11.610 $\pm$ 0.006	17.39	11.184 $\pm$ 0.006	0.907
63	16034850-5908462	325.459	-4.967	22.45	12.157 $\pm$ 0.006	18.38	11.452 $\pm$ 0.005	13.54	11.187 $\pm$ 0.005	0.319
64	13244123-5732572	307.398	5.034	13.44	12.589 $\pm$ 0.006	16.15	11.787 $\pm$ 0.004	12.33	11.197 $\pm$ 0.005	0.757
65	13250581-5737147	307.443	4.956	17.46	12.622 $\pm$ 0.006	17.43	12.197 $\pm$ 0.006	12.29	11.223 $\pm$ 0.005	0.728
66	13230231-5732044	307.180	5.076	15.14	12.392 $\pm$ 0.005	14.86	11.642 $\pm$ 0.004	15.05	11.229 $\pm$ 0.005	0.679
67	13291759-5756036	307.956	4.568	17.82	12.401 $\pm$ 0.005	20.66	11.551 $\pm$ 0.004	18.90	11.232 $\pm$ 0.005	0.658
68	15533785-5841294	324.755	-3.767	22.88	12.398 $\pm$ 0.007	24.62	11.539 $\pm$ 0.005	21.39	11.24 $\pm$ 0.007	0.748
69	13230496-5740301	307.168	4.936	15.03	12.435 $\pm$ 0.005	14.09	11.585 $\pm$ 0.004	11.69	11.245 $\pm$ 0.005	0.773
70	14111866-5841564	313.162	2.577	2.32	16.421 $\pm$ 0.038	3.48	13.805 $\pm$ 0.011	4.57	11.247 $\pm$ 0.004	1.712
71	13252392-5815193	307.400	4.321	18.81	12.556 $\pm$ 0.006	17.13	11.708 $\pm$ 0.005	18.05	11.270 $\pm$ 0.006	0.668
72	13110449-5816313	305.519	4.498	18.54	12.771 $\pm$ 0.007	20.86	11.760 $\pm$ 0.004	11.73	11.283 $\pm$ 0.005	0.599
73	15494968-5938518	323.771	-4.201	20.23	12.431 $\pm$ 0.007	19.71	11.711 $\pm$ 0.006	17.62	11.290 $\pm$ 0.006	0.559
74	13184510-5803260	306.550	4.622	16.72	12.495 $\pm$ 0.006	15.24	11.666 $\pm$ 0.004	15.92	11.292 $\pm$ 0.006	0.669
75	13375912-5830552	308.992	3.808	17.85	12.725 $\pm$ 0.007	20.51	11.662 $\pm$ 0.005	16.08	11.295 $\pm$ 0.007	1.128
76	15411178-5958487	322.708	-3.797	25.59	12.332 $\pm$ 0.007	23.86	11.597 $\pm$ 0.005	15.60	11.300 $\pm$ 0.007	0.733

Table B.1: (Continued)

ID	Designation	ℓ [$^{\circ}$]	b [$^{\circ}$]	R_{iso}^J [$''$]	J_{iso} [mag]	R_{iso}^H [$''$]	H_{iso} [mag]	$R_{iso}^{K_s}$ [$''$]	$K_{s(iso)}$ [mag]	E(B-V) [mag]
77	13261496-5806321	307.531	4.452	13.87	12.603 $\pm$ 0.007	13.31	11.680 $\pm$ 0.005	12.46	11.302 $\pm$ 0.006	0.754
78	15593992-6011524	324.367	-5.413	14.96	12.439 $\pm$ 0.006	13.95	11.838 $\pm$ 0.004	13.49	11.307 $\pm$ 0.006	0.350
79	13260044-5740001	307.559	4.894	20.64	12.595 $\pm$ 0.006	25.26	11.599 $\pm$ 0.004	14.31	11.309 $\pm$ 0.005	0.765
80	13072255-5706177	305.105	5.699	23.42	12.166 $\pm$ 0.006	21.38	11.466 $\pm$ 0.004	13.91	11.314 $\pm$ 0.006	0.353
81	13233881-5807498	307.186	4.475	21.84	12.375 $\pm$ 0.006	16.33	11.717 $\pm$ 0.004	15.25	11.329 $\pm$ 0.006	0.729
82	13162865-5834552	306.199	4.131	29.10	12.732 $\pm$ 0.008	19.62	11.929 $\pm$ 0.007	32.00	11.351 $\pm$ 0.006	0.855
83	15352962-6021129	321.914	-3.676	12.84	12.558 $\pm$ 0.007	13.55	11.833 $\pm$ 0.005	13.49	11.354 $\pm$ 0.006	0.815
84	16001432-6022217	324.306	-5.592	18.41	12.359 $\pm$ 0.007	17.98	11.627 $\pm$ 0.005	16.42	11.366 $\pm$ 0.007	0.348
85	14062149-5850413	312.505	2.627	3.69	16.535 $\pm$ 0.059	3.28	14.863 $\pm$ 0.021	6.09	11.368 $\pm$ 0.004	1.638
86	15582957-6017434	324.193	-5.392	23.04	12.325 $\pm$ 0.006	19.53	11.684 $\pm$ 0.005	19.04	11.387 $\pm$ 0.007	0.359
87	13122879-5829297	305.686	4.268	17.04	12.646 $\pm$ 0.007	19.93	11.681 $\pm$ 0.006	13.37	11.450 $\pm$ 0.008	0.719
88	13293320-5850554	307.855	3.658	21.62	12.551 $\pm$ 0.007	22.30	11.716 $\pm$ 0.006	19.61	11.455 $\pm$ 0.007	0.724
89	13305401-5649024	308.339	5.639	15.47	12.58 $\pm$ 0.006	17.05	11.877 $\pm$ 0.005	17.09	11.470 $\pm$ 0.006	0.861
90	15461984-5853195	323.893	-3.329	16.66	12.517 $\pm$ 0.008	15.84	11.815 $\pm$ 0.006	14.51	11.497 $\pm$ 0.007	0.614
91	15362079-5939018	322.414	-3.169	15.26	12.790 $\pm$ 0.009	15.31	11.959 $\pm$ 0.007	15.07	11.498 $\pm$ 0.008	0.899
92	15593698-6013057	324.349	-5.424	12.33	12.479 $\pm$ 0.006	11.64	11.849 $\pm$ 0.005	11.64	11.502 $\pm$ 0.006	0.347
93	15423118-5846270	323.572	-2.937	18.65	12.795 $\pm$ 0.009	21.60	11.808 $\pm$ 0.007	16.19	11.503 $\pm$ 0.007	1.221
94	14003382-5932322	311.599	2.161	11.82	13.059 $\pm$ 0.01	12.44	11.981 $\pm$ 0.007	11.53	11.506 $\pm$ 0.008	1.590
95	13504695-5923085	310.432	2.619	14.91	13.014 $\pm$ 0.009	14.54	12.001 $\pm$ 0.006	13.53	11.512 $\pm$ 0.007	1.462
96	15474167-5859274	323.968	-3.518	15.76	12.650 $\pm$ 0.009	15.92	11.842 $\pm$ 0.007	16.43	11.513 $\pm$ 0.009	0.596
97	13234507-5742547	307.252	4.885	11.79	12.696 $\pm$ 0.006	11.38	11.822 $\pm$ 0.004	11.82	11.518 $\pm$ 0.005	0.694
98	13323706-5701211	308.539	5.400	15.34	12.684 $\pm$ 0.006	16.32	11.810 $\pm$ 0.004	12.99	11.532 $\pm$ 0.006	0.855
99	15373145-6018419	322.143	-3.790	14.23	12.850 $\pm$ 0.009	15.05	11.940 $\pm$ 0.007	13.92	11.556 $\pm$ 0.008	0.718

Some galaxies shows inconsistent isophotal galaxy magnitudes, this is due to a failure in the algorithm that was used to calculate isophotal magnitudes.

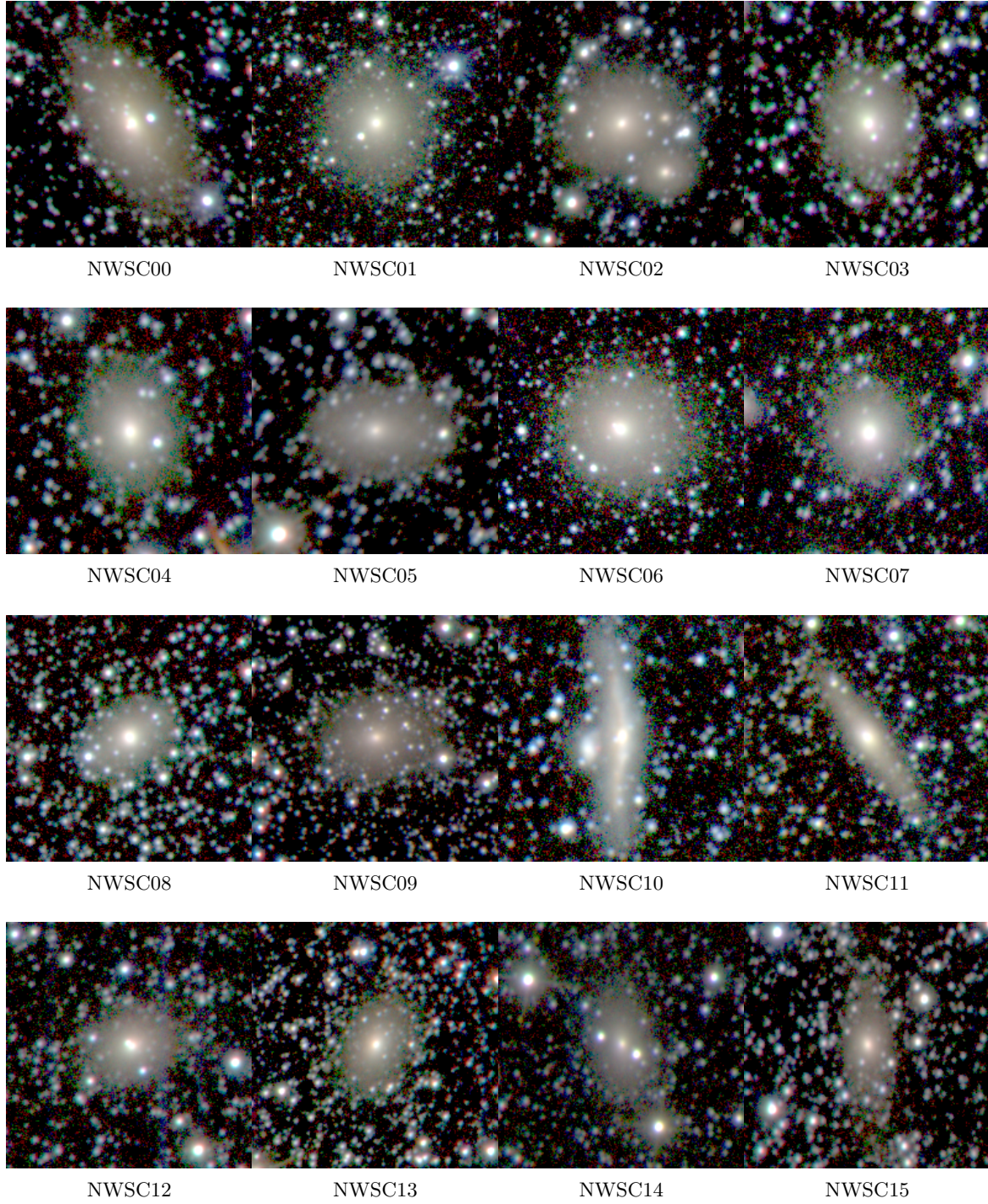


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC00-NWSC15). The postage stamps are $1'.5 \times 1'.5$.



Figure A.1: The brightest 100 galaxies in the NWSC (NWSC16-NWSC31). The postage stamps are $1'.5 \times 1'.5$ except for the galaxy NWSC23 which is $1'.4 \times 1'.4$.

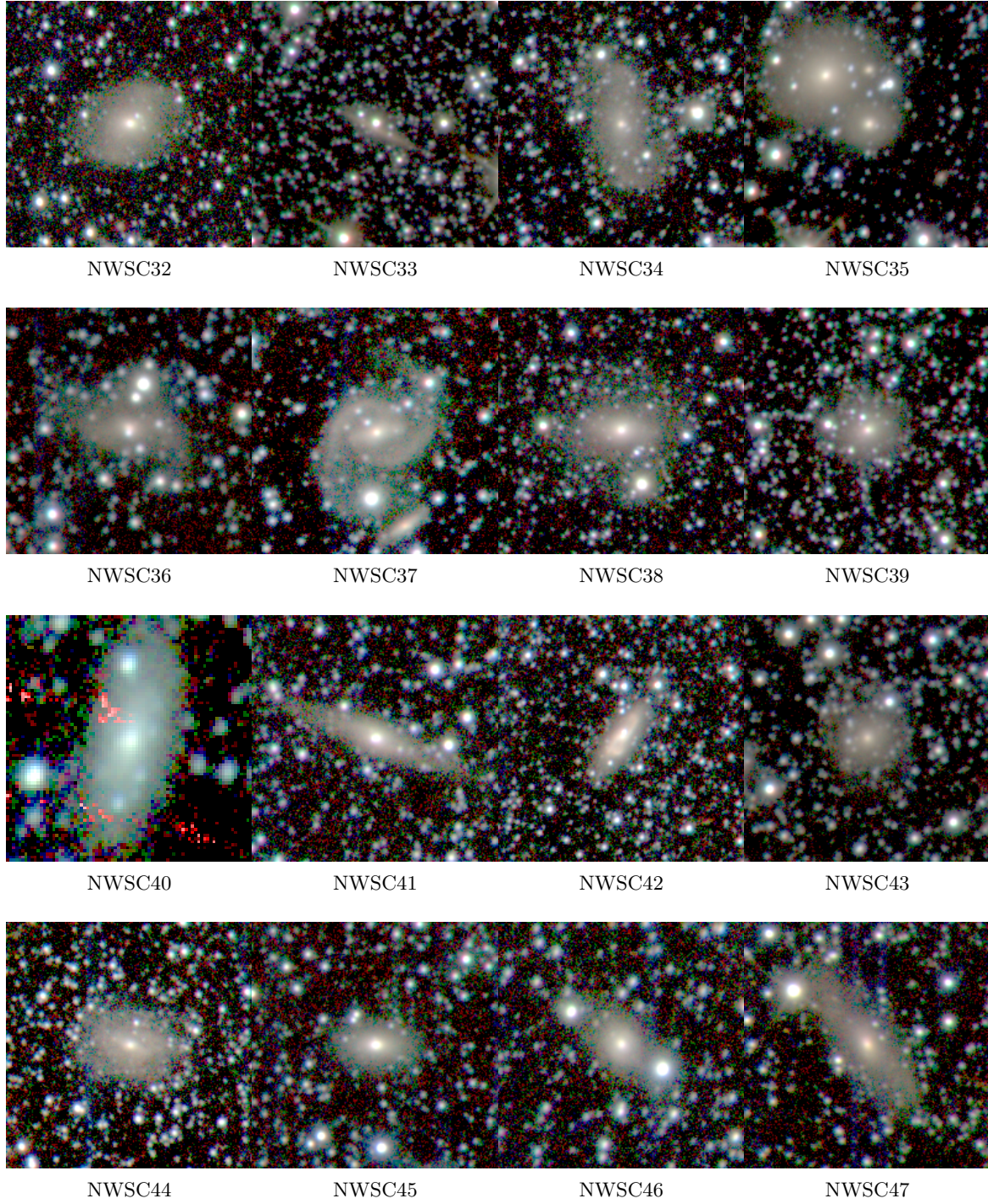


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC32-NWSC47). The postage stamps are $1'.5 \times 1'.5$ except for the galaxy NWSC40 which is $0'.6 \times 0'.6$.

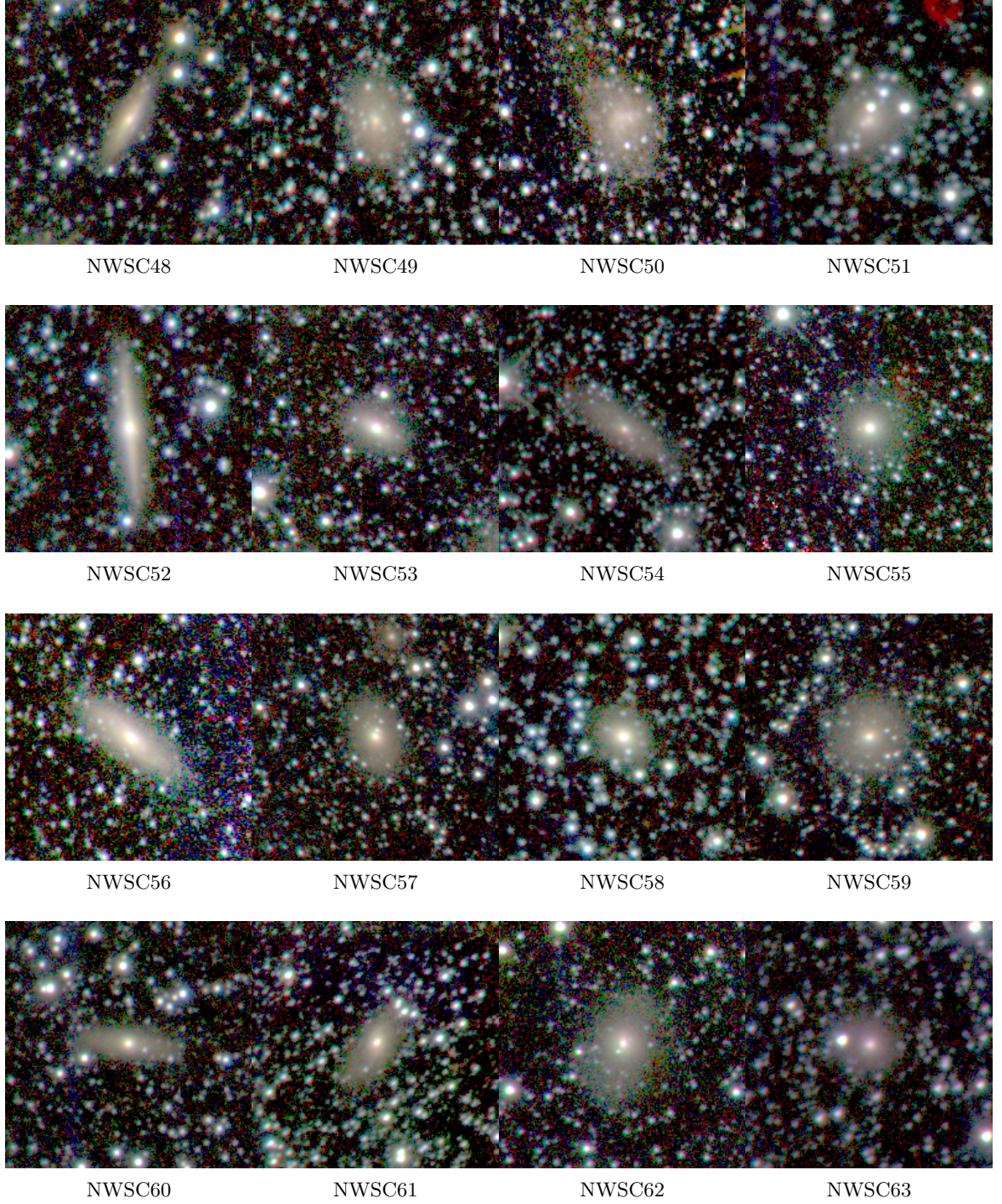


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC48-NWSC63). The postage stamps are $1'.5 \times 1'.5$ except for the galaxy NWSC56 which is $1'.4 \times 1'.4$.

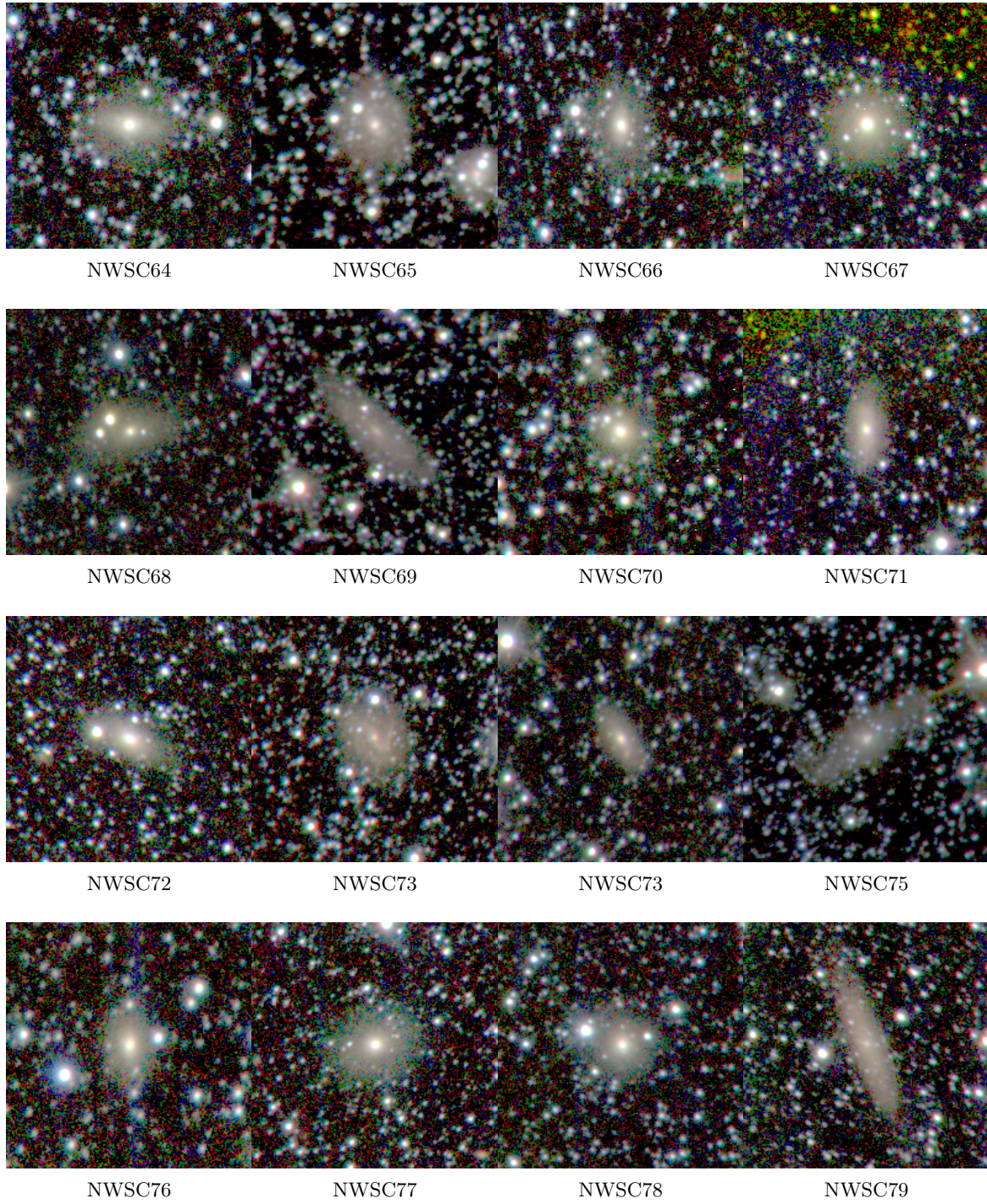


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC64-NWSC79). The postage stamps are $1'.5 \times 1'.5$.

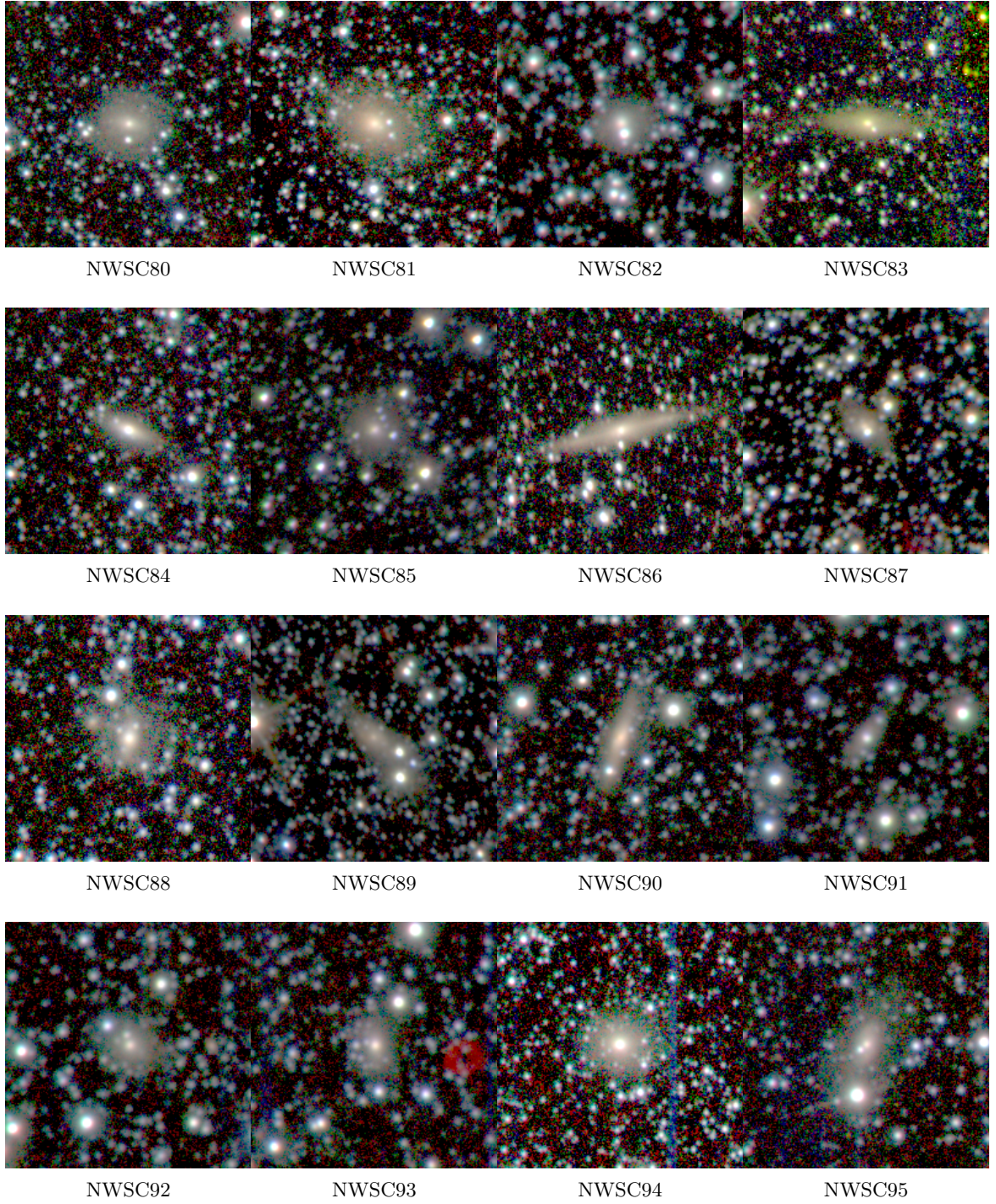


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC80-NWSC95). The postage stamps are $1'.5 \times 1'.5$.

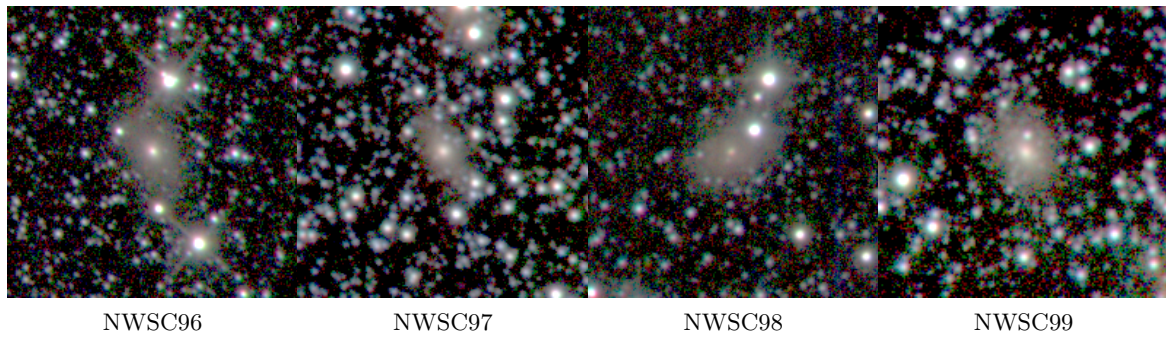


Figure A.1: The brightest 100 galaxies in the NWSC (NWSC96-NWSC99). The postage stamps are $1'.5 \times 1'.5$ except for the galaxy NWSC56 which is $1'.3 \times 1'.3$.

B

Observatory site conditions

In this section the site condition parameters like the variation of the sky background and seeing during the observation runs are discussed. These parameters can be of interest for future observations on the SAAO site in Sutherland. I will also discuss the variation of the calibration magnitude zero point (ZP) during the observation runs. This can shed some light on the reflective power of the IRSF mirror.

Sky background

The J and H bands sky background is dominated by the airglow (OH) emission. The K_s band sky is primarily due to emissions from the optical elements and support structure of the telescope with a significant amount from the airglow (OH) emission. Figure B.1 plots the sky (mag/arcsec^2) for all the observing nights in the ordinate, and the observing time in months in the abscissa. No year-to-year variations are seen in the night-to-night variations of the sky background in any of the three bands, while there is a noticeable variation in the K_s sky background on shorter time scales of (few months). This short time scale variation is seen better in Fig. B.2. Where I plot the sky background on the ordinate for all the observed fields over the four year survey program and the months when these fields were observed on the abscissa. The trend in the K_s band sky background is due to seasonal variations of the site temperature. This seasonal variation has been found as well in the site conditions for the 2MASS (Skrutskie et al., 2006; Cutri et al., 2006). It is more prominent in their data as they had almost continuous observing runs for a period of over three years.

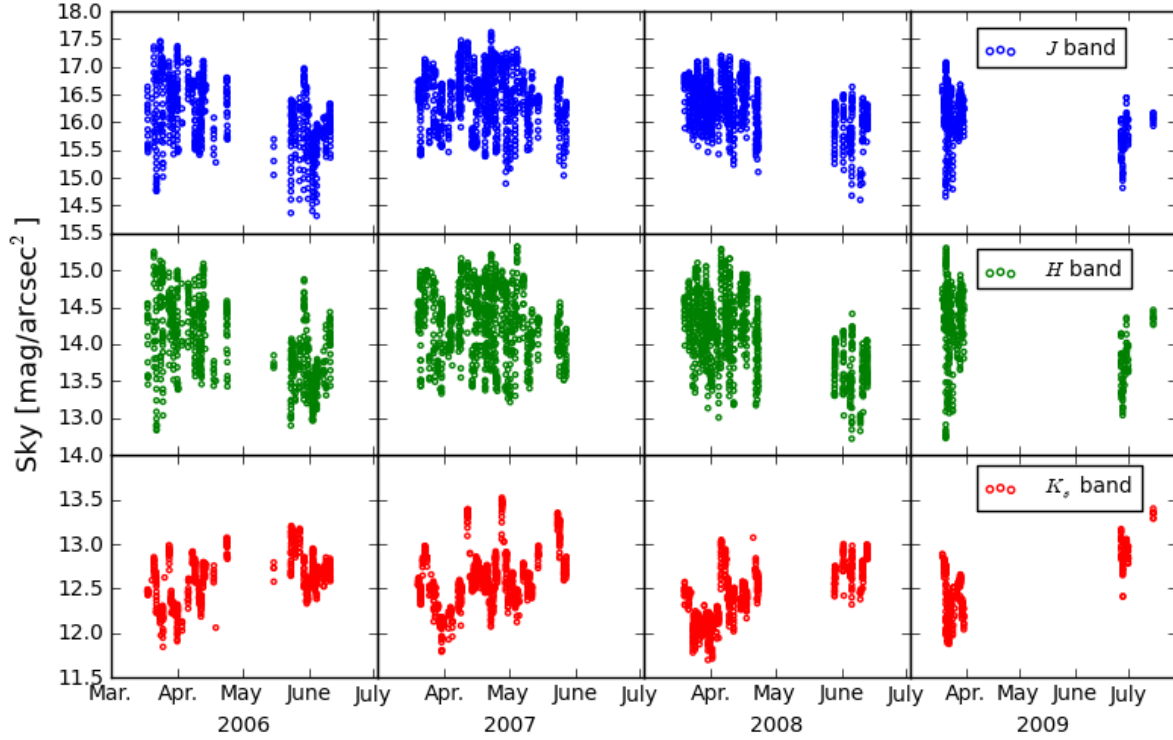


Figure B.1: The variation in the NIR sky background during observations. Top (J) band, middle (H) band and bottom (K_s) band. The K_s sky shows a short term variation trend over a few months.

Seeing

Figure B.3 shows the variation in the seeing conditions over the observing time over the four years of observations. The mean FWHM for the observed fields are plotted in the ordinate as a measure of seeing and the time of observations in months on the abscissa. No variations are seen in the short or long terms of few months or years respectively.

Magnitude zero point (ZP)

The reflective quality of a telescope mirror degenerates as a function of time. This reflects as a variation of the ZP over long time periods. To investigate this, I used the time variations in the magnitude zero point to serve as an indicator for the variations in reflective quality of the telescope mirror. Figure B.4 displays the variation of the ZP with respect to its mean value $\langle ZP \rangle$ (see Table 2.7) against the time in months.

The daily variations in the values of ZP are due to the slight variations in the photometric

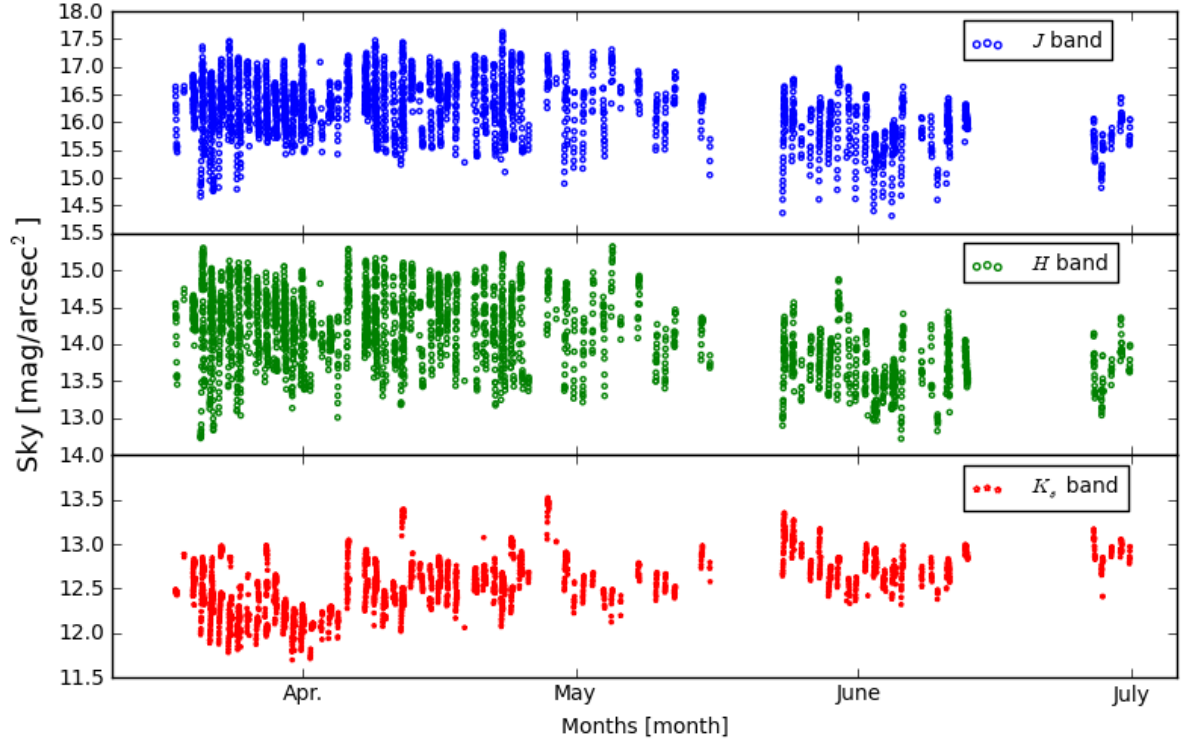


Figure B.2: The NIR sky variation. The sky variation (the ordinate) was plotted against the month when the observations were taken (the abscissa). Top (J) band, middle (H) band and bottom (K_s) band. This plot emphasises more the K_s band short term variation.

conditions over the course of a night. The more obvious variations in the values of ZP from year to year are due to the changes in the reflectivity of the telescope. This correlates well with the dates when the telescope mirror was cleaned. The mirror was cleaned in September 2006 which is notable for the mean zero point at the fields observed in 2007. They have a relative positive shift over the mean value in 2006. In 2008 the mean zero point had a relative negative shift as the mirror was not cleaned again until September 2008. The fields observed in 2009 again showed a positive shift.

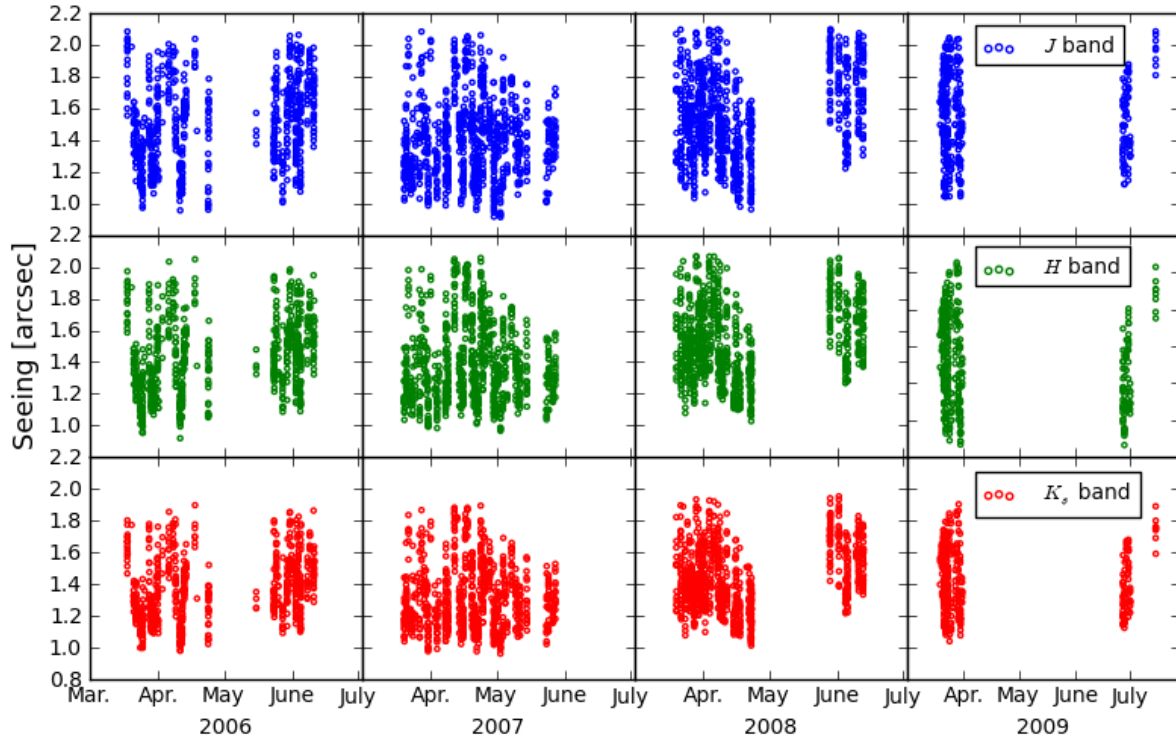


Figure B.3: Variation in seeing as a function of the observing time. Top: J band, middle: H band and bottom: K_s band.

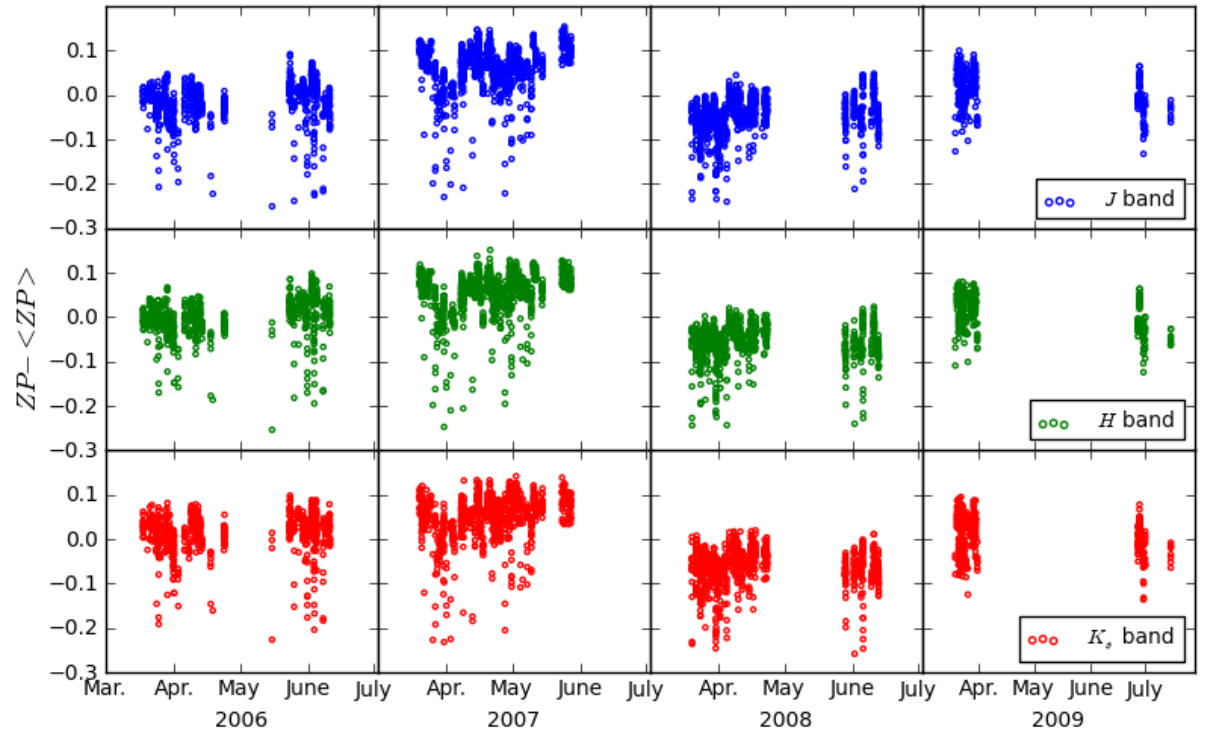


Figure B.4: Variation in the ZP as a function of the observing time. Top: J band, middle: H band and bottom: K_s band.

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