Galactic and extragalactic distance scales: some South African contributions

Michael Feast*

The work of South African astronomers in establishing and refining methods of measuring the distances of stars and galaxies is reviewed.

Introduction

To understand the Universe, we need to know its scale, and to understand the physics of the objects in it we need to know their distances and hence their absolute luminosities. Thus, from the time of the early Greeks and right up to the present day, astronomers have regarded the determination of distances as one of their main goals. South African astronomers have played, and continue to play, an important and prominent role in this work, on which our understanding of such matters as the nature and structure of galaxies and the evolution of stars rests.

At least since the time of Galileo, it was clear that if the Earth was in orbit around the Sun, the apparent position of a nearby star in the sky will vary with respect to distant background objects due to a parallax effect. This trigonometrical parallax, together with the radius of the Earth's orbit (the astronomical unit), gives the distance of the star. However, the stars are very distant and the first successful measurement of a stellar parallax was not made till 1831–33, when Thomas Henderson, HM Astronomer at the Royal Observatory, Cape of Good Hope, made measurements of the star Alpha Centauri, which he found to have a parallax of close to one second of arc (a distance of 3.3 light years compared with the modern value of 4.4 light years). Unfortunately, Henderson did not publish his work until 1839[1] and Bessel[2] has the credit for the first publication (in 1838) of a significant parallax (for the star 61 Cygni).

Aside from the Sun, Alpha Centauri is the closest star to us except for its faint, physical companion, Proxima Centauri, which was discovered by R.T.A. Innes,[3,4] the first director of the Transvaal (Union) Observatory (1912–1927) and which is slightly closer. Much of the work of the Royal Observatory, Cape, up to the time of its incorporation into the South African Astronomical Observatory (SAAO), in 1972, was devoted to astrometry, the measurement of positions, parallaxes and proper motions (the secular movement of stars on the sky due to their velocities with respect to the Sun).

In work which was complementary to observations on parallax, two of the directors of the Royal Observatory (David Gill 1879–1907 and Harold Spencer Jones 1923–1933) spent much effort on a precise measurement of the astronomical unit. Observations of solar system objects (planets and asteroids) from different places on the Earth can be used for this purpose. Even earlier, one of the main aims of Nicolas Louis de Lacaille, when he was at the Cape (1751–1752), was to measure the radius of the Earth, which then provided the scale for distances in the solar system. With the advent of space astrometry (for example, the Hipparcos astrometric satellite and the astrometric capabilities of the Hubble Space Telescope), South African astronomers became involved in the combining of this astrometry with ground-based photometry and spectroscopy, as will be discussed below.

The RR Lyrae variables

The modern era of astronomy in South Africa, especially astrophysical studies together with work on the structure and dynamics of our own Galaxy and its two dwarf neighbours, the Magellanic Clouds, can be dated from the coming into operation in 1948 of the 1.9-m reflector at the Radcliffe Observatory, Pretoria (a telescope now at SAAO, Sutherland). At that time it was the largest telescope in the southern hemisphere and put South Africa in a leading position. Amongst the very early results from this telescope was one that remains amongst the most significant made here. In 1952, David Thackeray (the Radcliffe Observer, that is, director) and Adriaan Wesselink, the chief assistant, announced at the Rome meeting of the International Astronomical Union[5] their discovery of RR Lyrae variables in the Magellanic Clouds, the first of which they had found in 1950 (Fig. 1). RR Lyrae variables are pulsating stars with periods shorter than 1 day and are important tracers of very old populations (they are found, for instance, in globular clusters, the oldest stellar systems known). Their presence in the Magellanic Clouds was contrary to the predictions of two of the best-known astronomers of the time, Harlow Shapley (at Harvard University) and

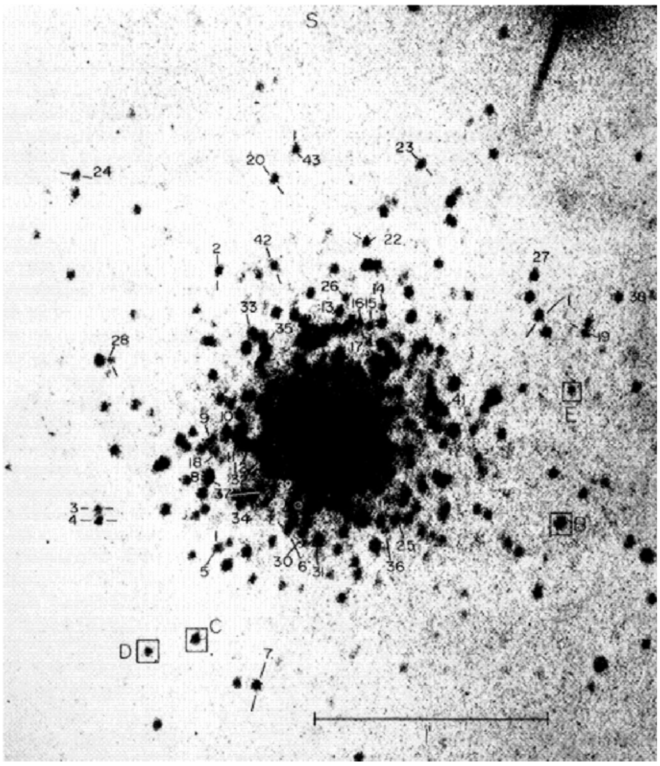

Fig. 1. A Radcliffe Observatory photograph of the globular cluster NGC 1466 with its associated RR Lyrae variables numbered. This is one of the three Magellanic Cloud clusters in which Thackeray and Wesselink found this type of variable star and which led to a doubling of the extragalactic distance scale. Tha bar represents 1 arcmin. See ref. 49.

*Department of Astronomy, University of Cape Town, Private Bag, Rondebosch 7701, South Africa. E-mail: mwf@artemisia.ast.uct.ac.za

Walter Baade (Mt Wilson and Palomar observatories). By 1952, the absolute brightness of RR Lyrae stars was at least roughly known. The Radcliffe work meant that the Magellanic Clouds were twice as far away as had previously been supposed. Independently, Baade had come to think that the extragalactic distance scale needed revision, but his evidence was much less strong than that of Thackeray and Wesselink. A full account of this period is given elsewhere.[6] This change in distance of the Magellanic Clouds had consequences for the size and age of the Universe. These were derived from the recession of distant galaxies (the expansion of the Universe). The distances of these galaxies were obtained by a series of steps whose scale was set by the brightness of the Cepheid variables (young pulsating stars with periods of a few to 100 days) in some of the nearer of them. The Magellanic Clouds also contain Cepheids and the absolute brightness of these stars was, as a result, found to be four times that which had been previously supposed. Thus the scale of the Universe was increased by a factor of two as was its age. This was fortunate as the age previously derived was less than the known age of the Earth. Although the extragalactic distance scale continues to be refined (it is currently uncertain, one standard error, to about 10 per cent), no changes as dramatic as that of 1952 have occurred since.

It generally happens that when one studies a class of objects in great detail, intriguing results appear. This has recently become clear with the RR Lyrae variables. It has long been known that they span a wide range of chemical compositions. Now work by an Italian group,[7,8] using an 8-m telescope in Chile, has shown that the detailed behaviour of these stars with composition varies in a complex way between the Large Magellanic Cloud (LMC) and another relatively nearby galaxy, the Sculptor Dwarf Spheroidal. This work requires 8–10-m class telescopes, since spectra are needed to determine abundances. It begins to look as if the RR Lyrae stars, having served as approximate distance indicators, may now be more useful in studying variations in population content from one galaxy to another in the Local Group (an isolated group consisting of dwarf galaxies clustered around our Galaxy and the Andromeda galaxy). This is the type of information we need to understand the evolution of dwarf galaxies, which are sometimes considered the building blocks from which larger galaxies are made. This is an area in which the Southern African Large Telescope (SALT) could make a major contribution and such work is in progress.[50]

Cepheids

Cepheids are, as mentioned, young pulsating stars. Their importance as distance indicators lies in the fact that they show a relation between period and luminosity. This was first recognized by Henrietta Leavitt[9] (of Harvard) on plates[3] taken at the Harvard (Boyden) station in Peru. (The Boyden station was later moved to Bloemfontein and now is part of the University of the Free State.) Once the zero point of this relation is set (for example, by the distance of the LMC), Cepheid brightnesses and periods can be used to estimate the distances of galaxies in which they occur. One of the main aims in launching the Hubble Space Telescope was to extend the discovery of Cepheids to galaxies at larger distances than had previously been possible and hence refine the rate of expansion of the Universe (the Hubble constant).

In view of their importance, a great deal of work on Cepheids has been carried out at SAAO (Sutherland) with the aim of placing their use as distance indicators on as firm a basis as possible. Much of this work has been photometric. Due largely to the fundamental work at the Cape of A.W.J. Cousins and his successors, the photometric precision obtained at Sutherland has rarely been equalled elsewhere. Photometry is usually carried out through filters, each isolating a particular spectral region. One difficulty in the use of Cepheids as distance indicators is that as young objects they often lie in regions where they are dimmed and reddened by dust clouds. SAAO work[10,11] showed how this dimming can be measured using multicolour photometry. Precise photometry both in the optical region and in the infrared[12,13] then showed that there was in fact substantial scatter in the period–luminosity relation in the LMC and that this was intrinsic rather than due to different amounts of dust absorption, as had been suggested. These investigations also revealed the photometric effects associated with the fact that the Cepheids in the LMC have a different chemical composition from those in our Galaxy. The LMC provides the slope of the Cepheid period–luminosity relation (e.g. ref. 14), but to use it we require an absolute calibration (the period–luminosity zero point). Even if we had an accurate distance to the LMC, this only gives the zero point appropriate to Cepheids with the LMC chemical composition. It so happens that the mean chemical abundance of Cepheids measured by the Hubble Space Telescope,[15] and on which the expansion rate of the Universe depends, is close to that of our Galaxy, not the LMC. Thus, the attempt to find a Cepheid zero point from observations in our own Galaxy has been a major South African concern. Four methods have been used.

In 1955 John Irwin (Indiana University) was on an extended visit to South Africa to make photoelectric observations of Cepheid variables at the Royal Observatory, Cape (now SAAO). He noticed that two of these seemed to belong to star clusters[16] and this was then confirmed from radial velocity observations.[17] This led to extensive work both in South Africa and elsewhere to find the distances of these clusters, as well as of others that were later found to contain Cepheids, and thus to derive the luminosities of these stars. The cluster distance is derived by matching the brightness and colours of the cluster stars with those in a cluster of know distance (generally the Pleiades or Hyades). A summary of the results obtained from South Africa and elsewhere is given in ref. 18. The second method is to use pulsation parallaxes, otherwise called the Baade–Wesselink method (after two of the astronomers mentioned earlier). One can measure spectroscopically the changes in the velocity of a Cepheid's atmosphere as the star pulsates. It is possible to combine these measures with changes in the star's brightness and colour to estimate the parallax. For technical reasons, the photometric variations are best measured in the near-infrared and a major programme to do this was carried out by David Laney and Robert Stobie at Sutherland.[19,20]

The method of determining the Cepheid zero point that is free of assumptions of an astrophysical or kinematic nature is to combine together the trigonometrical parallaxes of individual galactic Cepheids themselves. Until recently this was not possible. Even nearby Cepheids are too far away for the measurement of sufficiently precise parallaxes from the ground. However, when the Hipparcos astrometric satellite of the European Space Agency (ESO) was in the planning stage, a list of Cepheid targets was accepted from South Africa. The final results have uncertainties of less than one milliarcsec for the brighter stars and it proved possible[21] to use them to get a zero-point with an uncertainty equivalent to only 5 per cent in distance. Finally, analysis[22] of Hipparcos proper motions of galactic Cepheids was found to show clearly the effects of differential galactic rotation and these results could be combined with existing spectroscopic radial velocity measures to obtain a zero-point.

As a result of this work together with that by others elsewhere, the uncertainty in the basic calibration of the Cepheid distance scale is probably now as small as about 3 per cent in distance.[23] The expansion rate of the Universe as derived from Hubble Space Telescope observations of Cepheids in distant galaxies has a greater uncertainty, and values ranging from 72 to 60 km s^{-1} Mpc^{-1}* have been proposed.[15,24] These different values depend primarily on differences in the way the Hubble Space Telescope data are treated.

But the search for greater accuracy in the basic calibration goes on. F. van Leeuwen (University of Cambridge) has over several years been carrying out a major revision of the entire Hipparcos catalogue. South African astronomers are collaborating with him in analysing the Cepheid data. Such an analysis will use much photometry obtained at SAAO. South African astronomers have also been making observations at SAAO as part of a programme to obtain a limited number of very precise parallaxes of Cepheids using the Hubble Space Telescope.

One uncertainty we must still face is the possible variation of the chemical composition of Cepheids from star to star. We know too little about this; the high-resolution spectrograph intended for SALT will be ideal for such work. Important results on the dynamical structure of our own Galaxy are also likely to come from SALT observations of the radial velocities of distant Cepheids which are too faint for smaller telescopes. Such studies are important, for instance, in the determination of the mass distribution in our Galaxy and the problem of its dark matter content. The precision of Cepheids as distance indicators was demonstrated in SAAO work,[14] which established that the Small Magellanic Cloud is a long thin structure seen nearly end on (Fig. 2). This galaxy, which is about 2×10^5 light years from us, is only 6×10^3 light years in width but about 55×10^3 light years in length.

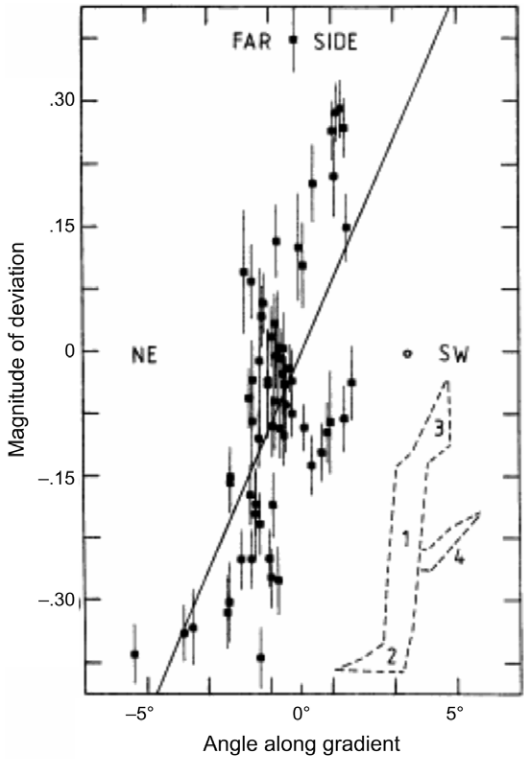

Fig. 2. The three-dimensional structure of the Small Magellanic Cloud and its great depth in line of sight as discovered using Cepheid variables. The ordinate axis is in stellar magnitudes and corresponds to a depth of about 55 thousand light years.

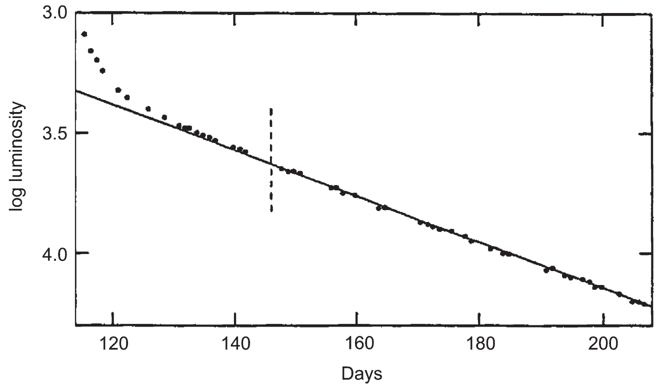

Fig. 3. SAAO observations, on a log scale, of the bolometric luminosity of Supernova 1978A, showing the linear decline between days 146 and 207 after outburst. The rate of exponential decline was found to be equal to the mean life of ^{56}Co and thus demonstrated that the radioactive decay of this isotope powered the light-curve.

Supernovae

Supernovae, because of their high luminosity in outburst, are key objects in determining the distances of very distant galaxies. The interest in supernovae has increased greatly since the recent evidence from them that the expansion rate of the Universe is accelerating. This work depends on one type of supernova (called SNIa), which is believed to have a rather uniform luminosity at maximum light. It would be important to have a check on the results obtained with this type of supernova, and a group of South African astronomers have recently joined an international collaboration with this aim. It is likely that spectra taken with SALT will be a significant part of the project. Another type of supernova (SNII) is known to be the endpoint in the life of massive stars (those with initial mass greater than about 8 solar masses). These supernovae have a range in peak luminosities and if we are to use them as distance indicators we need as much information on them as possible, so as to understand how their luminosities are related to their other observable properties.

The first opportunity to study a SNII in detail came with the occurrence of SN1987A in the Large Magellanic Cloud. This was the brightest and nearest supernova for nearly 400 years and, equally important, at a relatively well-known distance. This supernova was discovered (visually) at dawn in Chile and the first spectrum to be obtained was taken at Sutherland.[25] Extensive photometric and spectroscopic data were obtained at frequent intervals over the next 880 days. This provided the most detailed coverage obtained during that period. Besides detailed papers, a number of summaries were published (e.g. refs 26–28). Amongst the SAAO results perhaps the most striking was the discovery that between days 147 and 260 after outburst the total (bolometric) luminosity decreased strictly exponentially. The half-life of this decay (110.4 ± 0.6 days) is very close to that of the radioactive isotope ^{56}Co and was the key evidence that this isotope provided the power for SNII at this stage, something which had been conjectured theoretically but not certainly established (Fig. 3). At later times, the radioactive decay of ^{57}Co was also found to contribute significantly to the heating of the ejecta. At later times, too, the formation of CO molecules and of dust were observed.

Mira variables

Mira variables belong to populations of stars with ages intermediate between the very old RR Lyraes, with ages of about 14 billion years, and the young Cepheid variables, with ages in the

*Mpc = 3.26×10^6 light years.

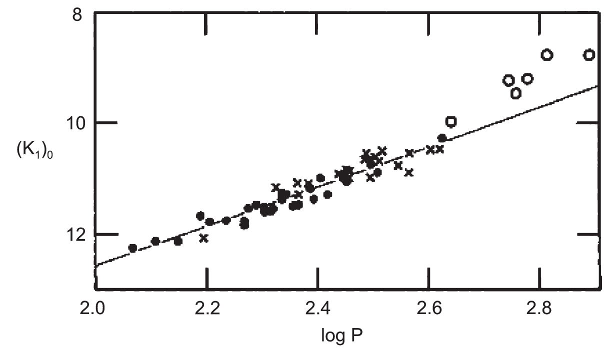

Fig. 4. SAAO observations of the brightness of Large Magellanic Cloud Mira variables observed in the *K* band (corresponding to 2.2 μm) (log scale), showing the period–luminosity relation. Filled circles denote oxygen-rich stars and crosses carbon-rich stars. Open circles denote Miras probably undergoing hot-bottom burning (see ref. 32).

range 10^7 to 10^8 years. They are therefore important tracers of such populations. Miras are cool, large pulsating stars with periods ranging from near 100 days up to about 2000 days. In approximately 10^9 years' time the Sun will evolve into a Mira and will then fill the solar system out to the orbit of the Earth. Miras come in two major classes: oxygen rich (O Miras) and carbon rich (C Miras). The carbon richness is due to the mixing at the stellar surface of the products of nuclear burning. From work at the Radcliffe Observatory, Pretoria, it has long been known[29] that there is a relation between the pulsation periods of O Miras and their galactic kinematics, indicating a useful period–age relation. South African studies of O and C Miras in the LMC showed that they follow rather precise period–luminosity relations (Fig. 4).[30,31] The period range of these relations has recently been considerably extended using further SAAO observations.[33] South African workers have also contributed to the absolute calibration of the O Mira relation using parallaxes[34] and globular clusters[35–37] to establish distances. The importance of this work in the extragalactic field was illustrated recently[38] by ESO astronomers working with the VLT (8 m) telescope in Chile. They used the O Mira period–luminosity relation to determine the distance to the remarkable radio galaxy, Centaurus A, which is probably an example of the collision of two large galaxies. The galaxy is 12.5 million light years away.

An absolute calibration of the C Mira period–luminosity relation has recently been obtained using their galactic motions and infrared photometry (P.A. Whitelock *et al.*, in preparation). These relations will be of importance for studies of dwarf galaxies within the Local Group of galaxies. An extensive search for Mira variables in these dwarf galaxies has been in progress for several years using the Japanese–South African Survey Facility (IRSF) at Sutherland (e.g. ref. 39). The aim of this work is not just to determine distance, but to study the intermediate age populations of these galaxies in which the older populations can be studied using the RR Lyrae variables discussed above. Infrared spectroscopy of Mira variables in the galaxies of the Local Group would be particularly valuable in understanding both this type of stars and the galaxies to which they belong. This could be undertaken if the proposal to extend the capabilities of the SALT prime focus spectrograph into the infrared is approved.

The distance to the centre of our Galaxy

The American astronomer, Harlow Shapley, long ago recognized[40] that the distribution of globular clusters meant the Sun belonged to a large stellar system whose centre lay many thousands of light years away in the direction of the constellation Sagittarius. Since that time, much effort has been put into a precise determination of this distance (R_o), because on it depends an understanding of the structure, dynamics and evolution of our Galaxy.

A number of methods have been used to measure R_o and South African astronomers have pioneered two of them. Young objects are in (nearly) circular orbits about this distant centre. By measuring, spectroscopically, the radial velocities of such stars at different distances from us, it is possible to estimate the distance of the centre about which they orbit. The first successful use of this method[41] was based on radial velocities of hot, massive stars (the OB stars) measured at the Radcliffe Observatory, Pretoria. A distance of 8.9 kpc (about 29 000 light years) was obtained. South African workers have continued to work on this problem and recently a revised estimate was made[22] using Hipparcos proper motions of Cepheid variables together with radial velocities measured by a Swiss group. This yielded 8.5 kpc with an uncertainty of about 0.5 kpc.

Many spiral galaxies contain a relatively dense 'bulge' of stars in their central regions. Our own Galaxy has a bulge, though at optical wavelengths much if it is obscured by dust in intervening parts of the Milky Way. However, there are a few relatively unobscured patches, and observations at the Radcliffe Observatory were used to discover both RR Lyrae and Mira variables in these regions.[42–44] There is a large range of periods amongst these Miras, showing the bulge consists of objects of a range of ages (see above), rather than consisting only of very old objects as has sometimes been suggested. Near-infrared photometry of these Bulge Miras together with the period–luminosity relation discussed earlier then gives a value for R_o (see refs 45, 46). A distance of 8.7 ± 0.7 kpc was obtained. A complication arises because there is evidence that the bulge is bar shaped (a triaxial ellipsoid) and indeed a survey at SAAO of Miras across the bulge[47] shows the mean distance of Miras on one side of the Centre is different from that on the other side. Quite recently, a remarkable result[48] has been established by a group of Japanese astronomers using the IRSF at Sutherland. They find that the Galactic Bar has a complex structure. The tilt of the bar to the line of sight is different in the central region from that further out. They use for this purpose the variation across the bulge in the brightness of a group of stars with well-determined colours and absolute luminosities (the red clump stars).

Conclusion

This review has aimed to give some impression of the contributions of workers in South Africa to one area of astronomy — the establishment of precise distance indicators for use both within our own Galaxy and for the extragalactic scale. It should be noted, however, that the references given are not exhaustive. This work (as indeed the whole of the South African astronomical effort) has been carried out by a small group of astronomers with equipment which is very modest by modern standards. It is hoped that the results achieved will be the basis of studies which will now become possible with the new Southern Africa Large Telescope.[50]

I thank P.A. Whitelock for her help with this article.

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