CEPHEIDS IN EXTERNAL GALAXIES

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1. INTRODUCTION

The study of Cepheids in external galaxies has been a continuous probing of the near-by distance scale accompanied by a refining and redefining of the Period-Luminosity relation itself. For example, the nearest two late-type galaxies of the Local Group, the Magellanic Clouds have always been the testbed for calibrations, from the pioneering optical studies of Leavitt (1907) to the recent infrared calibration of McGonegal et al. (1982) three quarters of a century later.

With time the data have improved in quality and in quantity but the methods of analysis and interpretation have so proliferated that the field might appear to be less well defined than it was at the turn of the century. Discussions of the problems have been so open that many have been driven to the conclusion that it is perhaps better to gauge the distances to galaxies using a variety of indicators, of secondary quality, rather than risk systematic errors at the start, through a complete reliance on one primary distance indicator. That situation, I believe, now has the potential for reversing itself.

With modern technological advances the entire field is now entering a new era; it is surfacing out of an uncertainty imposed on it by the available detection devices of 1950's and 60's. Optical and ultraviolet data will continue to yield important information on the atmospheric differences between Cepheids in external galaxies, but it is in being now able to move to significantly longer wavelengths that the power of Cepheids as quality distance indicators is being affirmed on all fronts. The following sections are intended to highlight the critical points of contention in the calibration of the cepheid distance scale with the ultimate conclusion in each case that infrared photometry holds the pragmatic answer.

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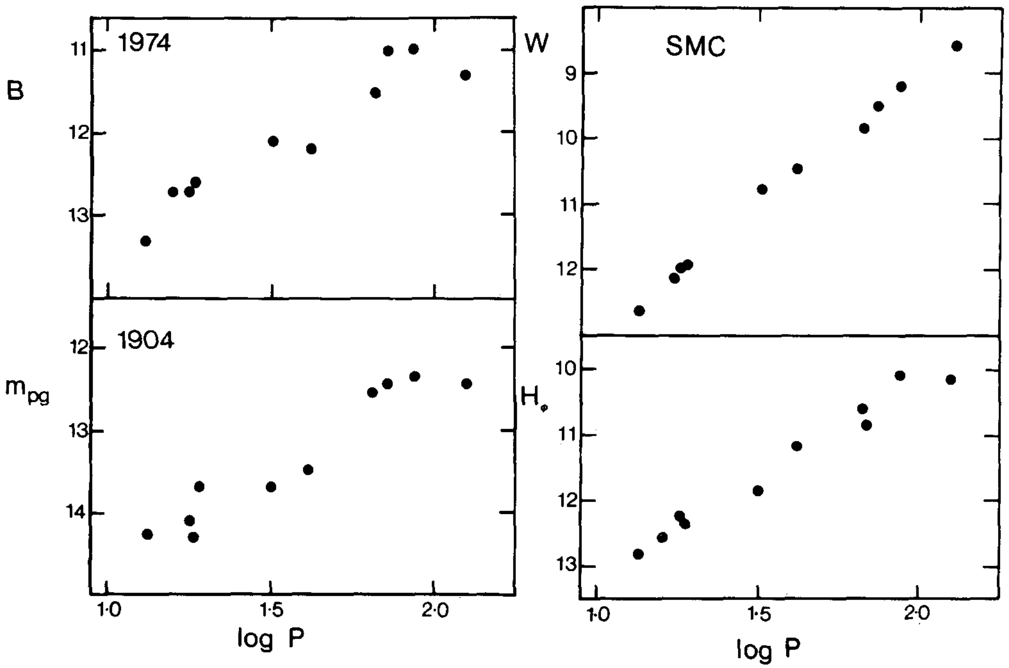

Fig. 1. Progress in the Period-Luminosity relation for long-period SMC Cepheids: (lower left), original maximum-light data from Leavitt showing scatter at fixed period, (upper left) same SMC stars observed photoelectrically show comparable (intrinsic?) scatter, (upper right) reddening-free P-L relation with dramatically reduced scatter (lower right), random-phase near-infrared data again relatively reddening independent and of reduced width.

2. SOME CONCEPTS UNDERLYING THE CALIBRATIONS

The most instructive way to view the cepheid calibration is as follows. Stephan's law states that, to first order, the luminosity of _any_ star can be described by two independently varying parameters: a mechanical/geometric term and a thermal/energetic term. Traditionally these parameters have been the radius and the temperature (colour), controlling the surface area and surface brightness, respectively. All stars therefore obey a Radius-Luminosity-Colour relation. Other pairs of independently varying parameters are certainly acceptable in determining the luminosity but the facts remain that two parameters are required and that their domain is the entire colour-magnitude plane.

So how can it be that Cepheids can have their luminosities determined by only one parameter, the period? The answer is simple. They cannot. They do not. Every star, pulsating or not, has an associated fundamental period of free mechanical oscillation. This period can be used as the mechanical/geometric term in Stephan's law and, it is independent of the thermal parameterization of the system. Accordingly, all stars obey a Period-Luminosity-Colour (PLC) relation; but, the periods of all stars are not observable. In principle, given the radius and mass distribution of any star its fundamental period could be calculated. Fortunately nature provides us with a select sampling of the infinite PLC by making certain stars naturally unstable in their fundamental frequencies. This constraint on the underlying PLC (ie. that there exist finite amplitude, therefore observable, pulsations) is known as the instability strip. Mathematically speaking such a constraint has nothing to do with the form of the underlying equation, it merely specifies the sample available for study.

In our world the constraining instability depends more narrowly on temperature/colour than on luminosity or period. This fact gives rise to an apparent statistical dependence of luminosity on period. Sandage (1958) was the first to fully realize that colour was still an active parameter, controlling the relatively narrow width of the Period-Luminosity trend (PLT).

Briefly, there is no single-parameter characterization for the luminosities of stars. Ultimately at least two parameters define the luminosity. Any observed, statistical correlation between just two variables must be due to an additional condition of constraint which is independent of, and not contained in, the underlying equation. The existence of an observed PLT is historically very fortuitous but equally, variations in that trend, from sample to sample, may be contingent as well, without necessarily arguing for changes in the underlying PLC.

The finite colour-correlated width of the observed PLT is comfortingly accommodated by additional theory and is parameterized in a linear fashion as follows

$$M_V = \alpha \log P + \beta(B-V)_o + \gamma \qquad (1)$$

is the PLC, subject to the equations of constraint

$$M_V(\text{blue edge}) = \delta(B-V)_o + \gamma' \qquad (2)$$

$$M_V(\text{red edge}) = \varepsilon(B-V)_o \quad \varepsilon' \qquad (3)$$

which define the blue and red edges of the instability strip, outside of which the pulsation amplitude drops to zero. Combining equations (1) and (2) gives rise to the PLT as judged by a trace of the blue/bright edge of the instability strip:

$$M_V(\text{blue edge}) = \frac{\alpha\delta}{1-\beta} \log P + \frac{\beta\delta'+\gamma\delta}{1-\beta} \qquad (4)$$

Variations in this trend could be due to changes in the strip position, the PLC or both.

At optical wavelengths the temperature sensitivity of the surface brightness is quite high. On the other hand infrared emissivities are notoriously shallower functions of temperature. Thus we would expect the magnitude width of an infrared instability strip to be significantly narrower than in the optical. The range in infrared luminosity over period is expected to remain the same as in the optical as these differences are dominated by radius differences, which are wavelength independent.

The narrowing of the infrared PLT is of immediate importance in distance determinations. The fitting procedure is more confined and intrinsic temperature-induced differences become less observable, even if present.

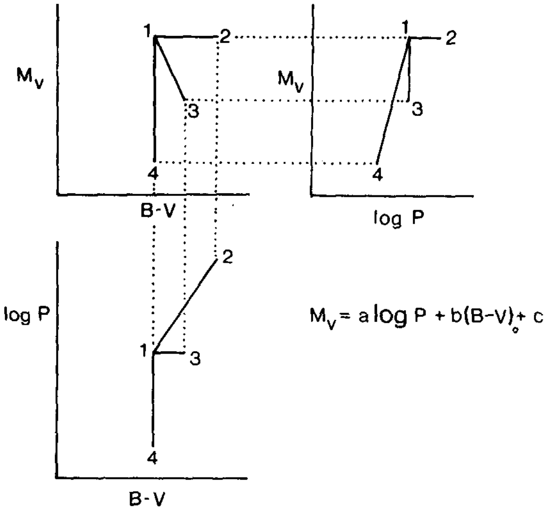

Fig. 2. The trace of stars of similar period (1-3) due to differential reddening and/or temperature effects give rise to a finite width in the M_V - log P plane but as shown each of the representations carries the same information: lines of constant colour are (1-4), lines of constant magnitude are (1-2) in each diagram.

3. REDDENING CORRELATIONS

As comforting as equation (1) may be from a theoretical point of view, the data that calibrate it in the observed world have some disturbing properties. For the extragalactic and galactic cluster cepheids Sandage and Tammann (1968) illustrated that the magnitude and colour residuals from the mean Period-Colour and Period-Luminosity trends were correlated as expected by equation (1) however the correlation was totally consistent with a value of $\beta \sim 3$ which could have been generated by differential reddening of the Cepheids rather than intrinsic colour differences.

In the LMC one Cepheid HV 2749 is notorious for being heavily reddened (Gascoigne 1969). Can it be the only example of reddening in the extragalactic sample or is it noteworthy because of the degree of its reddening ($A_V \sim 1$ mag) above the unknown average? An ingenious method for eliminating this uncertainty was first proposed by van den Bergh (1968) who formed the reddening-free Wesenheit function

$$W = V - R(B-V) \qquad (5)$$

where R is chosen to be the ratio of total-to-selective absorption $A_V/E(B-V)$, such that

$$W = V_o + A_V - R(B-V)_o - R\,E(B-V) = V_o - R(B-V)_o \qquad (6)$$

substituting equation (1) in (6)

$$W = \alpha \log P + (\beta - R)(B-V)_o + \gamma \qquad (7)$$

it can be seen that W has the same period dependence and zero point as the intrinsic PLC only its width (at constant period) is reduced. W effectively deals with the reddening of stars like HV 2749 in bringing them up into the main relation (Madore 1982). But apparently reorders points and changes the period slope of the observed relation (especially at long periods) indicating that differential reddening effects are widespread and even systematic with period.

Using galactic intrinsic colour relations alternative techniques have been employed to derive individual reddenings to Cepheids in the LMC. The results are inconclusive. Martin, Warren and Feast (1979) using very near infrared data (which is less sensitive to reddening than the optical) find small individual reddenings ranging up to E(B-V)=0.20 mag. Madore (1976a) using ultraviolet data finds larger reddenings (up to E(B-V)=0.35 mag) especially for the long-period Cepheids, as suggested by the W analysis.

A selective reddening of long-period Cepheids is especially important to the distance scale as these Cepheids are the first, if not the only, ones detected in the furthest galaxies. These stars are young and may still be associated with the dust complexes in which they were formed. Furthermore their low surface gravities and large atmospheric motions may lead to the self-production of circumstellar dust shells. Support for this hypothesis is found in the large Hα emission detected in a number of the longest-period Cepheids, such as HV 883, while the trend with period may have the same origin as the similar correlation found for Miras (DeGioia-Eastwood, Hackwell, Grasdalen & Gehrz, 1981).

4. METALLICITY

Forever muddying the waters of any search for a universal PLC is the question the effects of metallicity variations from galaxy to galaxy. A variety of inconsistent approaches to the problem exist. It is suggested (Sandage & Tammann 1969) that a universal (ie. metallicity-independent) PLC exists, that a universal instability strip exists and that metallicity controls the evolutionary tracks that variously populate this strip. Iben and Tuggle (1975) have given theoretical (pulsation/interior) arguments and calibrations for the way in which the blue edge and the underlying PLC might vary with metallicity such that

$$\begin{aligned} M_V &= -2.77 - 31.1\ \Delta Z\ (1 - 0.43\ \Delta Z) \\ &\quad -3.64 \log P + 2.63(1 - 0.37\ \Delta Z)(B-V)_o \end{aligned} \tag{8}$$

where $\Delta Z = Z - 0.02$

and finally Gascoigne (1974) has used model atmospheres (Bell and Parsons 1972) to estimate pure blanketing corrections independent of the interior solutions. One thing is agreed on however, lowering the metallicity produces brighter, bluer Cepheids at the level of a few tenths of a magnitude for the expected metallicity difference between the Galaxy and the SMC, for instance. From the pragmatic point of determining distances the only consolation that can be taken is the vain hope that some of the metallicity differences have so far compensated for extinction effects.

Direct photometric determinations of the metal abundances of the SMC Cepheids have been undertaken by Pel, van Generen & Lub (1981) and by Harris (1981) using reddening-free parameters. Their results are mutually consistent and agree with the HII region studies that indicate the mean metallicity of the SMC to be about a factor of 3 lower than the Galaxy. The LMC and other near-by galaxies are expected to have metal abundances bracketed by the SMC and the Galaxy.

5. THE INFRARED ADVANTAGE

As detailed by McGonegal et al. (1982) all of the major uncertainties (with the exception of the effects of metallicity on the interior/pulsation solutions) can be minimized by establishing the calibration in the near infrared. Sufficiently sensitive detectors are available so as to allow any Cepheid with a period obtained in the optical to now be measured with linear detectors in the 1-2 μm region. At the David Dunlap Observatory, a programme is now underway in which the basic calibration has been set up using the traditional galactic cluster and Magellanic Cloud Cepheids while a larger sample of Cepheids in each of the nearest late-type systems of the Local Group (M31, M33, NGC 6827, IC 1613, Sextans A) and the longest-period variables in NGC 300 and NGC 2403 are also being observed. This will provide a uniformly determined set of distances to most of the Local Group and the first independent measurements of distances to the Sculptor and M81 Groups of galaxies.

At the wavelength of the H band (1.6 μm) compared to the V band (4.4 μm) extinction is reduced by a factor of five (Savage and Mathis 1979). The temperature-induced width of the instability strip and the cyclical variations of the individual Cepheids are each reduced by a factor of four (Wisniewski and Johnson 1968) and finally the atmospheric blanketing/backwarming effects of metallicity variations are reduced by at least another factor of five (McGonegal et al. 1982). The efficiency and certainty with which infrared-based distances to Cepheids in external galaxies can now be obtained is sensational news and I believe that these determinations will stand as fundamental for many years to come. A single H-band observation of a single Cepheid observed at a random phase is sufficient to give a distance modulus good to ±0.2 mag.

6. BEYOND THE LOCAL GROUP

Only two other galaxies well outside the Local Group have had their Cepheids studied. NGC 2403 has been extensively investigated by Tammann and Sandage (1968) with the cepheid data yielding a wide range of distances, depending on calibration techniques and reddening corrections. This galaxy is probably an outlying member of the M81 Group. NGC 300 is a very similarly inclined late-type spiral associated with the South Polar (Sculptor) Group. It is certainly closer than NGC 2403 as Graham (1983) has been able to measure complete light curves for the Cepheids in NGC 300 unlike NGC 2403 where only magnitudes around maximum light were successfully measured.

Because of the extreme faintness of the Cepheids in these distant systems the photometry is already at the limit of present-day photographic techniques. Pre-exposure effects caused by the unresolved galaxy background and crowding by adjacent stellar images are two of the most obvious problems limiting these data. Ground-based panoramic linear detectors should be used as soon as possible to check the linearity and zero point of all such photographic studies. Space Telescope images should also be obtained to quantify the effects of crowding.

Easily said, at least one other galaxy in each group needs to be calibrated by Cepheids before back-to-front differences can be estimated and "group distances" determined. Unfortunately, in the north M81 itself has yet to be studied (Baade 1963) and additionally suffers from a bright bulge background component. In the southern hemisphere most of the other members of the South Polar Group are rather highly inclined and are likely to show a heavily reddened and/or crowded population of resolved stars, with NGC 7793 being a possible exception.

I think that it cannot be too strongly emphasised that in all future studies, be they from ground-based observatories or from the Space Telescope, two-colour photometry is absolutely essential. Simply put, one colour serves to discover the variables and their periods while the other colour corrects for reddening. While high-precision BV photometry over the cycles of interest is sufficient to do this through the Wesenheit calibration, all other things (metallicities and reddening laws, etc) being equal. However the most economical way to proceed is probably as follows: (1) obtain identifications and periods at a broad-band wavelength where the product of the detector sensitivity and cepheid light amplitude above the galaxy background will be maximized (the ultraviolet region beyond the Balmer jump shows a dramatic decrease in the unresolved contribution from the K giants while the cepheid amplitude at U is nearly twice that at V) (2) then obtain one or two phase points as far into the infrared as possible to minimize the temperature, amplitude, metallicity and reddening effects.

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