Secular Variation of the Mode Amplitude-Ratio of the Double-Mode RR Lyrae Star NSVS 5222076

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Abstract In 2008, a campaign of time-series observations (Hurdis 2009) was conducted in the *V* and *I* bands for NSVS 5222076, a double-mode RR Lyrae (RRd) field star in Bootes. Comparison of those results with the earlier observations of Oaster, Smith, and Kinemuchi (2006) suggested that a rapid and significant decrease might be occurring in the amplitude ratio, A_0/A_1, of the star's fundamental and first-overtone pulsation modes. To follow up on this interesting result, another campaign of time-series observations was conducted in 2009. We find that the amplitude ratio has indeed decreased in the *V*-band, from 1.93 in 2005 to 1.76 in 2008 to 1.48 in 2009.

1. Introduction

In his earlier paper on NSVS 5222076 (= GSC 03059-00636), Hurdis (2009) described the discovery by Oaster (2005) of the star's double-mode variability in Northern Sky Variability Survey (NSVS; Woźniak *et al.* 2004) data, and the subsequent series of 1,570 *V*-band observations of it by Oaster, Smith, and Kinemuchi (2006, cited as OSK hereafter). He further described how NSVS 5222076 is unusual among RRd stars in that its fundamental mode is dominant. OSK had measured the amplitude ratio for the fundamental and first-overtone modes, A_0/A_1, to be approximately 2, and had 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.

From his 2008 observations, Hurdis (2009) had estimated the amplitude ratio, A_0/A_1, to be about 1.4 for both the *V* and *Ic* bands. That number was estimated by eye with a ruler, from phase plots of the deconvolved pulsation modes that had been created with PERANSO version 2.20 (Vanmunster 2005). The estimate was made difficult by having caught only four good maxima over the fourteen nights of observation. Nevertheless, the data were sufficiently good for it to be clear that the amplitude ratio was definitely less than OSK's value of "approximately 2." This seeming decrease in A_0/A_1, if correct, signified a gain in strength of the first-overtone mode relative to the fundamental mode. It became apparent that more observations were needed, both to verify the result and to determine whether NSVS 5222076 is, perhaps, in the process of changing its dominant pulsation mode from fundamental to first-overtone.

In the globular cluster, M3, a few double-mode RR Lyrae stars have been observed to undergo changes in the relative strengths of the two pulsation modes (Clementini *et al.* 2004). In four such cases in M3 (V79, V166, V200, and V251), switching from one mode being dominant to the other has been observed (Corwin *et al.* 1999; Clementini *et al.* 2004; Clement and Thompson 2007). Clementini *et al.* (2004) observed that these changes can occur rapidly, over the span of a single year. They suggest that those stars are undergoing rapid evolutionary changes. The remarkable case of V79 in M3 is recounted by Clement and Thompson (2007). V79 has been observed for over a century, and has exhibited many changes, including an abrupt change of its fundamental period in 1897, and a switch in 1992 from being a single-mode (fundamental) pulsator to a double-mode pulsator with dominant first-overtone. Recent observations (Goranskij and Barsukova 2007), have revealed that a reverse switch has occurred, with the star returning to single-mode (fundamental) pulsation.

Observations of RRd stars are useful to modelers, because their two independent pulsation periods allow a unique determination of the star's mass (Clementini *et al.* 2004; Cox 1980). Observations of RRd mode switching, as described above, can provide even more information about a star's interior and evolution. To date, however, the only RRd stars that have been observed to have switched modes have been located in the crowded field of M3. On the other hand, NSVS 5222076 is a field star, located well out of the Galactic plane in Bootes. It is moderately bright (average $m_V = 12.94$), and well-placed for Northern Hemisphere observers. If it were, indeed, on the verge of undergoing a mode switch, it would provide a unique opportunity to study the event, unimpeded by the crowded star field of a globular cluster.

Having determined the need for more observations of NSVS 5222076 to verify that its amplitude ratio, A_0/A_1, is decreasing, it was decided to request time on the AAVSO Robotic Telescope Network (AAVSONet). The proposal was accepted, and the project was assigned to the robotic 28-cm Celestron telescope known as the Wright28, managed by coauthor Tom Krajci.

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, and including enough maxima, to allow the amplitude ratio, A_0/A_1, of the two pulsation modes to be accurately determined. b. Contiguously with the above *V*-band observations, observe the star in the *I*-band. c. By combining our *V*-band data with both the *V*-band data from the 2008 observing season (Hurdis 2009) and the *V*-band photometric data of OSK, expand the time baseline of observations, thereby permitting more precise determinations of the pulsation periods and their ratio, P_1/P_0. d. Determine the ratio of amplitudes, A_0/A_1, of the deconvolved fundamental and first-overtone modes for both wavelength bands.

3. Equipment and methods

Two telescopes were used for our observations. The Wright28 is a 28-cm (11-in) Celestron C11 Schmidt-Cassegrain, located at Tom Krajci's Astrokolkhoz Observatory at an elevation of 2,877 meters (9,440 feet) near Cloudcroft, New Mexico. It is equipped with an f/6.2 focal reducer, giving it a focal length of 1,720 mm. Its images were taken with a Santa Barbara Instrument Group (SBIG) ST-7XME CCD camera, with its pixels binned 2 × 2 to increase sensitivity. The filters used were Johnson-V and Cousins-I interference filters from Astrodon.

The second telescope was a Meade 40-cm (16-in) Schmidt-Cassegrain, permanently mounted at the first author's Toby Point Observatory, near sea-level on the south coast of Rhode Island. Its focal ratio of f/10 gives it a focal length of 4,064 mm. It is equipped with an SBIG ST-8XME CCD camera, with its pixels binned 2 × 2 to increase sensitivity. The photometric filters used were Johnson-V and Cousins-I from Custom Scientific.

Our observing procedure was to take continuous, alternating *V*-band and *I*-band exposures of 90-second duration throughout the night for as long as the star was at an air mass of 2.0 or less. To maximize the number of pulsation maxima captured in our data, the choice of observing nights was guided by an ephemeris created from the most accurate value available for the fundamental pulsation period (Hurdis 2009). With the Wright28 telescope, 1,186 *V*-band images and 1,154 *I*-band images were taken on thirteen nights, between JD 2454883 and JD 2454964. With the Meade telescope, 296 *V*-band and 304 *I*-band images were taken on four nights, between JD 2454938 and JD 2455023.

Differential photometry of NSVS 5222076 was performed with AIP4WIN version 2.3.0 (Berry and Burnell 2005). GSC 03059-00534 was used as the comparison star for all images, where $V = 14.035$, $I = 13.385$, and $V–I = 0.650$. For the Wright28 images, GSC-03060-00055 was used as the check star, for which $V = 13.576$, $I = 12.810$, and $V–I = 0.766$. For the Meade images, GSC-03060- 00569 was used as the check star, for which $V = 12.969$, $I = 12.313$, and $V–I = 0.656$. Henden (2008) performed the photometric calibration of the star field in April 2008, using the robotic telescope at Sonoita Research Observatory near Sonoita, Arizona. This calibration is available at ftp://ftp.aavso.org/public/calib/g3059.dat.

Two software packages were used to perform period analysis of the photometric data extracted from the images. These were PERANSO version 2.20 (Vanmunster 2005) and PERIOD04 (Lenz and Breger 2005).

4. Results

Photometry from the 1,482 *V*-band images from this year's study were combined with those from the 1,102 *V*-band images from 2008 (Hurdis 2009) and with the 1,570 points from Michigan State's *V*-band photometry (OSK 2006). The time baseline for this combined dataset was 1,609 days, permitting an improved determination of the pulsation periods. By use of the Deeming DFT algorithm in PERANSO, the fundamental and first-overtone periods were, respectively, determined to be $P_0 = 0.494050 \pm 0.000037$ day and $P_1 = 0.366894 \pm 0.000010$ day. The period ratio, P_1 / P_0 is, therefore, $= 0.7426 \pm 0.0001$, in good agreement with the 0.743 value found by OSK. Determination of P_0 and P_1 with PERIOD04 produced virtually identical results.

Figure 1 shows the PERANSO phase curve resulting from differential photometry of the 1,482 *V*-band images from this year's study. It is plotted for the calculated fundamental period of 0.494050 day. The different symbols for the data points indicate the seventeen different observation nights. Figures 2 and 3 show *V*-band phase curves for the deconvolved pulsation modes of NSVS 5222076. Figure 2 is plotted for the fundamental period of 0.494050 day, while Figure 3 is plotted for the first-overtone period of 0.366894 day. Here also, the different symbols for the data points indicate the seventeen different observation nights.

Figure 4 shows the phase curve for the 1,458 *I*-band images from this year's study, while Figures 5 and 6 show the *I*-band phase curves for the deconvolved pulsation modes.

The amplitude ratio, A_0/A_1, of the fundamental and first overtone pulsation components of a dataset can be accurately determined by using PERIOD04 to achieve a least-squares-fit of the calculated Fourier components to the light curve. This provides a more accurate estimate of modal amplitudes than the method previously used by Hurdis (2009). Therefore, the A_0/A_1 values reported in that reference for the 2008 observations are superseded by the values herein. Light curve fitting with PERIOD04 was done for each of the three data-sets, namely, the 2005 observations of OSK, the 2008 observations (Hurdis 2009), and the most recent 2009 observations. The fit to the 2009 *V*-band data is presented in Table 1, while that to the 2009 *I*-band data is presented in Table 2.

The amplitude ratio results were as follows. In the *V*-band, A_0/A_1 decreased from 1.93 ± 0.02 in 2005 to 1.76 ± 0.03 in 2008 to 1.48 ± 0.01 in 2009. This change is the result of both a decrease in the amplitude of the fundamental mode, A_0, and an increase in the amplitude of the first overtone mode, A_1. Amplitude ratio uncertainties were derived from the standard deviations calculated by PERIOD04 for the least-squares fits of the Fourier components to the measured light curves. The propagation-of-errors formula for quotients was used to determine the uncertainty of the ratio, A_0/A_1. These results are graphically illustrated in Figure 7, where the upper half of the figure shows the number and distribution of the time-series observations, while the lower half shows the time variation of A_0/A_1. In the *I*-

band, A_0/A_1 was virtually constant, at 1.56 ± 0.06 in 2008 and 1.52 ± 0.03 in 2009. (OSK did not observe in the I-band.) These results are illustrated in Figure 8.

The cause of the night-to-night modulation in amplitude and phase evident in Figures 2, 3, 5, and 6, is not yet clear. A PERIOD04 analysis of NSVS 5222076 data by Templeton (2009) suggests the presence of Blazhko-like amplitude modulation, but no Blazhko period can be found in the data. Another proposed cause of this amplitude and phase modulation is the influence of interaction terms involving both frequencies, such as $f_0 + f_1$, $2f_0 + f_1$, $f_1 - f_0$, etc. However, those terms had been removed from the data used to plot Figures 2, 3, 5, and 6, yet the amplitude and phase modulation remains. A remarkable example of amplitude modulation can be seen in Figure 1 for the pulsation maximum of JD 2454956 (2009 May 4–5) denoted by the diamond-shaped symbols. As shown in Figure 2, even when the effect of the first overtone mode has been removed from the data, the amplitude of that particular maximum was much below the norm. One can conjecture that this amplitude and phase modulation is due to random, non-periodic irregularities in the pulsation behavior of the star as it approaches a mode switch. Continued monitoring of NSVS 5222076 will be required to unravel the cause of this puzzling behavior. Interestingly, Blazhko-like amplitude modulation has also been reported for V79 in M3 (Goranskij and Barsukova 2007). The highly irregular behavior of V79 was mentioned above.

In conclusion, in the *V*-band at least, A_0/A_1 has been shown to be decreasing, so NSVS 5222076 may be evolving toward a mode switch in which the first-overtone mode becomes dominant. Continued observation of NSVS 5222076 will be needed to determine whether a mode switch is indeed imminent.

5. Acknowledgements

The authors gratefully acknowledge AAVSO Director Arne Henden for providing his Sonoita Research Observatory photometric calibration of the star field. They also thank Prof. Horace Smith of Michigan State University for his useful comments on amplitude-modulation and mode-switching in RR Lyrae stars. They are indebted, as well, to AAVSO Staff Astronomer Matthew Templeton for helpful discussions on PERIOD04, and for his use of that program to explore their NSVS 5222076 data for Blazhko-like effects.

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Table 1. PERIOD04 fit to 2009 *V*-band data on NSVS 5222076.

Frequency (cycles/day)	*Amplitude (magnitude)*	*Frequency (cycles/day)*	*Amplitude (magnitude)*
2.02409 ($=f_0$)	0.165	$4f_0$	0.023
2.72558 ($=f_1$)	0.112	$5f_0$	0.015
$2f_0$	0.070	$2f_1$	0.015
$f_0 + f_1$	0.032	$4f_0+f_1$	0.011
f_1-f_0	0.031	$3f_0+f_1$	0.011
$3f_0$	0.029	$6f_0$	0.005
$2f_0+f_1$	0.028		

Table 2. PERIOD04 fit to 2009 *I*-band data on NSVS 5222076.

Frequency (cycles/day)	*Amplitude (magnitude)*	*Frequency (cycles/day)*	*Amplitude (magnitude)*
2.02409 ($=f_0$)	0.107	$4f_0$	0.012
2.72558 ($=f_1$)	0.070	$2f_1$	0.012
$2f_0$	0.051	$3f_0+f_1$	0.008
$3f_0$	0.018	$4f_0+f_1$	0.007
$2f_0+f_1$	0.017	$3f_1$	0.007
f_0+f_1	0.016	$4f_1$	0.006
f_1-f_0	0.015	$6f_0$	0.005

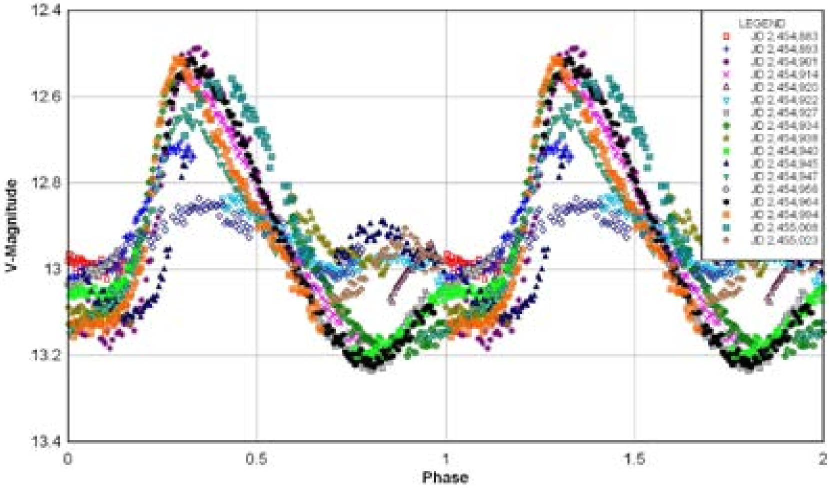

Figure 1. Phase curve of NSVS 5222076 resulting from differential photometry of 1,482 *V*-band images, plotted for fundamental period of 0.494050 day. Different symbols for data points indicate the seventeen different observation nights.

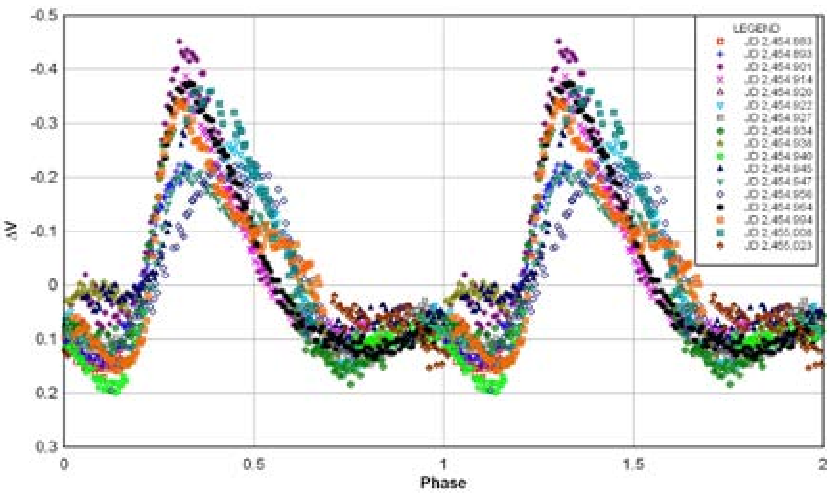

Figure 2. Deconvolved fundamental mode of NSVS 5222076. Phase curve for photometry of 1,482 *V*-band images, plotted for fundamental period of 0.494050 day.

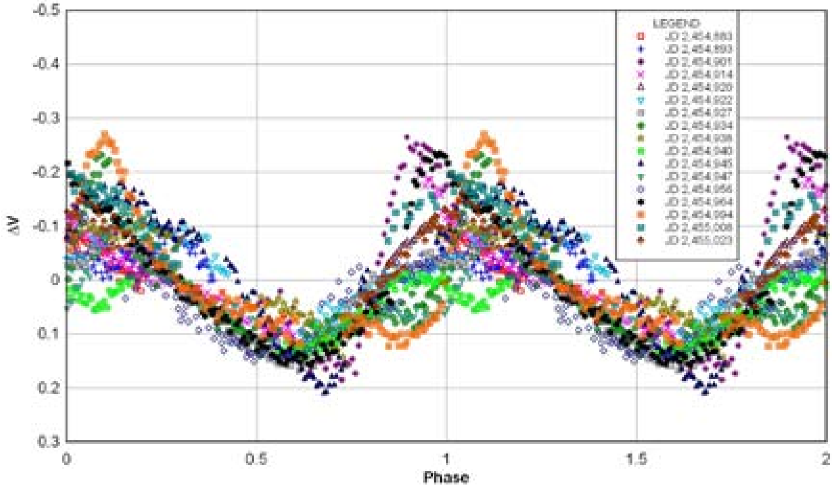

Figure 3. Deconvolved first-overtone mode of NSVS 5222076. Phase curve for photometry of 1,482 *V*-band images, plotted for the first-overtone period of 0.366894 day.

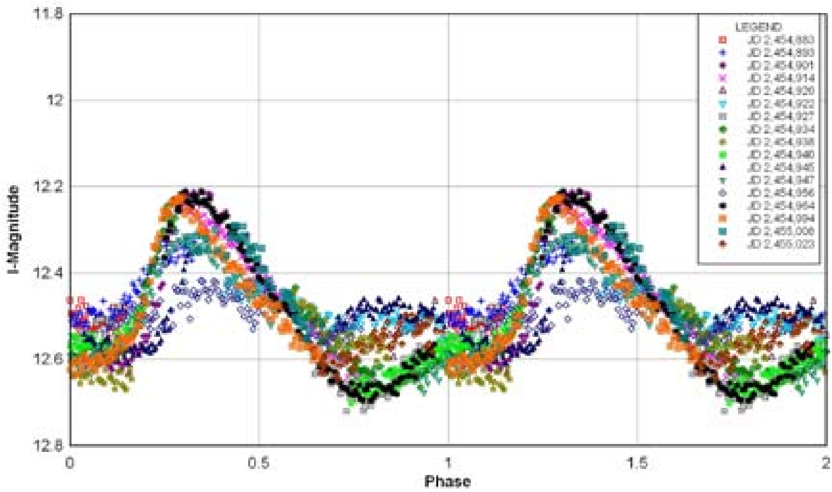

Figure 4. Phase curve resulting from differential photometry of 1,458 *I*-band images, plotted for fundamental period of 0.494050 day. Different symbols for data points indicate the seventeen different observation nights.

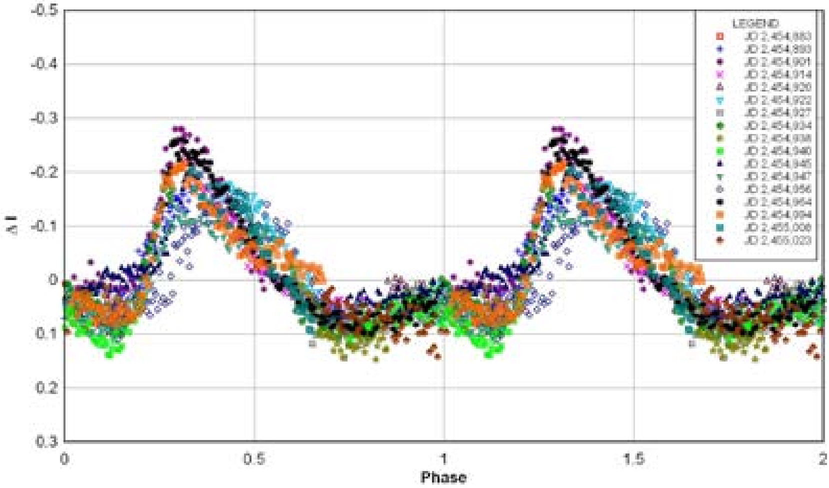

Figure 5. Deconvolved fundamental mode of NSVS 5222076. Phase curve for photometry of 1,458 *I*-band images, plotted for fundamental period of 0.494050 day.

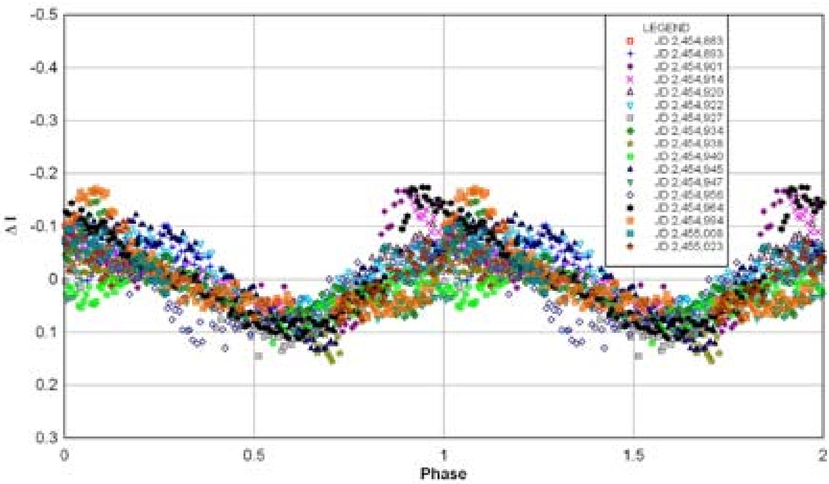

Figure 6. Deconvolved first-overtone mode of NSVS 5222076. Phase curve for photometry of 1,458 *I*-band images, plotted for the first-overtone period of 0.366894 day.

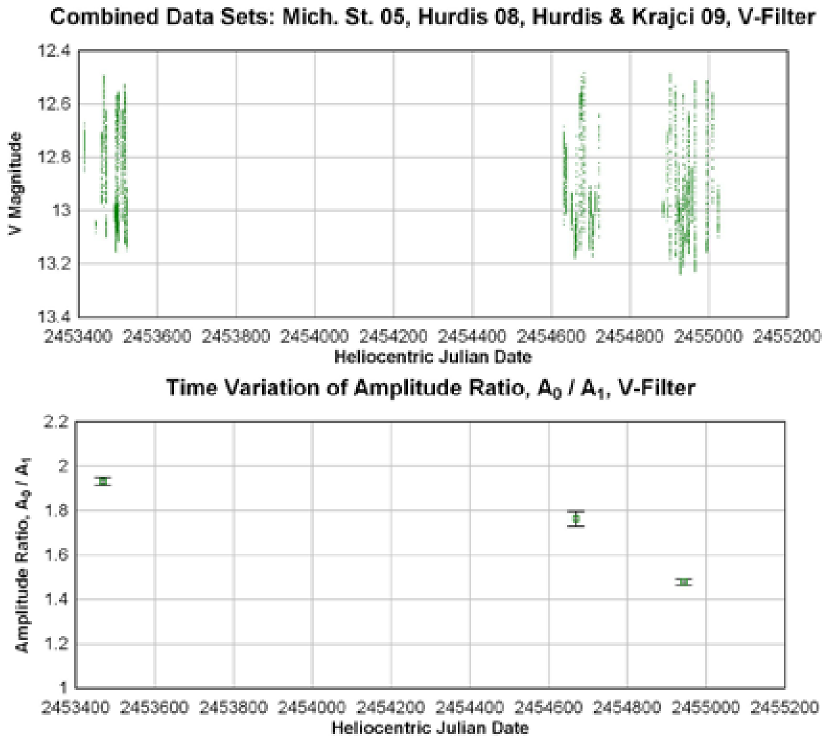

Figure 7. Secular variation of mode amplitude ratio, A_0/A_1, for *V*-band.

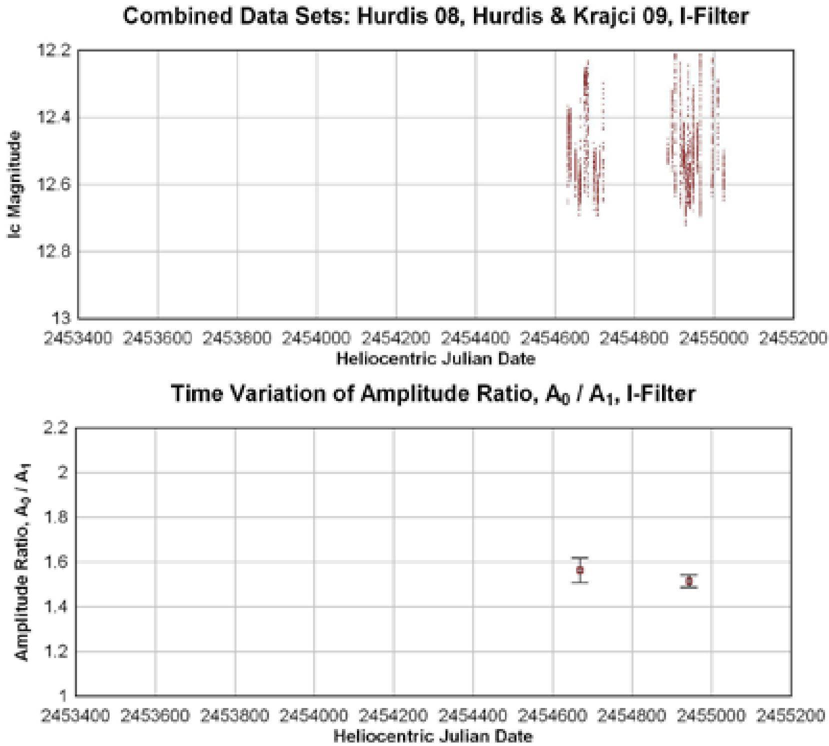

Figure 8. Secular variation of mode amplitude ratio, A_0/A_1, for *I*-band.