THE ASTROPHYSICAL JOURNAL, 273:539–543, 1983 October 15

THE DISTANCE TO NGC 6822 FROM INFRARED PHOTOMETRY OF CEPHEIDS[1]

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Received 1982 November 17; accepted 1983 March 28

ABSTRACT

H band observations have been obtained for nine Cepheids in the Local Group galaxy NGC 6822. The near-infrared period-luminosity relation is almost identical to those for the Magellanic Clouds and the Galaxy. Comparison with a calibration of the period-luminosity relation for these three galaxies yields a true distance modulus of 23.47 (± 0.11) mag, for $E(B-V) = 0.36$ mag. Several Cepheids in NGC 6822 seem to be affected by reddening internal to the galaxy.

Subject headings: galaxies: individual — galaxies: Local Group — stars: Cepheids

I. INTRODUCTION

NGC 6822 is one of four irregular galaxies in the Local Group. Previous estimates of the distance to NGC 6822 are based primarily on a single study of the Cepheids by Kayser (1967), in which the slope of the optical period-luminosity ($P-L$) relation was found to be similar to those for the Magellanic Clouds. Kayser obtained a true distance modulus $(m-M)_0 = 23.75$ assuming a foreground reddening of 0.27 mag. De Vaucouleurs (1978) has combined the Cepheid data with information on secondary indicators (specifically, the brightest blue supergiants and the brightest red variable in the galaxy) to obtain his estimate of 23.73. Tammann (1969) has used the color information provided by Kayser to derive a period-luminosity-color (P-L-C) relation for the galaxy. Combined with his relation for the Galaxy, he obtains a distance modulus of 23.95 for NGC 6822. A problem in all of this work is that NGC 6822 lies close to the galactic plane ($b = -18°$) and, as a result, corrections for interstellar extinction are very uncertain. Van den Bergh (1968, 1975, 1977) has attempted to circumvent the extinction problem by reanalyzing Kayser's Cepheid data in terms of the Wesenheit function, $W = \langle V \rangle - R_V(\langle B \rangle - \langle V \rangle)$, where $R_V = A_V/E(B-V)$ is the ratio of total to selective absorption. Provided the correct value of R is used, the W function is reddening free. Van den Bergh has used a number of different values for R to produce distance estimates ranging from 23.33 to 24.21. Van den Bergh's work also showed large deviations in the reddening estimates, with $E(B-V)$ varying from 0.19 to 0.37 mag, depending upon the emphasis placed on the data gathered by Kayser on foreground stars. Later work by van den Bergh and Humphreys (1979) investigated the possibility of internal reddening within NGC 6822 itself, and its effect on the P-L relation.

Recently, a new technique has been developed which minimizes the effects of reddening and has other advantages as well. By observing Cepheids in the near-infrared, a P-L relation can be constructed which is not only relatively insensitive to the reddening, but also has a much smaller temperature-induced width and is less affected by metallicity differences between galaxies. Observations of a large number of Cepheids in the Magellanic Clouds (McGonegal 1982; McGonegal *et al.* 1982; 1983*b*) show that *random-phase* near-infrared photometry produces a P-L relation with a smaller dispersion than time-averaged V band measurements. Furthermore, the curvature of the P-L relation at long periods is reduced in the near-infrared, in agreement with Madore's (1976) contention that long-period Cepheids suffer selectively greater reddening than do shorter-period ones.

Because the distance of NGC 6822 is so heavily affected by the choice of extinction values, and because it is next nearest Local Group member, we felt that this galaxy would be an excellent choice with which to extend the near-infrared Cepheid P-L relation. In the remainder of this paper we shall describe our observations of the Cepheids in NGC 6822, and derive a distance for this object, based upon comparison with the near-infrared P-L relation for the galactic calibrating

[1]Research reported in this paper used the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

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Cepheids. Comparison with previous studies will be made.

II. OBSERVATIONS

We have obtained near-infrared observations of nine of the 13 known Cepheids in NGC 6822. Seven of these objects were measured on the night of 1982 June 11/12 with the Multiple Mirror Telescope (MMT). Two Cepheids, V13 and V30, were measured by Dr. H. Campins with the NASA-Infrared Telescope Facility (IRTF) on the night of 1982 June 24/25. For five of the Cepheids which had already been observed, further measurements were obtained on the nights of 1982 September 8/9 and 12/13 with the 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO). All observations were in the H photometric band (1.65 μm). This band represents a compromise between the long wavelengths required to minimize the reddening and the background limitation imposed by the thermal emission of the optics in the telescope and photometer. On the MMT an aperture of 9″ was used, with a chop of approximately 10″. Owing to problems with one of the chopping secondaries, only five of the six mirrors could be operated, reducing the effective aperture of the telescope to 4.1 m. Because of the altitude-azimuth mounting of the MMT, the chop angle varies throughout the night, being north-south at the meridian. Care was taken not to observe any Cepheid when there was a possibility that the chop angle would produce contamination in the reference beam. The IRTF observations employed an aperture of 4″. A north-south chop of 6″ was used for V13, while for V30 the chop was increased to 30″. All observations at CTIO employed a 7″ aperture chopping 20″ in right ascension.

The standards observed were on the system described by Elias *et al.* (1982). All nights were photometric at approximately the 3% level; however, there is a possibility that thin cirrus could have interfered with the IRTF observations. Except for the night of September 8/9, when the seeing was approximately 3–4″, all measurements were made under seeing conditions of 1″ or better.

The H band magnitudes are shown in Table 1, along with their photometric errors. In addition, the periods of the Cepheids are shown (Kayser 1967). Individual comments follow.

V13: No apparent beam contamination.

V7: No apparent beam contamination.

V2: Definite contamination in main beam (faint star within 3″ of V2). Possible contamination in south sky beam (MMT). Probable effect < 0.2 mag.

V28: Definite contamination in main beam (faint star within 3″ of V28). Probable effect < 0.1 mag.

V29: Possible contamination in North sky beam toward end of integration (MMT).

V17: No apparent beam contamination.

V21: Possible beam contamination in both sky beams toward end of integration (MMT).

V5: No apparent beam contamination.

V30: No apparent beam contamination.

The uncorrected H band P-L diagram for NGC 6822 is illustrated in Figure 1. Error bars are shown where they exceed the size of the symbol used in the diagram.

III. THE DISTANCE TO NGC 6822

As can be seen from Figure 1, the galactic P-L relation fits the data of NGC 6822 very well; however, it should be possible to obtain independently the H band P-L relation for this galaxy. There are a number of points to consider before doing so. First, because of the large differences in the photometric errors obtained for the various Cepheids in NGC 6822, it is completely inappropriate to solve for the relation by using even weighting among the data points. On the other hand, if we solve for the P-L relation by weighting the Cepheids according to their photometric errors alone, only the brightest Cepheids will contribute to the solution significantly. It would be more appropriate, therefore, to augment the photometric errors by the intrinsic dispersion

TABLE 1

H BAND MAGNITUDES FOR CEPHEIDS IN NGC 6822

CEPHEID	log P	H MMT	H IRTF	H CTIO	$H_{adopted}$
V13	1.957	...	14.62±0.05	14.99±0.05	14.79±0.04
V7...........	1.816	15.28±0.04	...	15.03±0.05	15.18±0.03
V2...........	1.573	16.24±0.06	...	... ...	16.24±0.06
V28	1.540	16.01±0.08	...	15.86±0.06	15.91±0.05
V29	1.503	16.63±0.10	...	16.30±0.06	16.39±0.05
V17	1.285	16.39±0.07	...	...	16.39±0.07
V21	1.242	17.98±0.27	...	...	17.98±0.27
V5...........	1.126	17.31±0.11	...	...	17.31±0.11
V30	1.037	... ...	17.44±0.51	17.59±0.12	17.58±0.12

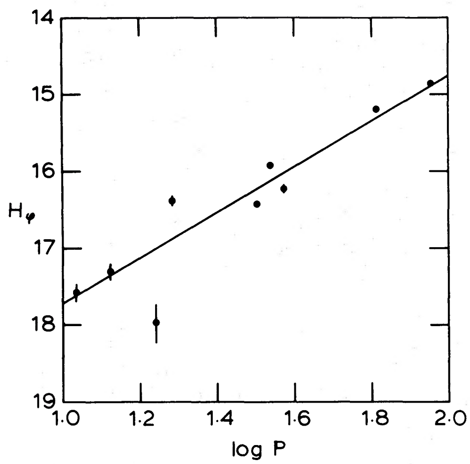

FIG. 1.—Period-luminosity diagram for NGC 6822. Periods are from Kayser (1967). The solid line shows the H band P-L relation for the Galaxy, $H = -2.92 - 3.01 \log P$, determined from 10 cluster Cepheids (Welch 1983) with a zero-point shift of 23.66 mag.

of the instability strip. This can be estimated from the P-L relation for the LMC (McGonegal *et al.* 1982), where the photometric errors for Cepheids of both long and short period are much less than the observed dispersion from the ridge line of the P-L relation. This is due to a combination of temperature and radius effects relating to the intrinsic strip width and random phasing of the observed points. For the LMC, we find a dispersion of approximately 0.25 mag. If we add this in quadrature to the photometric errors, the resultant weights for the least-squares fit remain approximately equal for all but the faintest three Cepheids. The formal solution under this condition is

$$H = 20.83(\pm 0.46) - 3.07(\pm 0.30) \log P. \quad (1)$$

Within the errors, the slope of the P-L relation for NGC 6822 is identical to that for the Galaxy and for the Magellanic Clouds (McGonegal 1982).

We can therefore fix the slope for NGC 6822 and compare the zero point to that for galactic Cepheids. McGonegal *et al.* (1983*a*) have found the galactic H band P-L relation to be

$$H = -2.84(\pm 0.14) - 2.95(\pm 0.14) \log P \quad (2)$$

for an unweighted fit for nine Cepheids. However, only seven of these objects are cluster Cepheids, and several of the longer period variables have limited phase coverage. Welch (1983) has obtained near-infrared observations which yield phase-averaged magnitudes for 10 cluster Cepheids. By assuming appropriate weighting corresponding to the uncertainties in the distance moduli to the Cepheids, he finds a significantly different P-L relation from that of McGonegal *et al.* (1983*a*), namely

$$H = -2.76(\pm 0.16) - 3.14(\pm 0.14) \log P. \quad (3)$$

Most of the difference between the two relations can be attributed to a single long-period Cepheid, RS Pup, which affects the slope of the P-L relation rather heavily. The observations reported by McGonegal *et al.* (1983*a*) were made when RS Pup was at minimum light, and this star still has a significant amplitude in the near-infrared.

Because of the uncertainties involved in the galactic P-L relation, we have chosen to fit the data for NGC 6822 to a P-L relation constructed from all the Cepheids observed in the Galaxy, the LMC, and the SMC. The slope calculated from all three galaxies is probably more accurate than that derived from the limited number of galactic Cepheids. A multiple regression routine has been created which simultaneously solves for the slope and the zero points for the three galaxies, using the data from Welch (1983) for the galactic Cepheids, and McGonegal *et al.* (1982; 1983*a*) for the Magellanic Clouds. Following Welch, for the galactic Cepheids the uncertainties were estimated to be 0.2 mag, except for two highly reddened objects, V367 Sct and TW Nor, whose distance moduli are probably uncertain by 0.5 mag. For the Magellanic Clouds, the uncertainties were adjusted so that the mean weight for a Cepheid was equal to the dispersion of an unweighted fit to each galaxy. The mean dispersion for both the LMC and SMC was 0.25 mag. Under the multiple regression fit, the following P-L relation is obtained:

$$H = -2.92(\pm 0.09) - 3.01(\pm 0.06) \log P. \quad (4)$$

It should be remembered that, while the slope of the P-L relation has been set by the Cepheids in all three galaxies, the zero point is determined solely by the 10 galactic Cepheids. If we now set the slope to be -3.01, the mean dispersion of the H band zero point becomes 0.07 mag for the galactic cluster Cepheids. The final distance modulus for NGC 6822 will incorporate this as the uncertainty of the zero point.

For NGC 6822, we again use the same weighting scheme, as the intrinsic dispersion of the P-L relation will still be similar to that found for random-phase observations of the LMC. Under this condition, the following relation is obtained:

$$H = 20.74(\pm 0.09) - 3.01 \log P, \quad (5)$$

implying that the apparent H band distance modulus for NGC 6822, $(m - M)_H = 23.66$. This must still be corrected for the small but appreciable H band extinction in NGC 6822 to obtain the true distance modulus. From the mean infrared galactic extinction curve of Rieke and Lebofsky (1983), we find that $A_H = 0.54(\pm 0.03)$ $E(B -$

V). As mentioned previously, estimates for the galactic reddening toward NGC 6822 vary from 0.19 to 0.37 mag, and possibly as high as 0.42 mag, if the reddening found for several OB stars in NGC 6822 is also applicable to the Cepheids (van den Bergh and Humphreys 1979). If we take a 0.36($\pm$0.06) mag to be the most likely value for the reddening, the true distance modulus of NGC 6822, $(m - M)_0 = 23.47(\pm 0.11)$. We have taken the error to be the quadratic sum of the errors implicit in the fits to the zero points of the galactic calibrating Cepheids and the Cepheids in NGC 6822, plus the uncertainty in the H band extinction.

Comparison of the distance modulus obtained in the present study with those derived on the basis of Kayser's (1967) optical work is not a simple matter. Many of the previous estimates used a distance modulus of 3.03 for the Hyades. This will affect the zero point of the galactic Cepheid P-L relation significantly.

In Table 2 are listed several published estimates for the distance to NGC 6822 that are either fully or partially based on Cepheid data. In column (1) the study and its publication year are found. Columns (2), (3), and (4) give the reddenings for NGC 6822, the LMC, and the value of $R_V = A_V/E(B - V)$ used. Column (5) shows the intrinsic distance modulus for NGC 6822 derived in the study. In column (6) we have defined a parameter, Δ_1, to be the difference in distance modulus between NGC 6822 and the LMC. This should be independent of the Hyades distance modulus and will only be affected by uncertainties in the reddenings toward the two galaxies. Kayser (1967) refers to the work of Gascoigne and Kron (1965) for the distance to the LMC. All the other studies base the LMC distance on several different methods which are discussed therein. In columns (7) and (8) second estimates for the distance to NGC 6822, and the difference between it and the LMC are shown. Here, however, we have used similar values for the reddening to NGC 6822 (0.36 mag) and to the LMC (0.05 mag), and have defined $R_V = 3.1$. Column (10) provides explanatory notes. At the bottom of the table, the mean and dispersion for the quantities, $(m - M)_{0,1}$, Δ_1, $(m - M)_{0,2}$, and Δ_2 are given.

It is immediately apparent that, regardless of the value of the Hyades distance modulus used in the various studies, the major factor contributing to the large differences among the distance moduli to NGC 6822 is the uncertainty in the reddening. For both the $(m - M)_{0,1}$ and Δ_1, the dispersion is well in excess of 0.3 mag. However, this decreases by a factor greater than 2 if a uniform reddening is applied. The difference in the dispersions shown by $(m - M)_{0,2}$ and Δ_2 may reflect the changed value for the Hyades distance, but this is not at all clear. It is also not surprising that the estimates for the distance to NGC 6822 should be so similar when uniform reddening is applied, since all but the present study are based upon the work of Kayser (1967). Our work, however, is almost insensitive to the reddening used [e.g., an error of 0.1 mag in $E(B - V)$ would change our distance modulus by 0.05 mag]. That these moduli agree fairly well with our value is a strong indication that the mean reddening toward NGC 6822 is high. It would therefore seem appropriate to use a value for $E(B - V)$ somewhere between the average foreground reddening of 0.27–0.3 mag and the extreme

TABLE 2

COMPARISON OF DISTANCE MODULI FOR NGC 6822

Study (1)	$E(B-V)$ NGC 6822 (2)	$E(B-V)$ LMC (3)	R_V (4)	$(m-M)_{0,1}$ (5)	Δ_1 (6)	$(m-M)_{0,2}$ (7)	Δ_2 (8)	Notes (9)
Kayser (1967)	0.27	0.05	3.0	23.75	5.25	23.44	4.94	1
van den Bergh (1968) ...	0.30	0.06	3.0	23.33	4.88	23.12	4.67	2
Tammann (1969)	0.27	0.08	3.0	23.95	5.36	23.55	4.80	3
van den Bergh (1975) ...	0.19	0.06	3.0	24.21	5.55	23.67	4.98	2
van den Bergh (1977) ...	0.27	0.05	3.4	23.53	5.12	23.34	4.91	2
de Vaucouleurs (1978) ...	0.18	0.11	3.4	23.73	5.42	23.41	4.82	2, 4
van den Bergh and Humphreys (1979)	0.42	0.05	3.0	23.04	4.63	23.32	4.89	5
Present work	0.36	0.11	3.1	23.47	4.76	23.47	4.73	6
Mean..................				23.63	5.12	23.42	4.84	
Dispersion				0.37	0.33	0.16	0.11	

NOTES.—1. Distance to LMC from Cepheid P-L relation alone (Gascoigne and Kron 1965).

2. Distance to LMC from several methods.

3. Distance to LMC from several methods; Cepheid P-L-C relation used instead of P-L relation. Distance to NGC 6822 based on Cepheid P-L-C relation.

4. Distance to NGC 6822 from Cepheid P-L relation, brightest blue supergiants, and brightest red variable.

5. Uses distance to LMC derived in van den Bergh (1977).

6. Distance to LMC from infrared Cepheid P-L relation.

value of 0.42 mag found by van den Bergh and Humphreys (1979) for the OB supergiants in NGC 6822. As mentioned previously, we have taken $E(B-V)=$ 0.36 mag to be representative of the mean for NGC 6822.

Our data also strongly support the view that the Cepheids in NGC 6822 suffer differing amounts of extinction. For example, the brightest Cepheid in the optical is V7, while we find in the infrared that the longest period Cepheid, V13, is significantly brighter than V7. The Cepheid V17 also exhibits a marked degree of brightening as the wavelength of observation is increased. From Kayser (1967) it can be seen that V17 lies near the regression line in the B band, but brightens relative to the other Cepheids in the visual. At H, V17 lies approximately half a magnitude above the regression line. We can also examine V2, V28, and V29, all of which have similar periods and thus should have similar colors. V28 is almost 0.4 mag fainter than the average magnitude of V2 and V29 at B, but brightens relative to these stars by about 0.2 mag in the V band. In the H band V28 is 0.4 mag brighter than the average of the other two stars. It is also worth noting that V2 brightens relative to V29 as the wavelength increases. It may be possible to attribute the dependence of relative luminosity upon wavelength to other causes, but it is most simply explained by differential reddening among the Cepheids within the galaxy.

IV. CONCLUSIONS

We have constructed the H band P-L relation for Cepheids in NGC 6822 and have used it to determine the distance to this galaxy. In form the relation is statistically identical to those independently determined for Cepheids in the Galaxy and the Large and Small Magellanic Clouds. A detailed comparison of the optical and infrared data indicates substantial differential reddening within NGC 6822 itself. The true distance modulus of NGC 6822 is 23.47($\pm$0.11) mag, based on an average reddening of $E(B-V)=0.36$ mag and using a calibration for the P-L relation which assumes a distance modulus of 3.29 for the Hyades.

We should like to thank the staffs of the Multiple Mirror Telescope Observatory and Cerro Tololo Inter-American Observatory for their help, and Dr. Richard Rudy for rendering assistance at the MMT. We also thank Dr. George Rieke for providing us the opportunity for using the infrared photometer at the MMT in advance of its commissioning as a facility instrument, and for valuable discussions during the analysis of the observations. We are grateful to Dr. Humberto Campins for providing us with the measurements of V13 and V30. This work was supported by the National Science Foundation and the Natural Sciences and Engineering Research Council Canada.

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