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Photometric study of the nova-like variable MV Lyrae during an enormous outburst in 1997

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Abstract. We report photometry of the novalike variable MV Lyr during the enormous outburst seen in 1997. We observed quasi-periodic oscillations with typical periods of 19, 29, 47 min, light variations at 0.1294 days (or its 1-day aliases) and amplitude $\sim 0^m.1$, and flickering consistent with a shot-noise model.

Key words: stars: oscillations – stars: novae, cataclysmic variables – stars: individual: MV Lyr – stars: flare – stars: binaries: close – stars: activity

1. Introduction

The history of close study of the cataclysmic variable MV Lyr spans half a century. MV Lyr was discovered as a variable star by Parenago (1946) and independently by MacRae (1952). It is a very blue nova-like star, clearly showing two brightness states: a high state with $B = 12^m - 12^m.5$, $B - V = -0^m.08$, $U - B = -1^m.0$ and a low one with $B = 17^m - 18^m$, $B - V = -0^m.35$, $U - B = -1^m.25$ (Walker 1954, Romano & Rosino 1980, Robinson et al. 1981).

It is often classified among the VY Scl stars or "anti-dwarf-novae", which spend their time mostly in a high brightness state and abruptly fall to faint states for a short time. However, during the last 20 years MV Lyr has behaved somewhat differently. In 1979 the star fell to a minimum which lasted 10 years. In that state MV Lyr showed outbursts of amplitude $1^m - 4^m$, but never reached its familiar high state. Outbursts can be divided into three types (Shugarov & Pavlenko 1998): most have "half widths" $\sim$ 2 days, some $\sim$ 7 days, and a very few about 100 days. In 1989 the star moved to its high state, which lasted until 1995. Since then MV Lyr has remained in a low state with its trademark signature of flares.

2. Observations

MV Lyr has been found to be both a soft (Mason et al. 1979) and hard (Cordova et al. 1981) X-ray source.

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Vojkhanskaya & Mitrofanov (1980) found circular polarization up to 2 per cent, and supposed that MV Lyr could be a polar. However further study did not confirm this classification (Efimov & Shakhovskoi 1980, Robinson et al. 1981). Ultraviolet observations made by Chiappetti at al. (1982) are consistent with the existence of an accretion disk at different brightness states. Perhaps MV Lyr could be an intermediate polar (Warner 1983).

According to Efimov & Shakhovskoi (1980) the distance to the binary is less then 160 pc, whereas Schneider et al. (1981) favor 320 pc.

From spectroscopic observations in the low state Schneider et al. (1981) found the orbital period to be $0^d.1336 \pm 0^d.0017$. In the high state Skillman et al. (1995) improved it to $0^d.1329 \pm 0^d.0004$. They suggested that the binary consists of a main-sequence red dwarf of 0.2–$0.3 M_\odot$ and a white dwarf of 0.6–$0.9 M_\odot$ with a low binary inclination ($i = 10° - 13°$).

The question of the photometric period is puzzling. All attempts to find a stable period were unsuccessful until Borisov (1992) and later Skillman et al. (1995) found periodic light variations during the high state. They interpreted them as superhumps with period 0.138 d, or 0.005 d longer the orbital period. MV Lyr was claimed to be a "permanent superhumper" during its high state, similar to the SU UMa-type dwarf novae (Warner 1985), which commonly show superhumps during their long outbursts (superoutbursts).

During the low state (outside of the brief outbursts) the light curve is sometimes very quiet, and Robinson et al. (1981) even suggested that the low state is caused by total cessation of mass transfer from the late-type companion. However, Andronov & Shugarov (1983), based on photographic observation during 5 nights, found "quasi-orbital" light variations with amplitude $\approx 1^m$. In the next low state Pavlenko (1998a) confirmed the existence of such variations with typical timescale 0.13–0.14 d, but with amplitude less then $0^m.1$, and also found low-amplitude light variations on a timescale ~ 4 d (Pavlenko 1998b), which might be connected with the precession period of the accretion disk.

Several photometric campaigns have been undertaken in the high state, but none so far in the low state, especially emphasizing the rapid variability occurring there. Here we present

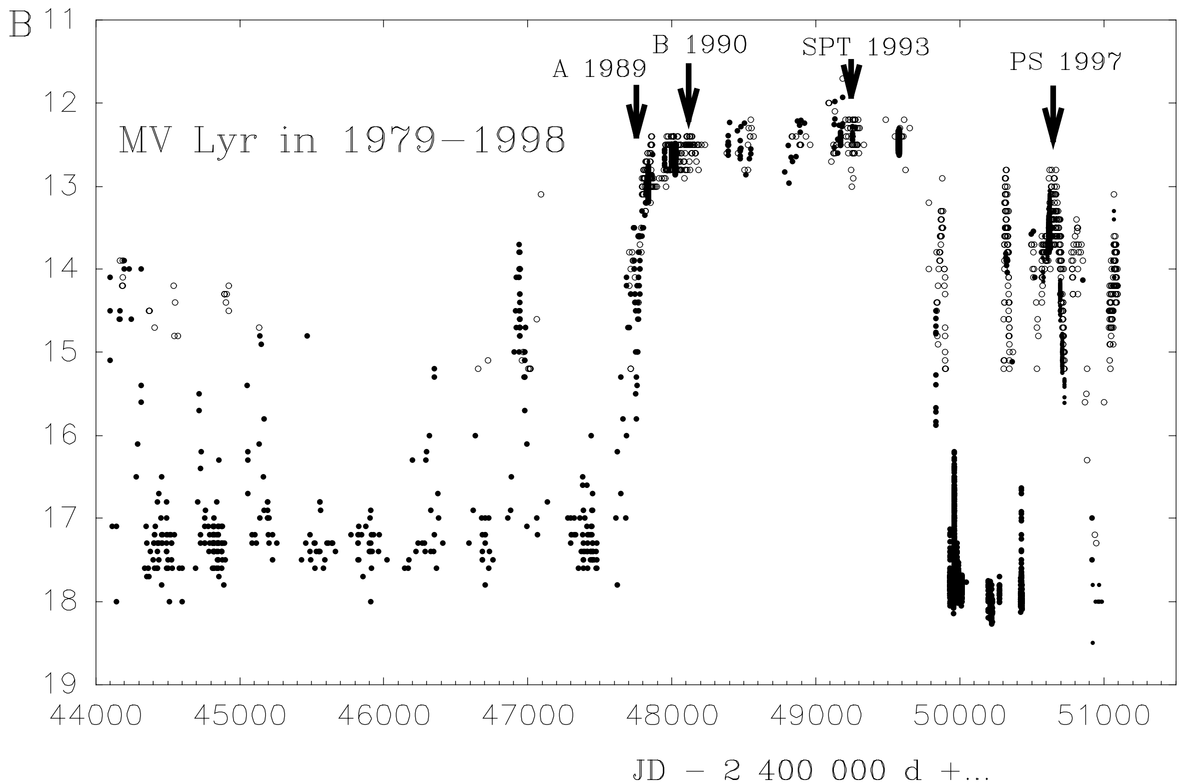

Fig. 1. The overall light curve of MV Lyr during 1979–1998. The B-magnitudes are plotted versus Julian date. The data taken from Pavlenko & Shugarov (1998), Pavlenko (1998b), Shugarov & Pavlenko (1998), Rosino et al. (1993), are marked by filled circles, and those from VSNET and VSOLJ by open circles. The arrows indicate the positions of intense observation (many-hours observational data set per several nights). The references shown by arrows on the light curve are: A1989 = Andronov et al., 1992, B1990 = Borisov, 1992, SPT1993 = Skillman et al. 1995, PS1997 = present paper.

our photometric studies during an enormous outburst which occurred during the low state of 1997.

Observations were carried out in June-October 1997 at the 60-cm telescope (Zeiss-600) of the Crimean Laboratory of the Sternberg Astronomical Institute with an electrophotometer, and at the tv complex of the 50-cm telescope (MTM-500) of the Crimean Astrophysical Observatory, equipped with a high sensitive tv tube (Abramenko et al. 1988, Castro-Tirado et al. 1993).

A total of ≈ 3000 brightness measurements were obtained on 11 nights of observation: during JD 615–625 at the Zeiss-600 and during JD 624–713 at the MTM-500. During JD 624–625 the observations at two telescopes were overlapped in order to check the difference in color systems. The total exposure was 26 hours. Several brightness estimates were also made before and after these dates, during JD 321–614 and after JD 850.

All observations were done in a system close to a standard B. The typical time resolution was 10–20 s at the 60-cm telescope and 40–50 s at 50-cm telescope, for an accuracy of 1–2 percent. Several comparison stars were used: the star N1 for observations at Zeiss-600 (the designation is given in Andronov & Shugarov 1982) and stars N8 and N5 (from Rosino at al. 1993) for observations at MTM-500. After reduction to the B system the zero-points of the data sets coincided within $0^m.03$, so no later correction was used.

3. The peculiarity of present low state

MV Lyr is currently in a low brightness state which has lasted three years. It has not much resembled the previous one, which lasted 10 years. To demonstrate this, we present the overall light curve of MV Lyr over the last 20 years (Fig. 1). This light curve was partially published (Pavlenko 1998b), but is here augmented by data from VSNET and VSOLJ, available at the server ftp://ftp.kusastro.kyoto-u.ac.jp, as well as our own new observations. The times of detailed study in the bright state are marked by arrows.

As mentioned above, the previous low state was punctuated by outbursts of different amplitude (Shugarov & Pavlenko 1998). The jumps in brightness reached no higher than $B = 14^m$, never quite to the high state level. At the present low state the small outbursts have not been observed, whereas large ones occur every 170–250 days. In all there were five such outbursts (and the sixth one is observing at present time). In accordance with the observed frequency of outburst, one could expect such an outburst within $JD50100$–50150, but the lack of data does not permit us to conclude whether the expected outburst occurred.

The frequency of these outbursts agrees with the Parenago-Kukarkin relation for dwarf novae (Kukarkin & Parenago 1934, Kholopov & Efremov 1976, Warner 1987) between amplitude

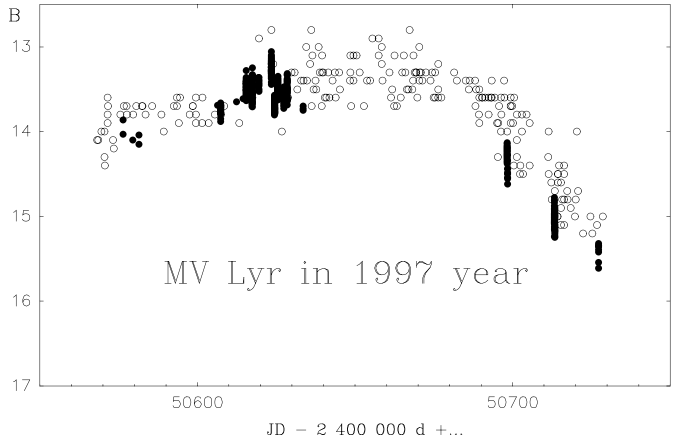

Fig. 2. Part of the overall light curve during the long outburst of 1997. Filled circles are data obtained by authors in the B system, and open circles are the visual estimates taken from VSNET and VSOLJ data bases.

and recurrence time. However, its decay time of $> 20d/mag$ is far too long to be consistent with the characteristic dwarf novae decay times given by Bailey (1975) and Warner (1987).

In contrast to the previous low state (1979–1988), the peak brightness of outbursts is now similar to the brightness of the true high state. So the description of the present state is somewhat ambiguous: regular outbursts superposed on the low state, or regular fadings from the high to the low state.

4. The 1997 outburst

The outburst of 1997 was the longest one ever seen. The flat outburst maximum had a slightly asymmetric shape: over ~ 130 days MV Lyr brightnened from 14^m to $13^m.5$, followed by decay (Fig. 2). Qualitatively this asymmetry of outburst plateau resembles the shape of the plateau of true high state itself (compare with those in Fig. 1), despite the much greater duration of the true high state. Typical light curves plateau of SU UMa superoutbursts have the opposite asymmetry.

5. Frequency analysis of the data set

Nightly light curves obtained during outburst maximum and decline show light variations with typical amplitude $0^m.4$, or slightly less. They also contain random flickering and quasi-periodic oscillations with typical timescales of tens of minutes, as well as the slower (hours) variations.

The original light curves for every night are given in Fig. 3. We analyzed the brightness changes with the Irregularly Spaced Data Analysis (ISDA) package (Pelt 1980, 1992). Prior to period search, we subtracted from the data a trend corresponding to the smoothed shape of the outburst.

5.1. Hourly variations

At first we analyzed the variability near the orbital period. Within ISDA we used different methods for different data sets: all data, and data only from the top of outburst. We found that the periodogram computed for the latter data set shows a better signal-to-noise ratio than those for all the data. In Fig. 4 the periodogram for these "top" data in the frequency range of 1–50 cycles/day is given. It is computed by the Stellingwerf method with the Abbe statistic, also known as the Lafler-Kinman statistic (Lafler & Kinman 1965). There the value of the statistic is less then 1 for trial periods close to the real one, and is close to 1 at other frequencies. In our analysis we give twice the value of the Abbe statistic.

There is a wide and double peak in the periodogram, centered on the 7.52 cycle/day orbital period. Surrounding this peak are components with 1-day aliasing. The data folded on the periods, corresponding to the two components close to the orbital period (0.1294 and 0.1487 d) give much smaller error then these on the periods of the remaining peaks. Because they are aliased, we cannot choose between them immediately.

5.2. Choice of likely period

Let's compare the closest period to the orbital one from different points of view.

The data folded on these two periods are shown in Fig. 5. They are binned into 20 intervals, and the standard deviation is marked by the vertical bars, which include the intrinsic variations - flickering and QPOs. The light curves are constructed for the same zero-epoch: $JD = 2450615.4047$. Both light curves have an amplitude about $0^m.1$ and an asymmetric shape.

If the real period is 0.1487 d, it could be interpreted as the period of a positive superhump (P_{sh}), because it exceeds the orbital period (P_{orb}). We then could examine the position of MV Lyr in the known empirical relation between the fractional period excess $\varepsilon = (P_{sh} - P_{orb})/P_{orb}$ and orbital period (Stolz & Schoembs 1981, 1984) for the known superhumpers with apsidal disk precession (Vogt 1982; Whitehurst 1988; Lubow 1991). This relation is shown in the upper panel of Fig. 6 for all superhumpers as of mid-1998 (Patterson 1998). The 2nd order polynomial fit is shown by line. MV Lyr in the last high state as well as the old nova V603 Aql are placed far below the relation, while MV Lyr in the present outburst is far above it.

The deviations of MV Lyr positions in both brightness states significantly exeed a scattering of the rest points over the line and fairly differ from each other. It is known that superhumps periods decrease from the time when they were first detected. However the differences in the MV Lyr deviations are too large to be explained as possible change in the superhump period: The differences between extremal values of superhump periods, normalized to the orbital periods, don't exeed 1,5 per cent for different superhumpers (see, for example, Patterson et al. 1993a, Leibowitz et al. 1994, Patterson et al. 1997).

The period of 0.1487 d implies that the period of apsidal precession $P_{prec} = 1.302$ d according to the relation

$$P_{prec}^{-1} = P_{orb}^{-1} - P_{sh}^{-1} \quad (1)$$

From another relation (Osaki 1985) we can estimate the accretion disk radius:

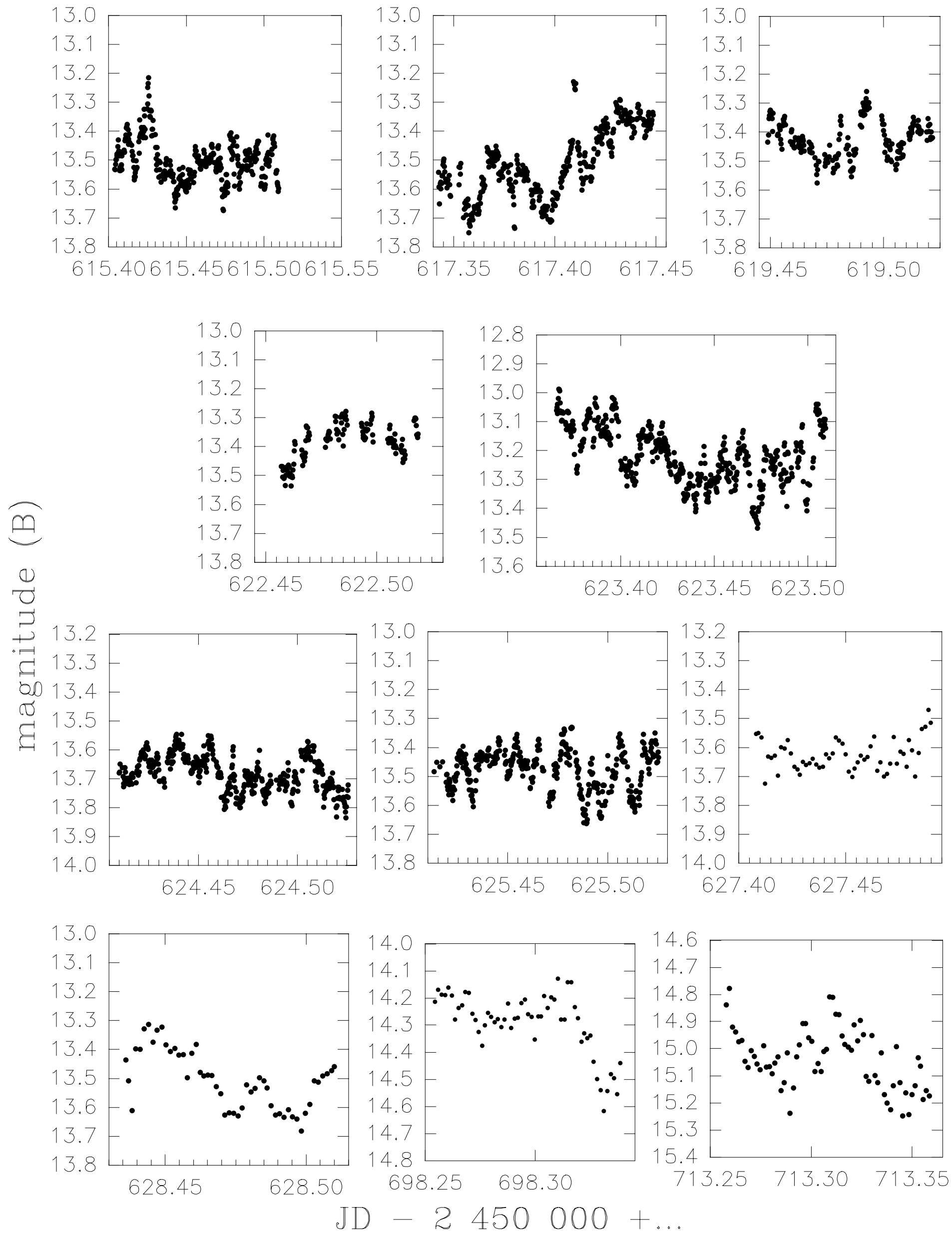

Fig. 3. Original light curves in B, obtained in June–October 1997. The abscissa is given in truncated Julian date.

$$P_{prec}^{-1}/P_{orb}^{-1} = 3/4 * [q/(1+q)^{1/2}] * r_d^{3/2}, \quad (2)$$

where q is the mass ratio of the secondary (m_2) to the primary (m_1). Taking $q = 0.43$ (Skillman et al. 1995) or more relevant for the case of tidal instability, 0.3, we obtain $r_d = 0.52$–$0.64a$. This is comparable or slightly larger then the primary's Roche Lobe, namely 0.45–$0.49a$ (Pringle & Wade 1985), where a is the binary separation.

On the other hand, a period of 0.1294 d might be interpreted as a negative superhump period as it is less than P_{orb}. Recently it has become known that a few cataclysmic variables display superhumps with negative period excess (Patterson et al. 1993b).

In this case $\varepsilon = -0.030$. This value is close to that for known negative superhumpers: the novalike TT Ari shows $\varepsilon = -0.035$ (Thorstensen et al. 1985, Udalski 1988), while the old nova V603 Aql shows -0.029 (Patterson et al. 1997), and the SU UMa-type binary V503 Cyg shows -0.025 (Harvey et al. 1995). The position of MV Lyr within the negative superhumpers is given in a lower panel of Fig. 6.

So the arguments considered above indicate that $P = 0.1294d$ is preffered over $P = 0.1487d$.

5.3. *Short-term light variations*

The second point is flickering and short-term light variations. In order to investigate them, we subtracted from the individual-night data the best fits with period 0.1294 d and calculated the power spectra for every nightly data set, using a standard (Deeming 1975) Fourier transform analysis.

Then we selected five power spectra for the longest observational runs showing the short-term light variations with highest amplitude. The average of these power spectra is shown in Fig. 7

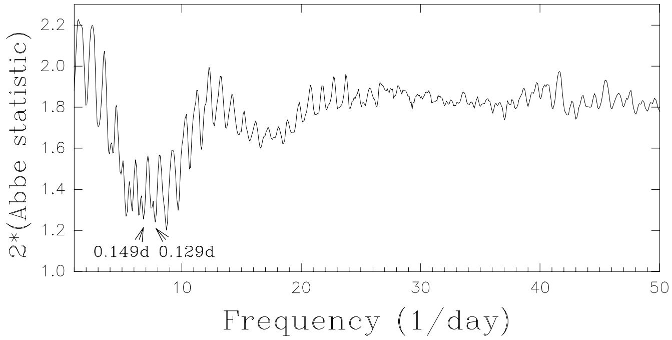

Fig. 4. The periodogram for MV Lyr (June data set) computed by Stellingwerf method in the region of 1–50 cycle/day. The two peaks closest to the position of the orbital period are marked by arrows.

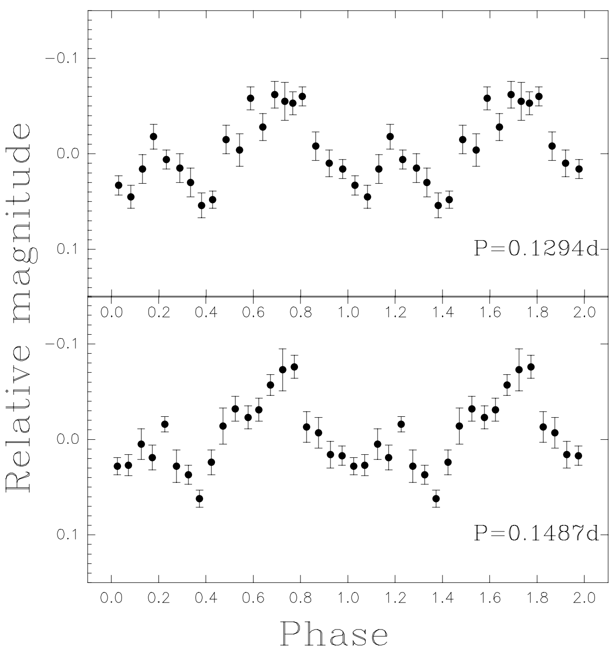

Fig. 5. Data folded on two trial periods: 0.1294 d (*upper panel*) and 0.1487 d (*lower panel*).

(a). The dip at low frequencies is caused by the subtraction of the best fit trend. The continuum is well fit to the function S(f) in the shot noise model (Panek 1980):

$$S(f) = (0.00105 \pm 0.00005)/\{1 + [(0.0176 \pm 0.0007) * f]^2\}, \quad (3)$$

where S is the power and f is the frequency, measured in c/day. In this model the flickering is described as the overlapping of a series of randomly occuring flares (shots) of well-defined shape. We found the e-folding time (decay time) of the flares to be 242 s.

Andronov (1996), using two short data sets of a single night, obtained decay times of 41 and 64 s for the high brightness state. Decay times determined for other CVs are 41–73 s for AM Her (Panek 1980); 160 s (Silber et al. 1997) and 92 s (Andronov, 1996) for BY Cam. All these are much shorter than we found for MV Lyr.

There are several broad peaks in the power spectrum which exceed the limits of the shot-noise model. They correspond to

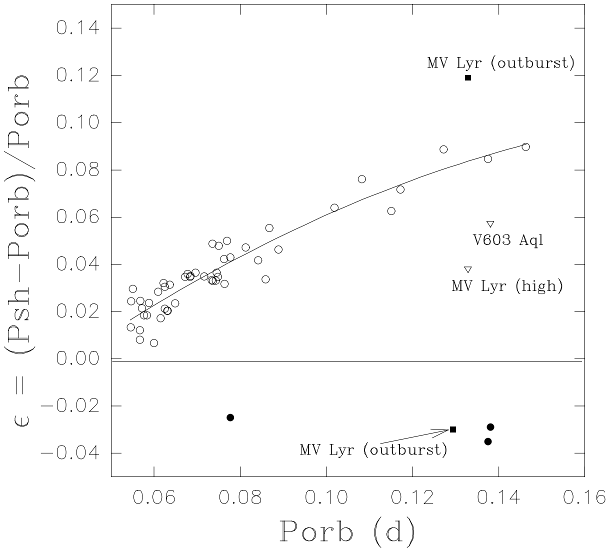

Fig. 6. The relation between fractional period exess and orbital period for both positive (open circles in upper panel) and negative (filled circles in lower panel) superhumpers. The deviated data of V603 Aql and MV Lyr in a high brightness state are marked by triengles. The present for two suspected periods of MV Lyr are marked by square.

periods of 19.2 min (most significant peak), 29 min, and 47 min (less significant peaks). We could see that these periods exist at least within ~ 4 months, but their phases are wandering and they are rather quasi-periods, not strong periods: If we calculate the periodogram for all data (which span about 4 months) with fixed zero epoch, these periods do not disappear, but their significanse decreases. This is demonstrated by the Fourier periodogram (Fig. 7b) and more clearly - the periodogram computed by the Stellingwerf method (Fig. 7c). Comparison with the mean power spectrum reveals that the period of 19.2 min is the most stable.

The mean light curve of the data, folded on this quasi-period, is shown in Fig. 8. Its amplitude is $0^m.04$. In constructing this light curve, we included all data from the June-October data set, even those which did not show the high-amplitude fast variations.

6. Brief review of QPOs in MV Lyr

Rapid light variations with a timescale of 1–30 min and amplitude about $0^m.4$ were first found by Walker (1954).

The 47-min QPOs have been observed by Borisov (1992) and Skillman et al. (1995) and 18–21 min by Andronov et al. (1992) in the high brightness state. In the low state the behaviour of MV Lyr is fairly quiet and short-period variations (as well as single flares) are rather rare events. It seems, that they could appear with a probability of 0.1–0.2. Thus Robinson in one of five nights observed ~ 20 min light variations with an amplitude of $0^m.1$–$0^m.3$ (Robinson et al. 1981). Pavlenko in 3 of 30 nights detected a single flare with typical time 15–55 min, and during one night a series of QPOs with a period of 37.6 min and amplitude $\sim 1^m$ (Pavlenko 1998b).

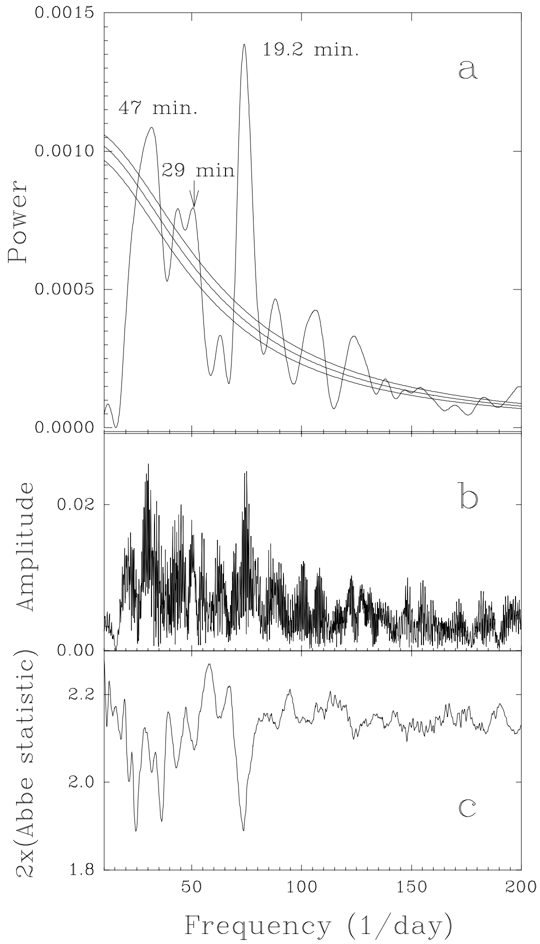

Fig. 7. a The mean power spectrum for the 5 selected nights. The region of a shot-noise model (in accordance with Eq. (3)) is shown by the lines. **b** Fourier periodograms for the all data. **c** Periodogram computed by the Stellingwerf method.

So, comparing all previous studies of MV Lyr, we have found that all the observed quasi-periodic oscillations (QPOs) occurred at the some preferred frequencies. They do not depend on the brightness state. However, in the low state such QPOs are very rare events, whereas in the high state one could detect if not one then the other listed QPOs.

The nature of the periods is unknown. Several approaches for explanation are possible.

1. The QPOs are caused by an inhomogeneous disk structure. If we suppose that the periods correspond to Keplerian orbits, the inhomogeneities are located at the middle and outer regions of the disk (0.21–$0.39a$).
2. QPOs are connected with oscillations of the ionizaton front near the inner Lagrange point, causing variations in the mass transfer rate about $0.05 * P_{orb}$ (King 1989). This value in our case is equal to p=9.6 min. The most prominent QPOs whenever detected occured at 19.2 min, or 29 min, or 38 min, or 47 min (or at both periods), suggesting 2p, 3p, 4p, and 5p! But a QPO at p itself was never observed, despite having adequate time resolution.

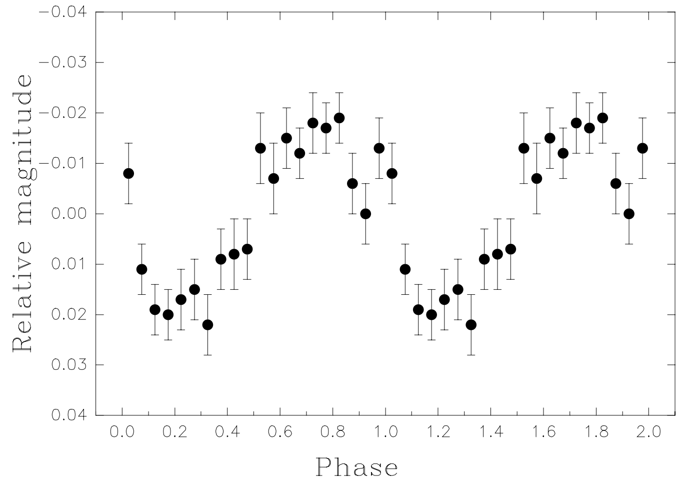

Fig. 8. All data, folded on the 19.2 min period and binned into 20 phase intervals.

7. Conclusion

MV Lyrae recently went into a low state after a 5-year residence in the high state, and its behavior has somewhat resembled dwarf novae with recurrence time of 170–200 d and an amplitude of $4^m - 5^m$. The decay time is, however, much longer than in dwarf novae.

– The data show light variations with a "quasi-orbital" period. The peaks are plagued by daily aliases, but the one closest to the orbital period is 0.1294 d, which might arise from retrograde motion of the accretion disk's line of nodes.
– During one outburst, we observed flickering which could be fitted to the shot-noise model with the decay time of a single outburst equal to 242 s.
– Stable QPOs with typical time of 19.2, 29 and 47 minutes have been found. They are 2, 3 and 5 times longer than the expected value for the variations of mass transfer rate near the inner Lagrange point.

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