Astronomy Letters, Vol. 23, No. 6, 1997, pp. 799–810. Translated from Pis'ma v Astronomicheskii Zhurnal, Vol. 23, No. 11–12, 1997, pp. 918–930.

1997AstL...23..799M

Quasi-Periodic Light Variations in Four Herbig Ae/Be Stars

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Received March 3, 1997; in final form, July 29, 1997

Abstract—The results of long-term photoelectric *UBVR* observations of four Herbig Ae/Be stars (V1331 Cyg, MWC 342, V633 Cas, and MWC 297) are presented. These objects exhibited variability in the range $0^m_.15$ to $0^m_.8$. Smooth light variations on a time scale of 70–140 days were observed. A rapid irregular variability with an amplitude of $0^m_.1$–$0^m_.2$ was superimposed on these variations. The long-term monitoring of MWC 342, V633 Cas, and MWC 297 also revealed smooth variations in the mean brightness from year to year. The results of a search for periodic light variations are reported. The time series are analyzed by the CLEAN method. Quasi-periods that varied over the range 10 to 50 days were detected in all four stars. Only V633 Cas showed a stable period of 35.5051, which was observed in the entire interval of observations. The observed period variability may reflect a spatial origin of these periodicities. It is assumed that the periodicities could be associated with high-latitude clouds of gas and dust.

INTRODUCTION

Recently, more and more attention has been given to the search for periodic light variations in young stars. These studies have mostly been successful for classical T Tau stars (CTTS) and for weak-line T Tau stars (WTTS). Many of these stars exhibit periods between 2 and 10 days which are associated with the rotation of stars with cool or hot spots on their surfaces. Cool spots are assumed to be a result of the presence of an extensive convection zone in the star. According to the current theory, no such zones can exist in stars of spectral types earlier than *F*, which Herbig Ae/Be stars are.

By now, variability, which is assumed to be irregular, has been detected in approximately 70% of the Ae/Be stars. Nevertheless, attempts to find traces of periodicities have not been abandoned. For example, Baade and Stahl (1989) detected quasi-periods of about $31^d_.5$ and 49^d in HR 5999. Having analyzed the light curves of five Herbig Ae/Be stars, Herbst *et al.* (1987) detected a 60^d period in only one star (Z CMa). In the well-known Ae/Be stars MWC 1080 (Grankin *et al.* 1992), TY CrA (Kardopolov *et al.* 1981), and T Ori (Shevchenko 1986), the observed periods are most likely associated with their binarity. In stars exhibiting irregular Algol-like dimmings (UX Ori stars), Zaitseva (1983) and Shevchenko *et al.* (1993a) found longer periods. Shevchenko *et al.* (1993b) gave a review of the studies in which periodicities were sought and classified Ae/Be stars by the detected periods. They proposed to divide the observed periodicities into three types: long-period variations with periods >1 year, medium-period variations with periods between 10 and 100 days, and short-period variations with periods from several hours to several days.

However, several factors hamper the search for periodic light variations in young stars. Many Herbig Ae/Be stars exhibit complicated photometric behavior (abrupt changes in brightness, complex trends, etc.). Some of the stars are very faint, preventing dense series of observations from being obtained. In addition, some Ae/Be stars are either embedded in bright nebulae or are their neighbors, which also makes it difficult to obtain accurate *UBVR* observations.

The list of Shevchenko *et al.* (1993a) includes 23 objects with periods that mainly lie in the range 10 to 100 days. From this list we chose several Ae/Be stars for a more detailed search of periodicities. Here, we present the results of our *UBVR* photometry and search for periods in four stars: V1331 Cyg, V633 Cas = LkHα 198 MWC 342 = V1972 Cyg, and MWC 297. This paper is the first in a series of articles devoted to a detailed search for periodic variations that is based on series of observations spanning many years.

OBSERVATIONS

We carried out the observations of V1331 Cyg, V633 Cas, MWC 342, and MWC 297 as part of the long-term program ROTOR (Shevchenko 1989); one of the goals of this program to search for periodic light variations in Herbig Ae/Be stars, T Tau stars, and related objects. We performed the *UBVR* photometry at Mount Maidanak using two 60-cm reflectors equipped with identical photon-counting photometers. We obtained most of the observations by the differential method using comparison stars (Straizhys 1977). The equipment, observing techniques, and reduction procedures are described in Shevchenko (1989). The results of the observations are summarized in Table 1, which

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Table 1. Photometry for four Herbig Ae/Be stars

Star	Epoch JD 2440000+	n	$\langle V \rangle$	$V_{min} - V_{max}$		$\langle U\text{–}B \rangle$	$\langle B\text{–}V \rangle$	$\langle V\text{–}R \rangle$
V1331 Cyg	6612–9647	896	$12\overset{m}{.}03$	$12\overset{m}{.}03$	$11\overset{m}{.}63$	0.42	1.07	1.05
			0.02			0.04	0.02	0.02
MWC 342	7446–9647	658	10.63	10.93	10.27	–0.23	1.21	1.53
			0.01			0.02	0.01	0.01
V633 Cas	5879–9635	492	14.17	14.58	13.86	0.41	0.96	1.23
			0.03			0.11	0.03	0.03
MWC 342	6609–9633	644	12.31	12.59	12.08	0.84	2.08	2.65
			0.02			0.06	0.02	0.01

gives the mean magnitudes and color indices, the epoch of observation, the number of observations, and the rms error of a single measurement.

V633 Cas and MWC 297 were classified by Herbig (1960) as Ae/Be stars long ago, while MWC 342 was included in the ROTOR program in 1988 on the basis of the data of Miroshnichenko (1988). Bergner *et al.* (1990) also provide evidence that this object is young and may belong to Herbig Ae/Be stars. V1331 Cyg was included in the program of observations on the basis of the data of Cohen and Kuhi (1978).

THE METHOD OF SEARCH FOR PERIODS

As was already noted above, many Ae/Be stars exhibit complicated photometric behavior; in addition, such factors as faintness of the objects, the presence of a nebula, etc. hamper the obtaining of dense and accurate series of observations. As a result, the time series of observations turn out to be far from evenly sampled, causing difficulties in analyzing them by the classical methods of spectral analysis.

Recently, methods have been developed for analyzing unevenly sampled time series. One of them is the CLEAN algorithm (Roberts *et al.* 1987; Terebizh 1992). The one-dimensional version of the CLEAN method, which is designed for analysis of unevenly sampled time series, is a modification of the two-dimensional CLEAN method that was originally developed by Hogbom (1974) for analysis in radio astronomy of two-dimensional brightness distributions constructed by aperture synthesis.

In order to estimate the significance of periods, we used a generalization of Schuster's periodogram to unevenly sampled time series called the LS spectrum (Terebizh 1992). We used the LS spectrum in the form proposed by Lomb (1976). Thus, the LS spectrum may be considered an independent method of search for periodicities in unevenly sampled time series. The formal parameter Q (Terebizh 1992) generalized to unevenly sampled series was used as a significance test for a period. The normalized parameter Q shows the percentage of cases in which a random time series exhibits peaks of the same height as those detected in the series under study. In the case of an unevenly sampled series, the random time series is understood to be the white noise with the same mean, variance, and distribution of the times of observation as those for the series under consideration (Terebizh 1992). Thus, the smaller is the parameter Q, the high is the probability that the period exists. We assume a period to be significant if $Q < 5\%$. In addition to the use of a purely formal estimation criterion, we assume a periodicity to be more significant if it is detected in three bands, *UBV*.

We searched for periods in the ranges 2 to 50 days and 10 to 200 days in the seasonal observations and in the entire series of observations, respectively. For a more reliable identification of periodicity in V1331 Cyg, MWC 342, and MWC 297, we searched for periods in the *BVR* bands. Because of the faintness of V633 Cas, we searched for periods in this object only in *V*.

V1331 Cyg

Our *UBVR* observations of V1331 Cyg cover the period 1986–1994. The light curve for 1989–1994 is shown in Fig. 1. The light curve for 1986–1988 is given in Shevchenko *et al.* (1991). During the observations, V1331 Cyg was moderately active: the amplitude of its V variability changed from $0\overset{m}{.}46$ in 1988 to $0\overset{m}{.}71$ in 1992. The total amplitude was $0\overset{m}{.}78$ in *V*. The variability amplitude increased from *R* to *B*. The light curve of V1331 Cyg exhibits smooth variations on a time scale of 75–140 days. Since these variations were seen over the entire 0.5–1 period in the observing season, we do not consider them periodic. Shorter period light variations seen over 1.5–2 periods were occasionally superimposed on this variability. Since in contrast to the other stars, the mean brightness of V1331 Cyg remained constant over the entire period of observations, we do not provide a general light curve of V1331 Cyg here.

We searched for periodic light variations in the range 2 to 50 days after removing the trend associated with the long-period light variations (75–140 days) mentioned above. An analysis of the light curve of V1331 Cyg from 1986 through 1994 revealed seven

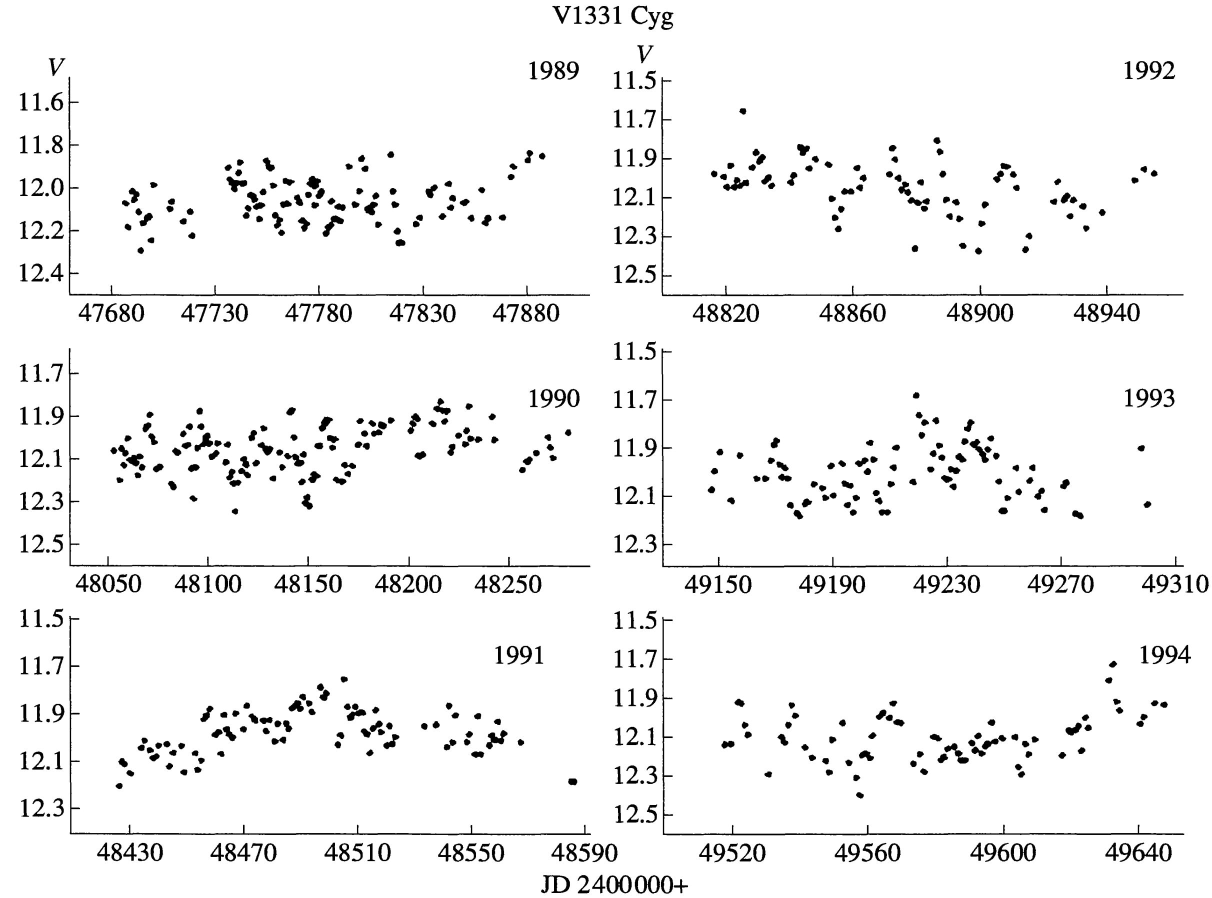

Fig. 1. A segment of the light curve of V1331 Cyg for 1989–1994.

peaks in the power spectrum with a fairly high significance. Figure 2 shows the power spectra separately for each year that we obtained by using the CLEAN algorithm. The detected periods lie in the range 11^d to 36^d. Each of these periodicities is distinguished in a limited time interval. The periods, the estimates of *Q*, and the time intervals in which they were observed are given in Table 2. The phase *V* light curves folded with the detected period are shown in Fig. 3. The average amplitude of the periodicity that we estimated by the least-squares method is $0^m_.2$ in *V*. All of the periods found are also distinguished in *B* and *R*. The shape of the phase light curves changes from season to season, which is attributable, in part, to the removal of the trend and, in part, to the peculiar behavior of the star. The shape of the periodicity may differ from a sine curve. The peak corresponding to the $18^d_.248$ period in the power spectrum for 1987 (Fig. 2) is not most pronounced. However, this peak is also present in the power spectrum in *B* and *R*, in contrast to the peaks corresponding to longer periods which are seen in the power spectrum only in *V*. The 36^d period in 1988 that we found by the CLEAN method differs somewhat from the period (32^d) that was found by Yurkevich's method (see Shevchenko *et al.* 1991). Estimation of *Q* from the LS spectrum for both periods leads us to conclude that our period is more probable.

MWC 342 = V1972 CYG

The light curve of MWC 342 for 1986–1994 is shown in Fig. 4a. The variability amplitude changes from season to season: from $0^m_.36$ in 1991 to $0^m_.59$ in 1994 in *V*, and increases when passing from long to shorter wavelengths, as is the case with V1331 Cyg, in agreement with the data of Bergner *et al.* (1990). MWC 342 is similar in the pattern of variability during the season to V1331 Cyg. Slow (70–120 days) light variations, on which light variations on a shorter time scale are superimposed, are also observed. At the same time, as can be seen from Fig. 4a, the mean brightness of MWC 342 undergoes changes on a time scale of several years, in contrast to V1331 Cyg, whose mean brightness remains constant.

An analysis of the light curve of MWC 342 by the CLEAN method revealed five peaks in the power spectra for different years with a fairly high significance.

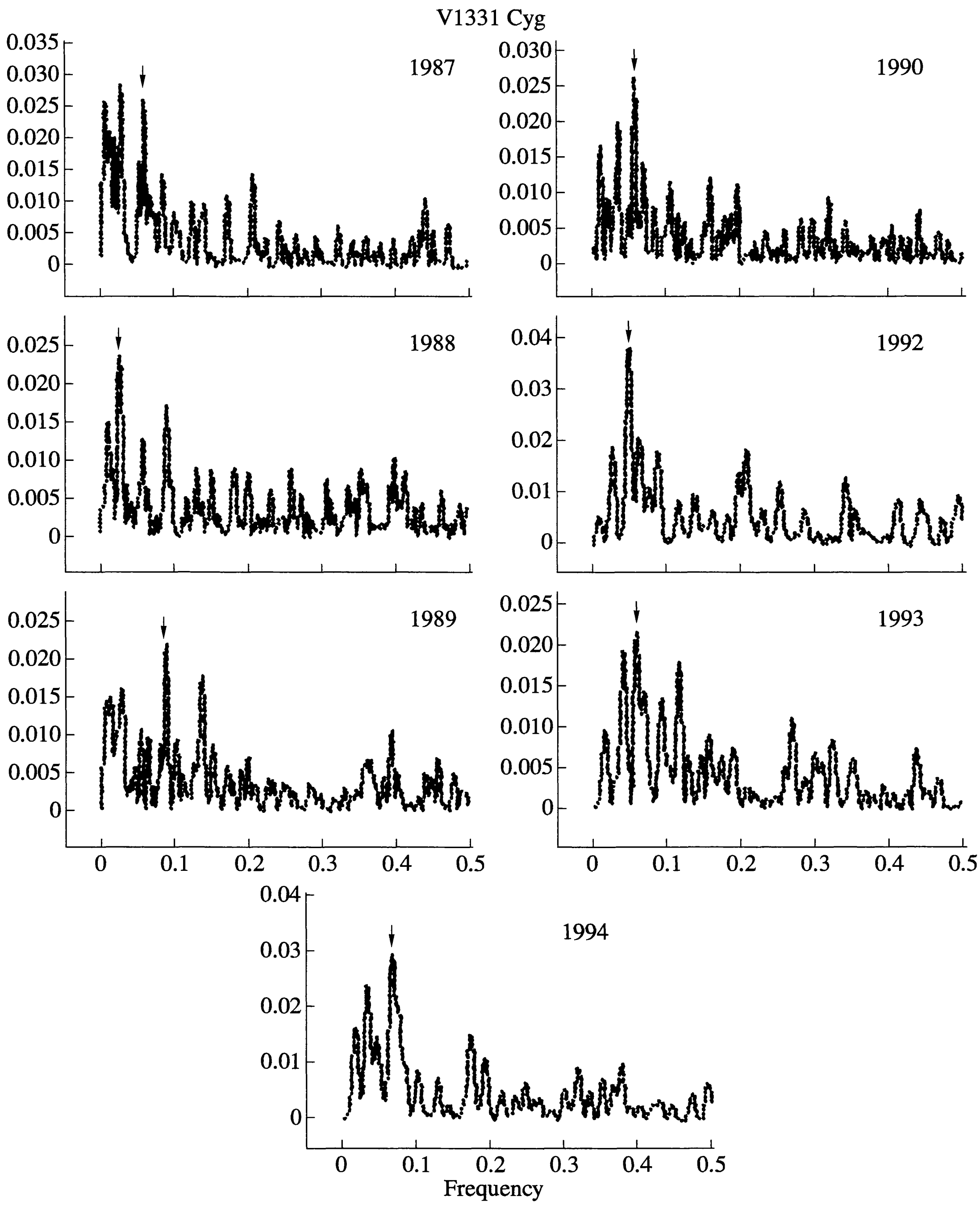

Fig. 2. The power spectra of V1331 Cyg obtained by the CLEAN method for the seasons in which periodic variations were detected. The spectrum was obtained after 100 iterations for the degree of cleaning of noise $g = 0.5$. The x axis is the oscillation frequency, and the @y axis is the absolute value of the dimensionless parameter P of the CLEAN method. The peaks corresponding to the probable period are marked by arrows.

The power spectra of MWC 342 for these years are shown in Fig. 5. The periods corresponding to the peaks lie between 14^d and 46^d. The results of our search for periodicities in the light curve of MWC 342 are summarized in Table 3. Figure 6 shows the phase light curves folded with the detected periods. The average amplitude of the periodicities is $0\overset{m}{.}17$ in V. In 1993, the CLEAN method revealed two prominent peaks in the power spectrum which correspond to probable periods of $12\overset{d}{.}05$ and $18\overset{d}{.}52$. These periods are not aliases. In order to find out which of these periods is true, we used a "whitening" procedure, i.e., the procedure of removing the single harmonic corresponding to the specified period from the time series (Terebizh 1992). After the

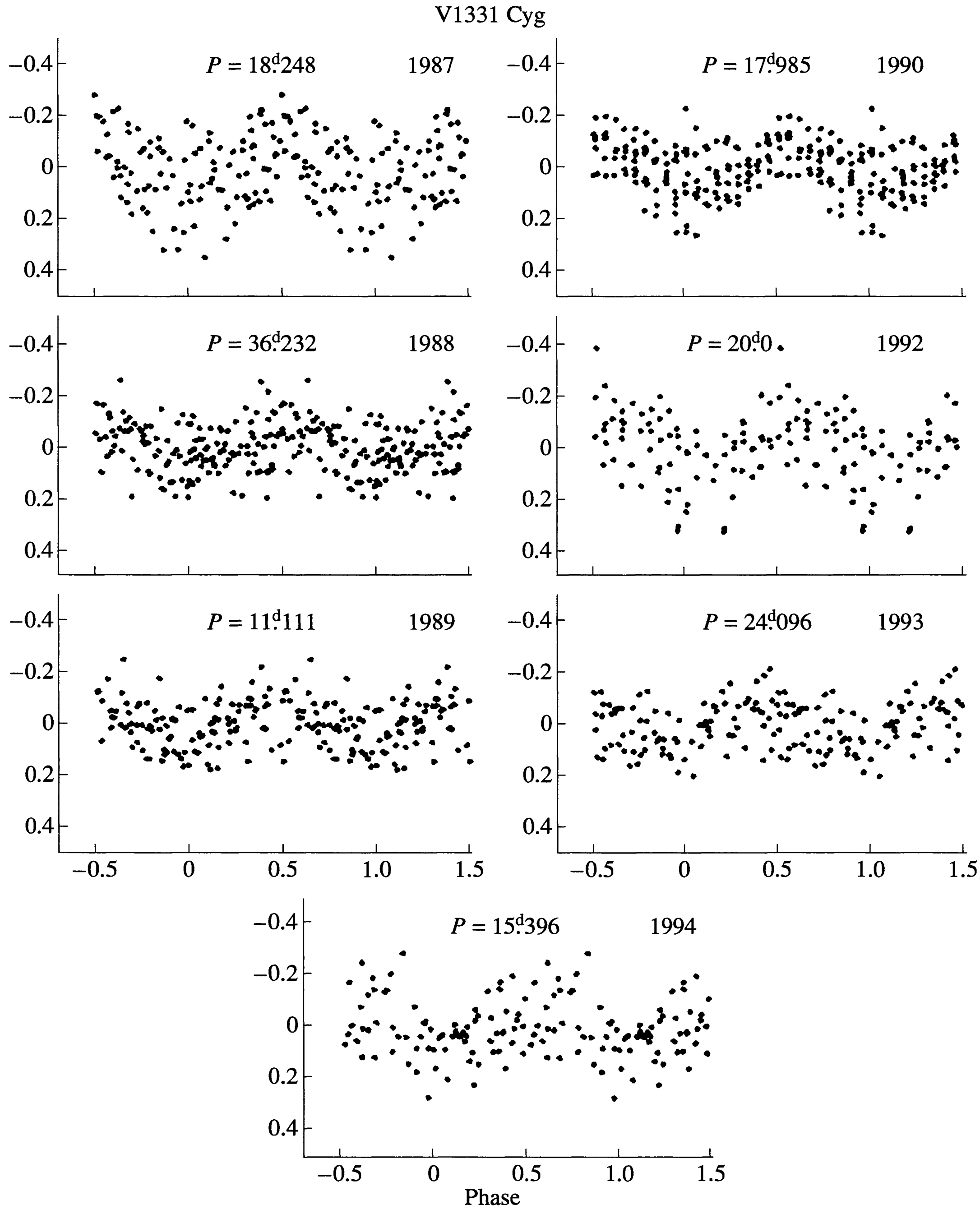

Fig. 3. The phase light curves of V1331 Cyg for the probable periods corresponding to the peaks marked by arrows in Fig. 2. The x axis is the phase of periodic variations, and the y axis is the magnitude of the star relative to the mean. The values of the periods are shown in the plots.

$18^{\mathrm{d}}.52$ periodicity was removed, the peak corresponding to the $12^{\mathrm{d}}.05$ period also disappeared. The corresponding period also disappeared in the phase diagram. After the $12^{\mathrm{d}}.05$ periodicity was removed from the time series, the peak corresponding to the $18^{\mathrm{d}}.52$ period was retained. Therefore, we assumed that $18^{\mathrm{d}}.52$ is the actual period. Bergner *et al.* (1990) point to the presence of a 132^{d} period revealed by the 1986–1989 observations and note that the period revealed by polarization observations is a factor of 2 shorter. An analysis of the entire series of observations by the CLEAN method shows a more significant peak near 66^{d}, which is a factor of 2 shorter than the 132^{d} period. We prefer the phase curve with the 66^{d} period to the curve with the 132^{d} period.

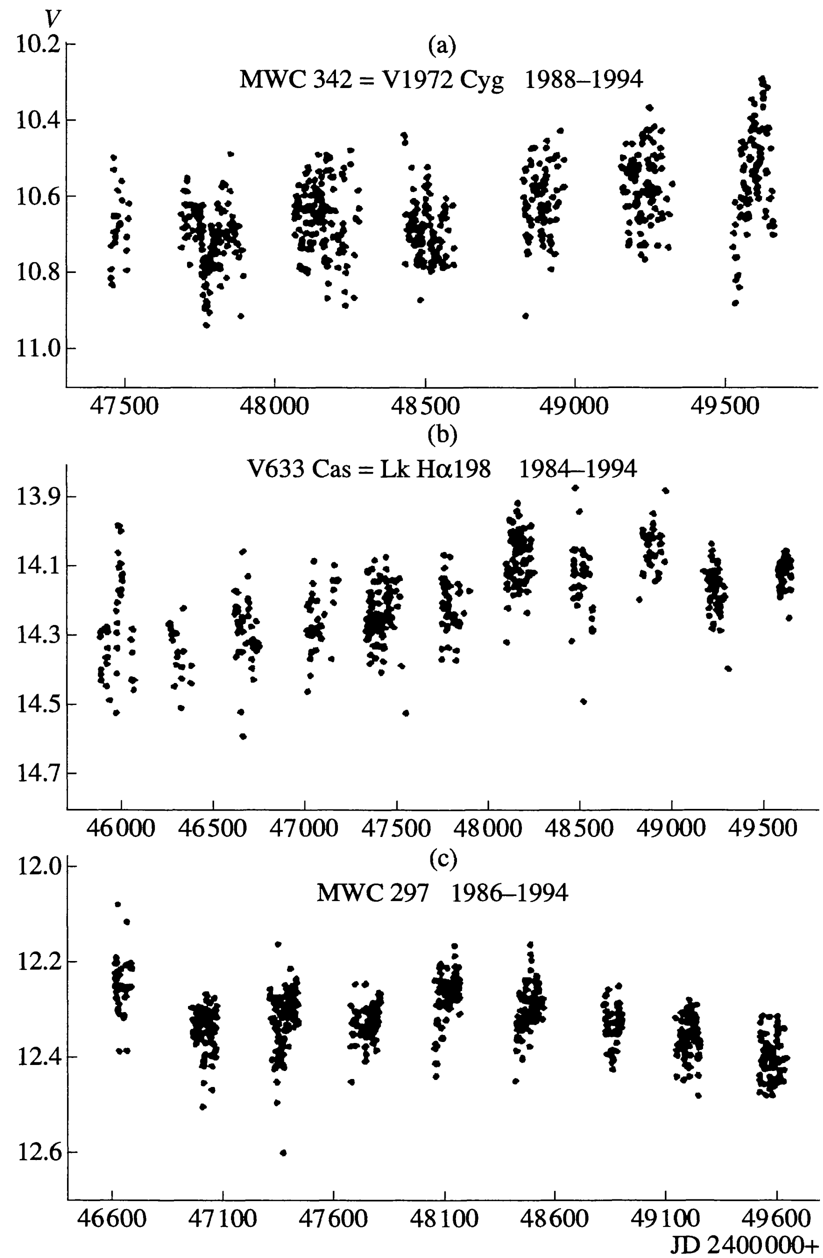

Fig. 4. The overall light curves for the three stars under consideration: (a) MWC 342 (1988–1994); (b) V633 Cas (1984–1994); and (c) MWC 297 (1986–1994).

V633 Cas = Lk Hα 198

The light curve of V633 Cas for 1984–1994 is shown in Fig. 4b. V633 Cas exhibits variability with the amplitude $V = 0^m.4$. Between 1984 and 1990, the brightness of the star steadily rose and then began to fluctuate about $14^m.1$. In 1984, a local brightness rise with an amplitude of $0^m.4$ that lasted for $\sim 32^d$ was observed.

Of all the objects studied here, the variability of V633 Cas seems most regular. An analysis of the entire observational material for 1984–1994 by the CLEAN method revealed a peak in the power spectrum corresponding to the $35^d.5051$ period (Fig. 7). The light curve folded with this period is shown in Fig. 8. The probability of this period is very high: $Q = 4 \times 10^{-5}$. However, the pattern of periodicity becomes more complicated when the light curve of V633 Cas is analyzed separately in each season. We detected several peaks in the power spectrum for separate years which were close to the main period. The phase diagrams of the periods corresponding to these peaks are shown in Fig. 8. The corresponding statistical data on the

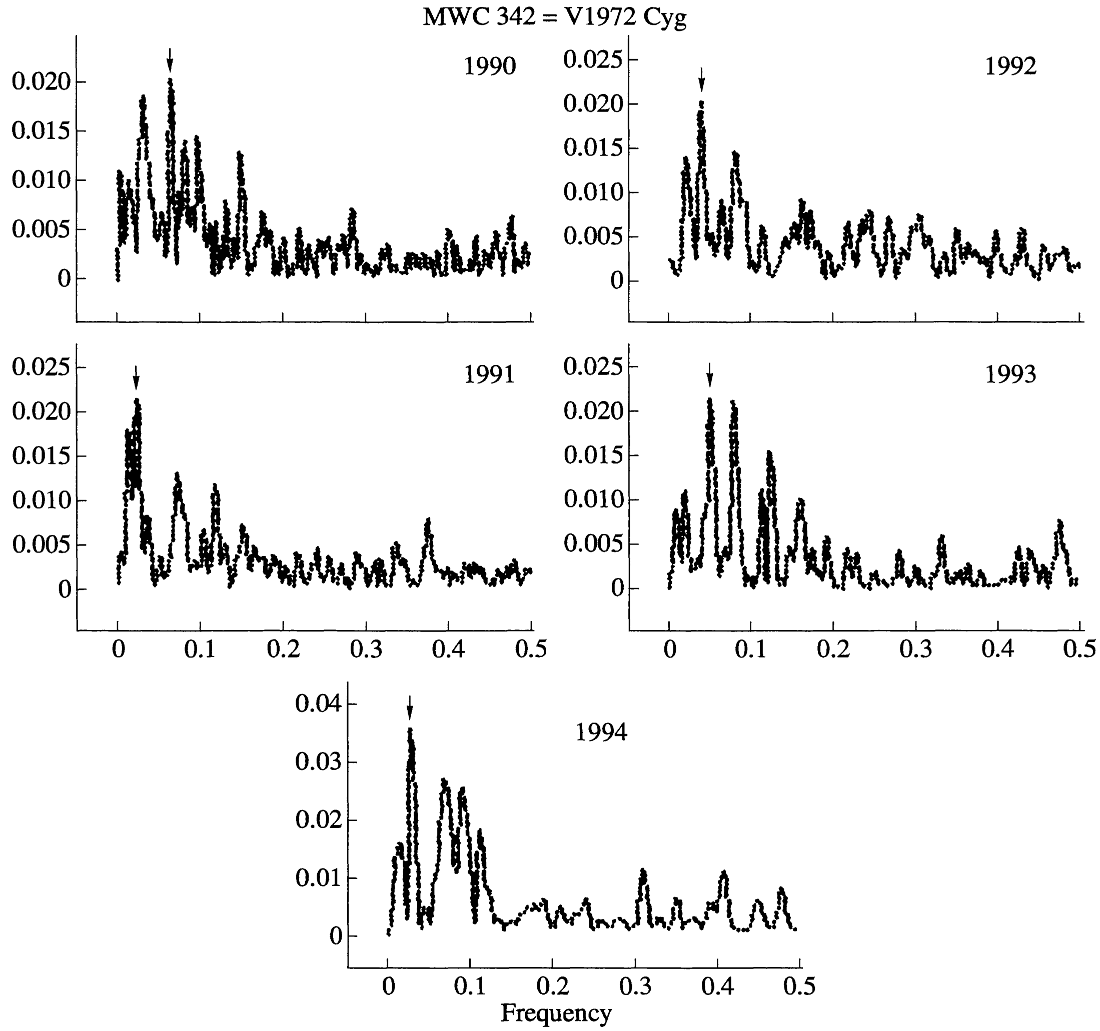

Fig. 5. The power spectra of MWC 342 obtained by the CLEAN method for the seasons in which periodic variations were detected. The notation is the same as in Fig. 2.

detected periodicities is given in Table 4. The $36^{\mathrm{d}}.695$ period, which is closest to the main period, is most pronounced in the phase diagram in 1990. Although we detected no periodic variations with a sufficiently high significance in 1989 by the CLEAN method, the power spectrum exhibits a peak close to the main period. In addition to the peak at the frequency of the period $P = 32^{\mathrm{d}}.258$ in 1988, the CLEAN method also revealed a peak in the power spectrum at the frequency corresponding to $P = 3^{\mathrm{d}}.7175$. However, the frequency of this peak is close to the frequency of one of the harmonics for $P = 32^{\mathrm{d}}.258$. When the harmonic with the $32^{\mathrm{d}}.258$ period is subtracted, the peak at the frequency of the $3^{\mathrm{d}}.7175$ period reduces and merges with the noise component. Although the peak at the frequency of the period $P = 19^{\mathrm{d}}.129$ is most significant in the power spectrum in 1993, the second significant peak is the peak at the frequency of the $33^{\mathrm{d}}.477$ period, which is also close to the main period of $35^{\mathrm{d}}.5051$. Thus, we detected four periods between 1988 and 1994 with a sufficiently high significance, which are close to the

Table 2. Periodic light variations in V1331 Cyg

Year	JD 2440000+	Period	Q, %
1987	6958–7178	$18^{\mathrm{d}}.248$	1.114
1988	7309–7521	36.232	0.143
1989	7687–7887	11.111	0.234
1990	8049–8279	17.985	0.001
1992	8815–8954	20.000	1×10^{-4}
1993	9146–9300	24.096	0.05
1994	9516–9647	15.394	0.05

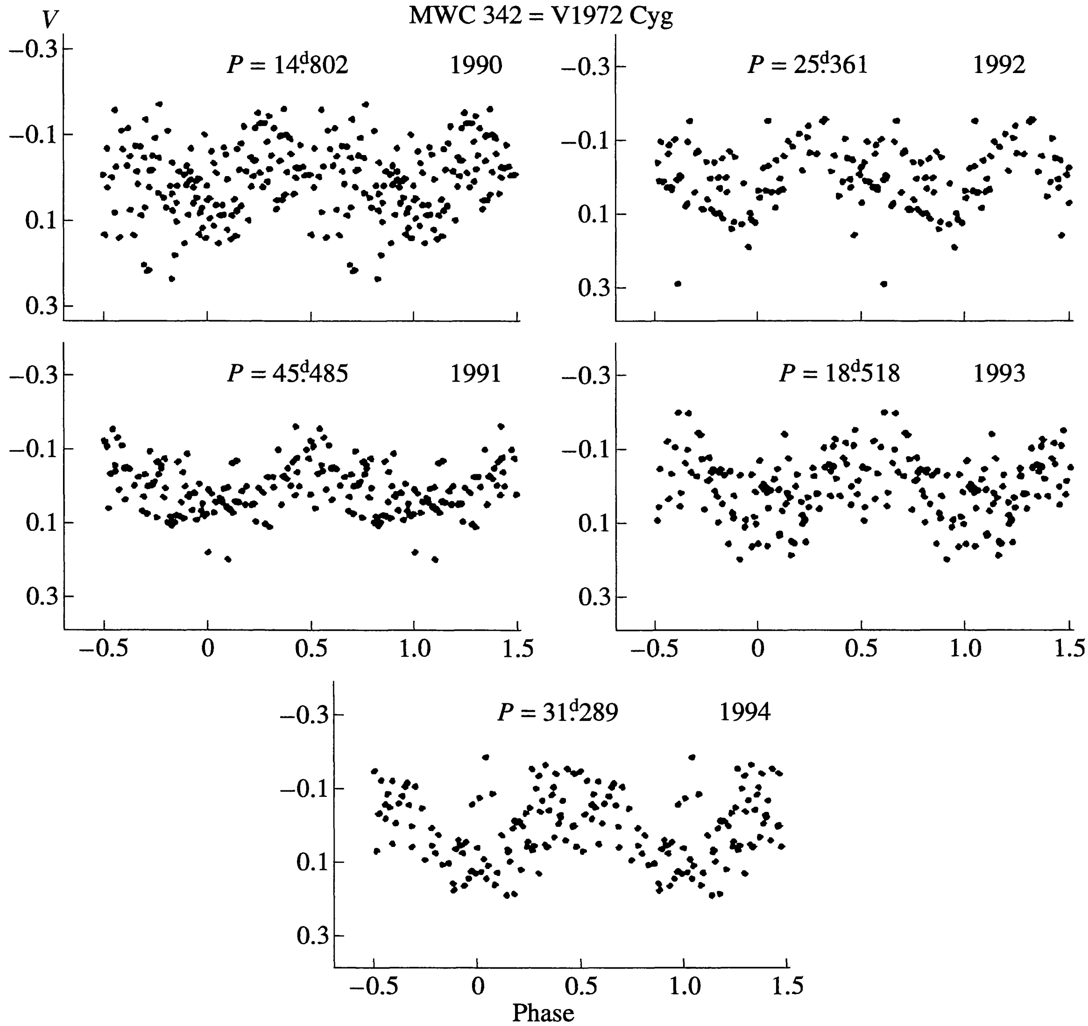

Fig. 6. The phase light curves of MWC 342 for the probable periods corresponding to the peaks marked by arrows in Fig. 5. The notation is the same as in Fig. 3.

main period. Their superposition appears to produce the resulting period of $35^{d}.5051$. We found no traces of periodicities in 1991 and 1992.

MWC 297

The overall V light curve of MWC 297 for 1986–1994 is shown in Fig. 4c. Of all the objects studied here,

Table 3. Periodic light variations in MWC 342

Year	JD 2440000+	Period	Q, %
1990	8056–8271	$14^{d}.802$	1.71
1991	8419–8586	45.485	2×10^{-5}
1992	8815–8952	25.361	0.41
1993	9141–9310	18.518	2×10^{-4}
1994	9514–9647	31.289	5×10^{-4}

MWC 297 is least active. The amplitude of its irregular variability is $0^{m}.2$, and only separate points increase the variability amplitude to $0^{m}.45$. The brightness of MWC 297, as that of MWC 342 and V633 Cas, smoothly changes on a time scale of several years (Fig. 4c). In 1994, we recorded a "blue" flare with an amplitude of $0^{m}.4$ in B and $0^{m}.12$ in V that lasted for 1 day. Unfortunately, no measurements were made in U at this time.

We searched for periodicities in the light curve of MWC 297 only in V and R, because the star was very faint in B. Over the nine years of observations, only in 1988 did the power spectrum exhibit a more or less significant peak at the frequency of the $24^{d}.32$ period. The probability of this period is estimated to be $Q = 4\%$. The power spectrum for 1988 is shown in Fig. 9a; Fig. 9b shows the phase R light curve folded with this period. The shape of the phase R and V light curves

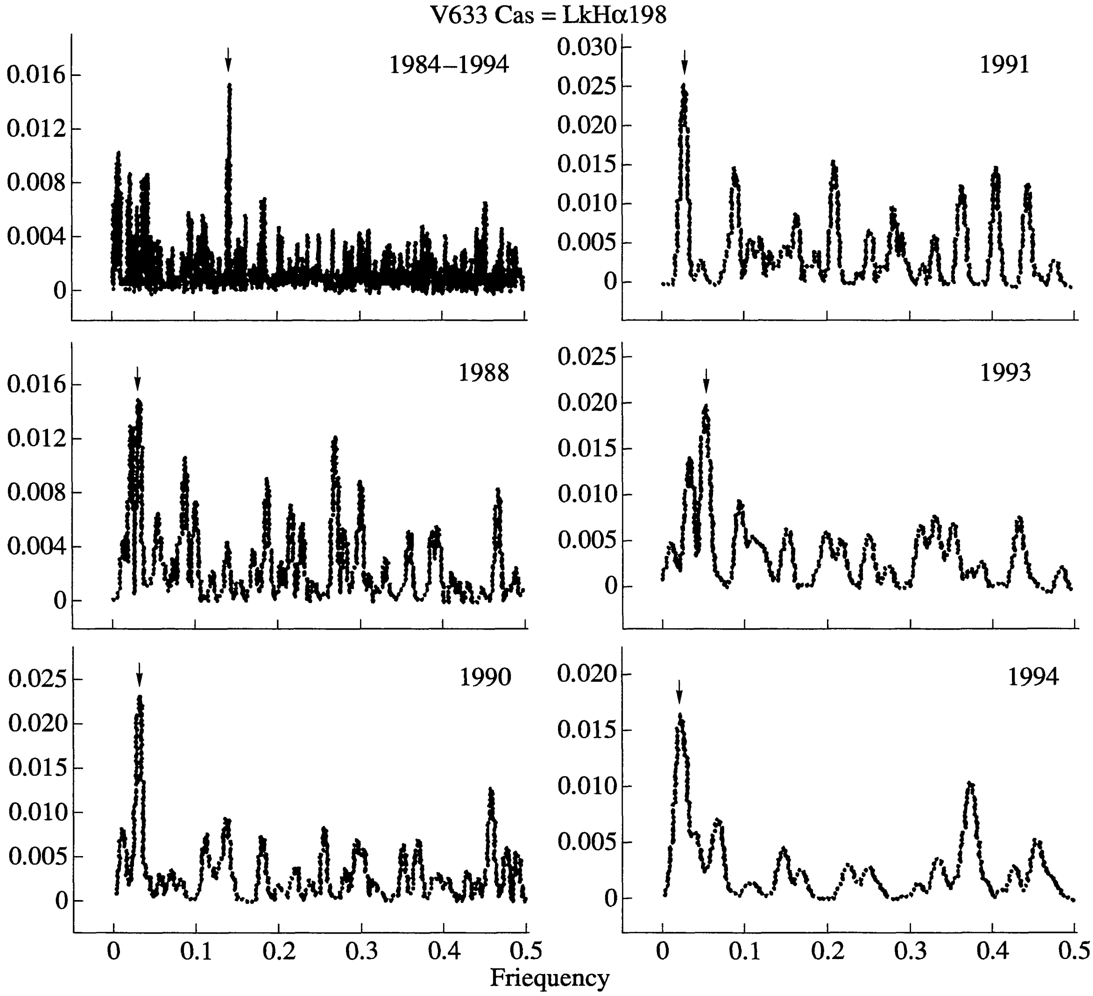

Fig. 7. The power spectra of V633 Cas obtained by the CLEAN method for the observing period 1984–1994 and separately for the seasons in which periodic variations were detected. The notation is the same as in Fig. 2.

indicate that the phase for the 24^d.32 period was not preserved during the observing season. In contrast to V1331 Cyg and MWC 342, the amplitude of the periodic variations in MWC 297 decreases when passing from the *R* band to shorter wavelengths, and this periodicity can hardly seen in *B*.

DISCUSSION

The observations of V1331 Cyg, V633 Cas, MWC 342, and MWC 297 indicate that these stars exhibit a medium-amplitude variability over the range 0^m.15 to 0^m.8 in *V*. The variability amplitude for V1331 Cyg and MWC 342 increases as one passes from *R* to *B*. There is almost always a rapid irregular variability with an amplitude of 0^m.1–0^m.2 which hampers the detection of periodicities. The light curves of V633 Cas, MWC 342, and MWC 297 show that the mean brightness undergoes slow variations on a time scale of several years. This effect was also observed in other Herbig Ae/Be stars (Shevchenko *et al.* 1993) and in T Tau stars (Shevchenko and Kondrat'ev 1997).

Our analysis revealed quasi-periodic processes in the light curves of all four Ae/Be stars mainly in the range 10 to 50 days with a sufficiently high significance. The light curves also exhibit light variations on a time scale of 70–150 days, which may be intervals of longer periods. However, because of the limited duration of the observing season, we could not trace them to the end. By analyzing the entire series of observations, we failed to detect any periodicities in the range 70–200 days. A shorter period (35^d.5051), which is traced over the entire interval of observations (1984–1994), was detected only in V633 Cas.

The fundamental parameters of the stars under consideration that we took from various papers are given in Table 5. The mass and luminosity of MWC 342 were estimated by determining its spectral type, B0 (ZAMS) (Bergner *et al.* 1990). As can be seen from the table, the

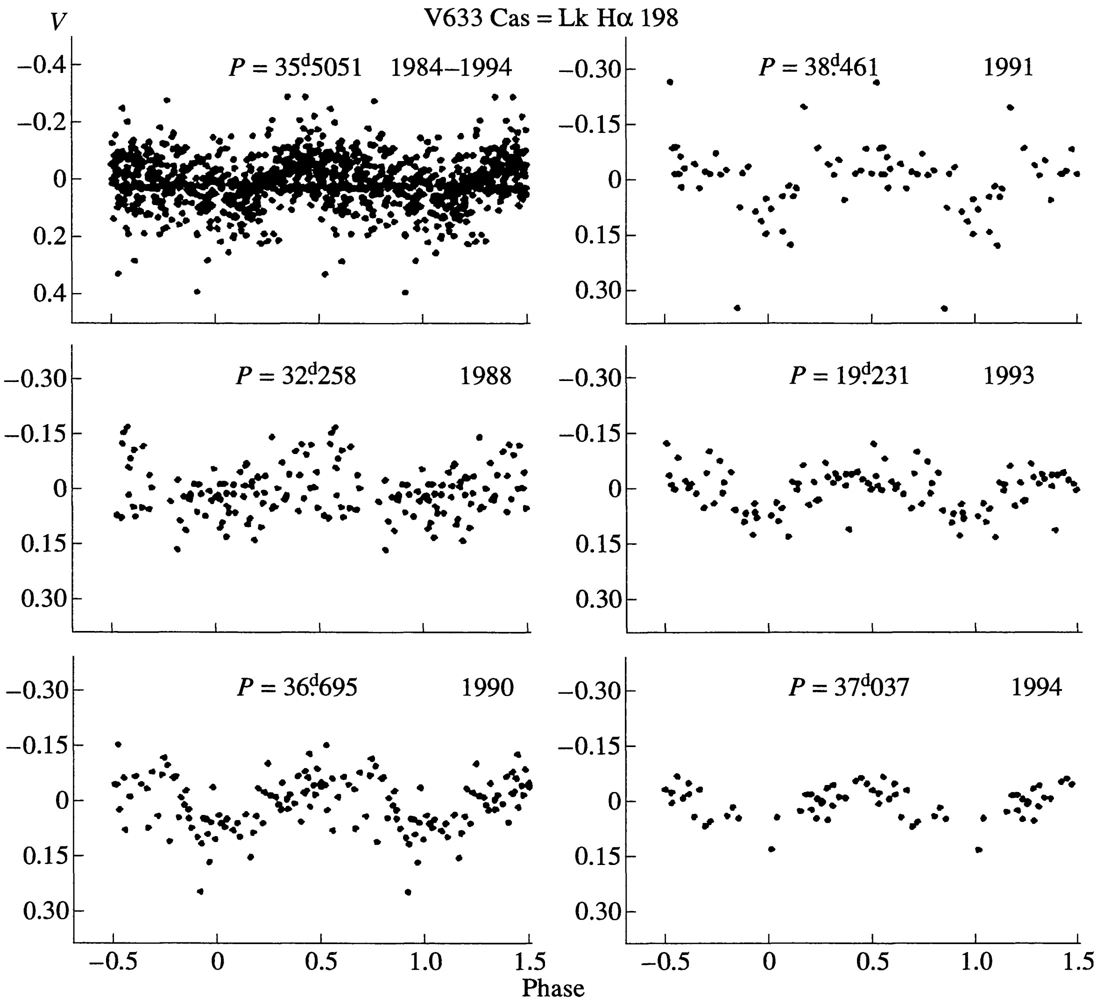

Fig. 8. The phase light curves of V633 Cas for the probable periods corresponding to the peaks marked by arrows in Fig. 7. The notation is the same as in Fig. 3.

luminosities of V1331 Cyg and MWC 297 are greatly overestimated for their spectral types, while the luminosity of V633 Cas is clearly underestimated for the spectral type B3e (Finkenzeller and Mundt 1984). Therefore, Hillenbrand *et al.* (1992) propose the spectral type A5 for V633 Cas. McMuldroch *et al.* (1993) suggest that V1331 Cyg may be in a pre-FU Ori stage. According to these authors, the bright ring nebula around V1331 Cyg is the remnant of an FU Ori-type flare that occurred in the past. At the same time, all stars have similar emission spectra. High-resolution spectra exhibit numerous hydrogen and Fe II emission lines, often with P Cyg profiles. The Hα line has a large equivalent width that ranges from 48 Å for V1331 Cyg (Cohen and Kuhi 1979) to 600 Å for MWC 297 (McGregor *et al.* 1984). The profiles of emission lines in V1331 Cyg and MWC 342 were found to be variable (Brosch *et al.* 1978; Chavarria 1981). As was noted above, all four objects have much in common in the photometric behavior. The detailed light curve of V1331 Cyg and MWC 342 are particularly similar. Therefore, based on the above data, we can assume that the observed periodicities are associated with the circumstellar surroundings rather than with the star itself. At the same time, it may also be noted that V633 Cas, which has the lowest luminosity, exhibits a period that is seen over several years, while MWC 297, which has

Table 4. Periodic light variations in V633 Cas

Year	JD 2440000+	Period	Q, %
1988	7328–7543	$32^{d}.258$	11
1990	8087–8234	36.695	2×10^{-5}
1991	8448–8562	38.461	2.4
1993	9164–9298	19.129	0.01
1994	9563–9635	37.037	0.148
1984–1994	5879–9635	35.5051	4×10^{-5}

the highest luminosity among the stars studied, exhibit quasi-periodic light variations in the nine years of observations only over one year.

There is mounting observational evidence that suggest that young stars are surrounded by circumstellar disks. Irregular Algol-like dimmings observed in some stars (UX Ori stars) are associated with edge-on disks (Grinin 1994). However, since the observed number of UX Ori stars is too great—about 25% of all the Herbig Ae/Be stars known to date, Herbst (1994) suggests that clouds of gas and dust, which he calls blobs, can also be encountered at high latitudes. The presence of high-latitude gas and dust structures is also admitted by the model of Appenzeller (1994).

According to McMuldroch *et al.* (1993) and Bastien and Menard (1994), the rotation axes in two of the four objects (V1331 Cyg and V633 Cas) have a great inclination with respect to the plane of the sky, and these stars are thus seen pole-on. Hillenbrand *et al.* (1992) do not rule out the possibility that MWC 297 is also an object seen pole-on. If this is the case, then the explanation of the observed periodic variations by the Keplerian revolution of gas and dust structures in an inhomogeneous gas and dust disk around the star runs into problems. In addition, since the phase light curves are nearly sinusoidal in shape, the size of an inhomogeneity must be comparable to the distance from it to the star. These problems can be partially removed by assuming that the observed periodicity is attributable not to the simple rotation of gas and dust clouds around the star but to the fact that these clouds are regular structures that form during the dynamical interaction with the surrounding medium. Eclipses by such gas and dust structures produce the observed pattern of periodicity. In order to obtain the observed range of periods, these structures must be at different distances from the star. The scatter in the periods that we found here may reflect the spatial distribution of these clouds. At the same time, a considerable number of clouds in high orbits are needed to obtain the observed number of periods.

In addition to the disk, there may also be an optically thick shell of gas and dust (The 1994) surrounding the star and a more extended, optically thin shell. In different models, the optically thick shell changes from spherical to disk-shaped. Shevchenko (1989) believes that this shell has the shape of a torus, and that it must be heated very nonuniformly due to nonstationary accretion. The observed pattern of periodic variations can also be qualitatively explained in terms of the dynamical processes in such an inhomogeneous, optically thick shell of gas and dust.

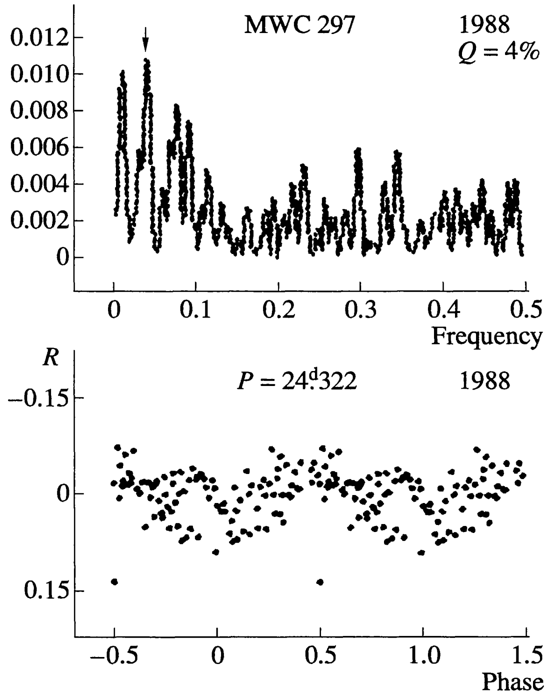

Fig. 9. (a) The power spectrum obtained for MWC 297 by the CLEAN method in 1988; (b) the phase R light curve of this star folded with the $24^{d}.32$ period [indicated in plot (a) by an arrow]. The notation is the same as in Fig. 2. In plot (a), the estimate of Q for the $24^{d}.32$ period is shown.

In summary, taking into account the results of other authors (Baade and Stahl 1989; Zaitseva 1983; Shevchenko *et al.* 1993), we assume that such quasi-periodic processes can be detected in a considerable number of Herbig Ae/Be stars. However, very detailed light curves with few gaps are needed for their detection, because the existing, rapid, irregular variability

Table 5. Physical parameters of four Ae/Be stars

Star	Sp	$L_*/L_\odot$	$M_*/M_\odot$	$R_*/R_\odot$	n_e	$\dot{M}/M_\odot$	References
V1331 Cyg	F	52	3	5	2.6×10^{10}	7×10^{-8}–3×10^{-6}	[1]
MWC 342	BO	2.5×10^4	16	5	5×10^{10}	65–4.7×10^{-6}	[2]
V633 Cas	B3	5×6	1.6	1.2		3.2×10^{-7}	[3]
MWC 297	O9–B1	10^5	26.5	9.1		10^{-6}	[3]

Note: [1] Chavarria (1981);
[2] Bergner *et al.* (1990);
[3] Hillenbrand *et al.* (1992).

severely complicates the identification of these periods. We can also assume that periodicities can be found in UX Ori stars during the time intervals the Algol-like minima are absent.

ACKNOWLEDGMENTS

I wish to thank M.A. Ibragimov and V.B. Kondrat'ev for participating in the observations and V.S. Shevchenko for helpful discussions. I also thank M.A. Pogodin and A.S. Miroshnichenko for valuable remarks. I am grateful to the International Science Foundation (grant no. MZA000) and the ESO C&EE Committee (grant no. A-02-48) for support.

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Translated by V. Astakhov