Two-Color Photometry of the Double-Mode RR Lyrae Star NSVS 5222076

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Abstract Observations of double-mode RR Lyrae stars are especially useful to modelers because their two independent pulsation periods allow a unique determination of the star's mass. Only recently identified as an RRd field star, NSVS 5222076 is bright and well-placed for Northern Hemisphere observers. Photometry time-series data were acquired in both the *V* and *I* bands. The *V* data, when combined with those of Oaster, Smith, and Kinemuchi (2006), allowed the periods to be determined more precisely as $P_0 = 0.49405$ day and $P_1 = 0.36690$ day. The amplitude ratio, A_0/A_1, was found to be about 1.4. Time variation of *V–I* color was also determined.

1. Introduction

The *Northern Sky Variability Survey* (NSVS; Wożniak *et al.* 2004) contains unfiltered photometry data, taken over a one-year baseline, for approximately fourteen million objects in the magnitude range $8.0 \leq m_V \leq 15.5$. From that database, Oaster (2005) discovered the nature of NSVS 5222076 as a double-mode RR Lyrae (RRd) star. Oaster, Smith, and Kinemuchi (2006, cited as OSK hereafter) followed up on her discovery by making 1,570 *V*-band observations of the star on sixteen nights over a 108-day baseline. From analysis of their data, they confirmed the star's double-mode nature, and determined its fundamental and first-overtone pulsation periods to be 0.4940 ± 0.0001 day and 0.3669 ± 0.0002 day, respectively.

NSVS 5222076 (= GSC 03059-00636) is a 13th magnitude field star located in Bootes (R.A. $15^h 46^m 26^s$; Dec. +44° 18' 47" (J2000.0)), conveniently located for Northern Hemisphere observers. For most RRd stars, the amplitude of the first-overtone mode pulsation is greater than the amplitude of the fundamental-mode pulsation. However, NSVS 5222076 is unusual among RRd stars in that its fundamental mode is dominant. Indeed, OSK measured the amplitude ratio for the fundamental and first-overtone modes, A_0/A_1, to be approximately 2. They pointed out that this unusually high amplitude ratio makes NSVS 5222076 a rarity, even among those RRd stars that have relatively strong fundamental-mode pulsation.

Observations of RRd stars and their cousins, the double-mode ("beat") Cepheids, are especially useful to modelers because their two independent

pulsation periods allow a unique determination of the star's mass (Clementini *et al.* 2004; Cox 1980).

2. Objectives

The objectives for the work reported herein were as follows:

a. Observe NSVS 5222076 in the *V*-band over a sufficiently long baseline to allow the shape of its light curve to be ascertained and its pulsation periods to be determined.

b. By combining these data with the *V*-band photometric data of OSK, expand the time baseline of observations, thereby permitting more precise determination of the pulsation periods and their ratio, P_1/P_0.

c. Contiguously with the above *V*-band observations, observe the star in the *I*-band. A light curve for NSVS 5222076 in the *I*-band has not previously been reported in the literature, so this would be a scientifically new result.

d. Determine the ratio of amplitudes, A_0/A_1, of the deconvolved fundamental and first-overtone modes for both wavelength bands.

e. From the contiguous *V*-band and *I*-band observations, determine the variation of *V–I* color as a function of time. This would also be a scientifically new result for NSVS 5222076.

3. Equipment and methods

The telescope used for this study was a Meade 40-cm (16-in) Schmidt-Cassegrain, permanently mounted at the author's Toby Point Observatory on the south coast of Rhode Island. On fourteen nights, between JD 2454631 and 2454720, continuous, alternating *V*-band and *I*-band exposures were made, starting shortly after twilight and ending when the star disappeared behind the observatory's roof. A total of 1,109 *V*-band and 1,051 *I*-band images were made, using a Santa Barbara Instrument Group (SBIG) ST-8XME CCD camera, with its pixels binned 2×2 to increase sensitivity. The filters used were Johnson-*V* and Cousins-*I* from Custom Scientific.

Differential photometry of NSVS 5222076 was performed with AIP4WIN version 1.4 (Berry and Burnell 2000). GSC 03059-00534 was used as the comparison star, where $V = 14.035$, $I = 13.385$, and $V–I = 0.650$. GSC-03060-00055 was used as the check star, for which $V = 13.576$, $I = 12.810$, and $V–I = 0.766$. Henden (2008) performed the photometric calibration of the star field in April 2008, using the robotic telescope at Sonoita Research Observatory near Sonoita, AZ. This calibration is available at ftp://ftp.aavso.org/public/calib/g3059.dat.

Period analysis was performed with the Deeming discrete Fourier transform (DFT) algorithm as provided in PERANSO version 2.20 (Vanmunster 2005).

4. Photometric uncertainty

The photometric uncertainty for both the 1,109 *V*-band and 1,051 *I*-band images was ±0.025 magnitude. While this uncertainty level was entirely adequate for period analysis with PERANSO, it proved to be too high for a precise determination of *V–I* color. To improve the signal-to-noise ratio, it became necessary to digitally stack images, and then redo the photometry. This approach resulted in 235 stacked *V*-band images, 231 stacked *I*-band images, and a photometric uncertainty of ±0.009 magnitude, or better.

5. Results

Figure 1 shows the phase curve resulting from differential photometry of the stacked *V*-band images from the present study, combined with the 1,570 points from Michigan State's *V*-band photometry (OSK 2006). While the agreement of the two datasets is gratifying, the chief advantage of combining them is that it expands the time baseline of observations (from 89 and 108 days, respectively) to 1,306 days, thereby permitting more precise determination of the pulsation periods. By use of the Deeming DFT algorithm, the fundamental and first-overtone periods were, respectively, determined to be $P_0 = 0.49405 \pm 0.00007$ day and $P_1 = 0.36690 \pm 0.00003$ day. The period ratio, P_1/P_0 is, therefore, 0.7426 ± 0.0001, in good agreement with the 0.743 value found by OSK. Note in the figure the presence of a bump prior to the rise to maximum. In RRab stars, such bumps are usually attributed to shock wave phenomena. OSK suggest that the interplay of the two pulsation modes modulates the amplitude of the bump.

Figures 2 and 3 show *V*-band phase curves from the present study for the deconvolved pulsation modes of NSVS 5222076. Figure 2 is plotted for the fundamental period of 0.49405 day, while Figure 3 is plotted for the first-overtone period of 0.36690 day. The different symbols for the data points represent the fourteen different observation nights. From these curves, the amplitude ratio, A_0/A_1, for the fundamental and first-overtone modes is estimated to be about 1.4, a value significantly less than the OSK estimate of "approximately 2." A gain in strength of the first-overtone mode relative to the fundamental mode would suggest rapid blueward evolution of the star on the horizontal branch (Clementini *et al.* 2004) over the three-year interval between the OSK observations and those of the present study. Further observations are needed to verify this result, which may perhaps indicate that NSVS 5222076 is in the process of changing its dominant pulsation mode from fundamental to first-overtone.

Figures 4 and 5 show phase curves for the deconvolved pulsation modes in the *I*-band. An *I*-band light curve for NSVS 5222076 has not previously been reported. The amplitudes of the *I*-band curves are about 60% those of their counterparts in the *V*-band. Hence, the amplitude ratio, A_0/A_1, for the fundamental and first-overtone modes is again found to be about 1.4.

Figure 6 is a graph of the time-variation of *V–I* color, determined from contiguous *V*-band and *I*-band observations. The values of *V–I* in Figure 6 vary over the range from +0.52 at the red end to +0.25 at the blue end. It would be of interest to assign values of effective temperature, T_{eff}, to those limits. However, further consideration reveals a number of difficulties in doing so. First, there is the issue of estimating the reddening. If we estimate a mean visual magnitude of 12.85 from Figure 1, and accept an absolute visual magnitude value of +0.71 for RR Lyrae stars in the galactic halo (Layden *et al.* 1996), we can calculate a distance for NSVS 5222076 of 2,680 parsecs, assuming no extinction. However, we know that even though it is out of the galactic plane, there must be extinction and reddening for a star at that apparent distance, i.e., it is both closer and bluer than it appears. The second difficulty in assigning values of effective temperature to Figure 6 is that T_{eff} is a function of metallicity, among other things, and the metallicity of NSVS 5222076, a Population-II star, has not been determined. So, it is clear that assigning values of T_{eff} to Figure 6 would be complicated, and that attempting to do so would likely be more misleading than informative. However, the amplitude of *V–I* color variation measured relative to the mean, $(V–I) = 0.14$, is less dependent on the factors mentioned above, so is likely to be reliable.

6. Acknowledgements

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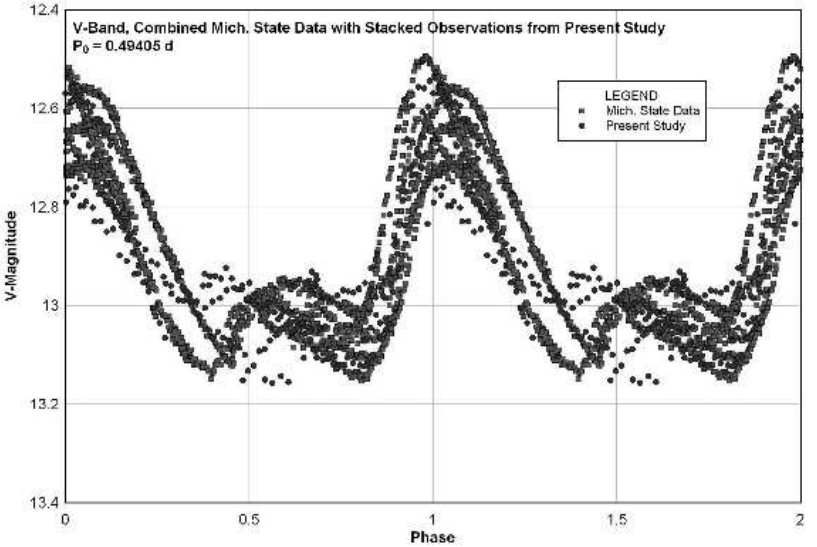

Figure 1. Phase curve for the Michigan State Univ. data of OSK, plus *V*-band photometry of 235 stacked images of NSVS 5222076.

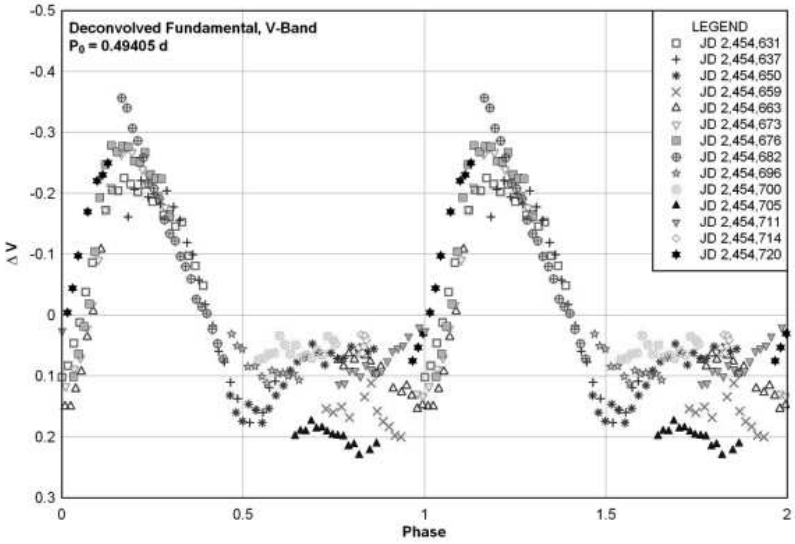

Figure 2. Deconvolved fundamental of NSVS 5222076. Phase curve for *V*-band photometry of 235 stacked images.

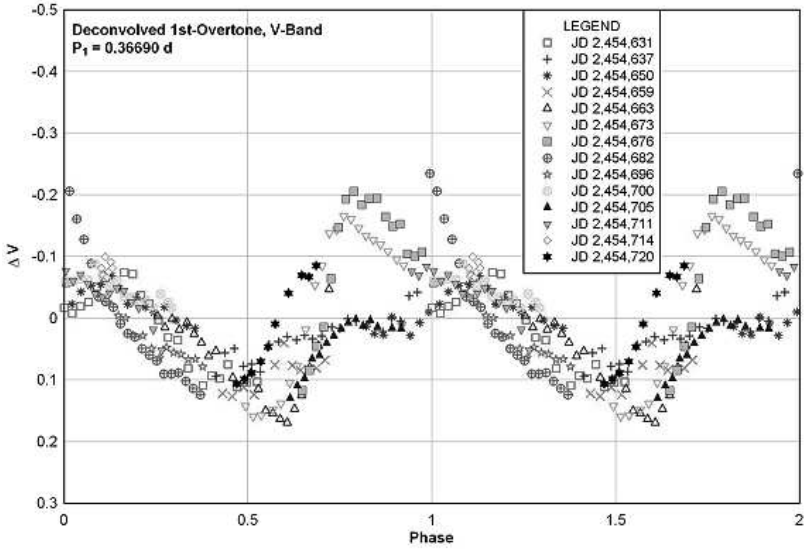

Figure 3. Deconvolved first-overtone of NSVS 5222076. Phase curve for *V*-band photometry of 235 stacked images.

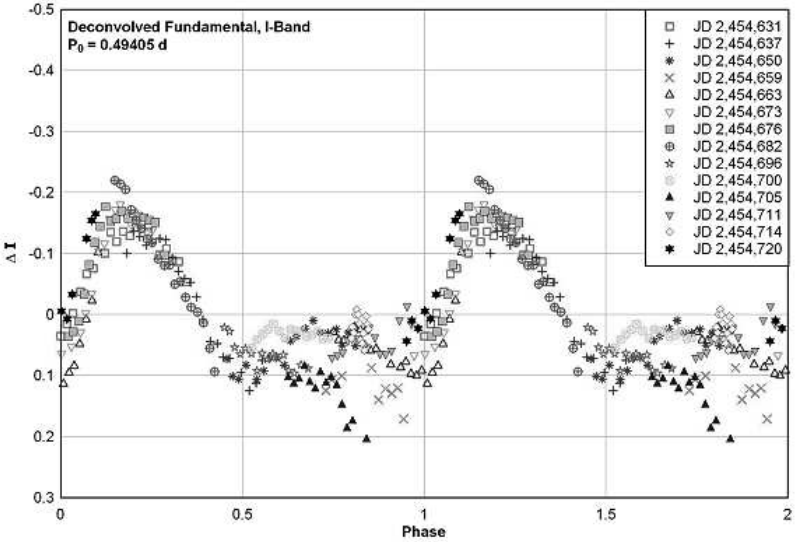

Figure 4. Deconvolved fundamental of NSVS 5222076. Phase curve for *I*-band photometry of 231 stacked images.

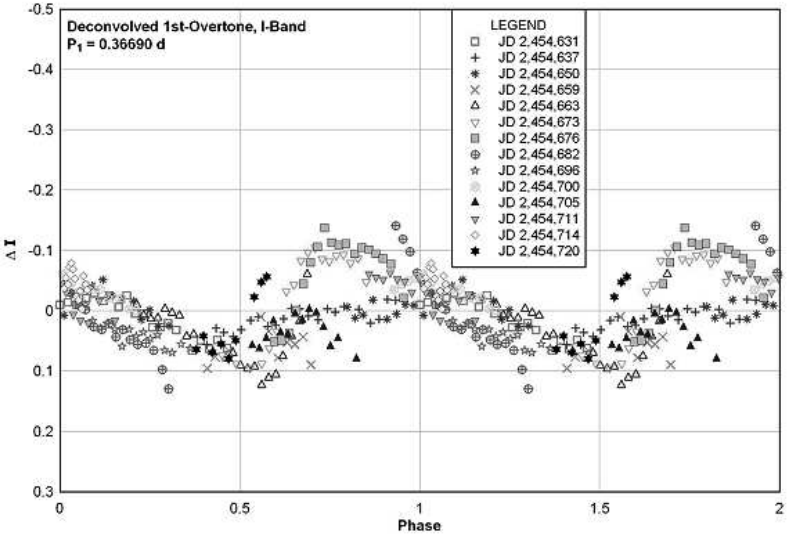

Figure 5. Deconvolved first-overtone of NSVS 5222076. Phase curve for *I*-band photometry of 231 stacked images.

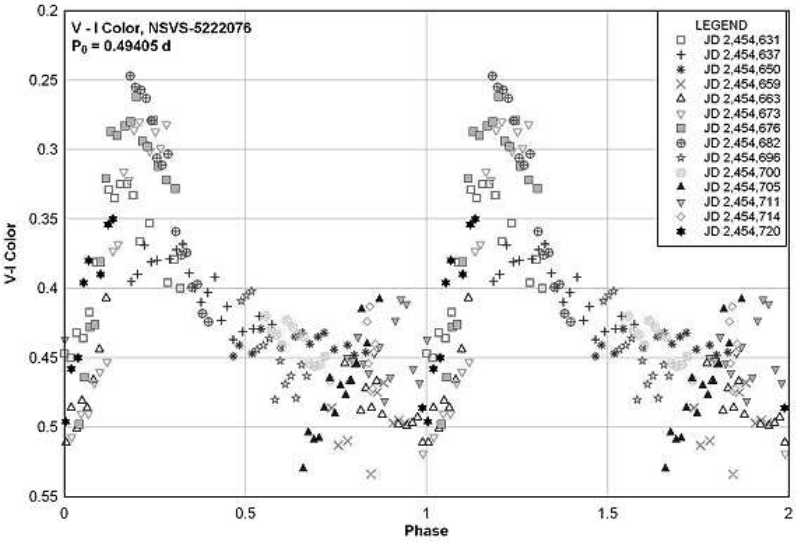

Figure 6. Phase curve for the *V*–*I* color of NSVS 5222076.