Distance to the RR Lyrae Star V716 Monocerotis

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ABSTRACT

We present high quality BVRI CCD photometry of the variable star V716 Monocerotis (= NSV 03775). We confirm it to be an RR Lyrae star of variability type ab (i.e. a fundamental mode pulsator), and determine its metallicity ([Fe/H] = −1.33 ± 0.25), luminosity (MV = 0.80 ± 0.06), and foreground reddening (E(B−V) = 0.05−0.17) from the Fourier components of its light curve. These parameters indicate a distance of 4.1 ± 0.3 kpc, placing V716 Mon near the plane of the Galaxy well outside the solar circle.

Subject headings: stars: distances — stars: variables: other — stars: individual (V716 Monocerotis)
1. Introduction

The classification of variable stars can often depend sensitively on the available observational data. For example, the periodic rapid brightness increase displayed by RR Lyrae stars can easily be confused with typical variability of cataclysmic variables (such as the start of a dwarf nova outburst) if only limited observations are available. A number of alleged cataclysmic variables (CVs) have been reclassified as RR Lyrae stars following more extensive observation (e.g. CG Muscae, Layden & Wachter 1997). As RR Lyrae variables are particularly useful objects for exploring Galactic structure and dynamics, owing to the availability of relationships between their observational properties and their distances, it is desirable to continue to reclaim misclassified RR Lyrae stars from the ranks of the CVs.

V716 Monocerotis (= NSV 03775) was first identified as a variable star by Hoffmeister (1949). It was categorized as a suspected CV or RR Lyrae variable by Kukarkin & Kholopov (1982). Koen & O'Donoghue (1995) ruled out the possible CV nature of V716 Mon by obtaining a spectrum (indicative of an A-type star) and several CCD and photoelectric data sets (showing an almost complete cycle of the characteristic light curve of an RR Lyrae star). Haefner, Fiedler, & Rau (1996) independently concluded that V716 Mon was an RR Lyrae star based on a steady decrease in its relative brightness of $\approx 0.44$ mag during a 4.75 hr CCD light curve. The CV catalog and atlas of Downes, Webbink, & Shara (1997) now lists V716 Mon as a “non-CV,” thus providing the final word in the tale of its long-running identity crisis.

We observed V716 Mon during the telescope orientation of the 1999 Cerro Tololo Inter-American Observatory (CTIO) summer student programs. We chose this object for two main reasons: (1) no calibrated photometry currently exists for it in the literature, and (2) it is located in a field that is not too crowded to perform reliable photometry at the plate scale of the CTIO Curtis Schmidt telescope ($2.32$ pixel$^{-1}$ – see §2). We present here the first calibrated $BVRI$ photometry of V716 Mon. We use our multi-color light curves to calculate several fundamental parameters of this RR Lyrae star, including its distance and position within the Galaxy.

2. Observation

We observed V716 Mon for 3 nights on 1999 January 27–29 UT using a $2048 \times 2048$ SITe CCD on the Curtis Schmidt telescope at CTIO$^8$. We utilized $BVRI$ filters with exposure times of 40 s, 20 s, 10 s, and 10 s, respectively. The filters were cycled in the sequence $BVRIIRVIB$ in order to minimize dead time due to filter wheel movement and obtain near-simultaneous multi-color light curves. We defined a region-of-interest $1024 \times 1024$ pixels in size and used a single amplifier for the CCD read-out. Including filter changes, this resulted in a typical cycle time of $\approx 30$ s between

$^8$See http://www.astro.lsa.umich.edu/obs/schmidt/
exposures. Table 1 lists the number of images and time coverage obtained on each night.

The images were reduced in the normal fashion using standard IRAF\textsuperscript{9} tasks. Instrumental magnitudes were measured using the IRAF task \textit{phot}. We obtained observations of photometric standard stars (Landolt 1992) on Jan 27 & 29. The standard star observations from Jan 27 (the better night) were checked against those from Jan 29, and the former were used to calibrate the Jan 27 data for V716 Mon and several field stars. These calibrated field stars were then used as secondary standards to calibrate the V716 Mon data on Jan 28 & 29. This gave photometric uncertainties on Jan 27 of $\sigma_B = 0.02$ mag and $\sigma_V = \sigma_R = \sigma_I = 0.01$ mag. The uncertainties on Jan 28 & 29 were $\sigma_B = 0.03$ mag and $\sigma_V = \sigma_R = \sigma_I = 0.02$ mag.

3. Analysis

Koen & O’Donoghue (1995) found a period of 0.565 d for V716 Mon from their CCD and photoelectric photometry data. We applied the phase dispersion minimization technique (Stellingwerf 1978) to our data, and confirm this period. Figure 1 shows the photometry data folded on $P = 0.565$ d. Clearly, V716 Mon is an ab-type RR Lyrae variable. Table 2 presents light curve parameters derived from the $BVRI$ light curves shown in Figure 1. These parameters include the intensity-mean magnitude ($\langle M \rangle$), the magnitudes at maximum light ($M_{\text{max}}$) and at minimum light ($M_{\text{min}}$), and the phase difference between minimum and maximum light ($\Delta \phi_{\text{rise}}$). The magnitudes are precise to within a few hundredths of a magnitude.

Using our data, we can derive a number of physical properties of V716 Mon, and thereby determine both its location within the Galaxy and to which stellar population it belongs. Fourier decomposition of a star’s light curve is a useful tool in this regard. It yields an amplitude and phase shift for each sinusoid (order) employed in the fit. For RR Lyrae stars, several empirical relations have been developed between these Fourier components and the stars’ physical properties (metallicity, luminosity, color, etc.; Jurcsik & Kovács 1996; Kovács & Jurcsik 1996, 1997).

We used code kindly provided by Jurcsik & Kovács to perform Fourier decompositions of the V716 Mon light curves in a manner consistent with that used to develop the empirical relations. Jurcsik & Kovács (1996) (hereafter referred to as JK96) used fits involving 15 Fourier orders. Using such high orders to fit our data yielded significant excursions (“wiggles”) within the phase gaps at $\phi = 0.55$ and 0.78 that do not appear in the light curves of other observed RR Lyrae stars. The excursions must be spurious artifacts. We therefore explored using between four and fifteen Fourier orders in our fits to the $V$-band light curve.

JK96 provided a compatibility test to determine whether an individual fit was reliable based on the value of a parameter, $D_m$. This is the maximum of the deviation parameters that are defined

\textsuperscript{9}The Image Reduction and Analysis Facility software, which is distributed by the National Optical Astronomy Observatories.
as the differences between observed and calculated Fourier parameters divided by the standard deviation of the Fourier parameter fits (see Section 4 of JK96). If $D_m < 3$, the fit was deemed compatible with the data. Figure 2a shows our $D_m$ values as a function of the fit order, $O_F$, with the dotted line marking $D_m = 3$. Only one fit ($O_F = 9$) formally satisfies the compatibility test, but fits with $6 < O_F < 11$ come close to meeting the test. When plotted over the data, these fits (in particular, $O_F = 9$) do a reasonable job of representing the observations. As we will show, the results based on these fits are similar, providing confidence that we have obtained Fourier deconvolutions that are meaningful in the context of determining the physical properties of V716 Mon.

JK96 derived an empirical relation between metallicity ([Fe/H]), period, and the phase shift $\phi_{31}$ (their Eqn. 3). Employing this relation, we obtained the [Fe/H] values shown in Figure 2b from the Fourier fits with 4–15 orders. Notice that the results for $6 < O_F < 11$ are clustered together and have small internal errors. We therefore adopt as our best [Fe/H] estimate the weighted mean of the individual [Fe/H] values derived from fits with $6 < O_F < 11$, where the weights are $(1/D_m)^2$. Since the results for individual fit orders are not independent, we estimate the error in [Fe/H] from the range of individual values ($-1.05$ to $-1.55$). We thus obtain $[Fe/H] = -1.33 \pm 0.25$ for V716 Mon.

Kovács & Jurcsik (1996) derived a similar empirical relationship between absolute magnitude, period, $\phi_{31}$, and the Fourier amplitude $A_1$. Kovács & Jurcsik (1997) (hereafter referred to as KJ97) improved this relation and extended it to include a reddening estimate. Figure 2c shows the absolute magnitude results from the fits with 4–15 orders. The results are highly consistent among the fits that used $6 < O_F < 11$, so we again adopt as our best estimate the weighted mean of the individual $M_V$ values derived from these fits (using the inverse-square of $D_m$ for the weights). The range of individual $M_V$ values (0.790 to 0.809 mag) is much smaller than the internal error in an individual estimate (0.063 mag), so we adopt the latter as our error estimate on $M_V$. Thus we find $M_V = 0.80 \pm 0.06$ mag for V716 Mon. The KJ97 absolute magnitude relation was calibrated using Baade-Wesselink luminosities. Other luminosity calibrations could result in a systematic decrease in $M_V$ by as much as 0.3 mag (Chaboyer 1999).

Again using the relations in KJ97, we determined the reddening from fits with $4 < O_F < 15$ (see Figure 2d). For $6 < O_F < 11$ the results are nearly independent of the fit order, so we adopt as our best reddening estimate the weighted mean of these values. For the error we use the quadrature sum of the external error (estimated from the range of values, 0.040 to 0.050 mag) and the internal error (estimated from the errors in the Fourier coefficients, 0.005 mag). Thus $E(B-V) = 0.05 \pm 0.01$ mag for V716 Mon.

We can compare this reddening estimate with several independent methods. Blanco (1992) developed a semi-empirical relation between $E(B-V)$ and the period, metallicity, and minimum-light ($B-V$) colors for ab-type RR Lyrae stars. Mateo et al. (1995) explored a similar relation involving ($V-I$) colors. Over the phase interval 0.5 to 0.8, the average colors of V716 Mon are
\[(B - V) = 0.46 \pm 0.01 \text{ mag and } (V - I) = 0.74 \pm 0.01 \text{ mag.} \]

The Blanco (1992) and Mateo et al. (1995) methods yield \(E(B - V) = 0.07 \pm 0.01\) and \(0.12 \pm 0.02\) mag, respectively. The dust map of Schlegel et al. (1998) yields a larger value of \(E(B - V) = 0.17 \pm 0.02\) mag. Despite its proximity to the plane \((b = +8.41\) deg), the reddening toward V716 Mon is surprisingly low.

We compute the distance to the star using the absolute magnitude and reddening values determined above, along with the average apparent magnitude derived from the Fourier fits \((V = 14.20 \pm 0.02\) mag). Using the low reddening value of 0.05 yields a distance of \(4.46 \pm 0.15\) kpc, while using the reddening from the Schlegel et al. (1998) maps gives \(3.76 \pm 0.15\) kpc. Given this uncertainty, we adopt \(d = 4.1 \pm 0.3\) kpc. Systematic changes in the assumed absolute magnitude zero-point scale this distance. The galactic coordinates of the star are \((l, b) = (229.61, +8.41)\) deg. At the adopted distance, V716 Mon lies 0.6 kpc above the Galactic plane and 11.1 kpc from the Galactic center (assuming \(R_0 = 8\) kpc). Given its metallicity and location, it could be a member either of the Galaxy’s halo population, or of the metal-weak tail of the thick disk population (Layden 1995). Radial velocity measurements and spectroscopic confirmation of the metallicity would likely remove this ambiguity.

4. Conclusions

We have obtained extensive \(BVRI\) photometry of the variable star V716 Mon. Its period and multi-color light curves indicate that it is an RR Lyrae variable of Bailey type ab (i.e. a fundamental mode pulsator). Using the empirical relations between light curve Fourier components and physical properties (JK96, KJ97), we estimate the star’s metallicity to be \([\text{Fe/H}] = -1.33 \pm 0.25\) dex, its absolute magnitude to be \(M_V = 0.80 \pm 0.06\) mag (internal error only), and its reddening to be in the range \(E(B - V) = 0.05 - 0.17\) mag. The resulting distance is \(4.1 \pm 0.3\) kpc, placing V716 Mon near the plane of the Galaxy well outside the solar circle.

We thank the anonymous referee, whose comments prompted an improvement in the analysis of these data. The CTIO REU Program is funded by the National Science Foundation (NSF). The CTIO PIA Program is funded by CTIO. CTIO is operated by AURA, Inc. under cooperative agreement with the NSF. This research made use of NASA’s Astrophysics Data System Abstract Service and the SIMBAD database operated by CDS, Strasbourg, France.

REFERENCES

Blanco, V. M. 1992, AJ, 104, 734

Chaboyer, B. 1999, in Post-\textit{Hipparcos} Cosmic Candles, eds. A. Heck, F. Caputo (Dordrecht: Kluwer Academic Publ.), 111
Downes, R., Webbink, R. F., & Shara, M. M. 1997, PASP, 109, 345

Haefner, R., Fiedler, A., & Rau, S. 1996, IBVS, 4366

Hoffmeister, C. 1949, Astr. Abh., 12, No. 1

Jurcsik, J., Kovács, & G. 1996, A&A, 312, 111 (JK96)

Koen, C., & O’Donoghue, D. 1995, ApJS, 101, 347

Kovács, & G., Jurcsik, J. 1996, ApJ, 466, L17 (KJ96)

Kovács, G., & Jurcsik, J. 1997, A&A, 322, 218 (KJ97)

Kukarkin, B. V., & Kholopov, P. N. 1982, New Catalogue of Variable Stars (Moscow: Publication Office Nauka)

Landolt, A. U. 1992, AJ, 104, 340

Layden, A. C. 1995, AJ, 110, 2288

Layden, A. C., & Wachter, S. 1997, PASP, 109, 977

Mateo, M., Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., & Krzeminski, W. 1995, AJ, 109, 588

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Simon, N. R., & Teays, T. J. 1982, ApJ, 261, 586

Stellingwerf, R. F. 1978, ApJ, 224, 953
Table 1. Log of Observations

| UT Date   | UT    | Time Coverage         | Number of Images |
|-----------|-------|-----------------------|------------------|
|           |       | HJD-2451000           | B   | V   | R   | I   |
| 1999 Jan 27 | 02:44–08:05<sup>a</sup> | 205.6197–205.8791   | 51  | 52  | 52  | 52  |
| 1999 Jan 28 | 02:28–09:00  | 206.6086–206.8779   | 101 | 101 | 101 | 101 |
| 1999 Jan 29 | 01:38–08:30<sup>b</sup> | 207.5741–207.8572   | 103 | 102 | 102 | 101 |

<sup>a</sup>Less 0.5 hr used for standard stars.

<sup>b</sup>Less 0.75 hr used for standard stars.

Table 2. Light Curve Parameters

| Parameter | B   | V   | R   | I   |
|-----------|-----|-----|-----|-----|
| ⟨M⟩       | 14.47 | 14.15 | 13.86 | 13.52 |
| M<sub>max</sub> | 13.47 | 13.38 | 13.26 | 13.08 |
| M<sub>min</sub> | 15.16 | 14.67 | 14.34 | 13.94 |
| Δφ<sub>rise</sub> | 0.14 | 0.15 | 0.14 | 0.14 |
Fig. 1.— Phased light curves ($P = 0.565$ d) of V716 Mon in the $B$, $V$, $R$, and $I$ bandpasses. All four light curves are shown on the same magnitude scale, and the data are plotted twice for clarity.
Fig. 2.— Results of the Fourier fits to the V716 Mon light curves. (a) The compatibility condition $(D_m)$ of JK96 is plotted as a function of the number of Fourier components used in the fit (i.e. the fit order). Fits with $D_m < 3$ (dotted line) are deemed to be compatible with the data. The estimated metallicity (b), absolute magnitude (c), and interstellar reddening (d) are plotted against fit order. The results are best determined using fit orders between 6 and 11. The dotted lines in (b)–(d) are the adopted, weighted-mean values based on these fits.