Double mode variables in M3

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Recent studies (Nemec and Clement 1989, Clement et al. 1997, Corwin, Carney and Allen 1999) revealed that M3 belonged to globular clusters rich in double mode RR Lyrae (RRd) stars. Using recent and earlier observations obtained at Konkoly Observatory and all the other available photometry of RRd stars, long term amplitude changes of both modes for the five known RRd stars have been followed.

Data

Both photographic (Bpg) and CCD (V) observations have been used. The data were divided into groups containing as many measurements as possible in a moderately long time interval. When different photometric observations belonged to the same group, zero point corrections were applied to match the photometries.

The effect of colour inhomogeneities on the amplitude ratios were tested by determining amplitude ratios using the different colours of all the available multicolour observations. The results are shown in Table 1. It can be seen, that the amplitude ratio depends on the colour system, but the effect is smaller than the other errors entering in the results.

In order to follow not only amplitude ratio changes but long term behaviour of the amplitudes, too, the amplitudes of the

Table 1: The colour dependence of the amplitude ratios of multicolour CCD observations. $(A_1/A_0)_B$, $(A_1/A_0)_V$, $(A_1/A_0)_I$ denote the measured amplitude ratios in Johnson–Cousins BVI_C colours.

Star	$(A_1/A_0)_B$	$(A_1/A_0)_V$	$(A_1/A_0)_I$
V68[1]	1.45 ± 0.16	1.33 ± 0.14	1.26 ± 0.17
V68[2,3,4]	1.05 ± 0.15	1.14 ± 0.02	1.12 ± 0.1
V79[2,3]		1.77 ± 0.03	1.78 ± 0.2
V99[3]		0.76 ± 0.05	0.67 ± 0.18
V166[3,4]	0.72 ± 0.18	0.60 ± 0.04	0.59 ± 0.25

Ref.: [1] Carretta et al. 1998, [2] Kaluzny et al. 1998, [3] Benkő et al., [4] Bakos et al.

early photographic materials were transformed according to Szeidl (1965). Similar amplitude transformation formulae were evaluated and applied to the additional data.

Periods

Each data group of the known RRd stars (V68, V79, V87, V99, V166) were analyzed applying Fourier technique by using the facilities of the program package MUFRAN (Kolláth 1990). First the period of the dominant mode was determined, then, after prewhitening the data with this frequency and its low order harmonics (2,3), the frequency of the other mode was searched for. If both the fundamental and the first overtone modes were equally dominant, the process was applied using each mode first, and consistent solution was accepted. It has to be mentioned, however, that the method turned to be very sensitive to the number of harmonics used in the prewhitening, especially in those cases, when the data set covered only few nights of observations.

If the spectral window did not allow to make clear distinction of the true period because of severe aliasing, then that possible frequency was accepted which was the closest to the frequency of the given mode as determined for the other observations.

Amplitudes

Using the actual frequencies of the fundamental and first overtone modes in each data set, least squares fit solutions were calculated in order to determine the amplitudes.

The fitting formula is

$$m(t) = a_{00} + \sum_{i=0}^{n} \sum_{j=1}^{m_i} a_{ij} \sin[2\pi j f_i(t - t_0) + \varphi_{ij}],$$

where the designations are the usual: the Fourier amplitudes a_{ij}, phases φ_{ij}, the epoch t_0, the frequencies $f_i = \nu_0, \nu_1, \nu_0 \pm \nu_1, 2\nu_1 + \nu_0, \ldots$, n the number of frequencies, and m_i the number of harmonics. As the parameters of the fits proved to be very sensitive to the number of harmonics and linear combinations concerned, we used only those components which actually appeared in the Fourier spectrum.

Amplitude ratios

The effect of the inhomogeneity of the photometry is smaller on the amplitude ratios than on the amplitudes. The Fourier amplitude of the fundamental mode and the first overtone are denoted as $A_0 (= a_{01})$ and $A_1 (= a_{11})$, respectively, and the modal content of the pulsation is quantified by the A_1/A_0 ratio. We would like to call the attention that the amplitude ratio defined above may differ significantly from the ratio of the total amplitudes which is generally used in the literature (Nemec and Clement 1989, Corwin et al. 1999).

Errors

The estimation of errors plays an important role in justifying long term amplitude ratio changes. The errors of the amplitude ratios were calculated by Monte Carlo simulation. Synthetic time series were generated using the actual frequencies, amplitudes and observational times of each data set. The initial relative phase of the modes was randomly chosen and white noise with variance corresponding to the original data was also added. Fourier amplitudes of the modes were determined in the same way as for the original data in 1000 simulations / each data set / each star. The results showed that the amplitude ratios were severely affected by the value of the initial phase relations of the modes in those cases when only few nights of observations were involved. The errorbars in Figs. 1–5. show the standard deviation of the amplitude ratios obtained from these simulations.

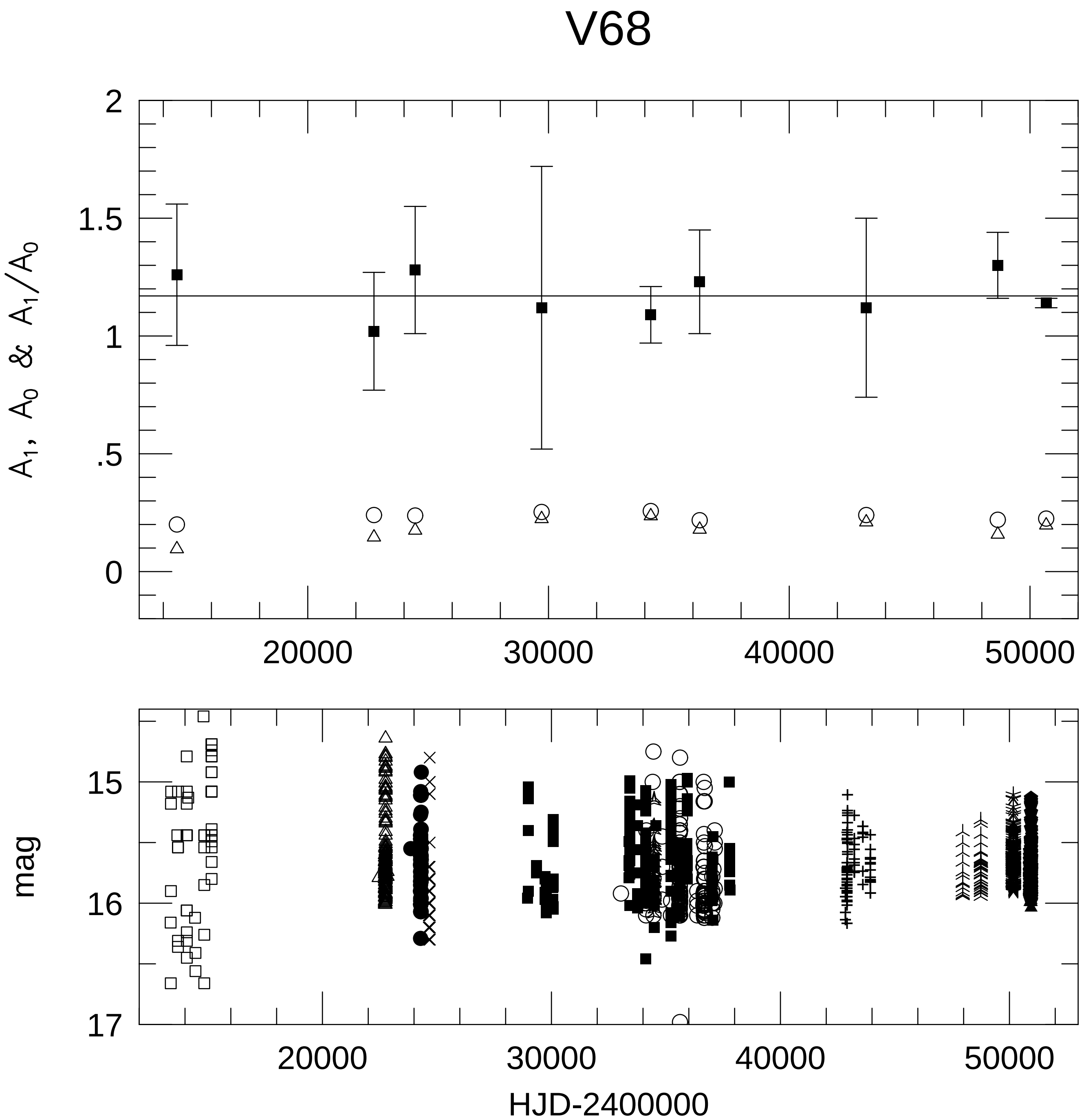

Figure 1. The star shows a strong double mode behaviour with moderately dominating first overtone pulsation. No definite amplitude ratio changes have been found. The frequency of the first overtone mode obtained for the different data sets is slightly increasing, in accordance with the shape of the O−C diagram shown by Szeidl (1965). In contrast, the period of the fundamental mode does not seem to change.

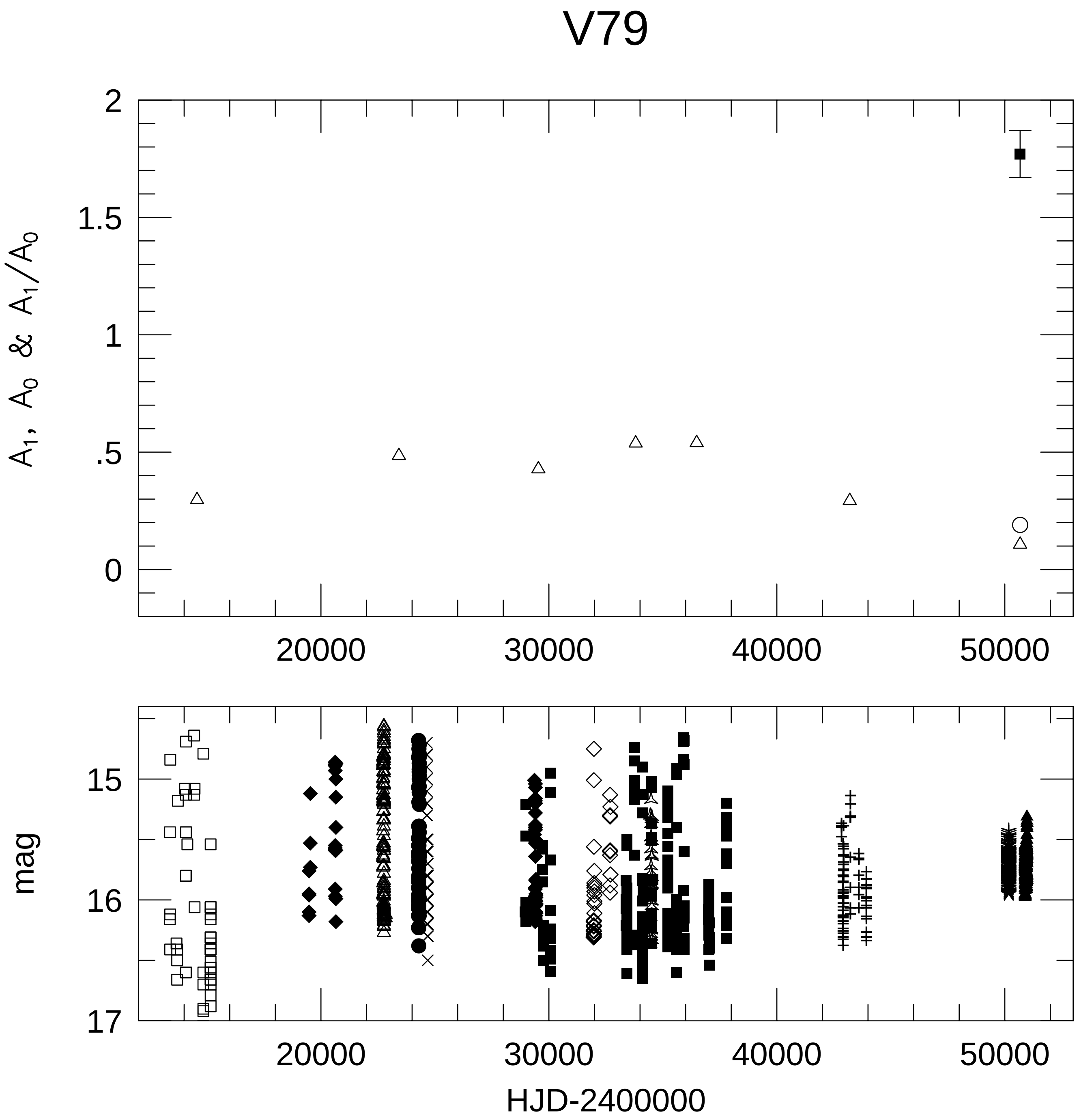

Figure 2. Our new CCD observations (Benkő et al.) confirmed the double mode nature of the star discovered by Clement el al. (1997). The spectrum is dominated by ν_1 which cannot be recognized in the spectra before the years of the 90s. The period of fundamental mode (P_0) started to decrease drastically in the middle of the century and it is still decreasing!

year	1925	1936	1962	1978	1996	1998
P_0[day]	0.4833	0.4833	0.4833	0.4802	0.4798	0.4791

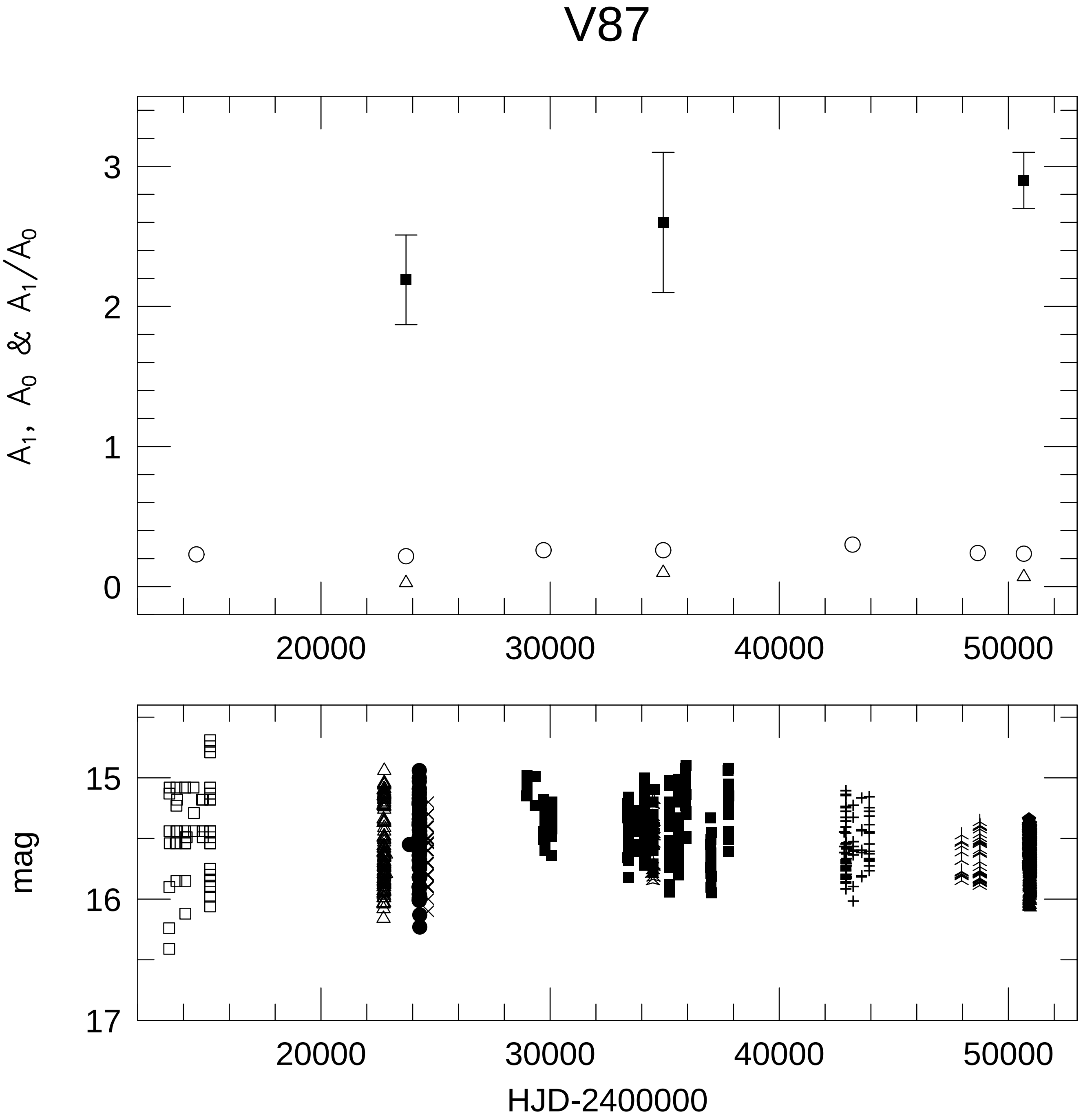

Figure 3. The double mode behaviour of V87 is only marginal. It is only possible to find ν_0 in the high quality and long enough data series. The period of the overtone pulsation (P_1) seems to be stable with $dP_1/dt < 7 \cdot 10^{-11}$ [days/day].

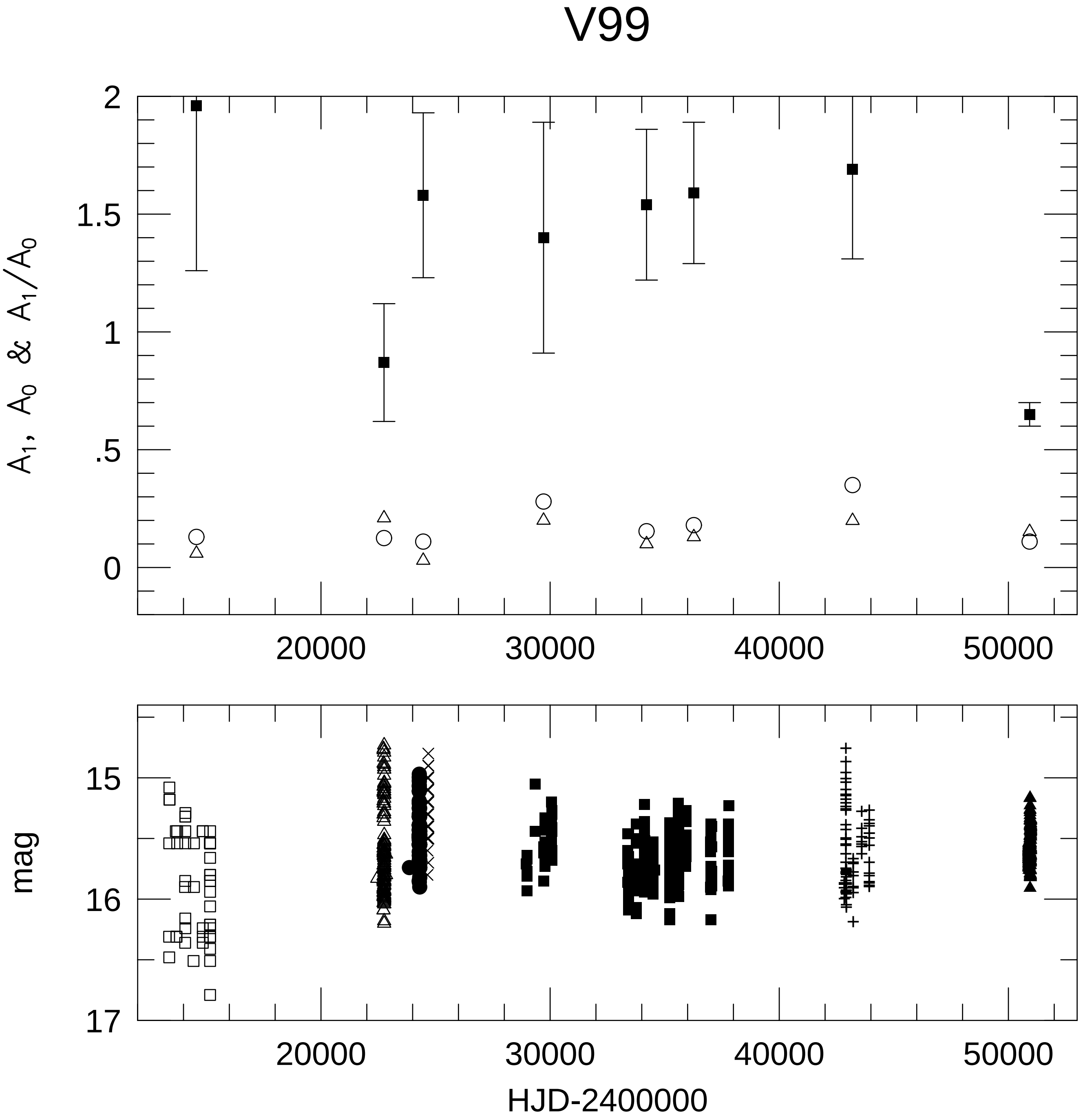

Figure 4. The amplitude ratio of V99 changed just recently according to our new CCD observations (Benkő et al.). If further observations confirm the dominance of the fundamental mode, then the star would be the first example for mode switch from the first overtone pulsation to the fundamental one. However, Larink's observations in the 20s also showed fundamental mode having been dominant then, which raise the possibility that there should be "random" changes occurring in the amplitude ratios instead of mode switch connected to stellar evolution. P_1 is decreasing while no changes are found for P_0.

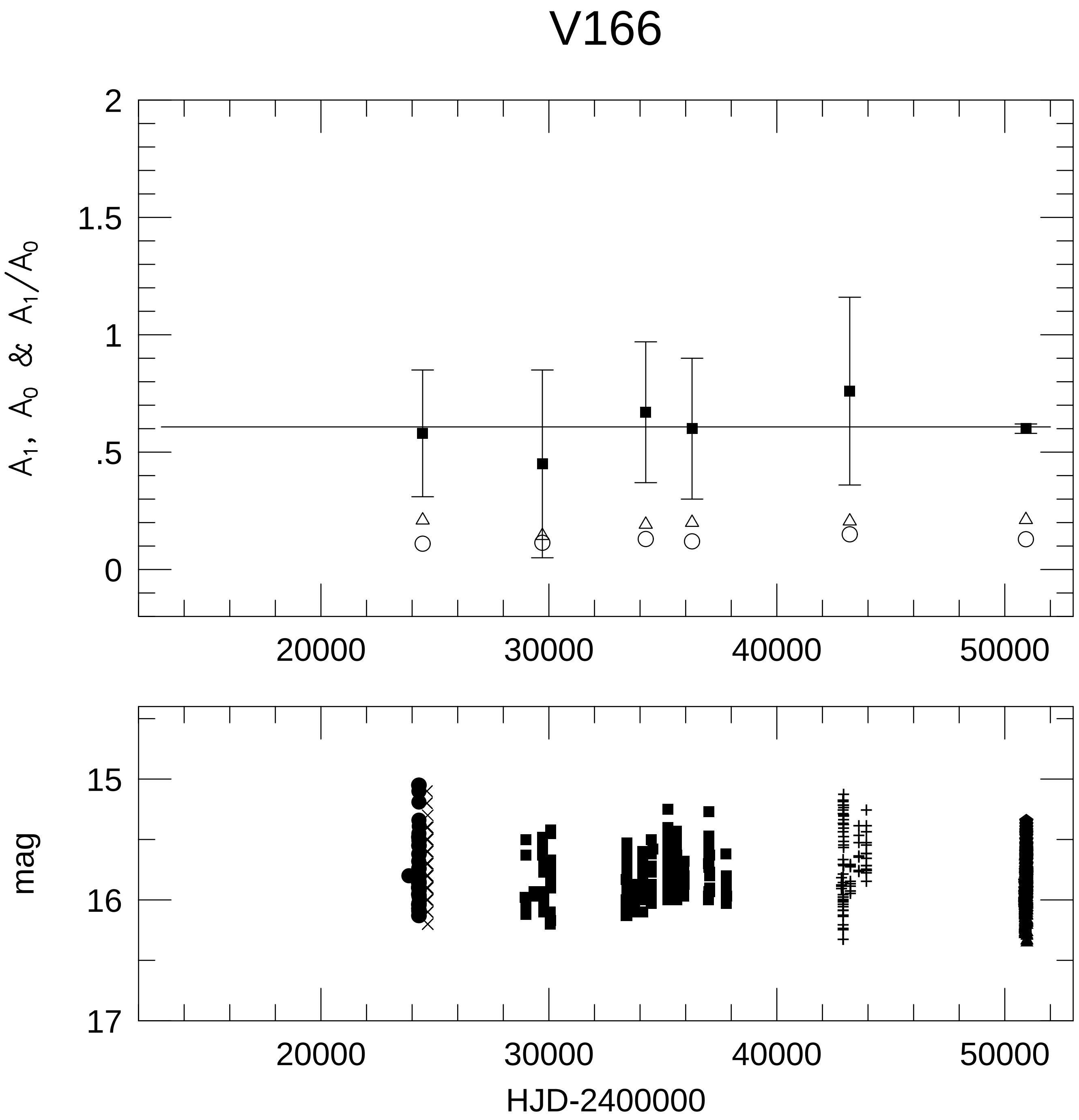

Figure 5. The star is one of the few RRd-s, where the fundamental mode dominates over the first overtone pulsation. The amplitude ratio is probably constants and no evidence is found for period changes as well.

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The upper panels in Figs. $1-5$ show the amplitudes and amplitude ratios of the RRd variables determined for the different groups of the data.

Symbols:

△	$A_0(=a_{01})$	–	fundamental mode amplitude
○	$A_1(=a_{11})$	–	first overtone amplitude
■	A_1/A_0	–	amplitude ratio

No errors of the amplitudes are shown as the amplitudes, although transformed, may be still affected by systematic differences of the photometric systems. The errors of the amplitude ratios are determined as described in the text.

The bottom panels show the time distributions of the observations.

Symbols:

□	–	Bailey (1913)
△	–	Larink (1922)
●	–	Müller (1933)
×	–	Greenstein (1935)
♦	–	Hett (1942)
◊	–	Belserene (1952)
■	–	Szeidl (1965, 1973)
○	–	Kukarkin and Kukarkina (1970)
⅄	–	Roberts and Sandage (1955)
+	–	Szeidl et al.
⅄	–	Carretta et al. (1998)
⋆	–	Kaluzny et al. (1998)
⋆	–	Bakos et al.
▲	–	Benkő et al.