DISTANCE INDICATORS IN THE MAGELLANIC CLOUDS

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INTRODUCTION

In talking about the overall distance scale of the Universe and the Hubble Constant, the Magellanic Clouds are good places to start. They are stellar systems large enough to contain stars, clusters and nebulae of all types, covering a wide age range. With modern telescopes and detectors, we are able to observe stars from the very bright down to those fainter intrinsically than our own Sun. From comparative studies, we may thus establish our basic calibrations of bright objects before moving out to measure the Universe at large. At the same time, the fact that both Magellanic Clouds are independently evolving galaxies, enables us to separate the effects of stellar age and chemical evolution on the calibrations that we make.

Two important series of papers by Sandage and Tammann (1974a, b,c,d, 1975a,b, 1976, 1982) and by de Vaucouleurs (1978a,b,c,d, 1979a, b,c) will be referred to many times in today's Discussion. There is some difference in emphasis. In setting up the distance scale, Sandage and Tammann take the viewpoint that each particular distance range has its most appropriate calibrator. For example, for nearby galaxies, Cepheid variables are given very high weight. De Vaucouleurs on the other hand, feels that as many classes of object as possible should be used to minimize the risk of gross errors arising from uncertainties in individual calibrators. Through all this work we should however remember Sandage and Tammann's warning that the scatter of calibrating parameter must be small or at least well known since the scatter can cause a bias which is not only systematic but is also one which can change with increasing distance.

As a partial introduction to today's discussion it is useful to review the 4 classes of distance indicators discussed by de Vaucouleurs. These are summarized in Table 1. I have made a few additions (in italics) which will be discussed by myself and others in more detail. To be considered as a Primary Distance Indicator, a calibrating object must (i) be measurable in nearby galaxies, (ii) have a small dispersion about a stable mean and (iii) be capable of calibration within our Galaxy by geometric methods. Note the importance of criterion (iii) which links

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 209–216.

https://doi.org/10.1017/S1539299600005165 Published online by Cambridge University Press

the extragalactic distance scale to the more local stellar distance scale. Such basic data as the distance to the Hyades cluster, the adopted solar motion and parallax determinations directly affect these calibrations.

TABLE 1

Primary Distance Indicators

1)	novae	2)	Cepheids	3)	RR Lyrae variables
4a)	B, A supergiants			4b)	eclipsing binaries

Secondary Distance Indicators

5)	bright red giants and *planetary nebulae*		
6)	globular clusters	7)	brightest blue stars
8)	red variables (supergiants and *miras*)		
9)	Hubble-Sandage variables	10)	large H II regions

Tertiary Distance Indicators

11)	*supernovae*		
12)	isophotal galaxy diameters	13)	total galaxy magnitudes
14)	*H I line widths*		

Quaternary Distance Indicators

15)	inner ring structures

Secondary Distance Indicators become needed because of the short range of the primary calibrators. In general these cannot be studied in the solar neighborhood but have to be less directly calibrated in the more distant parts of our Galaxy or in nearby stellar systems such as the Magellanic Clouds. Tertiary Indicators can be calibrated by means of galaxies whose distances are known from primary or secondary indicators. Quaternary Indicators are in turn based on the tertiary indicator calibration. Neither of these last two classes concern us in the present talk but they will be referred to by other speakers.

PRIMARY DISTANCE INDICATORS IN THE MAGELLANIC CLOUDS

1) Novae: The absolute magnitudes of novae in our galaxy are determined most reliably from a comparison between the observed angular expansion of the shell and its radial velocity. De Vaucouleurs (1978a), Pfau (1976) and Duerbeck (1981) review the available observations for this calibration while a theoretical discussion is given by Shara (1981). In the use of novae as distance indicators the main difficulty arises in their only infrequent appearance, especially in low mass galaxies, and the necessity for prompt, follow-up observations which are not always possible. In the Large Magellanic Cloud, for example, it is estimated that only 2 or 3 appear each year (Graham 1979) and of these, only a

fraction are found in the Cloud observing season and are followed up in sufficient detail to be useful. The situation is somewhat better for the Andromeda galaxy where many more have been found by Arp (1956) and by the Asiago group (Rosino 1964, 1970). Novae have been found to be good distance indicators within the Local Group. Using the best available modern detectors, there is hope of extending their use to distances as great as that of the Virgo cluster. Judith Cohen at Cal Tech has a major program underway which will make use of a new imaging CCD detector with the Palomar 60 inch telescope. Initially the search will be carried out for the spiral galaxies M81 and M101. At the same time, she plans to strengthen the basic galactic calibration through the detection and study of old nova shells.

2) Cepheid Variables: I shall say little about this very important distance indicator because it will be well covered in Madore's talk. Because one is able to observe a large sample of stars in any one system, it is possible to make detailed solutions for period-luminosity-color relations. Nevertheless, as de Vaucouleurs emphasizes, calibration questions do exist here because of the apparent sensitivity to differing chemical abundances and it is important not to depend uniquely on Cepheid distances without having some independent checks. We must also remember that the brightest Cepheids in a galaxy are often anomalous and it is best to obtain a sample covering as wide a range of apparent magnitude as possible. In a study of the Large Magellanic Cloud Cepheids, Martin, Warren and Feast (1979) show how powerful this distance indicator can be. To illustrate the way the Magellanic Cloud Cepheids can tie down distances to other galaxies, I show in Fig. 1 a comparison between their Large Cloud data and some CTIO observations of Cepheids in the nearby galaxy NGC 300. The form of the relation seems similar in both cases and the apparent distance modulus differential clearly determined.

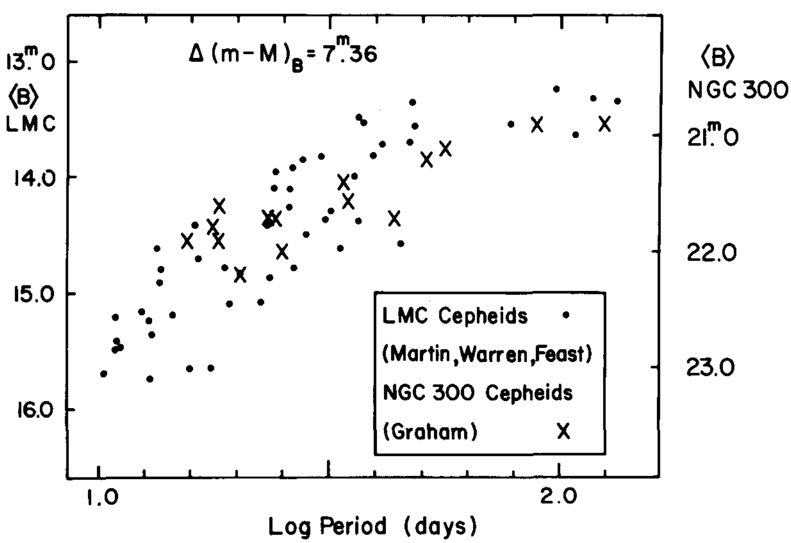

Fig. 1. - Comparison between Cepheids in the LMC and NGC 300.

https://doi.org/10.1017/S1539299600005165 Published online by Cambridge University Press

3) RR Lyrae Variables: Because of their intrinsic faintness, these are only useful as relatively nearby distance indicators. They are abundant in the Magellanic Clouds (Graham 1975, 1977). The usually accepted absolute magnitude, $M_V = +0.6$ is derived both from statistical parallaxes and the Baade-Wesselink method. Sandage (1981) has shown that there is an intrinsic dispersion with the magnitude depending on the precise location of the pulsating star within the instability strip and that absolute magnitudes can be refined with the additional knowledge of amplitude or color. Values of $\langle M_V \rangle$ both brighter and fainter than +0.6 have been proposed (Siegel 1981, Clube and Dawe 1980) but the traditional value still seems to be the one which agrees best with other indicators. An important feature of RR Lyrae variables is that being old and generally metal poor, they come from a different stellar population than that most commonly used for calibration purposes. Sometimes, as in dwarf elliptical galaxies, they are the best indicators that we have.

4a) B and A-Type Supergiants: Stars of this type are likely to be employed increasingly for distance determination. Work by Crampton (1979) and by Crampton and Greasley (1982) in both Magellanic Clouds involving spectral classification of OB supergiants has shown that good absolute magnitudes and distances can be obtained even when the chemical abundances are different in different samples. As with the Cepheids, it is important to include stars covering a range of apparent magnitude. Again the need is to avoid statistical effects arising from selection of the few brightest stars and to minimize the effect of spectroscopic peculiarities related to mass-loss and associated phenomena. Crampton has found that consistent absolute magnitudes and distances can be obtained for both Large and Small Magellanic Clouds. However, problems have been encountered with calibrations depending on the strength or appearance of hydrogen lines alone, particularly for the late B and A spectral types. Humphreys (1982) has drawn attention to a group of supergiants in the Small Cloud with spectral types B8-A5 which have anomalous colors and hydrogen lines too strong for their luminosities. Their visual luminosities based on membership of the Small Cloud are one to two magnitudes brighter than expected from the appearance of the hydrogen lines. A very similar group of stars has been identified in the Large Cloud by Fehrenbach and Duflot (1972), and by Sanduleak (1972). Various arguments support membership of these stars in the Magellanic Clouds and there is no good explanation of the spectroscopic anomaly.

4b) Eclipsing Binaries: Here is a good area for future work. In nearby galaxies many eclipsing binaries have been identified from their characteristic light variability. Knowing the relative brightnesses of the two components, and the effective surface temperatures, absolute magnitudes can be obtained by assuming a mass luminosity relation. Much of the Magellanic Cloud work, unpublished in detail,has been carried out by Gaposhkin. A summary of the methods involved is given by Dworak (1974). It is worth noting that the greatly improved sensitivity of spectrographs with new detectors has made it possible to get good spectral energy distributions, even good velocities,for faint objects at the 17th magnitude level and beyond. Far better effective temperature values can now be obtained then was formerly possible with only rough (B-V) colors. At present, however, with so few published data, the method carries low weight but it is a promising one for the future.

SECONDARY DISTANCE INDICATORS IN THE MAGELLANIC CLOUDS

5) Bright Old Red Giants and Planetary Nebulae: While these are not very precise indicators, they are useful for checking other values and for placing limits on the distances of galaxies out to about 5 Mpc. In all nearby galaxies that have been studied in sufficient detail, an underlying old population is found even in cases such as the Large Magellanic Cloud (Stryker 1981), where the principal burst of star formation has occurred more recently. In a Large Cloud field, Tifft and Snell (1971) found that the brightest red giants come in at visual magnitude 16.2, agreeing well with earlier work by Hodge. As an example of a typical application, I mention some work of my own (Graham 1982) in which I estimate the visual magnitude of the brightest red giants in NGC 55 and NGC 300 to be $23^{m}.0 \pm 0.3$. The corresponding distance estimate for NGC 300 is consistent with that derived from the Cepheids.

Although fewer in number, the planetary nebulae can also be used as distance indicators. They are detected by their strong [O III] radiation and distinguished from normal H II regions by their "stellar" point source appearance and from the faintness of reasonable candidates for the excitation source. Ford and Jenner (1979) have shown that planetary nebulae have a reasonably uniform maximum luminosity from galaxy to galaxy. However, for those galaxies with just a few planetary nebulae, only an upper limit can be placed because these nebulae are unlikely to be at an epoch of maximum luminosity. Jacoby and Lesser (1981) have used planetary nebulae to set upper limits to the distance of 5 nearby dwarf galaxies. Graham and Lawrie are studying some good candidates for planetary nebulae in NGC 300. In discussing the data, the luminosity function for planetary nebulae needs to be known. This has been determined by Jacoby (1980) from observations of fields in the Large and Small Magellanic Clouds. Here a high level of completeness has been achieved to about 3 magnitudes below the observed value for the brightest planetary nebulae.

6) The Brightest Star Clusters: The globular clusters are coming into increasing use as distance indicators. David Haynes perhaps will be talking about this more in his paper on the Virgo cluster. Here it is appropriate to point out that in the Magellanic Clouds and in other late-type galaxies, such as M33 and NGC 55 (Christian and Schommer 1982, Da Costa and Graham 1982), clusters are found which are bluer and younger than both those known in our own Galaxy and those observed around giant elliptical galaxies like M87 (Haynes 1977). In NGC 55, for example, the brightest globular cluster is blue, and strongly resembles the Large Magellanic Cloud cluster NGC 1866. It is about $0^{m}.8$ brighter in visual light than two apparently normal red clusters. Care must evidently be taken that we do not oversimplify and overextend the concept of a unique luminosity function when we use clusters as a distance indicator.

https://doi.org/10.1017/S1539299600005165 Published online by Cambridge University Press

7) The Brightest Non-Variable Blue Stars: As in the case of the planetary nebulae and the bright clusters, it is important to know the luminosity function of the brightest non-variable blue stars in galaxies before one can use them as distance indicators. Sandage and Tammann (1974a) pointed out that the luminosity of the brightest blue star depends on the luminosity of the parent galaxy and concluded that the observations can be understood by assuming there is a common luminosity function for the brightest stars. Humphreys (1982) has re-investigated the luminosity function of the brightest stars in the Magellanic Clouds. She finds that the luminosity function for the Small Cloud, at least at the upper end, deviates from that observed for both the solar neighborhood and for the Large Cloud. She suggests that rather than being a purely statistical effect involving the only the size of the sample, the relative number of the luminous stars may vary with the total mass of a galaxy. Chemical composition differences play an insignificant part but again care must be taken in the assumption of a unique luminosity function.

8) Red Variables: The brightest red supergiant variables have been proposed by Tammann and Sandage (1968) and by Humphreys (1978, 1979a,b, 1980a,b) as being extremely useful distance indicators. They are easily picked out from field stars and appear to have a constant maximum visual magnitude, regardless of a total luminosity of the parent galaxy or its chemical composition. Humphreys has confirmed the validity of this distance indicator for both the Large and Small Magellanic Clouds. In the infrared, however, Elias et al. (1982) have shown that abundance differences do influence the maximum H mag luminosity significantly.

The less luminous Mira variables are better distance indicators than once though although their use is probably restricted, like the RR Lyrae stars, to nearby galaxies only. Glass and Lloyd-Evans (1981) have found that a period-bolometric luminosity relation for Miras in the Large Magellanic Cloud shows a very small scatter. Miras are bright objects in the infrared and can be seen to large distances through heavy interstellar absorption.

9) Large H II Regions: As de Vaucouleurs points out, the use of giant H II regions as distance indicators is full of difficulties but the method continues to show promise for application to distant galaxies. The first evaluations of this parameter were made by Sersic (1960) and by Sandage (1962). A recent, more detailed assessment of the consistency and physical significance of the method was made by Kennicutt (1979a,b,c). Kennicutt questioned the use of subjectively measured H II region diameters as part of a distance scale calibration but was able to re-define and use diameters base on photo-densitometer measurements. Hodge's (1981) concern that we understand physically the calibrators we adopt is very pertinent here and it should be noted that the Magellanic Clouds offer a unique opportunity to study H II regions of all shapes and sizes with their exciting stars often in full view.

A new distance indicator, only just announced at this meeting, shows great potential importance. B.Y. Mills reports that a new radio

https://doi.org/10.1017/S1539299600005165 Published online by Cambridge University Press

search for supernovae remnants in the Magellanic Clouds has recently been completed in Australia using the Molonglo Observatory Synthesis Telescope. This has provided a sample of 29 positively identified supernovae remnants. Study of these indicates that their absolute luminosity distribution can be used to define a distance scale whenever the apparent luminosity is known. More details are given in Mills's (1983) contribution to IAU Symposium 101.

IMPORTANCE OF SPACE TELESCOPES IN FUTURE WORK

At this IAU General Assembly, we are all looking ahead to the tremendous contributions that the space telescopes of the 1980s are going to make to our knowledge of the Universe and it is appropriate to conclude with some thoughts about the possible interaction with Magellanic Cloud calibration work. The instruments of the greatest importance will be the NASA Space Telescope and HIPPARCOS astrometry satellite which are both scheduled for launch in 1985-1986. With many new parallaxes of high quality HIPPARCOS is going to promote several of our secondary distance indicators to the primary level. Parallaxes for red giants, subdwarf stars, and even cepheids as well as luminous blue stars come to mind. Distances to the Hyades and other nearby clusters should be tied down at last and the subdwarf main sequence calibrated so as to improve the sequence fitting procedure for globular clusters. The Space Telescope will be more suitable for the Magellanic Clouds themselves. Three of its features are of special interest, 1) the ability to detect and measure very faint objects, 2) the broad response to radiation from ultraviolet to infrared wavelengths, 3) the very high angular resolution. In conjunction with the HIPPARCOS results, it will be possible to derive firm distances for the Magellanic Clouds. The high resolution capability of the Space Telescope will make possible studies of the content of Cloud star clusters in as much detail as we presently see in their galactic counterparts.

In his recent review, Paul Hodge (1981) emphasizes the need to establish firmly basic nearby distances before we can move out with confidence further afield. The space telescopes of the present decade will do this for us and much of the current uncertainty of the size and age of our Universe will hopefully be cleared away.

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