A STUDY OF

THE GALACTIC STAR CLUSTER

NGC 2547

By

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Being a Thesis Presented in Part Fulfilment of the Requirements for the Degree of Master of Science in the Faculty of Science, University of Capetown.

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C O N T E N T S

PREFACE

The following thesis has been undertaken primarily as an observational study. Accordingly, theoretical discussions and speculations have been kept to a minimum, formulae in most cases being merely quoted and references given for their derivations. Since the observational techniques used are nearly all in standard practice, they have not been fully described, while descriptions of their reductions have been relegated to appendices.

It is a pleasure to record my thanks to the many people who have assisted me in the course of this work. Foremost among these is Dr. R.H. Stoy, Her Majesty's Astronomer to the Cape, who both suggested the topic and directed the ensuing research, putting at my disposal the facilities of the Royal Observatory. The smoothness with which this work has proceeded is in large measure due to his patient help. Much guidance and help was obtained from fruitful discussions with various members of staff of the Royal and Radcliffe Observatories, especially Dr. Evans, Chief Assistant, Royal Observatory, and also Prof. Irwin of Indiana University.

Acknowledgment is readily made to Mr. Driver of the Royal Observatory, who went to considerable pains in producing Plates I and II of this thesis. Finally, but whose trouble has been by no means least, my grateful thanks are due to Mrs. C. van der Merwe and Miss Y.A. Chaney for typing this thesis.

Department of Physics,
University of Capetown,
September, 1955.

J.D. Fernie.

CHAPTER I

INTRODUCTION

A casual glance at any star atlas reveals the fact that the apparent distribution of stars on the celestial sphere is not uniform. Closer inspection reveals that even in the Milky Way the areal density of stars is not constant, but that there are large gaps with only a few brighter stars in them and also, here and there, a tendency for the stars to cluster together.

These clusters are of many and varied forms, which have led to various systems of classification, but in general they conform to one of two broad groups. The first of these comprises the globular clusters, so called because of their apparent spherical symmetry. The globular clusters are in general characterised by the high density and number of their populations; some, such as ω Centauri, having as many as a hundred thousand members. They almost invariably contain intrinsic variable stars, notably the cepheid variables. The globular clusters are usually found to avoid the galactic plane and to lie at distances from us much greater than those clusters - the galactic clusters - which form our second group. This group, sometimes designated as "open" clusters, have usually a loose structure, a comparative paucity of members, very rarely contain variable stars, and are considerably smaller than the globular clusters. Typical examples of galactic clusters are the Pleiades and Hyades, which are among the nearest clusters to us. In contradistinction to the globular clusters the galactic clusters are rarely found far from the galactic plane, and in this is probably to be found the explanation of the fact that all the known galactic clusters lie comparatively close to us. For, as mentioned above, there are to be found in the Milky Way (i.e. the galactic plane) large gaps in the general background of stars. Typical of such gaps is the Coalsack near the foot of the Southern Cross. They are at present believed to be caused by the large clouds of interstellar dust and gas which obscure the light from the background stars rather than due to an intrinsic lack of stars in those directions, although the latter possibility is

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not to be excluded. It has been suggested that the great gap in Vela may actually be caused by our viewpoint of the edge of a spiral arm of our galaxy. However, the majority of these gaps are almost certainly due to gas and dust clouds. These may not necessarily be so dense as to completely obscure the light from the stars behind them, but by absorption and scattering they probably diminish to a greater or lesser extent all starlight reaching us. Nevertheless, the clouds are found to be heavily concentrated near the galactic plane and probably nearly our whole view of the galaxy, including its center is obscured by them. This, then, is probably why we find only a few galactic clusters (which lie close to the galactic plane), they being the ones too close to us to have their light completely obscured. Russian astronomers estimate there to be 13,000 galactic clusters in our whole galaxy.

There are also to be found stars which form groups or associations rather than clusters. These stars are not at once obviously associated, being spread over many degrees of sky (galactic clusters are rarely as much as one degree in diameter), and only statistical analysis of their proper motions and radial velocities reveal this association. As might be expected from this, both galactic and globular clusters often have many more members than are at once obvious from a superficial study of a star chart.

Fundamental to cluster research is the so-called Hertzsprung-Russell diagram, a relationship discovered first implicitly by Hertzsprung and later explicitly by Russell. It has various equivalent forms, the most common being a plot of absolute stellar magnitude against Spectral Type. Since the latter is not continuous but discrete it gives rise to a spurious fine structure of vertical lines in the diagram, and in modern work is more usually replaced by the yellow colour index (blue magnitude minus yellow magnitude) which is continuous and also a nearly linear function of spectral type. Spectral type is a function of stellar temperature, and absolute magnitude a function of stellar luminosity,

/and

and since these quantities change as a star evolves, the latter's position on the H-R diagram is not constant, but a condition of its age. Thus all theories of stellar evolution (which are largely to be tested by cluster research) are intimately concerned with the H-R diagram (sometimes known as the magnitude-colour array). It was long considered that all stellar populations present much the same sort of H-R diagram, but the work of Baade at Mt. Wilson and later at Palomar led to the belief that there are two (not very distinctly separated) types of population. Population I, comprised of slow-moving stars in the outer regions of spiral galaxies, galactic clusters, associations, etc. displays the classical H-R diagram, having its brightest stars blue. Population II, on the other hand, is comprised of high-velocity stars, stars in galactic nuclei, globular clusters, etc and presents an H-R diagram whose brightest stars are red. The two diagrams are displayed below:

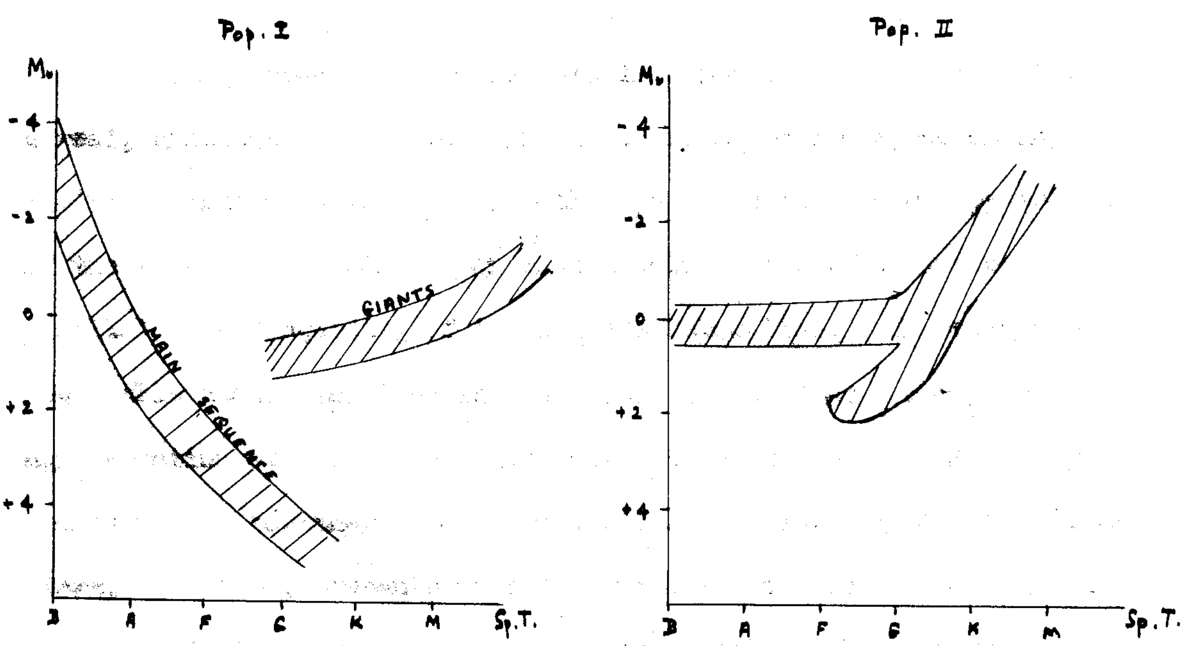

fig (1)

There is reason to believe that populations of the second type are older than those of the first. However, recent researches [4] on the Magellanic clouds have revealed the existence of globular clusters

/having

having the characteristics of population I, such clusters being apparently missing in our galaxy itself. There also exist clusters whose H-R diagrams are difficult to classify as population I or II, and it would seem, therefore, that the time is at hand when our definitions of galactic and globular clusters must be revised.

At present, galactic clusters are often classified according to their H-R diagrams. The classification has a number from one to three followed by the spectral type of the earliest star in the cluster. The numbers imply

1. no giant stars in cluster.
2. a mixture of giants and main sequence stars.
3. giant stars only.

Thus we have, for example, 1 - B_2, 2 - A_3, etc.

The importance of clusters lies in the fact that their members form a real, dynamical system (as opposed to an optical one) occupying a limited volume of space. That this is so is to be shown by an analysis of their proper motions and/or radial velocities, which indicates a parallelism and equality of their space-velocities. It would seem a reasonable assumption that such a system is not just a fortuitous agglomeration of stars, but that these member stars originated together and have been together throughout their lifetimes. Such a family of stars, therefore, presents us with a picture of stellar evolution in which the differences in stages are determined not by differences in age but by some other parameter such as mass or luminosity. Now, on the basis of various hypotheses and simplifying assumptions it is possible to predict [2] theoretically a star's movement on the H-R diagram in the course of its life. Similarly, the stages reached by various stars of differing initial masses after a given time are also predictable, as are also the rates of change from these stages. Thus the shape of a cluster's H-R diagram provides a check on these theoretical considerations

/and

and hence on our assumptions regarding the processes of stellar evolution within a star. Moreover, the density of stars on different portions of a H-R diagram of a large population is a statistical measure of the rate of change of the evolving stars from these areas. Yet another check is to be had from purely dynamical considerations of the differential motions within a cluster. Such considerations generally enable us to assign at least an upper limit to the age of a cluster (since an older cluster with the present motions would already have dispersed), thus providing some sort of check on the age of the cluster predicted on evolutionary grounds.

The fact that the depth (i.e. diameter) of a cluster is in the vast majority of cases negligible compared to its distance from us enables us to measure its distance, or rather apparent distance, with comparatively high accuracy. This arises from the fact that with this negligibility of depth we may assume that all the stars in the cluster are at the same distance from us. Hence, by measuring their apparent magnitudes and spectral types (or, what is equivalent, their apparent magnitudes and colour indices) we may plot directly a H-R diagram of apparent magnitude against colour. Now there exists a standard H-R diagram [3] of nearby stars with accurately known trigonometric parallaxes as a plot of absolute magnitude against colour. Since the evolutionary theories mentioned before postulate that the sequences of all H-R diagrams are the same, we may compare the main sequence of our cluster diagram with that of the standard, finding it to be displaced by a certain number of magnitudes. This displacement (the distance modulus) was originally assumed to be due merely to the falling off of the radiation with distance and an application of the inverse-square law was assumed to yield the distance of the cluster. In 1930, however, Trumpler [4] showed by statistical means that inter-stellar space is not perfectly transparent and that a correction for absorption must be applied to the above estimates of distance. Matters were further complicated by the discovery that this absorption is constant in neither direction nor colour, falling off rapidly with increasing direction from the galactic

/plane.

plane, and approximately inversely with the wavelength. From this arose the conception of the "colour-excess" of a star. For a given type of colour index, the difference between a star's observed colour index and its intrinsic colour index (obtained from its spectrum) is its colour-excess. This differential absorption of a star's light is spoken of as the 'reddening' of the star. Fortunately, however, later work with six-colour photometry[5] showed that the ratio of general (total) absorption to differential (specific) absorption is constant. On the assumption that nearby stars are practically unreddened an idea of the reddening of any other star may be had from a comparison of its colour with that of a nearby star of the same spectral type. Hence, from the known ratio above and this reddening is obtained some measure of the correction to be applied for general absorption.

We see, then, that quite a fair determination of distance may be made photometrically. For the nearer clusters having well-determined proper motions and radial velocities we may adopt geometrical methods of determining the distance, and besides others, there is the statistical method by which Trumpler arrived at his conclusion of inter-stellar absorption. He began by classifying some one hundred galactic clusters on the basis of their structural appearance, degree of population, etc. He then proceeded to make the assumption that clusters of the same class have (at least) similar linear dimensions, and hence the angular diameter of a cluster in a given class becomes inversely proportional to the distance of the cluster. Calibrating his scale by the nearest clusters he discovered that the differences in distance determined photometrically from that determined by this method increased systematically with the distance. He was led to conclude that it must be interstellar absorption of the starlight which made the cluster distances too great as determined photometrically.

Cluster distances, therefore, besides the very limited distances determined by direct Trigonometrical parallaxes, are among the most accurately known of all astronomical distances. This has a number of important bearings. Firstly, in globular clusters it makes possible the determination of the zero-point of the cluster-type cepheid variables. Secondly, it yields an accurate measure of the distances of our nearest extra-galactic neighbours, namely the Magellanic Clouds. Thirdly, it yields important information about the structure of our own galaxy, since the clusters serve to map it out, giving an estimate of its size, the possibility of it possessing spiral arms, etc. A novel method of determining the distance of the galactic centre has recently been evolved by Weaver[6], using as a basis the distances and radial velocities of galactic clusters. This also added evidence for the need of revising the zero-point of the classical-cepheids.

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It is a well-known fact that the main sequence of the H-R diagram has a definite scatter, being, in fact, a band. Since it is only in the last decade that the advent of the photo-multiplier cell has made easy the measurement of stellar magnitudes accurate to .04 magnitudes or better, it was long in doubt whether this band-width was real or due to observational errors. In 1950 Eggen [7] instigated a lively controversy by claiming to have found from a study of several galactic clusters and nearby stars a fine-structure in the main sequence. Several workers, notably Johnson, repeated Eggen's observations but failed to isolate any of the five sub-sequences reported by him. It is quite possible that the disparity of their results may have been due to the use of inaccurate transfer equations when converting from one system of magnitudes to another. The controversy has not yet been satisfactorily resolved.

It arises from a solution of the gravitational equations of General Relativity [8] that light, in escaping from a gravitational field must appear to have its wavelength increased. For objects such as stars (and stars are the only bodies massive enough to produce any measurable effect) the increase varies as M/R, where M is the star's mass and R its radius. The effect is detected as a spurious Doppler shift and is usually expressed as a velocity, i.e. in kilometres per second. To test the theory stars are required whose true radial velocities are known from sources other than measures of their own spectra and whose ratio of M/R is comparatively large. Such stars are to be found in binary systems having one component a white dwarf; the comparatively large, light companion giving a measure of the system's radial velocity. Sirius and its companion was one of the first of such systems to be tested. Another type of system containing suitable stars is provided by those galactic clusters containing O-type stars. These stars are exceedingly luminous and accordingly massive, yet, belonging to the main sequence, have only moderate radii. The less luminous stars in the cluster are used to determine the system's radial velocity. Trumpler [9] was the first to make such measures on galactic clusters and found shifts of up to about +10 km/sec (the predicted shift for the sun is 0.61 km/sec), which are equivalent to about 300 solar masses if estimates of the radii are made from radiation considerations. Such masses are very much greater than those determined by other means and are considered to be incorrect. These stars are sometimes designated as 'Trumpler Stars'.

The foregoing discussion will play a large part in the preparation of any present programme of work on galactic clusters. It is a moot point as to whether, in a field as poorly studied as the southern hemisphere, it is better to make a moderately accurate survey of a few of the above topics in several clusters, or to make as complete a study

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as possible of only one cluster. In the case of the present thesis considerations have further been dictated by the time available, and with this in view, plus also the desirability of a firm grounding in this field of research, a study of only one cluster has been made. This cluster, N.G.C.2547, was selected since it was one of Trumpler's initial hundred clusters not yet fully investigated and it was available for observation in the summer and autumn months.

It will be realized that one of prime observations on a cluster will lie in the accurate photometry of its members, magnitudes in two colours being essential, with three or more preferable. This has been done for NGC2547, three-colour (ultra-violet, blue, yellow) photo-electric photometry on seventy of its members being carried out to an accuracy (p.e.) of about a hundredth of a magnitude.

No measures of the gravitational shift of spectral lines have been attempted since the earliest stars in the cluster are two of type B3. Nevertheless, it has been attempted to obtain a satisfactory value of the radial velocity of the cluster.

As material for a study of the cluster's dynamics the proper motions of the seventy brightest members have been measured on Astrographic plates with a 'baseline' of 62 years.

Finally, photographs in various colours and exposures and on various telescopes have been made of the cluster and its surroundings for the purpose of population counts and studies of the surrounding nebulosity.

AN IDENTIFICATION LIST FOR STARS IN NGC. 2547.

Throughout this thesis cluster stars are designated only by serial numbers (which increase with Right Ascension), and there follows here a list of these numbers with their corresponding numbers in various star-catalogues, should the star appear therein.

GLOSSARY: C.P.D. - Cape Photographic Durchmusterung.

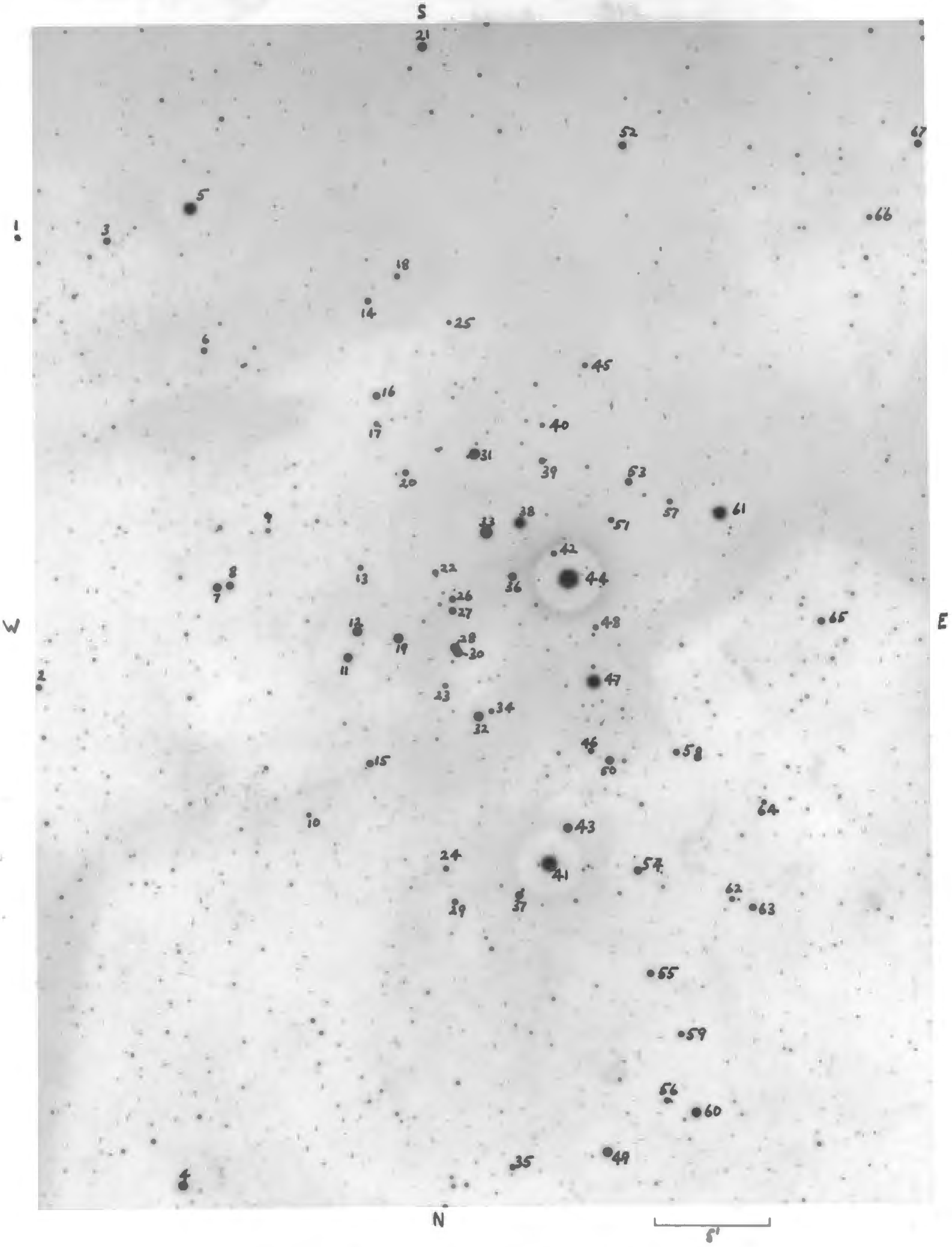
Z.C. - Cape Zone Catalogue (1900).

F.Z.C. - Cape Faint Star Zone Catalogue (1939).

TABLE I.

Ser.No.	C.P.D.		F.Z.C.	Z.C.
1.	-49° 1508			
2.		-48° 1479		
3.	1510		3836	
4.		1484		5423
5.	1513			5426
6.	1514			
7.		1485	3851	
8.		1486	3853	
9.		1487		
10.		1492		
11.		1493		5444
12.		1495		5447
13.		1496		
14.	1520		3868	
15.		1497	3867	
16.		1498	3870	
17.		1499		
18.	1521			
19.		1500		5455
20.		1501	3872	
21.	1523			5461
22.		1503		
23.		1506		
24.		1505	3877	
25.	1524			
26.		1509	3879	
27.		1508	3878	
28.		1510		5463
29.		1507		
30.		1511		5464
31.		1512		5467
32.		1513		5469
33.		1514		5470
34.		1515		
35.		1516		
36.		1517		5473
37.		1518		5474
38.		1519		5475
39.		1520	3889	
40.		1521		
41.		1522		5476
42.		1523		
43.		1524		5479
44.		1525		5480
45.	1528			
46.		1527	3894	
47.		1528		5482
48.		1529		
49.		1530		5484
50.		1531		5485
51.		1532		
52.	1531			5487
53.		1533	3898	
54.		1534	3899	
55.		1536		5490
56.		1537	3902	
57.		1538		
58.		1539	3904	
59.		1540	3905	
60.		1541		5498
61.		1543		5506
62.		1544		
63.		1546	3919	
64.		1547		
65.		1551	3928	
66.	1537			
67.	1540		3938	

Plate I



The Central Portion of NGC 2547

CHAPTER II.

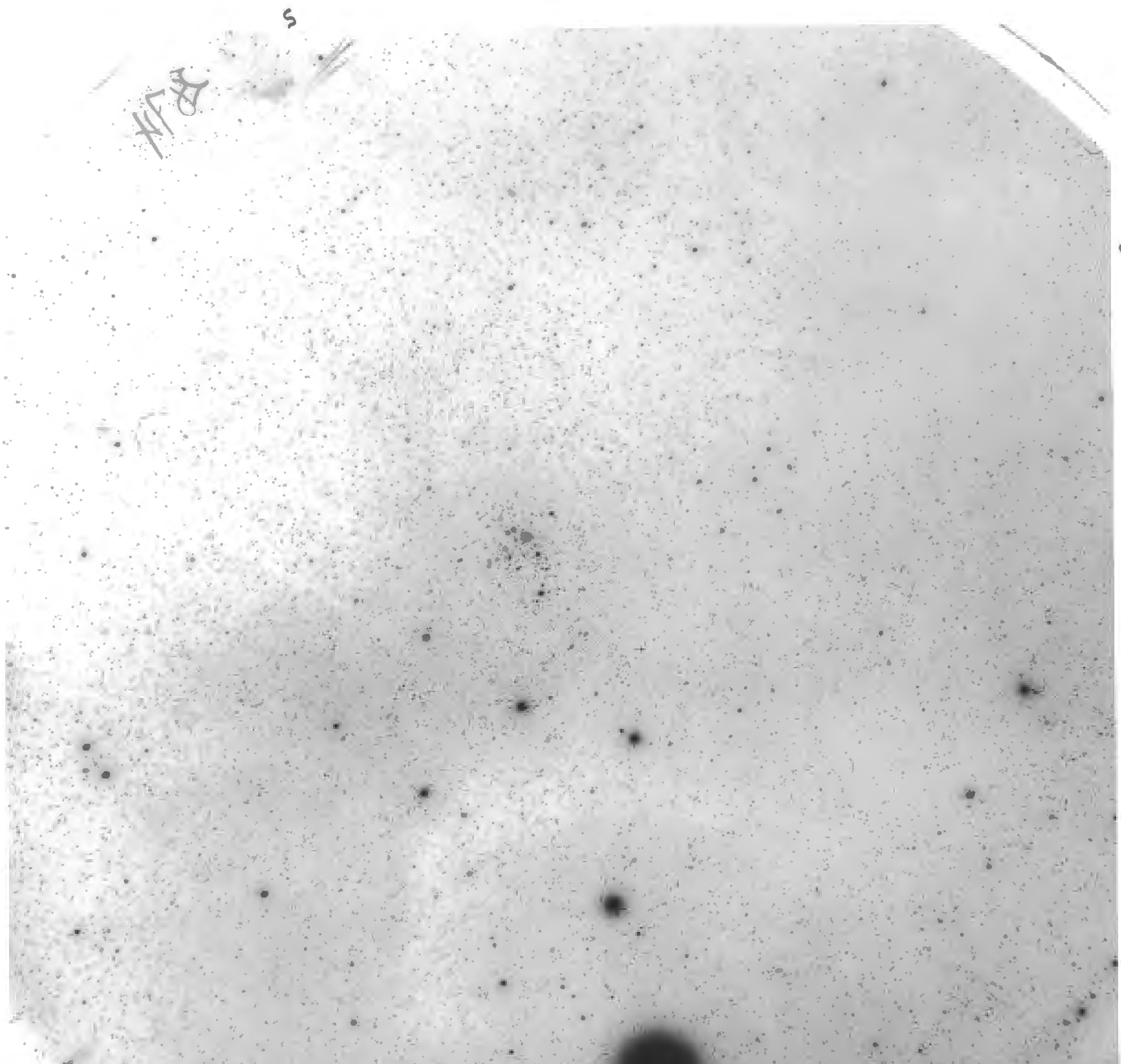
General Observations.

Plates I and II show general views of the cluster and its surroundings. Plate I is an enlargement from a plate taken with the 24 inch refractor of the Royal Observatory. It is a sixty minute exposure using an IAZ emulsion with no filter. The 24 inch refractor is designed for photographic work and has a focal lenght of about 265 inches, giving a plate constant of some 30".6 per mm. It has several companion telescopes on the same mounting, among them an 18 inch refractor designed for visual work, and with this various plates were taken using yellow filters. The 24 inch was also used in conjunction with ultra-violet filters both for photometric purposes and to study the surroundings in Ultra-violet light. However, nothing unusual was found on these plates and their sole use was in the photometry. Fuller details of these exposures are given in chapter III.

Since the 24 inch refractor has only a small field of view (about 1¼ x 1¼) and it was of interest to study the more extensive surroundings plates were kindly taken for us on the 32 inch Schmidt telescope of Armagh-Dunsink-Harvard observatories at their Boyden station near Bloemfontein. This very fast telescope takes circular plates of 10 inch diameter covering almost 5 across a diameter. We have three plates of 12 minutes exposure on Kodak 103-aO emulsion, reaching a threshold magnitude equivalent to probably that of the 60 min. IAZ exposure on the 24 inch. These plates are not of the highest quality but this is no way the observer's fault as the cluster was unavoidably at a high zenith distance when the exposures were made.

NGC2547 lies in an interesting situation. Its 1950 co-ordinates are: Declination $-49^{\circ}\ 00'$, Right Ascension $8^{hrs}\ 8^{m}.5$, which is equivalent to a galactic longitude of about $234^{\circ}.6$ and galactic latitude $-8^{\circ}.0$. This places it in the constellation of Vela, about two degrees south of γ-Velorum. The Schmidt plates show what appears to be a definite

Plate II



The Cluster Surroundings

association of stars near γ-Velorum, although it is the opinion of Prof. Irwin that NGC2547 does not belong to this association. A search of the 1952 Yale catalogue of parallaxes reveals that only about two of these stars have had their parallaxes measured (it is interesting to note that γ-Velorum itself does not seem to have a published parallax and since it is a peculiar Wolf-Rayet star its spectrum does not yield an easily evaluated estimate of distance), these being of the order of 0".02 which corresponds to a distance of some 50 pc -very much less than the distance of NGC 2547 (see Ch.III) .

The cluster is also interestingly situated in that it lies close to the great gap in the Milky Way in Vela between the False Cross and γ-Velorum. In actual fact the gap shows up on the Schmidt plates as lying about $1\frac{1}{2}°$ to the south-east of the cluster, which places the latter somewhat too far away to be of any great value in a study of this interstellar dust cloud. There are several other galactic clusters nearer the latter which should be worthy of closer attention. However, NGC 2547 lies close enough to make one suspect the possible presence of differential absorption within the cluster.

The classification of the Cluster on Trumpler's[10] system presents some slight difficulty. The questions of cluster membership and spectral types will be discussed in later chapters, but it appears probable that the cluster has one giant star among its members. Unfortunately, no spectrum of this star (24) is as yet available, and its classification rests only on photometry. It certainly does not appear to be main-sequence star, but if a giant it has a remarkably high colour-excess. Its cluster membership seems well-established from the proper-motion criteria. Also, such a giant would render the cluster unique in having a gaint fainter than its brighest main-sequence members (see evolutionary discussion in main Chapter III). However, assuming that this star is a giant, the cluster is to be classified as type 2-b3.

NGC 2547 is an unusually thin and irregular cluster, having a decidedly elongated appearance transverse to the galactic plane, The brightest stars form an almost spiral structure, this being especially marked in the inner part of the spiral from star 33 through 47 and 41 to 24.

/This

This is of interest from the point of view of the substantiation or otherwise of certain Russian researches. Markaryan [1], of the Burakan Observatory, claims that those clusters whose brightest members are of type O-B2 all have either multiple star systems such as the Orion Trapezium or star-chains. The existence of these star-chains, not only in clusters, is disputed by many other astronomers. A difference of one sub-class is not so great as to exclude the possibility that NGC 2547 belongs to Marakaryan's class and does exhibit these star-chains, although it seems doubtful as to how one might proceed to prove their reality in space.

It is of considerable interest in dynamical studies to have some estimate of the total number of stars forming the cluster, plus, also, some indication of its total mass. Having made an estimate of the cluster's radius, one is then enabled to compute and average density for the cluster - a factor of vital importance in determining the cluster's resistance to disrupting forces. To this end population counts were undertaken on the photographic (IAZ) plate exposed for sixty minutes through the 24 inch. It is estimated that the threshold photographic magnitude on such a plate after such an exposure is between 17.0 and 17.5, implying, therefore, that the population deduced from these counts is only that portion of the cluster population whose apparent magnitude is brighter than 17.0 - 17.5 photographic. However, using the distance modulus of $8^m.1$ determined in chapter III, this implies that the section of population thus omitted must consist of stars of absolute magnitude fainter than about +9 pg, i.e. of type later than say K5 or Mo, of which one would not expect there to be a majority in such a cluster. They are also the stars of the lowest mass.

The main requirement of a population count for the purpose of determining cluster population and radius is the determination of the areal density of stars as a function of distance from the cluster's centre. Let this function be $f(r)$. Let K be the density of background stars (assumed constant), so that ideally $f(r)$ is asymptotic to K. However, in practice $(f(r) - K)$ becomes less than the statistical

/fluctuations

fluctuations in K after r, the distance out, exceeds a certain value, say <u>a</u>. Then <u>a</u> may be taken as the radius of the cluster. This is illustrated in fig. (ii).

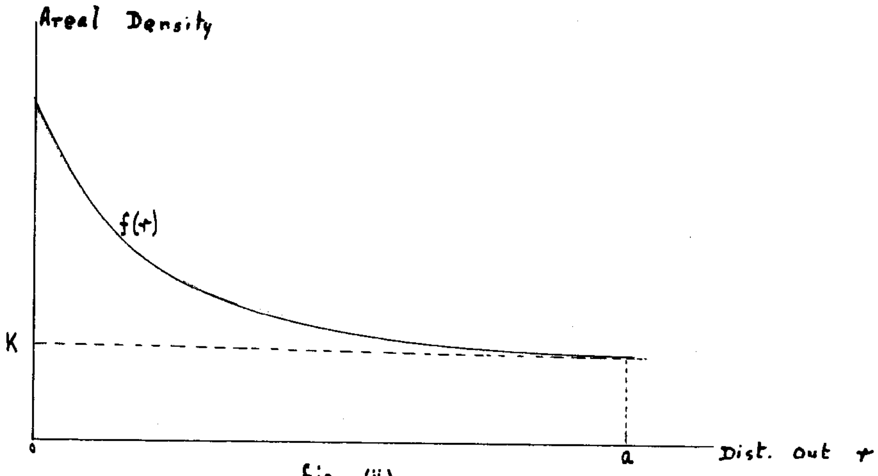


fig. (ii)

$$\text{Total Area under curve} = \int_0^\infty f(r)\,dr$$

$$\text{Area above background density K} = \int_0^\infty f(r)\,dr - \int_0^\infty K\,dr$$

$$= \int_0^a f(r)\,dr - Ka$$

Mean value of $f(r)$ above background density is:

$$\overline{f(r)} = a^{-1}\int_0^a f(r)\,dr - K$$

Hence, total number of stars in cluster brighter than threshold magnitude is:-

$$N = \overline{f(r)} \times \text{area of cluster}$$

$$= \overline{f(r)} \times \pi a^2$$

i.e. $$N = \pi a \int_0^a f(r)\,dr - \pi a^2 K \quad \ldots\ldots\ldots(1)$$

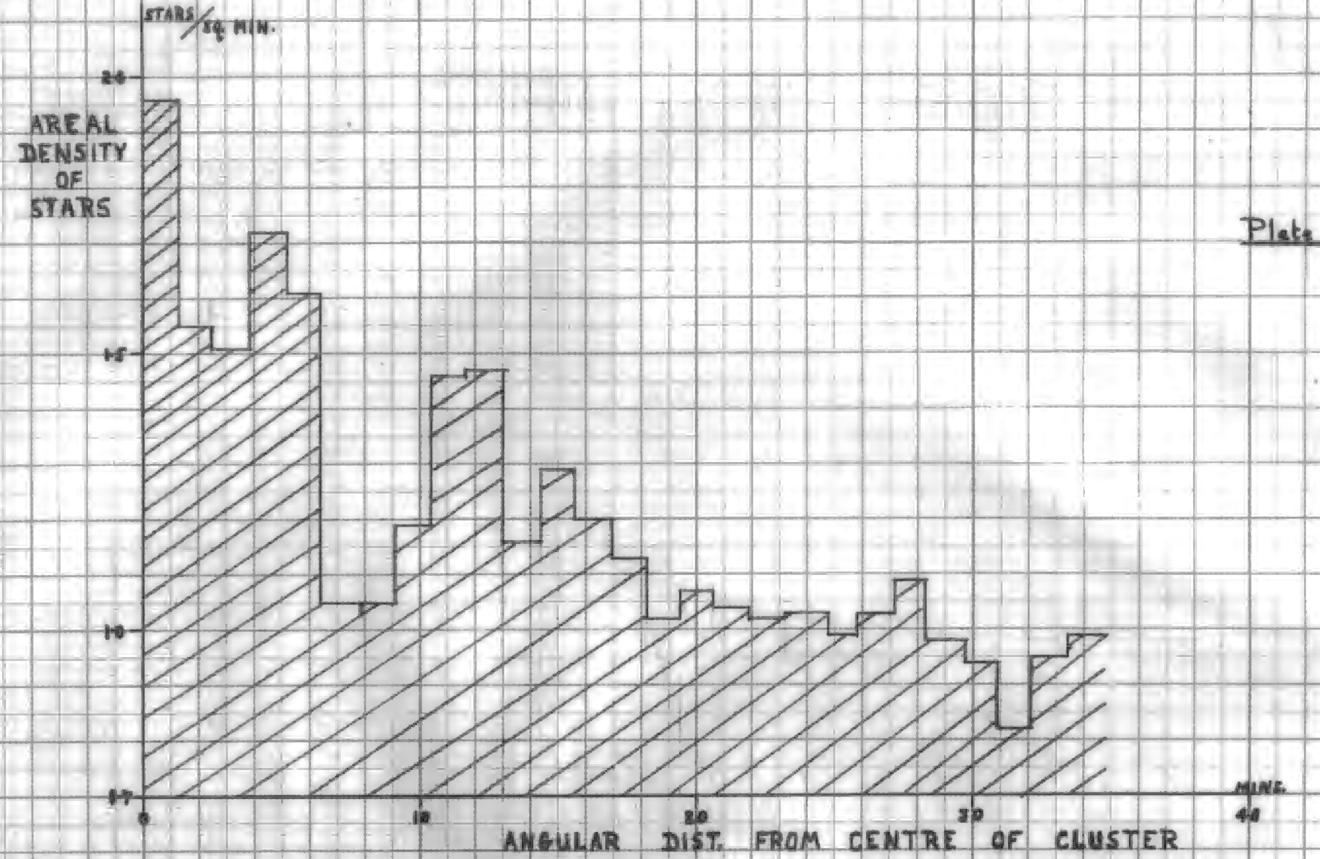


Plate III : The areal-density function

It is possible to deduce the actual space distribution of stars from the areal distribution by the numerical integration of von Zeipel's equation:

$$\phi(r) = \frac{1}{\pi}\int_r^R (x^2-r^2)^{1/2}\frac{d}{dx}\left\{\frac{1}{x}f'(x)\right\}dx$$

where x replaces our r above and r is the true (spacial) distance from the centre, R being the cluster radius. (See Smart's Stellar Dynamics for the derivation and discussion). However, it is considered that NGC2547 possesses neither sufficient density of population nor spherical symmetry to make these computations of any real value.

In practice our density function f(r) is determined in the form of a histogram, as shown in plate III.

A series of concentric rings whose diameters successively increased by about 1.3mm was drawn on cellophane paper. These were also divided into quadrants to make each count shorter and so less susceptible to errors arising through fatigue. A total of twenty-seven such rings was found sufficient to cover the photographic plate. From a study of the Schmidt plates it was decided to adopt as the cluster centre a position half-way between the stars 44 and 30. The grid was then superimposed on the photographic plate with its centre in the position given above and the two securely taped together, after which they were placed on a viewing box having a transparent screen lit from the rear by an electric lamp. The counting was done through an elementary compound microscope magnifying about twentytimes which could be held in the hand but steadied against the plate with the help of an encasing tube. The number of star images lying between successive pairs of rings was then counted, but no attempt was made to classify the counts according to the stellar magnitude. In the case of the brightest stars a correction was estimated to compensate for the fact that the size of their images must obliterate some of the faint star images near them plus also a correction for the finite width of the rings themselves. The grid was then removed, and the diameters of the rings measured on a travelling microscope. The measurements in centimetres were converted into minutes of arc using a plate constant of 30".64 to the millimetre. Finally, the areal

/density

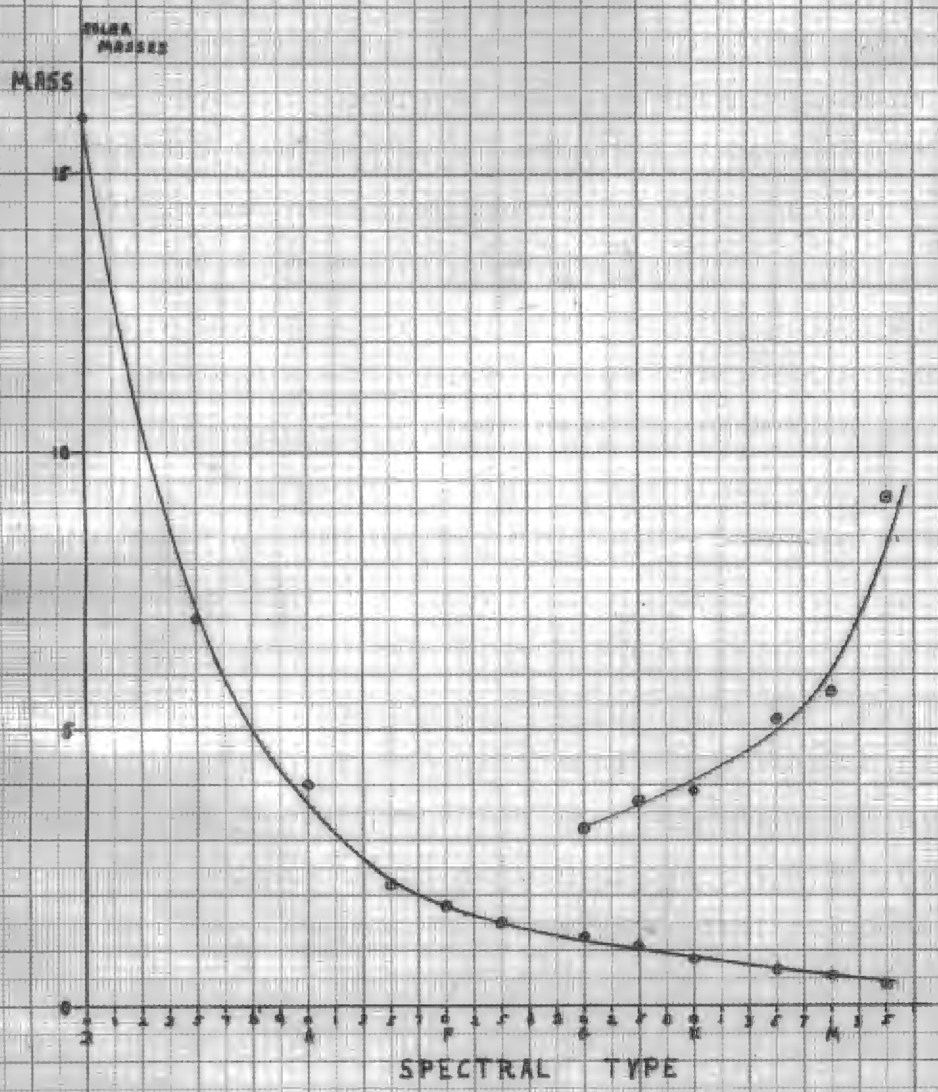


Plate IV :

The mass-spectral type function

density of stars per square minute was computed for each pair of rings. The results are shown plotted in Plate III.

A large degree of the scatter in this histogram is due to the spiral structure of the cluster mentioned above, but the marked drop in density at about 31'.5 from the centre may well be due to an interstellar cloud. From the histogram we deduce the following constants:-

$$a = 37' \pm 2'$$

$$K = 0.97 \pm .03 \text{ stars/sq.mm.}$$

$$f(r)dr = 43.8 \pm 0.2 \text{ stars/mm}$$

Substituting these results in equation (1), we get:-

$$N = (37 \times 3.142 \times 43.8) - (3.142 \times 37^2 \times 0.97)$$

$$= 919 \pm 96 \text{ stars}$$

Since we are interested only in estimating orders of magnitude, and also to partly compensate for those cluster members fainter than mpg = 17, we shall adopt a cluster membership of ~1000 stars.

It is interesting to note that Trumpler finds for the value of the cluster radius only 17'. A distance modulus of $8^m.1$ places the cluster at a distance of 417 pc, so that an angular radius of 37' corresponds to a spacial radius of 4.5 pc. Hence the volume of the cluster ($= \frac{4}{3}\pi r^3$) is about 383 cubic parsecs.

To estimate the total mass of the cluster we have to make use of plate IV, showing the mass-spectral type function* and plate V, showing the distribution of spectral types among sixty-two of the brighter stars NGC 2547. From this we find that these sixty-two stars contribute a mass of about 200 solar masses. The remaining 900 odd stars must all be later than type Go, and for these we may adopt a mean mass of about one solar mass each. Thus the total mass of the cluster is of the order of 1100 solar masses, and its average density ($= \frac{\text{total mass}}{\text{vol.}}$) about 2.8 solar masses per cubic parsec. This result will be used in later discussions.

* This function is taken from Hynek's "ASTROPHYSICS", p. 466.

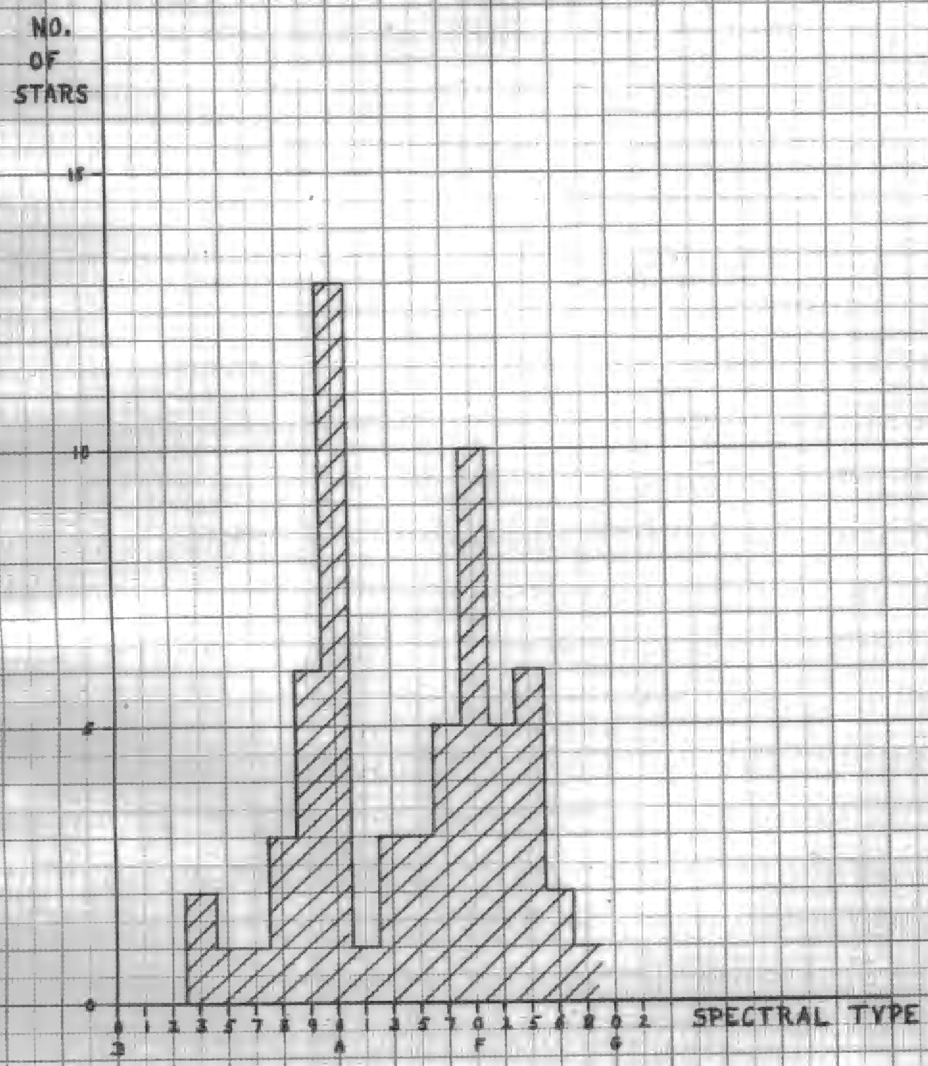


Plate V :

The frequency of spectral types

CHAPTER III.

Photometry.

The main instrument used in the actual photmetry of NGC2547 was the 24 inch refractor, both photoelectric and photographic photometry being undertaken with it. Three-colour photoelectric observations were made on sixty-seven C.P.D. members in the cluster, and these supported by taking photographs through suitable filters, which were later photometered on the Royal Observatory's Schilt photometer.

The instruments and procedures used were those which are in routine use by the staff of the Royal Observatory and have already been very fully described elsewhere [11]. Accordingly, only a brief outline is presented here.

The photo-multiplier tube at present in use is an E.M.I. tube, type 5659. It has eleven stages (dynodes) operated at about 115 volts per stage. The output is fed by co-axial cable into a D.C. amplifier of fairly conventional design, after which the amplified signal is recorded on a Brown potentiometer. The latter has a ten-inch chart driven electrically on which a pen describes a line whose height above the zero mark varies linearly with the energy input from the star (the photo-multiplier and amplifier being also linear). The P.M. tube is so mounted at the focus of the telescope that it may be used in conjunction with various filters and diaphagms. There is also a means whereby the diaphragm may be viewed through an eyepiece to check that the star is correctly centered in the diaphragm. The diaphragm in constant use throughout this work was 1.5 mm in diameter, equivalent to about 46 seconds of arc. This was large enough not to require adjusting of the focus for chromatic aberration when changing filters, and also to accomodate blurring of the image caused by seeing conditions. The three colours in which a star was photometered were blue, yellow and ultra-violet. and for these the following filters were employed. For the blue, a 2mm Schott BG12 in conjunction with a GG 13 to remove the ultra-violet, for the yellow an

/ Omag

Omag 302, and for the ultra-violet a Corning Glass 9863. The latter is thought to have a slight red leak to the red of 6600 A-U., but since the star's photometered were all bluish and the tube sensitivity is very low to the red of 6500 A-U this was ignored. None of the filters have had their spectral transmission's measured accurately, since these are always modified by P.M. tube and telescope characteristics.

Three-colour photometry was also attempted photographically. For this the following emulsions and filters were used:
Blue: 3mm on IAZ with GG 13 filter, 24 inch refractor.
Yellow: 30 min. on 10" H.P.3 with W8 filter, 18 inch refractor.
U.V. 60 min. on IAZ with U.V. filter, 24 inch refractor.

The resulting plates were photometered on a Schilt photometer. This is a standard photometer (densitometer) working on a principle briefly this. The plate is held in a movable holder and may be viewed through eyepieces. The light from a small lamp, which is run from a stabilized voltage supply is focussed on the plate and through to a photronic photo-cell, whose output is fed to a moving -coil wall-galvanometer. By means of a rheostat in the lamp circuit a reading of 100 divisions is obtained on the galvonometer scale when the light is focussed on the plate background next to a star image. The latter is then quickly moved into the light beam and the resulting galvonometer reading recorded. A plot of the log of such a reading versus stellar magnitude gives a smooth, nearly linear curve. These curves were calibrated by using as standards the measures of those stars whose photo-electric magnitude determinations were considered accurate to better than 0.01 mag. by reason of their internal consistency.

In the photo-electric observations it had been hoped to obtain sufficient observations to reduce the probable errors in all colours of all sixty-seven stars to less than $\pm$ 0.01 mag. This was done in the majority of cases, entailing between three and six observations per star, the greatest probable error among the remaining minority being $\pm$ 0.018 mag., and the overall probable error $\pm$ 0.0008 mag. The probable error was found

/to

to be a function of the stellar magnitude, rising in a slow curve with numerically increasing magnitude. These curves were sensibly the same for the blue magnitude (b) and the blue-ultra-violet index (u-b), but in the case of the blue-yellow index (b-y) the curve failed to drop to this value for the brighter stars. This is attributed to the fact that the majority of observations were made to the west of the meridian, i.e. over Cape Town and suburbs, in which part of the sky there is to be found a considerable amount of scattered yellow light from street-lights, advertising signs, etc. In the case of one star, number 8, the probable error of the blue magnitude could not be reduced to anything like ± 0.01 mag., and it is thought that this star might be variable in brightness although not in colour. Variable stars are not unknown in galactic clusters, but are decidedly uncommon, while the evidence available in this case indicates an even more uncommon form of light-curve. Further doubt arises from the angular proximity (33") of star number 7, whose light may possibly have contaminated the earlier observations, although especial care was taken to exclude it in the later observations. The whole question seems still in doubt, and only further observation can decide. The present series of observations is plotted in plate XII.

One of the major difficulties accompanying astronomical photometry is the comparison of one worker's results with another's. Not only do filter characteristics vary, but so do telescope optics and electronic equipment, making transfer equations from one system to another entirely empirical, requiring observations of certain standard stars on each system. Such observations being to hand, the procedure usually adopted is to obtain linear equations by least-squares solutions, although such equations are rarely entirely satisfactory owing to a break down in linearity of a (u-b) versus (b-y) plot at about spectral type Ao, caused by ultra-violet absorption in the Balmer lines. In our case here it has been found best to adopt two-parameter transfer equations, except in the case of the conversion of the (b-y) index.

The standard three-colour system which is rapidly coming into international use is that of Johnson and Morgan[3], denoted by B, V, U (their

/yellow

yellow colour is almost exactly the international photo-visual one, hence the V). Johnson and Morgan photometered some three hundred stars both north and south of the equator with precision accuracy, their system thus being available to both Southern and Northern Hemisphere observers. Unfortunately, the observation of these standard stars at the Royal Observatory is not yet complete, and the transfer equations here adopted are still of a temporary nature, especially as regards the zero points which may have an error of up to ± 0.05 magnitude in them. However, the equations used are these:-

$$(B-V) = 0.91(b-y) + 0.28$$

$$(U-B) = 2.94(u-b) - 0.54(b-y) - 4.74$$

$$B = b - 0.10(b-y) + 0.20$$

It is to be noted that originally a zero point of - 4.69 was adopted for the (U-B) equation, but that this yielded a mean ultra-violet reddening for the cluster which was negative (i.e. "blue-ing"). Since this is a physical impossibility, and the zero-point of the (B-V) equation considered fairly accurate the ultra-violet zero-point was arbitrarily adjusted by - 0.05 so as to make the ratio of the mean excesses in the ultra-violet indices 0.72 as determined by Johnson and Morgan.

The results thus transformed are tabulated below:-

TABLE II

Serial Number	V	B-V	U-B	Estimated Sp. Type	Serial No.	V	B-V	U-B	Estimated Sp. Type
1.	10.87	+ 0.37	+ 0.03	Fo	34.	10.96	+ 0.46	- 0.19	F6
2.	10.68	+ 0.29	- 0.05	Fo	35.	10.45	+ 0.37	- 0.24	Fo
3.	10.08	+ 0.47	- 0.06	F5	36.	9.82	+ 0.11	- 0.08	Ao
4.	9.14	+ 0.13	- 0.01	A3	37.	9.83	+ 0.06	- 0.07	Ao
5.	8.20	- 0.08	- 0.64	B9	38.	8.38	- 0.05	- 0.47	B7
6.	10.65	+ 0.32	- 0.05	Fo	39.	10.22	+ 0.44	- 0.08	F5
7.	9.37	+ 0.03	- 0.10	Ao	40.	10.95	+ 0.50	- 0.01	F5
*8.	9. 63	+ 0.04	- 0.05	Ao	41.	7.27	- 0.12	- 0.70	B3
9.	11.45	+ 0.20	+ 0.01	A7	42.	10.99	+ 0.34	- 0.22	Fo
10.	11.38	+ 0.38	+ 0.08	Fo	43.	9.27	+ 0.08	- 0.17	B9

Table II Continued/.......

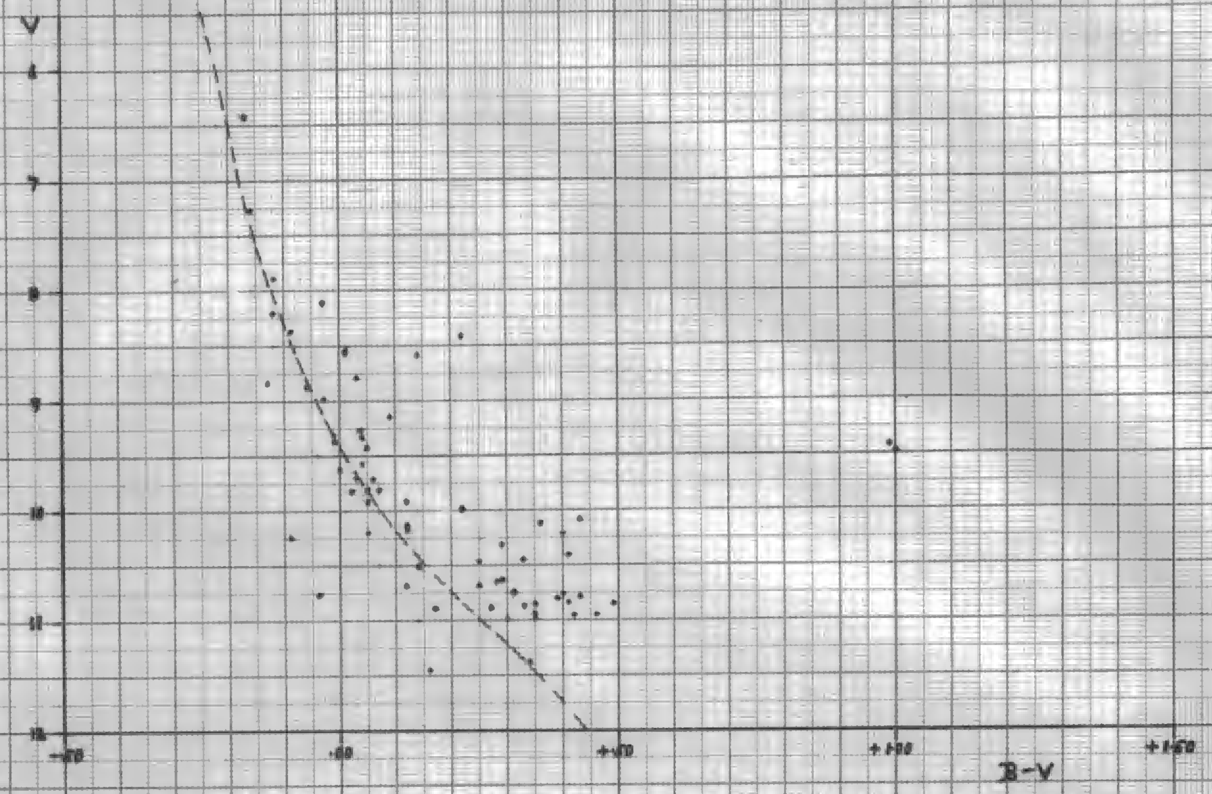
TABLE II (CONTINUED).

Serial Number	V	B-V	U-B	Estimated Sp. Type	Serial Number	V	B-V	U-B	Estimated Sp. Type
11.	8.58	+ 0.18	+ 0.02	A5	44.	6.42	- 0.13	- 0.72	B3
12.	8.99	+ 0.01	- 0.23	B9	45.	10.89	+ 0.21	+ 0.10	A5
13.	10.89	+ 0.31	- 0.20	Fo.	46.	10.47	+ 0.29	- 0.05	A7
14.	9.49	+ 1.04	+ 1.01	K3	47.	7.89	- 0.08	- 0.60	B8
15.	10.14	+ 0.16	- 0.03	A7	48.	10.85	+ 0.53	+ 0.06	F8
16.	9.94	+ 0.16	+ 0.01	A5	49.	8.41	+ 0.26	+ 0.03	A7
17.	10.94	+ 0.39	- 0.05	F2	50.	9.43	+ 0.09	- 0.12	B9
18.	10.78	+ 0.47	- 0.13	F5	51.	10.76	+ 0.44	- 0.11	F6
19.	8.79	+ 0.07	- 0.09	Ao	52.	9.72	+ 0.07	- 0.08	Ao
20.	10.31	+ 0.33	- 0.04	Fo	53.	9.99	+ 0.26	+ 0.01	A7
21.	9.33	+ 0.03	- 0.17	B9	54.	10.24	- 0.05	- 0.68	B8
22.	10.63	+ 0.33	+ 0.08	Fo	55.	9.7~~9~~2	+ 0.10	- 0.07	Ao
23.	10.85	+ 0.39	- 0.05	F2	56.	10.41	+ 0.45	0.00	F5
24.	9.43	+ 1.03	+ 1.02	K2 III ?	57.	10.80	+ 0.43	- 0.08	F5
25.	9.60	+ 1.85	> + 2	?	58.	10.12	+ 0.40	- 0.17	F2
26.	10.51	+ 0.18	+ 0.36	?	59.	10.76	0.00	- 0.74	Ao ?
27.	10.17	+ 0.16	+ 0.09	A3	60.	8.56	+ 0.05	- 0.25	Ao
28.	9.33	+ 0.08	+ 0.20	A1	61.	8.84	- 0.09	- 0.62	B5
29.	10.69	+ 0.16	+ 0.02	A3	62.	10.75	+ 0.35	- 0.05	Fo
30.	9.57	+ 0.08	+ 0.02	Ao	63.	9.92	+ 0.09	- 0.09	Ao
31.	8.56	+ 0.05	- 0.29	B9	64.	10.99	+ 0.39	- 0.14	F2
32.	8.87	- 0.02	- 0.26	Ao	65.	9.80	+ 0.09	- 0.04	Ao
33.	8.11	+ 0.01	- 0.26	B8	66.	10.84	+ 0.45	0.00	F2
					67.	10.20	+ 0.09	- 0.21	Ao

* The magnitude given is the median one.

Plate VI :

Magnitude - Colour Array



The magnitude given is the median one.

The spectral types were estimated as follows. There were available the spectra of nine stars (obtained for radial velocity measures), from which the spectral types of those stars were determined (by Dr D.S. Evans). From the tables of mean colours published by Johnson and Morgan [3] the colour excesses in the yellow index of each of these stars was determined, and the mean of the nine values applied to the remaining observed (B-V) indices. Since this index is a single function of spectral type, an estimate of the latter may be made from it, using the mean values of the colours given by Johnson and Morgan. All the types in table II are of luminosity class V except number 24, which appears to be of class III. Magnitude and the (U-B) index have been taken into account in defining the type more closely, and this has given rise to difficulty in classifying stars such as numbers 26 and 59, where the two colour indices given widely divergent results. In general, the (U-B) index has been subordinated, since the coefficient multiplying (u-b) in the transfer equation is large, resulting in a magnification of any small error in (u-b). In general, any estimate of spectral-types given above is not to be relied on to more than say ± 2 sub-classes.

Star 25 appears to be either a highly reddened giant or one of peculiar spectral type. In either case, its proper-motion shows it to be a non-cluster member.

The frequency of occurence of each spectral-type among these bright stars is shown plotted as a histogram in plate V. It has already been used in chapter II to estimate the mass contributed to the cluster by these stars.

Plots of magnitude and the two colour indices against each other are shown in plates VI, VII and VIII. Plate VI is the usual magnitude-colour array, equivalent to a Hertzsprung-Russel diagram. The dotted curve represents the mean position of the Johnson and Morgan's standard array displaced by 8.5 magnitudes. It would seem best to adopt 8.4 ± 0.1 magnitudes as the apparent distance modulus. This has still to be corrected for general absorption which we derive from plate VIII, the colour-colour array, where again the dotted curve represents Johnson and Morgan's standard display. We find the mean reddening in (B-V) from this to be 0.11 magnitudes, and adopt as ratio of general to selective absorption 3.0, as determined by Morgan, Harris and Johnson [20]. This yields a general absorption of 0.33 magnitudes, which makes the final distance modulus 8.1 magnitudes. We now use the well known formula based on the definition of absolute magnitude M and the inverse-square law:

$m - M = 5 \log r - 5$ where m is the apparent magnitude and r is the distance of the star

Thus $8.1 = 5 \log r - 5$

or $r = 417 \pm 19$ pcs.

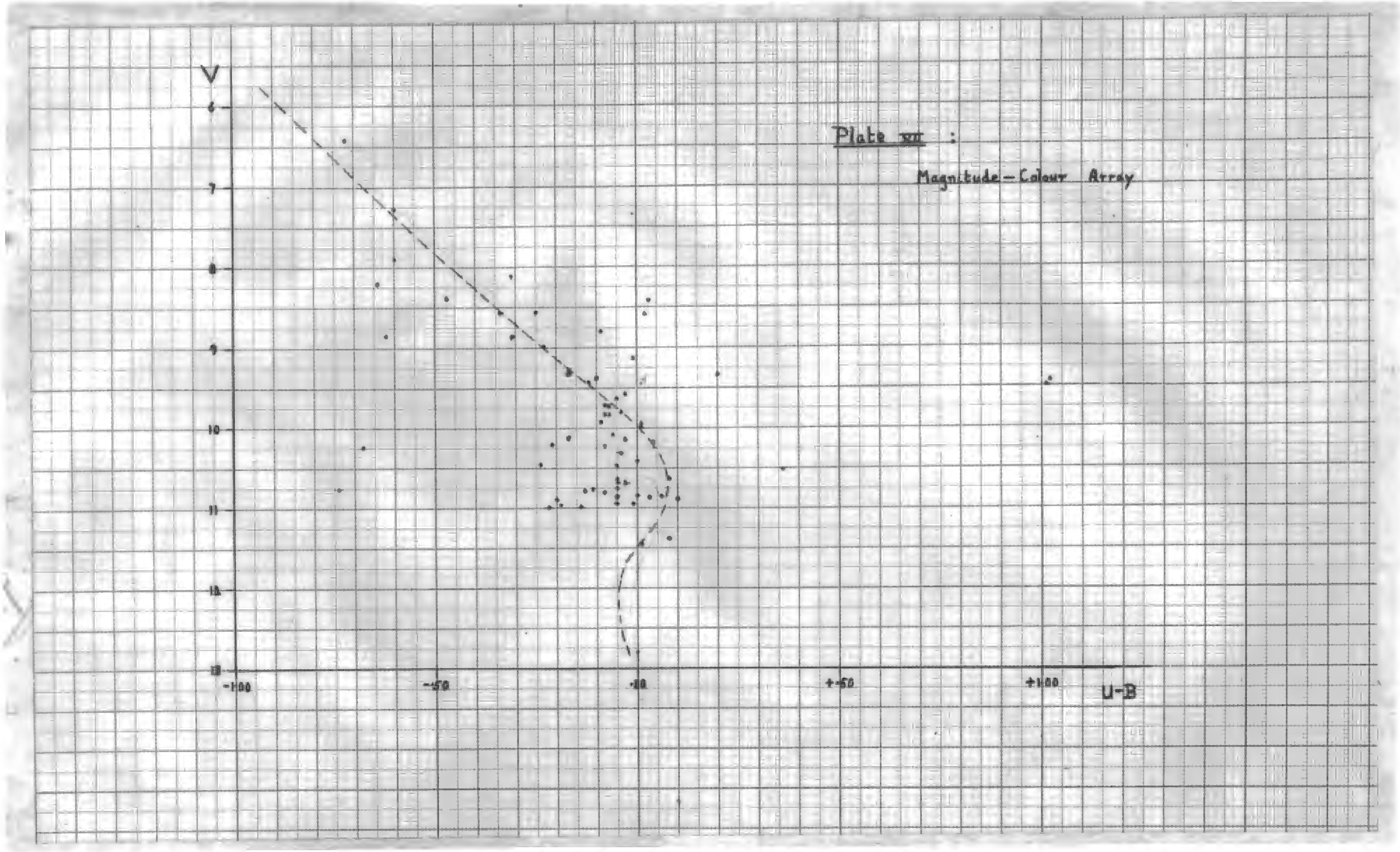


Plate VII :
Magnitude – Colour Array
V
6
7
8
9
10
11
12
13
-1.00
-.50
.00
+.50
+1.00
U-B

This is a good deal nearer than Trumpler's[4] estimate of 690 p.c. It yields a value of the general absorption as 0.79 mag./kpc (visual) whereas Trumpler[4] found 0.67 mag./kpc (photographic), despite the fact that the photographic (blue) absorption should be greater than the visual (yellow).

Of the two stars on plate VI at about B-V = +1.00 only one appears to be a cluster member (from proper-motion criteria). This star, 24, we can only assume to be a giant, since an enormous amount of reddening would otherwise be required to account for its displacement from the main-sequence, none of which is exhibited by those stars near to it. However, in a recent paper[12] Johnson and Sandage point out that in all clusters so far studied, those containing yellow giants have the main sequence always absent for absolute magnitudes brighter than the giant sequence —— a condition not fulfilled in this case if 24 is a giant. Since this would profoundly affect current ideas on stellar evolution we must point out the necessity for obtaining a spectrum of this star to make certain whether or not it is a giant.

Two other peculiarities are evident from plate VI. One is the failure of the brightest stars to rise above the standard main-sequence, a phenomenon observed in nearly all clusters and also predicted on current theories of stellar evolution. The other is the large number of stars which lie above the main sequence between B-V = +0.2 and +0.5.

The magnitude-colour array is the locus of constant time cutting across the individual evolutionary tracks of the stars. Briefly, current theories[2,13] expect first the hottest stars to slowly rise above the main sequence and then move much more rapidly on a horizontal track across the diagram into the giant region, from where they once more slowly rise into the super-giant region. Thus a cluster's H-R diagram gradually alters, the main sequence peeling off from early to late type and moving into the giant region, until eventually we have a diagram similar to that of M67, where nearly all the stars are on the giant sequence. Accordingly, the tendency at present is to interpret a cluster's H-R diagram as a condition of its age. On this basis, NGC2547 would appear to be about the age of the Pleiades, say 5×10^7 years. However, the three peculiarities of its magnitude-colour array, viz. the presence of a giant fainter than the brightest main sequence stars, the failure of the latter to rise off the standard array and, thirdly, the large number of fainter stars which are above the standard array, would appear to contradict the above evolutionary theories. It may also be of significance that all those stars lying furthest from the standard array (excepting those at B-V = +1.00) appear from their proper motions to definitely belong to the cluster.

Plate VII shows another magnitude-colour array, in this case employing the ultra-violet index. As indicated before, the latter index

/is

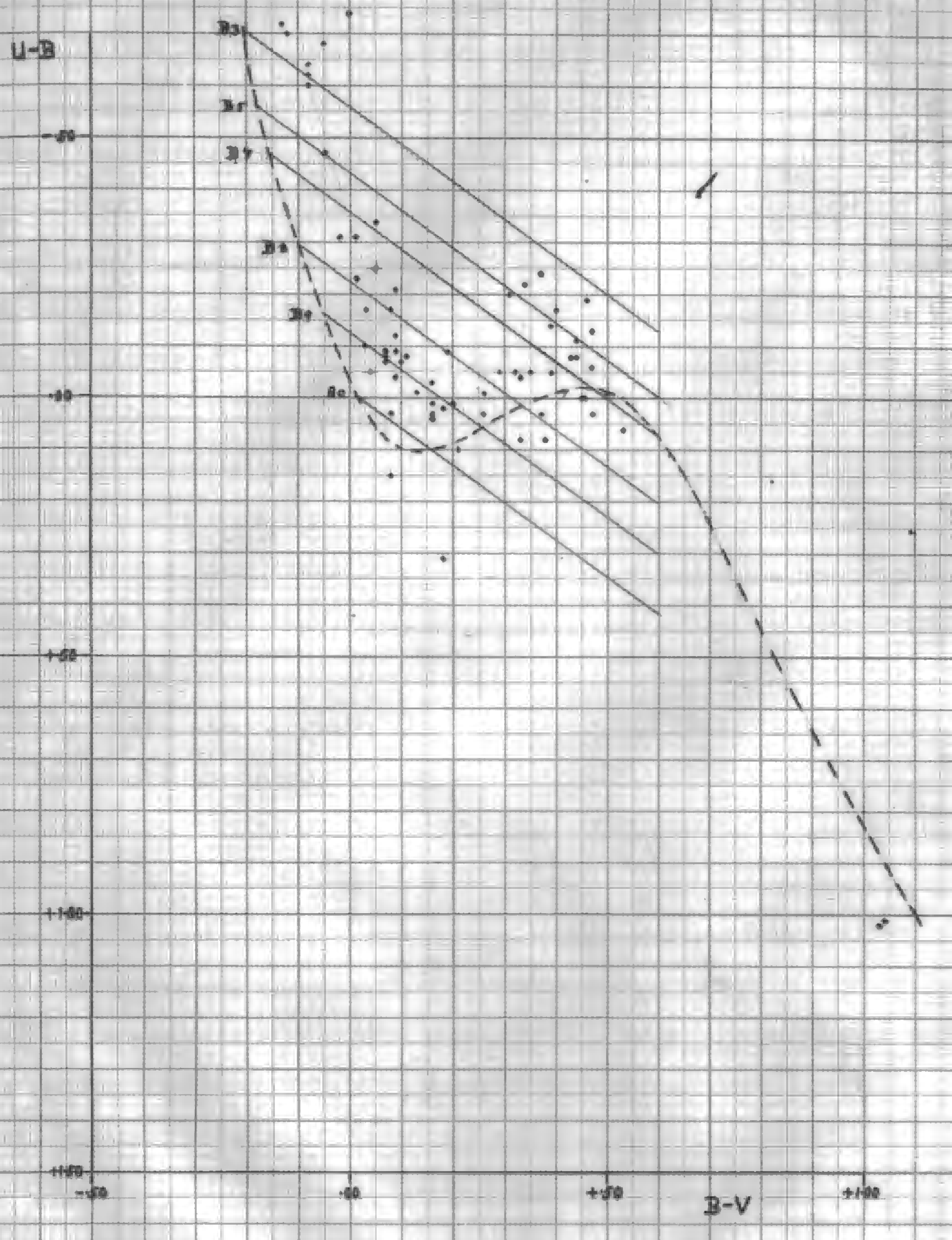


Plate VII :

Colour - Colour Array

is considered of lower accuracy than the (B-V) index, a view which seems to be borne out by the larger scatter of this array. Accordingly, only two peculiarities are pointed out. They are, firstly, the high density of points all to the left of the standard array at about V = 10.5 (reddening would tend to displace them to the right), and, secondly, the fact that all the stars forming the very steep sequence between U-B = -.74 and U - B = -.60 all appear to be cluster members, although the two at U-B = +.20 and U-B = +.36 are doubtful members. There seems no likely explanation of these facts on current theories.

Plate VIII displays a plot of the two colour indices against each other, with Johnson and Morgan's standard array superimposed. The parallel lines are the reddening lines (i.e. the track of stars of same spectral type but increasingly reddened) for each spectral type, as determined by Johnson and Morgan. The horizontal portion of the curve is caused by ultra-violet absorption in the Balmer lines, which become strong in the A-type stars. There are several interesting points exhibited by those stars at the top of the diagram. The two stars at the top and farthest to the left are both almost without doubt of the type B3V, yet both lie considerably above the indicated reddening line for B3 stars. The possible explanations for this would seem to be i) their colours are incorrect owing to either an error in the transfer equations or observations, ii) Johnson and Morgan's mean colours for B3 stars are incorrect or iii) the reddening line is of different or variable slope. Of these, the transfer equations are certainly suspect - more so, we feel, than the observations. The error here may be as great as ± .05 mag. which would certainly account for the phenomenon. Otherwise we feel a reddening line of variable slope is the more likely explanation, since J. & M. give as the slope 0.72 ± 0.03 over the range measured - an interval which makes but small difference to the lines on our diagram. There are many other stars of less certain type which apparently fail to lie close to a reddening line.

The other two stars at the top of the diagram at B-V= 0.00 and -0.05 are peculiar in that while they appear to be cluster members and their colours indicate early B stars, their magnitudes are three to four magnitudes fainter than the other early B stars. It would seem, therefore, that they are sub-dwarf stars, which again appears inconsistent with present evolutionary theories.

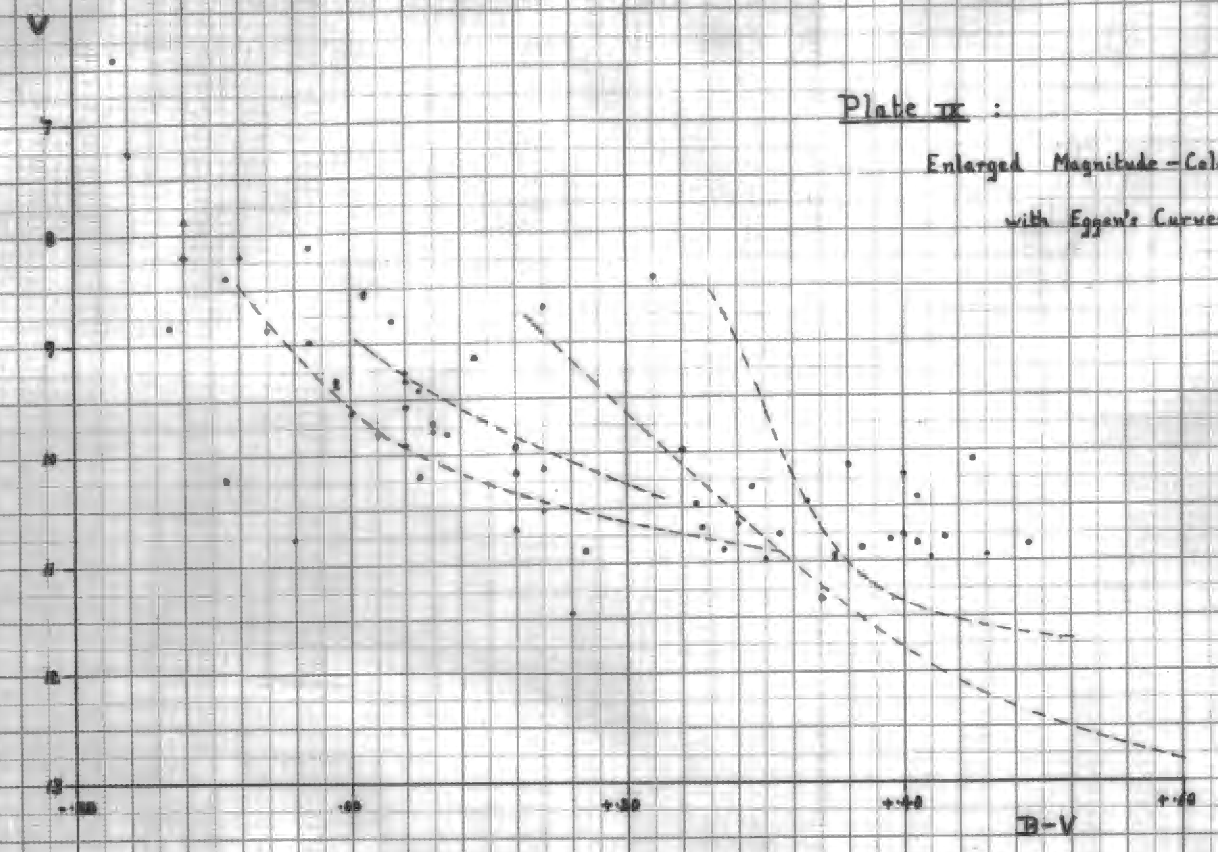
It seems indicated by the diagram that those stars which lie high above the standard array at about B-V = + 0.4 may be highly reddened B5 or B3 stars, but this seems improbable in view of the fact that they are fairly evenly distributed across the cluster and none of the other stars near them are so highly reddened. This would require very localised patches

/of

Plate IX :

Enlarged Magnitude – Colour Array

with Eggen's Curves



of very high absorption - a differential effect which seems unlikely.

Finally, in plate IX we have the application of the observations to Eggen's thesis [7] - that there exists a fine structure of the main sequence. The broken curves are those which Eggen derived for the Pleiades, transferred to Johnson and Morgan's system by plotting his Pleiades observations against theirs. As shown by the diagram, the result appears inconclusive, especially since both curves and points have been transferred to a system other than those in which they were originally observed. Nevertheless, Eggen's curves might be made to fit with only moderate modification.

To show that the scatter of these magnitude-colour arrays is largely real, we need only to use the results of chapter II with the distance modulus. If we consider the cluster spherically symmetrical with a diameter of 10 pcs and distant 420 pcs., then, using the usual approximations to total differentials:

$$m = M + 5\log r - 5 \quad = \quad M + 2{\cdot}15 \log_e r - 5$$

$$\therefore \Delta m = \frac{\partial m}{\partial r}\Delta r \quad = \quad \frac{2{\cdot}15}{r}\Delta r \quad = \quad \frac{2{\cdot}15}{420} \times 10 \quad = \quad 0{\cdot}052 \text{ mag.}$$

which gives rise to an almost negligible scatter on the diagram.

CHAPTER IV

Proper Motions.

There were available two photographs of NGC 2547 taken for proper-motion work at earlier epochs. One was in the standard survey made with the astrographic telescope in 1893 and the other taken on the 24 inch refractor in 1938.

The astrographic telescope is one of an international set of almost identical telescopes designed specifically for astrographic work. It is of 13 inch aperture and 135 inches focal lenght, which gives a plate constant of 59".81 per mm. The history and design of both the astrographic and 24-inch telescopes are very fully described by Gill in his "History and Description of the Cape Observatory".

Two further plates were taken on these telescopes of such exposures as to give images of approximately equal density on old and new plates. The respective emulsions and exposures were:
Astrographic: 20 min. on Monarch (old) 15 min. on IAZ (new).
24-inch: 60 minutes on IAZ (old and new).

It is estimated that the threshold magnitude of the astrographic plate is between mpg = 12.0 and 12.5 , while that of the 24-inch between 17.0 and 17.5. Accordingly, it had been intended to use the latter plates for determining the absolute motions (since much fainter and hence probably more distant reference stars could be used), and the former for determining the internal motions of the cluster. However, after the 24-inch plates had been measured and reduced, it was found that the resulting proper motions did not in any way agree with those few already catalogued. The reason for this appears to be as follows, a not uncommon phenomenon of long-exposure plates.

During such a lenghty exposure it is quite probable that slight guiding errors will occur and the stellar images be displaced for short periods, although these displacements are only very slight. Since the displacements will only be for a short period before the observer corrects the telescope, only the brightest stars will produce latent images of sufficient density to

/be

be detectable after development. Accordingly, the images of brighter stars are slightly elongated while those of the faint reference stars are not, the elongation actually being a function of magnitude since the photographic image grows with brightness. Moreover, since the exposure is so long the images are so large that this elongation is not explicitly detectable by the eye, although it does affect the setting of the cross-hairs of the measuring microscope. Thus, the determined proper-motion is partly spurious, being a function of magnitude. That this explanation was correct seemed shown by actually plotting the measured motions against stellar magnitude, which gave a very steep curve tapering off with faintness of star.

Ultimately, therefore, only the astrographic measures were used, these plates being of short exposure. Regarding the differential (internal) motions little need be said. They are simply the motions of the stars with respect to their own mean motion, i.e. the vector sum of the differential motions is zero. The probable error in the proper-motion (μ) is about $\pm$ 0".003, which gives rise to a probable error of several degrees in the position angle (θ), depending on the latter's value. (The tangent of the position angle is the ratio of the components of μ, and an error in one <u>or</u> the other of these alters θ – a differential error likely since the two components are measured separately and μ deduced from them. See appendix II).

The absolute motions were determined using as reference stars eighteen twelfth magnitude stars which are standard stars used in routine proper motion determinations at the Royal Observatory, that is, their own proper motions are known and can be allowed for. One further correction must be applied - that for galactic rotation. This was kindly computed by Mr Lourens, head of the astrometric department at the Royal Observatory, and was very small, being, negligible in μ_α and +0".003 in μ_δ. The resulting absolute motions were compared with the published catalogue values where they existed and the algebraic sum of the residuals found to be very nearly zero. Finally, a weighted mean was taken of these two determinations and later Cape determinations which had been derived by positional studies. The weighting was done on the basis of length of

/interval

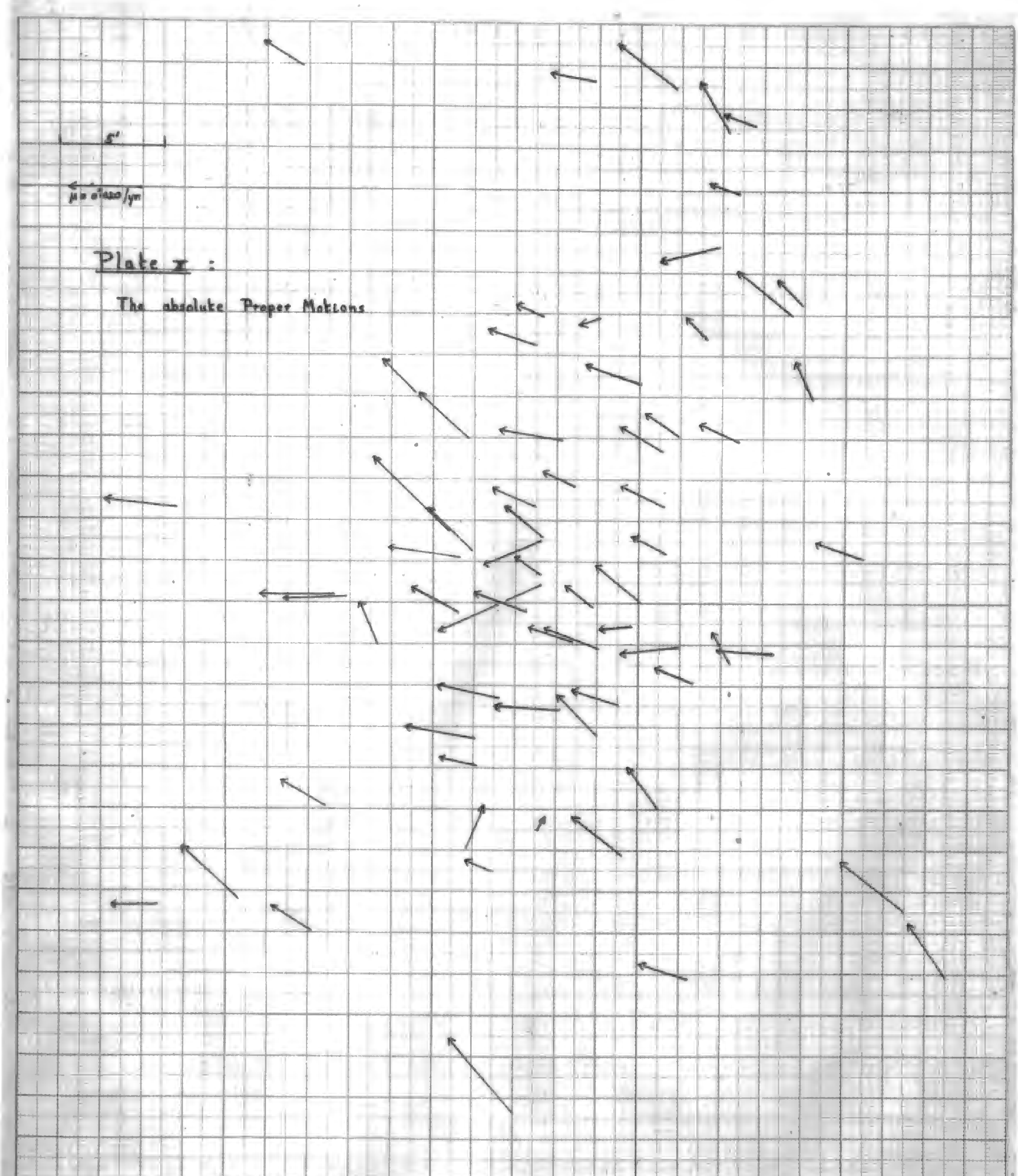


Plate II :

The absolute Proper Motions

interval between old and new plates used in a determination (the base-line). The formula adopted was

$$\text{Weighted Mean} = \frac{2\,Cn + Co + 3F}{6}$$

where Cn represents the later Cape determinations

Co represents the old Cape determinations (catalogue)

F represents Fernie's determinations.

The probable error of the weighted mean is about ± 0".001.

Table III contains the values of the absolute motions and their components in Right Ascension and Declination, the former's position angle and the position angles and values of the differential motions. The final column indicates the status of a star regarding its cluster-membership. The code is a: Definitely a cluster member.

b: Uncertain.

c: Definitely not a cluster member.

TABLE III

Star	ABSOLUTE μ_α	μ_δ	μ	θ	DIFFERENTIAL μ	θ	Cluster Member
	".001	".001	".001	Deg.	".001	Deg.	
1	- 13	00	13	270	2	101	a
2	- 20	+ 02	20	276	10	281	a
3	- 16	+ 15	22	313	14	322	a
4	- 11	+ 07	13	302	7	8	a
5	- 11	+ 07	13	302	13	35	a
6	- 12	+ 07	14	300	5	6	a
7	- 21	00	21	270	8	259	a
8	- 18	- 01	18	268	5	214	a
9	-05	+ 12	13	337	11	52	a
10	- 09	+ 09	13	315	6	4	a
11	- 21	+ 21	30	315	27	350	a
12	- 20	+ 03	20	279	20	253	a
13	- 13	+ 07	15	298	4	337	a
14	+ 05	+ 12	13	23	26	68	c
15	- 14	+ 13	19	313	9	345	a

Table III Continued/.......

TABLE III (CONTINUED)

Star	ABSOLUTE μ_α	μ_δ	μ	θ	DIFFERENTIAL μ	θ	Cluster Member
16	- 10	+ 02	10	281	2	161	a
17	- 20	+ 03	20	279	7	267	a
18	- 07	+ 03	08	293	7	98	a
19	- 13	+ 13	18	315	6	340	a
20	- 18	+ 04	18	282	1	180	a
21	- 18	+ 21	28	319	3	225	a
22	- 15	+ 05	16	288	3	288	a
23	- 12	+ 05	13	293	2	307	a
24	- 13	+,04	14	288	3	22	a
25	+ 02	+ 04	04	27	16	94	c
26	- 29	- 13	32	246	21	247	b
27	- 07	+ 05	09	205	5	75	a
28	- 17	- 07	18	248	10	180	b
29	- 07	+ 03	08	293	2	104	a
30	- 11	+ 09	14	309	3	39	a
31	- 18	+ 01	18	273	7	163	a
32	- 18	+ 03	18	280	7	276	a
33	- 12	+ 04	13	289	1	225	a
34	- 09	+ 04	10	284	2	117	a
35	- 13	+ 02	13	279	6	251	a
36	- 08	+ 06	10	307	8	305	a
37	- 06	- 02	06	252	9	135	b
38	- 16	+ 06	17	290	2	146	a
39	- 13	+ 04	14	288	6	100	a
40	- 11	+ 11	16	315	6	20	a
41	- 14	+ 11	18	308	7	24	a
42	- 09	- 01	09	264	7	155	a
43	- 16	+ 05	17	288	2	342	a
44	- 13	+ 11	17	310	3	68	a
45	- 08	+ 11	14	324	9	49	a
46	- 12	+ 07	14	300	1	90	a

Table III Continued/...........

TABLE III (CONTINUED)

Star	ABSOLUTE μ_α	μ_δ	μ	θ	DIFFERENTIAL μ	θ	Cluster Member
47	- 13	+ 06	14	296	6	207	a
48	- 10	+ 05	11	297	2	109	a
49	- 17	+ 13	21	308	7	308	a
50	- 10	+07	12	305	3	68	a
51	- 17	- 02	17	263	9	210	a
52	- 13	+ 04	14	287	9	151	a
53	- 11	+ 04	12	290	5	58	a
54	- 06	+ 06	08	315	5	80	a
55	- 16	- 04	16	256	8	206	b
56	- 09	+ 15	17	330	17	165	a
57	- 05	+ 09	10	331	8	68	a
58	- 11	+ 05	12	295	3	79	a
59	- 09	+ 03	09	288	4	55	a
60	- 09	+ 03	09	288	6	171	a
61	- 16	+ 01	16	274	7	196	a
62	- 14	+ 11	18	309	6	321	a
63	- 07	+ o7	10	315	2	135	a
64	- 05	+ 11	12	336	7	59	a
65	- 13	+ 04	14	288	1	206	a
66	- 18	+ 14	23	308	6	342	a
67	- 11	+ 16	19	326	11	60	a

SIGN CONVENTION:

+ towards North and East

- towards South and West.

Position angle : From North through East

Mean value of absolute motion : 0".0149 ± 0".0048 (Std. dev.)

Mean value of direction : 298°

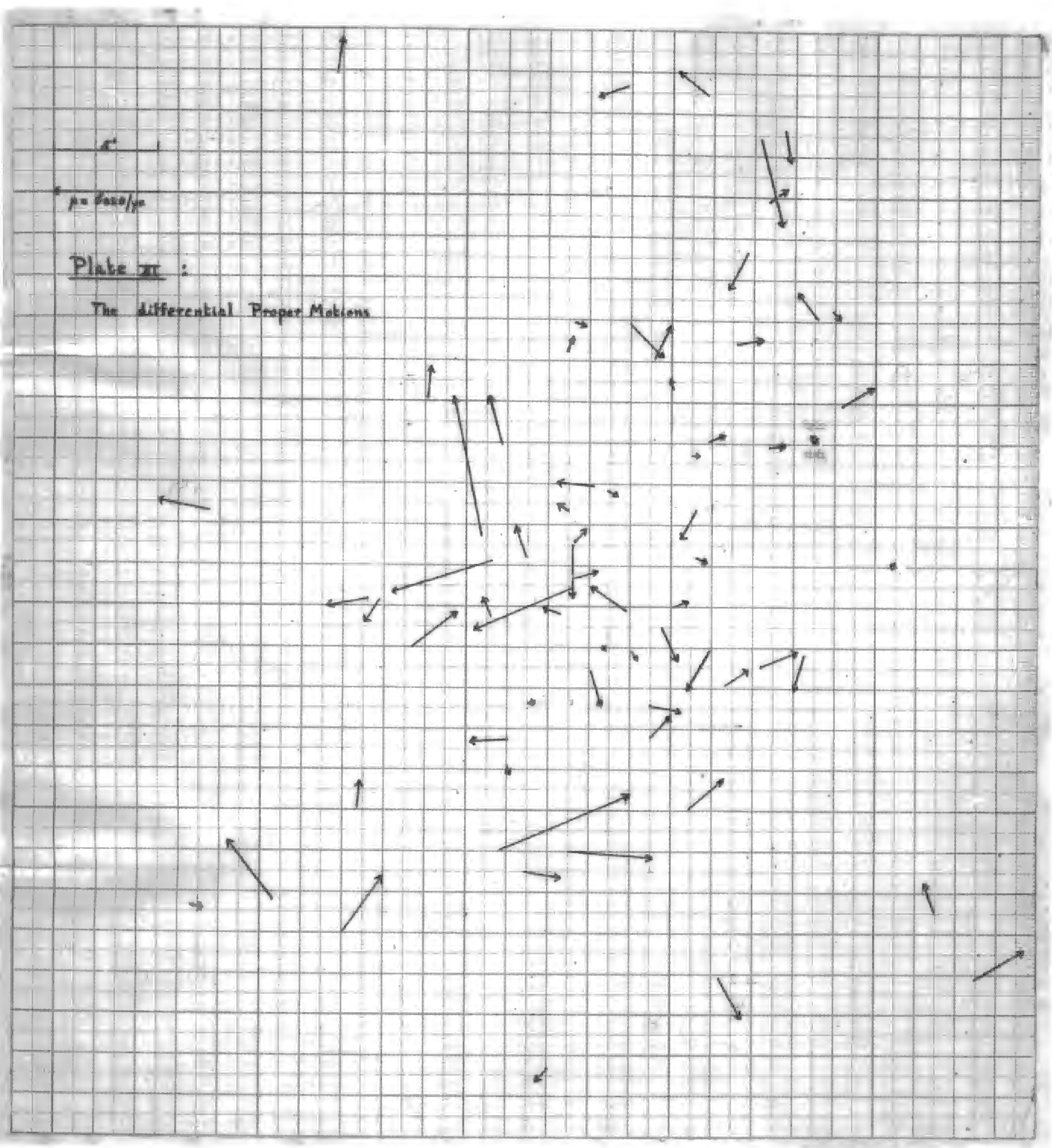


Plate XI :

The differential Proper Motions

The absolute and differential motions are plotted vecterially in plates X and XI respectively. Plate X is useful in deciding whether or not a star belongs to the cluster, but the errors are too great to make worthwhile the computation of a convergent point for the cluster, especially since considerable suspicion has recently[14] been thrown on the classical methods of computing this. (Note: Tracks which are parallel in space appear to converge to a point in a two-dimensional projection. Knowledge of the angular distance of the cluster from this point, plus the values of the proper motion and radial velocity of the cluster enable the cluster's parallax to be computed).

Plate XI is of interest in that it should make possible a decision regarding the expansion or contraction of the cluster. However, at a cursory glance the motions seem fairly randomly distributed in direction, but closer inspection reveals that there is a preponderance of motions outward from the center, especially along the minor axis. There seems little evidence that the elongation of the cluster is increasing apprecia-bly. Elementary reasoning shows that the time of expansion calculated from proper motions and angular distance from the centre is approximately the same as that calculated using true distance and space velocities. We find a value for this time of the order of 7×10^4 years, which is a remarkably short period when, as was indicated in chapter III, the expected age of the cluster was about 5×10^7 years, i.e. the expansion has been proceeding for only some one thousandth of the cluster's lifetime. It seems difficult to account for such a phenomenon, and one is led to suspect that either this expansion is spurious and merely a result of a peculiar distribution of errors in the determined motions or that the age of the Pleiades (from which the value of 5×10^7 years is obtained) is a good deal less than is thought at present. There are, in fact, grounds for believing that the Pleiades are younger than this in that the most luminious stars among them have not yet started to move horizontally across the H-R diagram - an occurrence to be expected in a cluster of this age; but it is exceedingly doubtful whether they are so much younger.

Chandrasekhar[15] has developed an expression for the time of

/relaxation

relaxation (i.e. the time required to set up a Maxwellian distribution of velocities in the cluster) of a cluster. In its final form it reads

$$T_e = 8.8 \times 10^5 \sqrt{\frac{n\bar{R}^3}{m}} \cdot \frac{1}{\log n - 0.45} \quad \text{years}$$

where n is the number of cluster members
m is the mass of a typical star
$\bar{R}$ is the "average" radius of the cluster.

According to this table we find for a cluster such as ours a value of Te of 10^8 years. Since we suspect from Plate XI that such a distribution of velocities does not at present exist in the cluster, we presume that the cluster is at least younger than 10^8 years.

A cluster of stars is always subjected to two major forces, the first being the gravitational attraction between its members holding the cluster together, and the second a tidal force due to galactic rotation which tends to disrupt the cluster. Chandrasekhar has calculated formulae showing at what density of a cluster the latter force becomes predominant, causing the cluster to break up. We find for NGC 2547 that its density (2.8 solar masses /cub.pc) is at least fourteen times this critical density, but that in another 2 x 10^5 years at its present apparent rate of expansion this critical density will have been reached and the cluster begin to disrupt.

In conclusion, therefore, we may say that although NGC2547 appears to be in a state of rapid expansion, this expansion does not seem to be increasing the cluster's present elongation, which we presume to be due to an initial distribution of the stars at birth. The cluster's age would seem to be less than a hundred million years.

CHAPTER V

Radial Velocities.

It had been intended to obtain a reasonably reliable value for the cluster's average radial velocity, and December and January were spent at the Radcliffe Observatory, Pretoria (where observers are stationed by the Royal Observatory who carry out all the latter's radial velocity observations), in the hope of obtaining the required spectra. However, only a limited time was available for this program and, this, together with the most rainy summer for eleven years in Pretoria resulted in only nine spectra being obtained, all of different stars (it is generally agreed that at least three observations per star are required before the measured radial velocity becomes reliable).

The instruments used for the observations were the 74 inch reflector and its Cassegrain spectrographic equipment. The latter has been fully described by Jackson in 'Nature' 167, p. 169, Feb., 1951. Briefly, it has a collimator 2.5 inches in diameter and 45.4 inches e.f.l. which feeds a parallel beam onto two 64° prisms, having faces 2 5/8 x 5 inches. There is a choice of four cameras to photograph the resulting spectrum, the one employed in this case being of f3.7 focal ratio and giving a dispersion of 49 A.U./mm at H . The slit has a variable 'dekka' (to give various transverse widths of a spectrum), the one used here being the "c" dekka which gives a spectrum 0.44 mm wide. The star-light may be interrupted by a prism before the slit so as to focus light from an iron arc onto the latter to provide a comparison spectrum from which the radial velocity may be measured. The temperature of the spectrograph is thermostatically controlled to within 0.2°C.

The emulsion used for photographing the spectra was Kodak II-a0, a clean, medium speed emulsion designed for spectrographic work.

The spectra were measured under a Hilger travelling microscope reading to one micron and designed largely for this purpose. The method of reduction and corrections to be applied are described in appendix III.

Table IV contains the resulting radial velocities with their probable

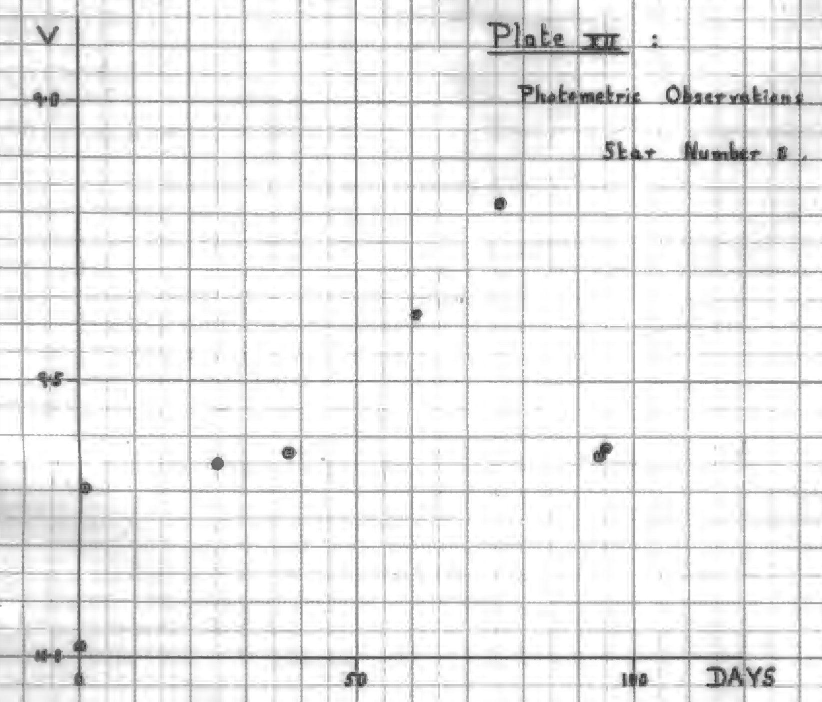


Plate XII : Photometric Observations of Star Number 8.

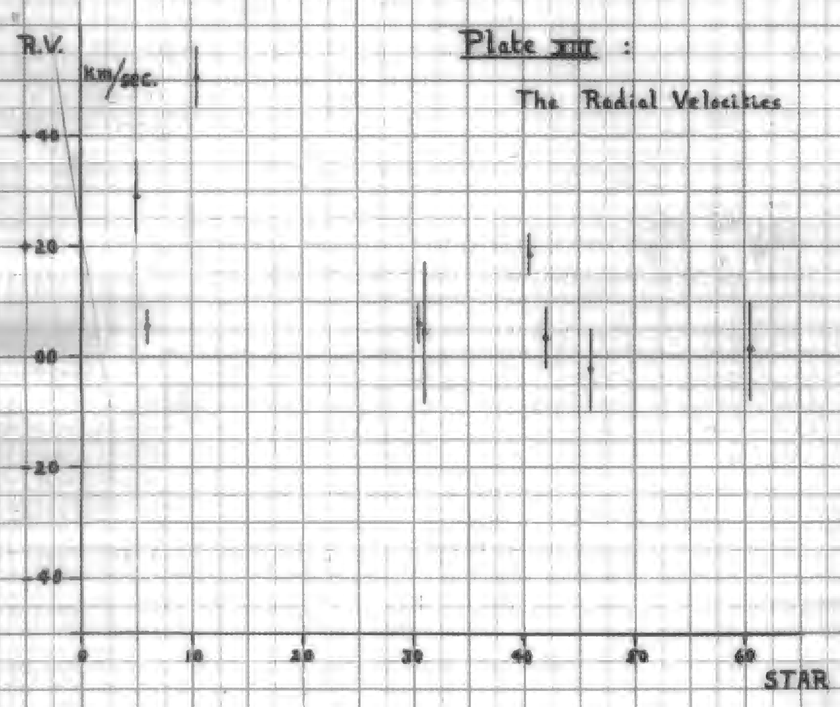


Plate XIII : The Radial Velocities

errors (estimated from the consistency of the determinations from the various lines). The weighted mean was determined by weighting each observation with the inverse square of its probable error, but omitting the result for star 11, which is peculiarly high, as is its proper motion.

Star	Radial Vel. km/sec.	Probable Error km/sec.
5	+ 29.0	± 6.5
7	+ 5.7	2.7
11	+ 50.6	5.4
31	+ 6.0	3.6
32	+ 4.5	13.1
41	+ 18.7	3.3
44	+ 3.7	5.3
47	- 2.1	7.1
61	+ 1.4	9.4

Weighted Mean: + 9.4 ± 2.3 km/sec.

These values are displayed in plate XIII.

Finally it may be added that none of the spectra showed any appreciable presence of the inter-stellar CaII line at 3934 A.U.

Summary.

We have carried out a series of observations on NGC 2547 and have arrived at the following results for the cluster.

1) The cluster is situated near the dark cloud in Vela and differential absorption effects may, therefore, be present.

2) NGC 2547 is a loose elongated galactic cluster, exhibiting an approximately spiral structure among its brighter members. Its population is of the order of a thousand members, contained within an average angular radius of 37'. The estimated total mass of the cluster is about 1100 solar masses, giving a mean cluster density of 2.8 solar masses per cubic parsec.

3) Distance: 417 parsecs, and therefore radius 4.5 parsecs.

4) The cluster appears to possess one giant member.

5) The test of Eggen's thesis is inconclusive, but we consider the observations to be partly incompatible with modern evolutionary theories.

6) The cluster has a mean proper motion (absolute) of $0''.0149$ per year in a mean direction of N 298 E.

7) Differential proper-motions indicate an expansion of the cluster, especially along its minor axis, which appears to have been proceeding for some 7×10^4 years, although the expected cluster age is of the order of 10^7 years. However, the distribution of velocities is probably not Maxwellian, which implies that the cluster is less than 10^8 years old. It is fourteen times denser than the critical density at which disruption is caused by galactic forces, but should reach this critical density in about 2×10^5 years.

8) The mean radial velocity of the cluster is +9.4 km/sec.

APPENDIX I.

Reduction of Photo-electric Observations.

The photo-electric observations were made in three colours, namely yellow, blue, ultra-violet, which are designated y,b,u, respectively. Although the final zero-point of the observations must be determined from observing the standard stars of the system in which the results are to be presented, in cluster work it is customary to make these observations a separate "tie-in" program and to adopt secondary standards within the cluster for night-to-night work. Thus in NGC 2547 four such standard stars were used, being numbers 33, 38, 5, 43. They were selected on a basis of being widely distributed across the cluster and also being free of nearby stars. A night's observing program would begin and end with one of these standards, and every third observation was of one of them, this being necessary to determine the variations in and corrections for absorption of the starlight due to seeing conditions. Arbitrary zero-points were adopted for these observations. Ultimately, the four standard stars were compared with E-region standards and the above arbitrary system reduced to the E-region system (actually, only b and (b-y) were so reduced, since (u-b) standards do not yet exist in the E-regions). The transfer equations from the E-region system to Johnson and Morgan's were supplied by the Royal Observatory, that for the (u-b) index being based on only a few observations.

A correction must be applied to the observations to allow for the change in atmospheric absorption with changing zenith distance [16, 19]. Since this absorption varies nearly linearly with the secant of the zenith distance (z) up to nearly all values of z in which photo-electric observations are made, this correction takes the form:-

$$Cz = Co + (k1 - k2Co) \sec Z$$

where Cz is the observed colour reduced to a standard zenith distance

Co is the observed colour reduced to outside atmosphere

k1, k2 are coefficients.

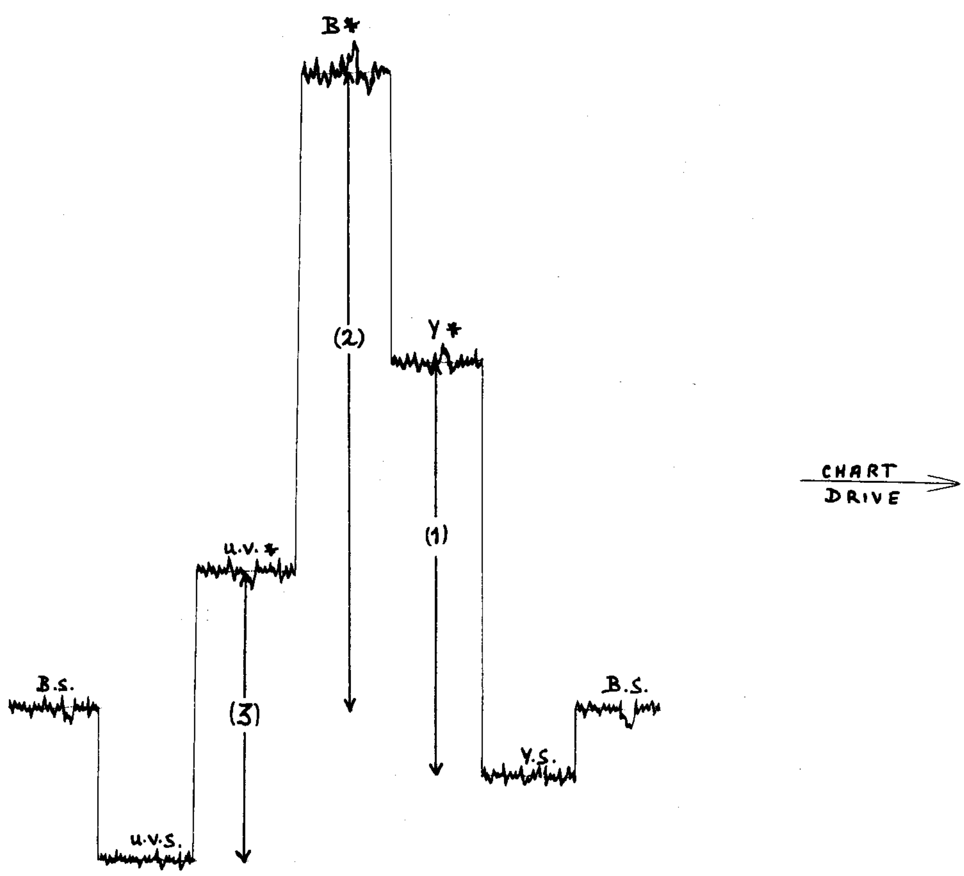
Tables of these corrections have been compiled by the staff of the Royal Observatory and were used here. Sec z is observed directly from a scale plumb-bob on the telescope.

Observations on a/......

Observations on a single star are made in the following sequence. Blue sky (i.e. sky through blue filter), yellow sky, yellow star, blue star, ultra-violet star, ultra-violet sky, blue sky. It is necessary to observe the sky next to the star since some skylight is admitted with the star-light, and the skylight varies with azimuth and lunar phase. The observation is closed with the blue-sky again to detect any drift in the amplifier. Each such exposure lasts for about thirty seconds, depending on seeing-conditions. At times of full moon the sky brightness may be so great as to actually require suppressing the dark-current reading of the apparatus off the chart by biassing the amplifier, so that a higher gain may be used on the latter to enable greater differentiation between star and sky-light.

Since deflections on the recording chart are proportional to energy input at the telescope, it is the logarithms of the deflections which are proportional to stellar magnitude (or, rather, inversely so). To avoid computation, special logarithmic measuring scales have been prepared at the Royal Observatory which read directly in stellar magnitudes.

Thus a typical chart recording of a blue star may look thus:-



(1), (2), and (3), represent the measurements to be made. Results recorded at time of observation include identification number of star, mean sidereal time of observation, gain of amplifier, sec Z scale reading, notes on seeing conditions, size of diaphragm, identification number of amplifier, etc.

The measurements and reduction may then conveniently set out as shown on page 34a:-

STAR	GAIN	SEC Z	SID. TIME	1	2	3	3-2	2-1	Extinc. b	u-b	b-y	GAIN	b'	(u-b)'	(b-y)'	b	(u-b)	(b-y)	b	(u-b)	(b-y)
From Observing Book				Measured on Chart					From Tables			Stellar Magnitude corresponding to ampl. gain (from tables) (v)	(v) + (i)-(iv)	(ii)-(iv)	(iii)-(iv)	Corrections to eliminate residual (adopted - observed) in standards.			Corrections applied to b', (u-b)', (b-y)'		
				(i)			(ii)	(iii)	(iv)												

APPENDIX II

Reduction of Proper Motions.

A star's proper motion is, by definition, its apparent angular motion on the star sphere at right angles to the line of sight, and is usually expressed in seconds of arc per year. The measurement of proper motion is, therefore, usually made by photographing the star field at two epochs as widely seperated as possible and then measuring the relative shift between the initial and later positions of a star image with respect to the faint background star images. To a first approximation the latter stars may be assumed so faint and, therefore, probably so distant that their own angular motions are negligible. A linear shift on the plate can be interpreted as an angular shift once the focal length of the photographing telescope is known.

One of the two photographic plates must be exposed through the glass supporting the emulsion to enable the two emulsions to be brought into contact when measuring without having one field of view laterally reversed. Exposures are such as to produce images not too large and of approximately equal density among corresponding images.

The plates are mounted in a measuring microscope and clamped together in such a position as to have the two images seperated by an arbitrary small distance (~1mm) in both x and y co-ordinates. The plates are, in fact, mounted on a carriage way which can move in both co-ordinates and viewed through a fixed microscope, the cross-wires in whose eyepiece are movable by amounts to be read on micrometer drums. The pitch of the latter are 0.5 mm and enable positions to be read to 0.0005 mm. The position of the plate holder, and, therefore, a star image on the plate, can be read off millimetre-scales alongside the carriageway to about 0.1 mm. This position is required both for identification purposes and also the following reason. Since the plate-constant is, in fact, slightly variable across the plate owing to telescope optics, shrinkage of the gelatin, etc.,, the measured interval between star images is partly a function of the position of the image on the plate. This function is assumed linear, of the form - $ax + by + c = o$ - and having different co-efficients for x and y

measures./............

measures. These coefficients are determined from the measures of the faint reference stars and serve also to smooth out variations in measure and motion of these stars.

As indicated above, measurements are made in both the x and y co-ordinates (i.e. the components of an interval are measured) which correspond to right ascension and declination respectively. The origin of the co-ordinates is the centre of the plate. Usually sixteen reference stars are selected per plate, four in each of the quadrants (-,+), (+,+), (-,-), (+,-). Then the computations may conveniently be set out as follows. (We show only the comps. for the ref. stars. Those for the others are exactly the same except that now the coeffs. are already determined).

Let (x,y) be a star's co-ordinates and (Δx , Δy) be the measured intervals. Then we may set out the computations as on the following page.

	x	y	Δx	Δy	$\Delta' = \bar{\Delta} - \Delta$ Δ'x	Δ'y	$\Delta'' = a_x x + b_x y + c_x$ Δ''x	$\Delta'' = a_y x + b_y y + c_y$ Δ''y	$\Delta\Delta = \Delta'' - \Delta'$ ΔΔx	ΔΔy	$\mu = f(\Delta\Delta)$ μ_α	μ_δ
1	−	+	″	″	″	″	″	″	″	″	″	″
	−	+	″	″	″	″	″	″	″	″	″	″
	−	+	″	″	″	″	″	″	″	″	″	″
	−	+	″	″	″	″	″	″	″	″	″	″
2	+	+	″	″	″	″	″	″	″	″	″	″
	+	+	″	″	″	″	″	″	″	″	″	″
	+	+	″	″	″	″	″	″	″	″	″	″
	+	+	″	″	″	″	″	″	″	″	″	″
	Sums of first four				Sums of first four							
	Sums of last four				Sums of last four							
3	−	−	″	″	″	″	″	″	″	″	″	″
	−	−	″	″	″	″	″	″	″	″	″	″
	−	−	″	″	″	″	″	″	″	″	″	″
	−	−	″	″	″	″	″	″	″	″	″	″
4	+	−	″	″	″	″	″	″	″	″	″	″
	+	−	″	″	″	″	″	″	″	″	″	″
	+	−	″	″	″	″	″	″	″	″	″	″
	+	−	″	″	″	″	″	″	″	″	″	″
	Sums of first four		$\overline{\Delta x}$	$\overline{\Delta y}$	Sums of first four		$f = \frac{\text{Mean Plate Constant (in secs. per mm.)}}{2\,(\text{Epoch 2} - \text{Epoch 1})\ \text{in years}}$					
	Sums of last four		(Means of Δx, Δy)		Sums of last four							

$$a(\Sigma x_1 + \Sigma x_3) + b(\Sigma y_1 + \Sigma y_3) + 8c = (\Sigma \Delta' x_1 + \Sigma \Delta' x_3) \quad \text{and} \quad = (\Sigma \Delta' y_1 + \Sigma \Delta' y_3)$$

$$a(\Sigma x_2 + \Sigma x_4) + b(\Sigma y_2 + \Sigma y_4) + 8c = (\Sigma \Delta' x_2 + \Sigma \Delta' x_4) \quad \text{and} \quad = (\Sigma \Delta' y_2 + \Sigma \Delta' y_4)$$

$$a(\Sigma x_3 + \Sigma x_4) + b(\Sigma y_3 + \Sigma y_4) + 8c = (\Sigma \Delta' x_3 + \Sigma \Delta' x_4) \quad \text{and} \quad = (\Sigma \Delta' y_3 + \Sigma \Delta' y_4)$$

$$a(\Sigma x_1 + \Sigma x_2) + b(\Sigma y_1 + \Sigma y_2) + 8c = (\Sigma \Delta' x_1 + \Sigma \Delta' x_2) \quad \text{and} \quad = (\Sigma \Delta' y_1 + \Sigma \Delta' y_2)$$

(Least-squares) solutions of above four equations give a_x, b_x, c_x.

And

(Least-squares) solutions of above four equations give a_y, b_y, c_y.

The factor 2 appears in the denominator of the "f" equation since the pitch of the micrometer drums is 0.5mm.

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Appendix III.

Determination of Radial Velocities from Prismatic Spectra.[17]

The dispersion in a prismatic spectrum is, of course, not constant, and one of the best interpolation formulae used to represent it is that of Hartmann, which reads $(\lambda - \lambda_o)(N - N_o) = C$. (The representation is improved if the second bracket is raised to the power 1.2, but generally the extra computation involved in preparing tables is unjustified). Here λ is the wavelength, N the corresponding scale-reading on the measuring microscope, and C a constant, depending on the spectral range. Theoretically λ_o is a constant of the spectrograph only.

The actual measurement and reduction of a spectrogram may conveniently be set out in a table of seven columns thus:

N	Nr	Nv-Nr	Correc.	NObs. (star)	ΔN (star)	ΔV

where N contains measurements of both comparison arc lines and stellar lines, the readings increasing numerically towards the violet. To eliminate personal error the plate is then reversed in the microscope and the readings repeated, now increasing towards the red and their decimals entered under Nr.

Permanent tables are prepared, calculated directly from the Hartmann formula, having form

λ	N_v	$2N_v$	f

The derivation of the factor f will be given later, but it is contained only in tables of stellar lines. To avoid possible blends these latter lines have to be carefully selected according to the spectral type of the star.

Only the decimals of $2N_v$ are entered and it will be seen that these should be identical with those under $(N_v - N_r)$. Owing, however, to the formula's inexactitude this condition will not be fulfilled, and the correction to be applied to the observed values to yield the calculated values is entered under 'Correc.' for the arc lines. These corrections are plotted against N_v (observed) and the corresponding corrections for the stellar lines read off. Application of these corrections yield values entered

/under

under N_{obs}^{stars}, which should, were no Doppler effect present, be precisely equal to the values of 2No calculated for the stellar lines. Owing to the Doppler shift, however, they will in general not be equal, and the difference (cal.-obs.) is entered under ΔN^{star}. Multiplication of each value of this by its corresponding factor f yields the apparent radial velocity (ΔV) of the star in km/sec. The weighted arithmetic mean of the ΔV is adopted as the star's apparent radial velocity.

Calculation of f:

We have by Doppler's principle

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

$$\text{or} \quad V = c \cdot \frac{\Delta\lambda}{\lambda} = \frac{c}{\lambda} \cdot \frac{\Delta\lambda}{\Delta N} \cdot \Delta N \doteqdot \frac{c}{\lambda} \cdot \frac{d\lambda}{dN} \cdot \Delta N$$

By Hartmann's formula:

$$\log(\lambda - \lambda_0) + \log(N - N_0) = \log C$$

Differentiating:

$$\frac{d\lambda}{\lambda - \lambda_0} + \frac{dN}{N - N_0} = 0$$

Thus

$$\frac{d\lambda}{dN} = \frac{\lambda_0 - \lambda}{N - N_0} = -\frac{(\lambda_0 - \lambda)^2}{C}$$

Hence, from above,

$$V = \left[-\frac{c}{\lambda} \cdot \frac{(\lambda_0 - \lambda)^2}{C} \right] \Delta N = f' \cdot \Delta N$$

Since the tables were calculated using $2N_v$, we have

$$V = f \cdot \Delta N \quad \text{where} \quad f = \tfrac{1}{2} f'$$

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Correction of the Apparent Radial Velocity:

The radial velocity of a star so deduced is the mean radial velocity of the star with respect to the observer during the exposure of the spectogram. For comparison purposes radial velocities are usually referred to the sun, and the apparent radial velocity requires a number of corrections before the star's heliocentric radial velocity is arrived at.

(i) Diurnal Correction:-

This correction takes out that component of the velocity due to the observer's rotation with the Earth.

It is $C_d = -0.465 \cdot \rho \cdot \cos\phi' \cdot \sin t \cdot \cos\delta$ km/sec

where ρ is the Earth's radius at ϕ'

ϕ' is the observer's geocentric latitude

t is the star's hour angle at mid-exposure

δ is the star's declination.

(ii) Annual Correction:-

This correction takes out that component of the velocity due to the Earth's motion round the Sun. It is

$$C_A = v \cdot \cos\beta \cdot \sin(\odot - \lambda) + v \cdot e \cdot \cos\beta \cdot \sin(\pi - \lambda) \text{ km/sec}$$

where $v = 29.765$ km/sec

λ, β are respectively the longitude and latitude of the star

$\odot$ is the longitude of the sun.

π is the mean longitude of the sun at perigee

e is the eccentricity of the Earth's orbit, $= 0.01675$

Other corrections may be applied, including the correction for the observer's motion round the barycentre of the Earth-Moon system, correction for perturbation of the Earth by other planets, etc, but these are generally considered negligible and committed.

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GLOSSARY

PARSEC: The distance of an object which would exhibit an annual parallax of one second of arc (1 p.c. = 3.26 light years).

ABSOLUTE MAGNITUDE: The apparent magnitude which a star would have were it placed at a distance of ten parsecs.

LUMINOSITY CLASS: Each spectral sub-class may be further divided according to the luminosity of the star, which is designated by a Roman figure after the spectral sub-class (e.g. M5 III, K2 V, etc.,), which runs from I for super-giants to V for dwarfs. The classification is made by comparing the intensities of various spectral lines. See Hynek's "ASTROPHYSICS" for further explanation.

PROPER MOTION: The angular displacement of a star on the celestial sphere in one year due to its relative velocity in space.

"EARLY" and "LATE" TYPE: These phrases refer only to the spectral type, running from O-type to M-type or later. They do not necessarily imply a time scale.