# MAGELLANIC CLOUD AND OTHER EXTRAGALACTIC CEPHEIDS: SOME CURRENT TOPICS

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## INTRODUCTION

Table 1 lists galaxies in which Cepheids are known. The early work on the detection and period determination for these stars forms the basis of subsequent studies. These later studies include the infrared photometry of Cepheids pioneered by the Toronto group and the efforts by various workers to improve the optical photometry. An example of the importance of this latter work is the recent study of M33 by Sandage (1983) in which a revised magnitude scale leads to a distance modulus 0.67 greater than that previously adopted.

Table 1.

| | |
|---|---|
| M31 | Baade and Swope 1963, 1965 |
| M33 | Sandage 1983 |
| IC1613 | Sandage 1971 |
| NGC 6822 | Kayser 1967 |
| LMC | many writers |
| SMC | many writers |
| NGC 2403 and the M81 group | Tammann and Sandage 1968 |
| NGC 300 | Graham (proceeding) |
| Sextans A | Sandage and Carlson 1982 |
| WLM ) | |
| Sextans B ) | |
| NGC 3109 ) | Sandage and others |
| IC5152 ) | (cf. Sandage and Carlson 1982) |
| Leo A ) | |
| Pegasus ) | |

So as to avoid too much overlap with other reviews this paper concentrates on a limited number of topics, mainly related to Magellanic Cloud Cepheids. The aim is to see what these Cepheids tell us about the physical and chemical properties of Cepheids and to assess their potential as distance indicators. Work on Magellanic Cloud Cepheids has been recently reviewed (Feast 1984) and the present paper emphasises work since that review was written. Useful references to various aspects of work on extragalactic Cepheids are: Sandage (1972), van den Bergh (1968, 1977), Fernie (1969), Sandage and Tammann (1981).

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## CHEMICAL ABUNDANCES OF EXTRAGALACTIC CEPHEIDS

So far the Magellanic Clouds are the only galaxies other than our own for which attempts have been made to determine the chemical abundances in Cepheids. Three methods have been used: (1) Washington four colour photometry (Harris 1981), 1983); (2) Walraven five colour photometry (Pel, van Genderen and Lub 1981, Pel 1981, Pel 1984); (3) Rough curves of growth (Laney 1983). The results are given in Table 2.

Table 2. Abundances [A/H] in Magellanic Cloud Cepheids.

| | LMC | SMC |
|---|---|---|
| Harris | -0.09 | -0.65 |
| Pel et al. | -0.2 | -0.6 |
| Laney | -0.06 | -0.50 |
| Adopted | -0.15 | -0.60 |
| Depletion Factor (D) | 1.4 | 4 |

The Washington four colour results are calibrated partly from galactic stars of known metallicity and partly from the models of Kurucz (1979) and Bohm-Vitense (1972). The Walraven results depend on Kurucz (1979) models. The adopted values (Table 2) are close to those derived from HII regions (cf. Laney's tabulation).

The Washington data shows an apparent scatter in abundance in both Clouds. The most likely cause is either a real spread in abundance in each Cloud or else the effect of a range of temperatures at a given period (i.e. the effect of finite width of the instability strip), or of course a combination of both. Harris (1983) tentatively suggests that there may be a real spread in [A/H] of ±0.10 in the LMC and ±0.15 in the SMC. The work discussed below on the reddenings of Magellanic Cloud Cepheids and on the P-L-C relation leaves rather little room for abundance variations. Evidently this matter needs further study. It may be possible to combine the Washington and the BVI data for individual Cepheids to provide self consistent reddenings, intrinsic colours and abundances.

## THE SIGNIFICANCE OF ACCURATE INTERSTELLAR REDDENINGS FOR MAGELLANIC CLOUD CEPHEIDS

Caldwell and Coulson (1984a) have now thoroughly investigated the use of BVI colours to derive accurate individual reddenings of Cepheids and have derived reddenings for both LMC and SMC Cepheids. In the SMC these results depend to a large extent on 1060 BVRI observations of 53 Cepheids (Caldwell and Coulson 1984b). The reddenings are based on the B-V/V-I intrinsic line of Dean et al. (1978) corrected for abundance effects using Bell-Gustafsson (1978) models. We are of course dependent on the accuracy of the models for the reddening zero points, but within this framework the reddenings are not very sensitive to the abundances. A change in [A/H] of 0.1 (D = 1.26) only changes $E_{B-V}$ by 0.011. For the sample of Cepheids observed the mean reddenings are 0.074 (LMC) and 0.054 (SMC). Mean values close to this are found for a range of other types of object in the Clouds.

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Both Harris (1981) and Isserstedt (1976, 1980) have used indirect arguments based on Cepheids to suggest that the ratio $R = Av/E_{B-V}$ in the SMC is different to that in the Galaxy. Harris finds R to be three times larger in the SMC than in the Galaxy. If this were really so it would seriously complicate the discussion of Magellanic Cloud Cepheids. Fortunately it is possible to derive R rather directly from infrared photometry of some highly reddened A type supergiants in the SMC and a value close to the galactic value (3.1) is found (Feast and Whitelock 1984).

For the sample of Cepheids studied the dispersion in reddenings is remarkably small in each Cloud. The observed dispersions are only 0.037 (LMC) and 0.026 (SMC). Some of the scatter will be due to observational errors in the colours. Making allowance for this reduces the dispersions to 0.032 (LMC) and 0.019 (SMC). This result has several important consequences.

(1) It is not reasonable to assume there is no real scatter in the reddenings. This means that there is very little leeway left for any significant spread in the intrinsic line. We conclude that the BVI locus is narrow and that reddenings of high precision can be obtained from it.

(2) The fact that the relative values of the derived reddenings are at least as accurate as the observed scatter is of relevance to the discussion of the P-L-C relations. Recent suggestions that the P-L-C relation is not firmly based depend essentially on adopting a much greater spread in Cepheid reddenings than is consistent with the BVI data (cf. Feast 1984 and references there).

(3) Although the derived reddenings are relatively insensitive to abundance the observed scatter in $E_{B-V}$ values places limits on the scatter in abundance. For instance Harris (1983) suggest a possible scatter of ±0.15 in [A/H] in the SMC. This would produce an apparent scatter of ±0.016 in $E_{B-V}$. The observed scatter corrected for observational uncertainty is only 0.019 so that such abundance effects would make the real reddening scatter negligible which appears somewhat unlikely.

The ability to derive reddenings of high accuracy from BVI photometry will, one hopes, be exploited to the full in our own and nearby galaxies.

## THE P-L-C RELATION AND THE STRUCTURE OF THE MAGELLANIC CLOUDS

It was shown by Martin *et al.* (1979) that, for LMC Cepheids with individually determined reddenings a P-L-C relation was a distinctly better fit than a P-L relation. Caldwell has been re-investigating this problem for both Clouds allowing for a possible distribution of Cepheids along the line of sight. This is a particularly illuminating study as it shows the power of Cepheids to determine accurate relative distances within the Clouds. The potential of Cepheids in this regard was shown some years ago by Gascoigne and Shobbrook (1978). They observed Cepheids on the far eastern and western edges of the LMC and confirmed de Vaucouleurs'(1960) model of a flattened system tilted with respect to the line of sight.

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It would be valuable to obtain BVI reddenings for these Cepheids to improve the accuracy of the discussion. However even the available sample of LMC Cepheids with individual reddenings shows clear evidence of a tilt. Taking this tilt into account the scatter about a P-L-C relation is very small (0.10 ± 0.01). Purely internal errors in magnitudes, colours and reddenings lead to an estimated scatter of 0.08 ± 0.01). Within the accuracy of the observations therefore the P-L-C relation may be considered an exact relationship. Furthermore the thickness of the LMC disc must be very small.

Most Cepheids are expected to be on their second crossing of the instability strip. If first crossing Cepheids were numerous they would be expected to introduce a scatter in the P-L-C relation which is not found. There is also no room for significant scatter due to abundance variations, binarity or other effects. Caldwell (cf. Feast 1984) has estimated the effect of abundance on the P-L-C zero point. Using this we can estimate roughly that a scatter in [A/H] of ±0.10 as proposed by Harris for the LMC when added to the internal scatter given above would lead to a predicted total scatter of ±0.13. This is becoming uncomfortably large compared with the observational scatter of 0.10 ± 0.01 and suggests at least tentatively that the scatter in abundance is less than Harris estimates.

The case of the SMC is particularly interesting. Here again a P-L-C relation and a tilt can be determined simultaneously. The tilt found is remarkably large (70°). There have been indications from work on early type stars (e.g. Ardeberg and Maurice 1979, Florsch et al. 1981) and from a preliminary report on infrared observations of Cepheids (Welch and Madore 1984) that there is a considerable depth to the SMC. Mathewson and Ford (1984) have interpreted 21cm work to mean that the SMC is divided into two sub-clouds. It is possible that the new results could be represented by groups of Cepheids at distinctly different distances rather than by a single plane. The distances involved are large Δ (Modulus) ∿0.4 (i.e. ∿13 kpc). This in fact is just about the separation of fragments expected if the SMC were disrupted ∿2 x $10^8$ years ago by a close passage of the LMC (cf. Mathewson 1984).

The model of the SMC as a tilted plane may thus be too simple a picture. Nevertheless even on this fairly crude model the fit to the data is very good. The scatter is only 0.11 ± 0.01, comparable to the value in the LMC. Despite the small value, Caldwell's error analysis suggest that there is some small extra scatter in addition to the internal photometric errors. This is likely to be due to the complex structure of the SMC but it remains possible, at least in principle, that the presence of first crossing Cepheids or other causes contribute.

The superiority of a P-L-C relation to a P-L relation is shown by the fact that the scatter about the latter is 0.23 (LMC) and 0.28 (SMC) compared with 0.10 and 0.11 respectively for the P-L-C relation.

The ability to determine relative distance moduli of Cepheids to an accuracy of 0.10 (including photometric and reddening errors) is very impressive. It is rather striking that this power of the Cepheids has not yet been exploited to the full in our own Galaxy.

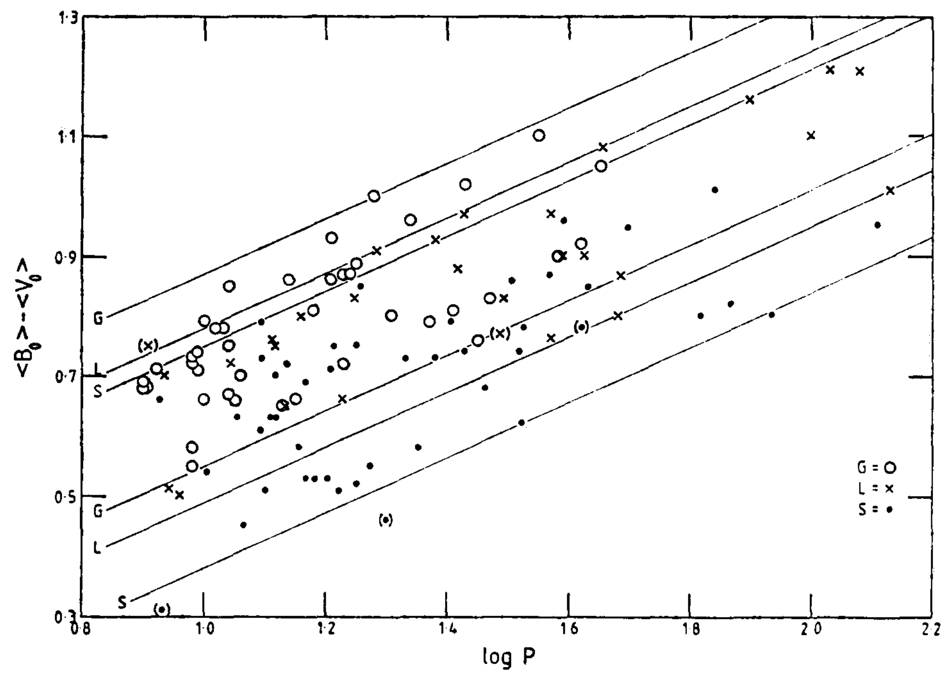
For our understanding of Cepheid variables it is important to have an accurate value for the coefficient of the colour term (β) in the P-L-C relation. Initially it was difficult to disentangle the colour term from interstellar reddening. Martin et al. (1979) were able to do this and obtained β = 2.70 from a maximum likelihood solution which is the appropriate method for such a multivariant problem. A least squares solution is inappropriate but the value found (β = 2.18) at least gives some lower limit to β. Feast and Balona (1980) and Balona (1984) have investigated the effects of errors in the reddenings on the value of β. These turn out to be small, perhaps reducing β from 2.7 to ∿2.6. Caldwell (private communication) has now studied this problem extensively for both the LMC and the SMC taking into account effects due to the structure of the Clouds discussed above. It is fairly obvious for instance, that if we assume that all the scatter (above the internal photometric errors) is due to real differences in distance moduli of the Cepheids, unconstrained by any overall structure of the Clouds, this will give a solution which is mathematically similar to one in which the bulk of the errors are in the V magnitudes. This is the limit in which a least squares solution applies and it is not surprising therefore that in each Cloud a low value of β (∿2.1) is found. This is an extreme case and the most physically realistic models yield values of β near 2.5 in both Clouds. Because there is some sensitivity to the models, to the period range selected and to the ratio of total to selective absorption used, the standard error is estimated at 0.3.

Within the errors the values of β are the same in the LMC and the SMC. Considerably higher precision is required to determine whether or not there is a dependence of β on metallicity as suggested theoretically (e.g. Gascoigne 1974).

PERIOD-COLOUR RELATION

Figure 1 shows the $(\langle B\rangle - \langle V\rangle)_o$ against log P plot for Cepheids with BVI reddenings in the LMC and SMC together with galactic Cepheids with BVI reddenings (or equivalent) in Dean et al. (1978) and in the same period range. Dean et al. determined a slope for the galactic relation (over a wider period range than plotted here) of 0.46. Lines of this slope are used in Figure 1 to define the limits for the three galaxies. Each galaxy populates a strip of considerable width. There is no evidence that the slope varies from galaxy to galaxy. The widths are also not significantly different (Galaxy = 0.32, LMC = 0.29, SMC = 0.37). On Johnson's temperature scale for supergiants this corresponds to a width of about 750K. With such a wide instability strip and the possibility that this will be non-uniformily filled, it is difficult to determine precisely the mean colour displacement from galaxy to galaxy. The LMC strip shown is 0.08 to the blue of the one for the Galaxy and the SMC strip 0.07 bluer still. Some of this is due to the effects of abundances on the (B-V) colours and it is not yet clear whether there are any significant variations of the temperature limits to the strip with metallicity.

Figure 1. The Period-Colour strips for the Galaxy (G), LMC (L) and SMC (S).




The widths of the P-C and P-L relations are of course related. There is evidence that both these strips become narrower at shorter periods (e.g. the P-L relation of Martin et al. (1979) in the LMC and the P-C relation in the Clouds and in the Galaxy of Butler (1976, 1978), Martin (1980) and Dean et al. (1978) see also Pel and Lub 1978). The theoretical work of Deupree (1980) in fact suggests that the instability strip will decrease in width at lower luminosities. This problem needs further careful examination since there is always the possibility of a spuriously narrow strip resulting from observational bias against fainter, redder variables.

The recent work by Sandage (1983) in M33 shows a P-L strip which fits that of the LMC well. There is no evidence that any galaxy violates the P-L relation of the Magellanic Clouds although there is the well known problem of the small slope (and small scatter) in IC1613. Sandage (1971) has attributed this to poor filling of the instability strip.

## RADII AND SURFACE BRIGHTNESS

It is important to compare Cepheids in our Galaxy with those in other galaxies in as many ways as possible to check for any fundamental differences. The period-radius relation provides one way of doing this. Radii can be determined by combining light, colour and radial velocity curves and until recently no radial velocity curves had been determined

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for extragalactic Cepheids. A programme has been in progress for some while at ESO using CORAVEL to determine velocity curves for long period Cepheids in the LMC and SMC (Imbert and Prévot 1981). Photon counting systems on spectrographs can also be used to determine velocity curves for Magellanic Cloud Cepheids and a few Cepheids have been studied in this way at SAAO. 3 Cepheids in the LMC and one in the SMC with log P $\sim$ 1 give radii which fit the mean period-radius relation for galactic Cepheids (Balona 1977). They also show that the slope of the surface brightness-colour relation (A) is the same (2.30 ± 0.15) in the Clouds as in the Galaxy (2.15 ± 0.02).

## INFRARED WORK ON MAGELLANIC CLOUD CEPHEIDS

The Toronto workers have pioneered the use of JHK infrared magnitudes in the study of extragalactic Cepheids. They have shown that even random phase observations define a P-L relation of acceptable accuracy ($\sigma = 0.25$). The application of this method to Cepheids beyond the Magellanic Clouds has been summarized by Madore (1984). Laney and Stobie (1984) have obtained high accuracy JHK photometry of a sample of LMC and SMC Cepheids. One aim has been to obtain good light and colour curves so that the infrared behaviour of Cepheids can be studied in detail. Some Cloud Cepheids have quite large light amplitudes ($\Delta H \approx 0.5$). A P-L relation

$$H_o = 3.37 \log P + \gamma \qquad \sigma = 0.14$$

is found for the LMC and the main body of the SMC. However as with the BVI data a significant reduction in errors is obtained (especially when all the SMC observations are used) by introducing tilts to the Clouds and a colour term. The tilts strongly support the parallel BVI results. In particular the infrared work confirms the great range of distances in the SMC found from the BVI data.

The observations also strongly suggest that in a P-L-C relation of the form

$$H_o = \alpha_1 \log P + \beta_1 (J-K)_o + \gamma_1$$

there is a significant colour term with $\beta_1 \approx 3 \pm 1$. An infrared colour coefficient of about this amount is in fact anticipated from the observed optical value of $\beta$ and the present results therefore provide additional confirmation of the optical value. For many applications of course the infrared P-L relation quoted earlier is quite satisfactory.

It has long been known that the very long period Cepheids (P > 100 days) are anomalously faint with respect to linear P-L and P-L-C relations in BV wavelengths in both Clouds. The results of Laney and Stobie show that the effect persists into the infrared. It cannot therefore be due to the effects of circumstellar reddening (as has sometimes been suggested) unless the extinction is essentially neutral. An explanation of these Cepheids is much to be desired.

## ZERO POINT OF THE P-L-C RELATION

Work on the zero point of both the P-L-C and the (infrared) P-L relations was summarized recently (Feast 1984 see also Schmidt 1984) and distance moduli of 18.7 (LMC) and 19.2 (SMC) were adopted. Support for these distances comes from the OB stars in the Magellanic Clouds

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(Crampton 1979, Crampton and Greasley 1982). On the other hand some recent work suggests that these distance moduli may be too large by about 0.2 (e.g. Hβ photometry, Schmidt 1984, Balona and Shobbrook, 1984, Balona 1984). There are welcome signs that new observational data will help materially to solve this problem. For instance, besides the Hβ work, there is an extensive re-investigation by Pel (1984) of the cluster NGC 6087 which contains the Cepheid S Nor. Another example is the cluster NGC 6067 which probably contains two Cepheids (Coulson and Caldwell, 1984). Walker and Coulson (1984) have obtained a greatly improved c-m diagram of this cluster using a CCD camera. Their new result tends to support the Shobbrook-Balona distance scale.

The present calibration of the P-L-C zero point is probably good to 0.2. Hopefully the accuracy will be considerably improved in the near future.

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