IV. GALACTIC KINEMATICS AND DISTANCES

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THE GALACTIC DISTANCE SCALE

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Recent work on the distance scale of the Galaxy has largely been in the direction of refining previously established methods. The RR Lyrae variable stars appear to be better distance indicators than was once thought and they have been used in determining R_o, the distance to the Galactic center. R_o is probably somewhat less than 10 kpc but greater than 7 kpc. Most methods point to a value near 8.5 kpc.

1. INTRODUCTION

In reviewing the present state of the Galactic distance scale, it is encouraging to find that there have been no major revisions over the past decade or so. This is not to imply that the field has become inactive but rather to note that several major investigations have verified with improved precision, results obtained earlier from more fragmentary data. There has been little development of new methods but considerable refinement of those already established.

2. CALIBRATIONS WITHIN THE SOLAR NEIGHBORHOOD FOR YOUNG STELLAR POPULATIONS

The distance to the Hyades cluster, an important base for several determinations of the distance scale, has undergone revision. Van Altena (1974) discussed the several methods employed for this and adopted in summary a distance modulus of $3^m.21$ (± .03). More recently, a new evaluation has been made by Hanson (1978) using a new set of absolute proper motions. The distance modulus of $3^m.30$ (± .06) is independent of previous determinations. This 25% increase over the value in use prior to 1970 does not affect distance scales in general use by a corresponding amount. Van den Bergh (1977) has pointed out

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that the change should be only about half of this because 1) some calibrations of distance indicators bypass the Hyades completely and 2) the distance scale for the Cepheid variables is sensitive to the assumptions made in the sequence fitting of the calibrating clusters to the Hyades.

Other recent work on the calibrations of young stellar populations in the solar neighborhood is independent of the Hyades modulus. Crawford (1975) (1978) has just completed definitive calibrations of uvby, β photometry in terms of intrinsic color and absolute magnitude for B and F - type stars. The zero points of the calibrations are based on the parallaxes of nearby F stars. Crawford has also recalibrated the luminosities of some of the MK spectral classes and finds good agreement with the calibration published by Blaauw (1963). For individual O and early B stars, the average error in absolute magnitude derived from the hydrogen line index remains large. In a calibration of Hγ measurements, Balona and Crampton (1974) find an average uncertainty of $0^m.6$ for O, early B and supergiant stars while the expected error for late B stars is much smaller, probably no more than $0^m.3$.

3. CALIBRATIONS OF OLD STELLAR POPULATIONS

Variable stars of the RR Lyrae type are important representatives of the oldest stellar populations because they can be easily identified to faint apparent magnitudes. They appear to be better indicators of distance than was once thought. Observationally, absolute magnitudes for RR Lyrae stars come from 3 sources: 1) stellar systems whose distances are known. 2) statistical parallaxes. 3) application of the Baade-Wesselink method. Some results are summarized in the following Table.

THE ABSOLUTE MAGNITUDE OF RR LYRAE STARS

Method	Object	$\langle M_V \rangle$
Stellar systems	globular clusters: Sandage (1970)	$0^m.6 \pm 0^m.2$
	Magellanic Clouds	
	LMC : Graham (1977)	0.7 ± 0.2
	SMC : Graham (1975)	0.5 ± 0.2
Statistical parallaxes	Heck (1973)	0.5 ± 0.2
	Hemenway (1975)	0.5 ± 0.4
Baade-Wesselink	Metal weak stars: McDonald (1977)	0.55 ± 0.2
	Metal strong stars: McDonald (1977)	0.85 ± 0.2
	McNamara and Feltz (1977)	0.9 ± 0.2

The Magellanic Cloud values depend on assumed distances moduli of $18^m.5$ and $19^m.0$ for the Large and Small Clouds respectively. If, as

Eggen (1977) believes, a modulus of $18^m.25$ is more appropriate to the Large Cloud then the corresponding value above would need to be increased accordingly. While there is some sign of a dependence of absolute magnitude on metal line strength, it may not affect the Galactic calibration. Tamm et al. (1976), Butler et al. (1976), and Rodgers (1977) have shown that the RR Lyrae stars encountered in the Galaxy away from the immediate vicinity of the Sun, generally have weak metal lines even in the crowded region of the Galactic bulge. A time averaged mean visual magnitude $\langle M_V \rangle = 0^m.6 \pm 0^m.2$ is probably appropriate for the RR Lyrae stars. Oort and Plaut (1975) note that a dispersion greater than $0^m.2$ in the mean magnitude will give unreasonable space densities within the fields that they studied.

Because of their high integrated luminosities, globular clusters are important probes in studies of our own and other galaxies. The most basic method of calibration is the sequence fitting procedure described by Sandage (1970). Harris (1976) has recently written a comprehensive paper on the subject. He discusses various methods of estimating distances for known globular clusters and concludes that the most reliable method of distance determination is based on the assumption of a mean absolute magnitude for RR Lyrae stars in globular clusters. Adopting $\langle M_V \rangle = 0^m.6$, he derives distances for 111 globular clusters in this way.

4. THE DISTANCE TO THE GALACTIC CENTER

Dense obscuration, much of which is in thick dust clouds within 2 kpc of the Sun, prevents direct estimates of the distance to the Galactic center. Proceeding less directly, methods generally fall into one or other of two classes: 1) observation through relatively clear "windows" a little above or below the plane to determine the distance of maximum density or symmetry for objects known to be concentrated towards the Galactic center. 2) study of the dynamics of stars at the same distance from the center as the Sun.

Studies of the space distribution of RR Lyrae stars are typical of the first category. An important investigation of this type was made by Oort and Plaut (1975). In 5 relatively clear fields, 980 variable stars were detected and measured. Because of the coarse nature of the photographic magnitudes, interstellar absorption could only be taken into account in an average way. Assuming an average photographic magnitude $M_{pg} = \frac{1}{2}(M_{max} + M_{min}) = 0^m.7$, a mean distance to the Galactic center, R_o, of 8.7 ($\pm$ .23) kpc was derived.

A similar method, based on the newly determined globular cluster distances has been followed by Harris (1976). As with the RR Lyrae stars, one must look away from the Galactic plane to obtain a sample which is reasonably complete with distance. Harris finds that the most reliable solution for R_o is obtained by restricting consideration to globular clusters more than 2.5 kpc from the plane. This yields 8.5 kpc with an uncertainty of ± 1.6 kpc. Harris notes that his estimated error includes an uncertainty of $\pm 0^m.3$ in the absolute magnitude of the RR Lyrae stars which corresponds to a distance error of ± 1 kpc. The results in the first Table suggest that this estimate may be excessive.

The distance to the Galactic center can also be found by observing remote OB stars with nearly the same distance from the Galactic center as the Sun. One version of the method consists of determining the galactic longitude at which stars with a known distance have zero radial velocity with respect to the Sun. The method was applied most extensively at Radcliffe Observatory. Balona and Feast (1974) determine $R_o = 9$ kpc with a range of 7.7 - 10.9 kpc. The method is unfortunately very sensitive to streaming motions whose systematic effects are difficult to evaluate. In a rediscussion with improved Northern Hemisphere data, Crampton et al. (1976) find $R_o = 8.4$ (±1) kpc.

An interesting new method has come from Toomre (1972) who combines observations of local mass density with theoretical disk models and investigates the conditions under which the disk can remain stable. He concludes that $R_o = 7$ kpc is too small and $R_o = 10$ kpc is too large to satisfy these constraints. Rybicki et al. (1974) report a development of this method which leads to a distance of 9.0 kpc. Eggen (private communication) also points out that with R_o as low as 7 and plausible values of the Oort constants, there would be an uncomfortably large number of high velocity stars with unbound orbits at present in the Galaxy.

In summary, it can be seen from the following Table that recent work favors a distance to the Galactic center, R_o, somewhat less than 10 kpc but greater than 7 kpc. A straight mean of 8.7 kpc is found. The quoted errors are not independent and reflect uncertain systematic effects. A mean error of 1 kpc therefore remains in this average value.

DISTANCE TO THE GALACTIC CENTER

RR Lyrae Stars:	Oort and Plaut (1975)	8.7 (±0.6) kpc
Globular Clusters:	Harris (1976)	8.5 (±1.6)
Solar distance O and B stars:	Crampton et al. (1976)	8.4 (±1)
Galactic disk:	Toomre (1972) Rybicki et al. (1974)	9.0 (±1)
	Average	8.7 (±1) kpc

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DISCUSSION

Bok: What role can the Magellanic Clouds play in future calibration problems?

Graham: In the Magellanic Clouds we can now observe stars all at the same distance but with a large variety of ages, to luminosities as faint as that of the Sun. They are ideal places to check the distance indicators of various types. Chemical abundances in the Large Magellanic Cloud appear nearly normal compared to those in the Sun, but the abundances of some elements in the Small Cloud are found to be comparatively low. In the Small Cloud it will be possible to examine the effects of these anomalous abundances on the various calibrating objects and thus enable us to extend the Galactic distance scale with some assurance to more remote stellar systems.

Schmidt-Kaler: Although the most recent stream parallax of the Hyades yields the modulus m_o-M = 3.4, the trigonometric parallaxes (including some new Van Vleck values) yield the old value, 3.0, exactly. This is due to a systematic correction of +0".004 of the Jenkins Catalogue relative parallaxes which I find necessary in a recent study.

Muzzio: I would like to make a comment on the use of H_β photometry: although the β-index is independent of the star's color if both the narrow and wide filters have the same mean wavelengths, such is not always the case. In fact, published transmission curves for the two filter sets used to establish the β-system show that one of them should yield β values strongly dependent on the star's color (about $0\overset{m}{.}022$ increase in β with every 1^m increase in color excess). This effect explains also most of the difference between the calibration curves obtained for B and for A-F stars. Because the third set of filters used to establish the standard system also requires the use of those different curves, it is not unlikely that that set is influenced by the same problem too (there are no published transmission curves for it). Present calibrations may thus need some revision and β observations should be corrected by including a color term.

Graham: Observers using interference filters should be careful of effects such as these. Much of Crawford's work was done with a single set of filters, so I doubt that the calibration work will need revision.

de Vaucouleurs: I should like to call your attention to the circular argument involved in "calibrating" the RR Lyrae by way of the Magellanic Clouds using a distance derived from Cepheids calibrated by one method only (and using incorrect absorption corrections).

Graham: The Magellanic Cloud distances are derived from a number of distance calibrators, not just from the Cepheids (Westerlund, B. E.: 1974, in "Galaxies and Relativistic Astrophysics", B. Barbanis and J. D. Hadjidemetrion, eds. (Berlin: Springer-Verlag), p. 39.)

Kraft: I hope colors can be obtained for individual RR Lyrae, so that E(B-V) can be estimated directly. One can also pray that finding charts will be published for the individual variables.

Graham: The Blancos are planning to determine colors for individual RR Lyraes.