VARIABLE STARS AND THE COSMIC DISTANCE SCALE

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INTRODUCTION

For three quarters of a century pulsating variable stars have lain at the foundation of the extragalactic distance scale. The construction of larger telescopes, advances in detector technology, hard work by observers, and our understanding of stellar structure have all contributed to the expansion of the realm of the Cepheids to the distance of M101. Now, with the advent of Hubble Space Telescope (HST), we can look forward to the detection of Cepheids in the Virgo cluster and the removal of much of the remaining uncertainty in the Hubble constant.

It is an appropriate time, therefore, to think about some of the details of applying period luminosity (P-L) relations for variable stars to galaxies with necessarily different histories of star formation and chemical evolution.

EFFECT OF CHEMICAL COMPOSITION ON P-L RELATIONS

The first realization that P-L relations were different in different stellar populations had a major impact on the distance scale (Baade 1956). Nowadays, informed by knowledge of stellar evolution, we tend to talk about the masses and chemical composition of classes of variable stars, but we are still asking the same question: are there important second parameters in the P-L relation?

For model Cepheids Stothers (1988) has recently found that to first order at constant period:

$$\delta M_{bol} = 0.8\ \delta Y - 1.8\ \delta Z$$

and

$$\delta M_V = 0.5\ \delta Y - 2.8\ \delta Z$$

which is an almost insignificant composition dependence.

Several lines of argument concur that multiwavelength observations of Cepheids offer the best means of determining the distances of these stars. One can integrate the energy distribution given BVRIJHK photometry to measure bolometric magnitudes directly. Without bolometric corrections one is in a better position regarding the continuing choice between P-L and P-L-C relations (Feast and Walker 1987). And one can also determine the reddening to individual Cepheids (Freedman 1985).

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An empirical test of the composition dependence of the P-L relation has not yet been successfully carried out. Freedman (1988c) has devised such a test, employing the metallicity gradients exhibited by disk galaxies, but the application to M 31 is currently incomplete. One can also look for discrepancies between the Cepheid distance moduli and the Population II distance moduli for galaxies of differing metallicity.

However, this raises the subject of the composition dependence of the absolute magnitude of RR Lyrae stars. In this case the theoretical expectation (Iben and Renzini 1984) is:

$$\log L = 1.73 + 1.40(Y - 0.3) - 0.073(3 + \log Z)$$

for RR Lyrae stars at a specific effective temperature. This metallicity dependence is shallower than that found by Sandage (1989) by considering the amplitudes of RR Lyrae light curves. A trend in the relation between M_{bol} and log Z is seen in the Baade-Wesselink measurements of RR Lyrae stars by Jones et al. (1988), Clementini and Cacchiari (1989), and Liu and Janes (1989). Carney (1988) indicates:

$$M_{bol} = 0.20[Fe/H] + 1.03$$

Böhm-Vitense et al. (1989) point out the sensitivity of Baade-Wesselink results to the transformation from color to effective temperature. The dependence of this transformation on metallicity because of line blanketing makes the coefficient of [Fe/H] in this equation problematical. A further opportunity to determine this coefficient exists with HST observations of the horizontal branches of M 31 globular clusters. Measurement of the composition dependence of the absolute magnitudes of RR Lyrae stars would greatly strengthen the Population II distance scale.

Table 1. Cepheid Distance Moduli for Local Group Dwarf Irregulars

Galaxy	$(m-M)_o$	O/H x 10^4	Source*
IC 1613	24.1	0.4	McAlary, et al. (1984)
	24.3±0.1		Freedman (1988a)
NGC 6822	23.4±0.2	1.7	McAlary, et al. (1983)
Sex A and B	25.5±0.1	0.2	Sandage & Carlson (1985b)
Sex A	26.0±0.4		Walker (1987a)
WLM	24.8±0.1		Sandage & Carlson (1985a)
NGC 3109	26.1±0.1		Demers, et al. (1985)

* These are the original references. The tabulated values are taken from Walker (1987b).

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Returning to the composition dependence of the Population I distance scale, one notices in Table 1 the range of chemical composition exhibited by the dwarf galaxies in the Local Group with Cepheid distance moduli. These moduli have been summarized and put on a scale consistent with an LMC modulus of 18.47 by Walker (1987b). Table 1 indicates the oxygen abundance (Vigroux, et al. 1987) for the system and gives original reference for the Cepheid photometry. For most of these galaxies RR Lyrae stars are detectable from ground based telescopes. Given accurate RR Lyrae distances to these galaxies, the composition dependence of Cepheid distance moduli would then be apparent.

A Population II distance estimate for IC 1613 is already available. IC 1613 is a low metallicity dwarf with [O/H] = -1.2. Fitting the red giant branch tip to this galaxy yields $(m-M)_0 = 24.2 \pm 0.2$ (Freedman 1988b) in agreement with the Cepheid modulus. It will be interesting to confirm this by observing RR Lyrae stars.

M 31 AND M 33

These galaxies provide consistency checks on our understanding of variable star P-L relations. Table 2 contains the most recent estimates of the distances of M 31 and M 33. For M 31 Walker (1987b) has updated earlier Cepheid data to a standard P-L relation and $A_V = 0.33$. This should not be considered inconsistent with $A_B = 0.31$ for halo RR Lyrae stars adopted by Pritchet and van den Bergh (1988), because of the intrinsic reddening of Cepheids (e.g., Freedman, 1985).

In M 33 $A_V = 0.3$ has been adopted for Cepheids in Table 2. The wavelength sequence of (m-M) suggests that a higher value might be appropriate. But the P-L relation for supergiant LPVs in M 33 (Mould 1987) is in opposition to this trend. Application of this form of the

Table 2. Distance Measurements for M 31 and M 33

Indicator	M 31	Source	M 33	Source
Cepheids B,V	24.2	Baade & Swope (1963)*	24.5±0.1	Christian & Schommer (1987)*
Cepheids R,I			24.5±0.1	Mould (1987)*
Cepheids H	24.3±0.1	Welch et al. (1986)*	24.2±0.1	Madore et al. (1985)
LPVs K			24.6±0.1	Mould (1987)
GB tip	24.4±0.3	Mould & Kristian (1986)	24.6±0.3	MK with $M_V = 0.8$
RR Lyr	24.2±0.2	Pritchet & van den Bergh (1987, 1988)	24.45±0.2	Pritchet (1988)
Novae	24.0±0.2	Cohen (1985)		

* Using P-L relation and $A_V = 0.33$ (Walker 1987b) for M 31 and $A_V = 0.3$ (Feast 1988) for M 33.

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LPV distance indicator (Bessell and Wood 1984) without bias requires that supergiant and asymptotic giant branch LPVs should be separable. Supergiants and AGB stars are certainly in very different evolutionary phases (Wood, Bessell and Fox 1983), and the supergiant P-L relation has a different slope from that of AGB stars (cf. Feast, 1989). This distinction between extreme Population I LPVs and lower mass AGB Miras is an example of the symbiosis between the study of stellar evolution and the extragalactic distance scale.

The large number of Cepheids found by Kinman, Mould and Wood (1987) in the course of the LPV survey also deserve attention, particularly in the present context because six candidates for Population II Cepheids were identified in M 33. No follow-up work has been carried out on these stars as far as I know, but my estimate is that their bolometric magnitudes are in the range (-4.6, -3.8). The mechanism proposed by Gingold (1976) places these stars in the instability strip during thermal pulses of the helium burning shell of low mass AGB stars with very thin remnant envelopes of hydrogen fuel. These excursions are called "blueward noses" or "blue loops". Two of these stars would have the longest known periods of the W Vir class and certainly deserve further investigation. If this identification is correct, there may be a higher percentage of Population II Cepheids in earlier type galaxies.

To conclude the subject of the distances of these galaxies, from Table 2 the mean value of $(m-M)_0$ for M 31 is 24.2. The mean value for M 33 is 24.5. The consistency of these partially separate distance indicators is better than 10% in distance (r.m.s.). There are some obvious gaps in Table 2 to be filled and there is a need for a better study of the reddening problem.

H_0 FROM CEPHEID DISTANCES TO GALAXIES

Because peculiar and infall velocities in the local supercluster are comparable to the Hubble flow, one cannot determine H_0 by simply measuring the distances to a random assortment of nearby galaxies at redshifts of a few hundred km·sec^{-1}. Consequently, one must use a high quality primary standard candle (Cepheids) in nearby galaxies to calibrate a reliable secondary distance indicator (such as the infrared Tully-Fisher method, or IRTF) which is luminous enough to reach galaxies with redshifts up to about 5000 km·sec^{-1}, well beyond any substantial Hubble flow deviations. Thus, an important goal for HST is to derive accurate distances to a number of appropriately selected galaxies in the 3 to 20 Mpc range by using the Cepheid P-L relation. It will then be possible to use the distances to these galaxies to calibrate the IRTF and a number of other secondary distance indicators for extension into the smooth Hubble flow.

Figure 1 shows how an accurate Cepheid P-L relation lies at the heart of such a plan. Therefore it is essential to ensure an accurate calibration of the zero-point in this relation. This should be accomplished by a multi-pronged attack involving a) improved main sequence fitting to younger clusters in the LMC: b) horizontal branch

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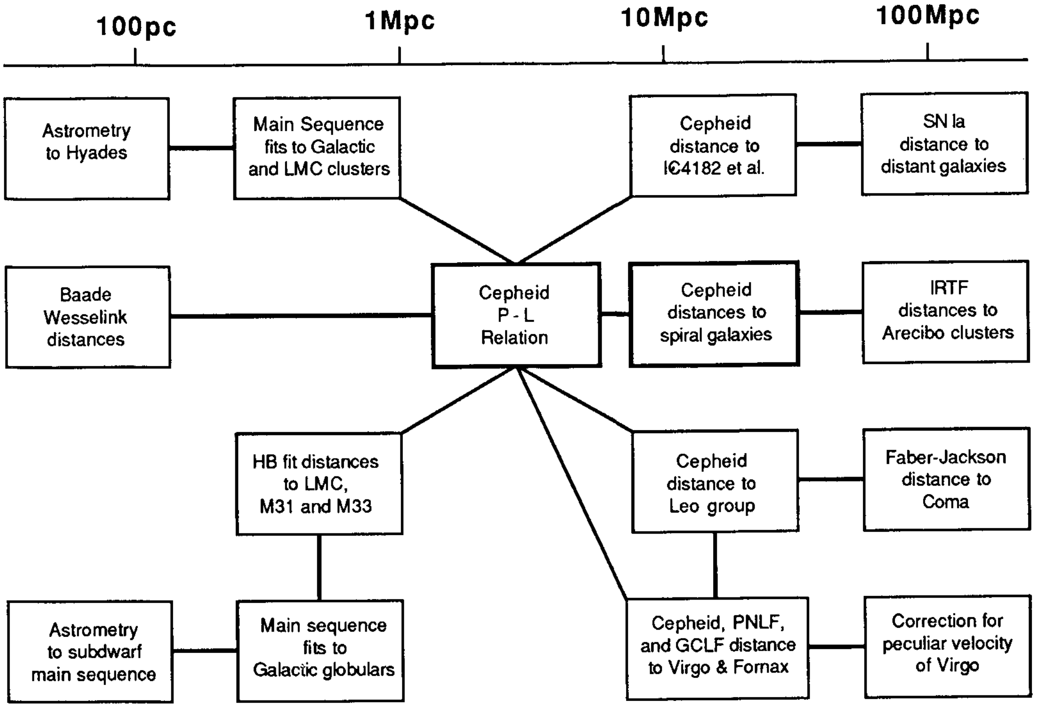
distances to globulars in the LMC, M 31 and M 33; and c) application of the Baade-Wesselink method to Galactic Cepheids.

The main body of the work for HST, however, is the application of this P-L relation to measure the distances of a substantial sample of spiral galaxies. In the 1970s in their classical series of papers on the extragalactic distance scale, Sandage and Tammann talked about a "twilight zone" as one stepped out from the Milky Way towards the unperturbed Hubble flow, in which the distance scale became fuzzy. This twilight zone still exists; it extends from the Local group to the Virgo cluster; it is this region that HST can fill with accurately determined galaxy distances.

The direct route to H_0 from a sample of spirals with Cepheid distances is to construct for the first time a reliable and fully populated calibration of the IRTF, and hence measure distances to a set of galaxy clusters located between 4000 and 10000 km·sec^{-1} away, and observed at 21 cm with the Arecibo radiotelescope. Although no perfect standard candle exists, one can nonetheless rank distance indicators by the degree to which they meet objective criteria, such as: 1) Is the candle luminous

Figure 1. In this program the Cepheid P-L relation is calibrated within 1 Mpc and applied to spiral galaxies at typically 10 Mpc. These measurements in turn calibrate secondary distance indicators which reach out to 100 Mpc.



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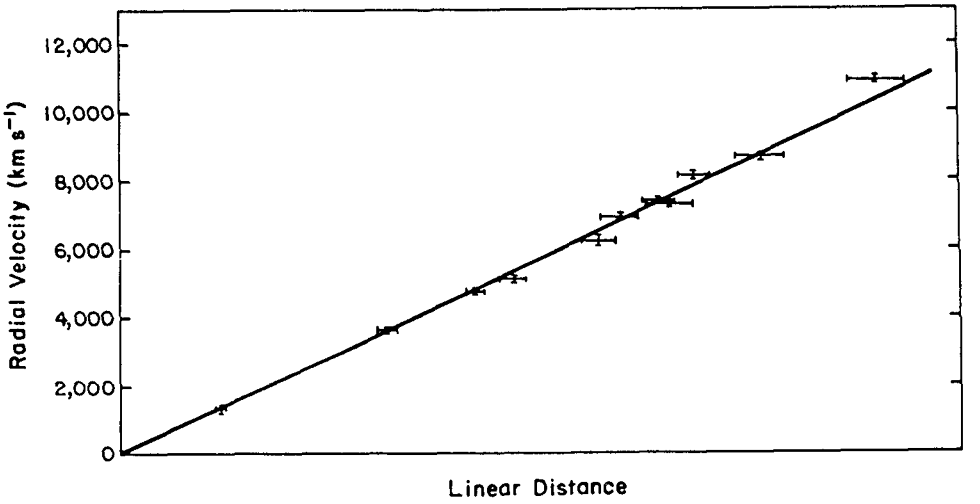
and easily identified? 2) Is a physical (rather than a statistical) basis for the luminosity criterion well understood? 3) Are the measurables objective, well-defined, and easy to determine? 4) Is there a demonstrably low dispersion based on large samples of data? Aaronson and Mould (1985) have made the case that Cepheids and the IRTF relation best meet these criteria.

The basis of the case for the IRTF as a secondary standard candle is Figure 2, which shows the velocity-distance relation for 11 nearby galaxy clusters from the work of Aaronson et al. (1986), derived from IRTF moduli to about 150 cluster spirals. To within the measurement errors there is no deviation from linearity. One simply needs to attach an absolute scale to the abscissa of Figure 2.

Of course, one distance indicator alone is not a basis for a conclusive measurement of H_0. Careful choice of the sample of spiral galaxies can support the calibration of a number of other secondary distance indicators. By including IC 4182 in the sample one can empirically calibrate the SN Ia standard candle with one of the few galaxies closer than Virgo which have measured light curves for such supernovae. This standard candle can then be applied to distant ($cz > 3000$ km·sec^{-1}) galaxies where several such supernovae have been recorded. The distances provided by such a program will make it possible to test the accuracy of the brightest resolved stars as standard candles. By measuring Cepheid distances to the Leo group, one can provide an additional calibration for three secondary indicators which are best applied to early type galaxies. The planetary nebula luminosity

Figure 2. The velocity-distance relation for eleven galaxy clusters, using moduli determined from the IR/HI relation. The velocity of Virgo (the lowest redshift cluster) has been corrected for infall and the remaining velocities have been corrected for the dipole anisotropy of the microwave background.



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function (PNLF; see Ford et al. 1988) and the globular cluster luminosity function (GCLF; see Harris 1988) are two standard candles which can be easily and routinely observed in Virgo ellipticals. The Faber-Jackson relation, like the IRTF, can be applied to large distances, once appropriately calibrated (Dressler 1988).

The scope of this program is shown schematically in Figure 1. The other secondary indicators will provide important checks and interlocks on a determination of H_0 through the IRTF. One can also attempt to measure direct Cepheid distances to spirals on the far side of the "twilight zone", namely in the Virgo and Fornax clusters. These observations will be difficult even with HST. However, secure distances to Virgo and Fornax may be almost sufficient to lay to rest the H_0 controversy.

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