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Discovery of monochromatic quasi–periodic oscillations in the optical spectrum of the intermediate polar RXJ0558.0+5353 (V405 Aur)

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Abstract. We present the results of optical dynamic spectropolarimetry and spectroscopy of the intermediate polar RXJ0558.0+5353 (V405 Aur) obtained at the 6 m telescope (BTA) with the multichannel photon–counting system (scanner) in a high time resolution mode from March, 1996 to December, 1998. As a result of analysis of the photoelectron events which were tagged by polarization, wavelength and time, the Monochromatic Quasi–Periodic Oscillations (MQPOs) or the statistically significant features in the spectral composition of photoelectron noise in the narrow wavelength passbands (1 Å) were detected in power spectra. The strong (amplitude up to 60% in 2000 s exposures) polarized (dominating alternatively only in one of the two circularly or linearly polarized spectra) monochromatic (FWHM in power spectra 2–3 Å) oscillations with periods of 273 ± 6 s corresponding to the first harmonic of the spin frequency of the white dwarf, mainly in the profiles of emission lines with a coherence time of 1500–2000 s were detected. We confirm our previous conclusions which were derived from the observations of PQ Gem (Somov et al., 1998a,b).

Key words: binaries: close – stars: individual: RXJ0558.0+5353 (V405 Aur) – stars: magnetic fields – cataclysmic variables

1. Introduction

Cataclysmic variables (CVs) are semi–detached binary systems in which a white dwarf primary star accretes matter from a Roche lobe–filling late–type dwarf secondary star. Magnetic CVs include systems with the sufficiently magnetized white dwarfs and form two subclasses: polars, known as AM Her stars, are synchronous systems in which $P_{spin} \approx P_{orbit}$, where P_{spin} is the spin period of the white dwarf and P_{orbit} is the orbital period (Cropper, 1990), and intermediate polars (IPs) known as DQ Her stars (Patterson, 1994). The subclass of IPs includes the objects containing magnetic, rapidly and asynchronously rotating ($P_{spin} \ll P_{orbit}$) white dwarfs. The magnetic field of the white dwarf in IPs (0.1 – 20 MG) is strong enough to affect the trajectory of accretion flow. The presence of a rapid periodicity in the light curve, usually at optical or X–ray wavelengths, is one of the principal criteria for membership in this class (IPs) of stars.

RX J0558.0+5353 (V405 Aur) is a ROSAT source identified in the framework of the ROSAT Galactic Plane Survey (Motch et al., 1991). A cataclysmic variable $V = 14.6$ mag was found as an optical counterpart of the soft ROSAT source. The follow-up observations revealed the oscillations in the soft X–ray flux with a pulse period of 272.74 s. The optical spectroscopy determined a binary period of 4.15 hours. Pulsations in the optical band with a period of 272.785 ±0.003 s were detected too (Haberl et al., 1994). The folded light curve of the star showed a non–sinusoidal pulse with a pulsed fraction of 10.8% (Ashoka et al., 1995). However, time–series CCD photometry revealed optical variations similar to the X–ray variations seen by ROSAT but with a period of 545.4565 s, which is twice the early reported X–ray period (Skillman, 1996). A period of 545.4565 s was also detected in UBVRI and X–ray observations (Allan et al., 1996).

The results of the last observations indicate conclusively that the white dwarf spin period is 545 s, and the 273 s period corresponds to the first harmonic of the spin frequency. Periodic variations in the circular polarization with a period of 544.4 ± 4.8 s and semiamplitude of $1.8 \pm 0.16\%$ were also discovered (Shakhovskoj & Kolesnikov, 1997). Time–resolved optical spectroscopy detected pulsations (Still et al., 1997) in the resolved line profiles of Hα, with a pe-

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riod of 273 s. A "corkscrew" pattern in the pulsed Hα, Hβ, Hγ and HeII 4686 Å emission lines was found too. The detected emission-line pulsations had an amplitude of 1.1–2.7 % in the HeII and Balmer emission lines with the 545 s spin period of the white dwarf comparable with 3.5–4.8 % for the continuum double–peak pulsations. The periodogram also showed dominant features at frequencies 2ω and $2(\omega-\Omega)$, where ω and Ω are the spin and orbital frequencies, respectively (Harlaftis & Horne, 1999).

Our optical spectral and spectropolarimetric (with the circular and linear polarization analyzers) observations of PQ Gem (RE 0751+14) discovered Monochromatic Quasi–Periodic Oscillations (MQPOs) or statistically significant features in the spectral composition of the photoelectron noise in the narrow wavelength passbands (Somov et al., 1997; 1998a,b). Power spectra exhibited strong, dominating alternatively in one of the two polarized spectra, MQPOs with periods of 13.3–15.2 min in the vicinity of the spin period of the white dwarf (13.9 min), mainly in the profiles of emission lines.

Among the IPs discovered in the ROSAT survey, RX J0558.0+5353 and PQ Gem show polar–like magnetic fields. This strongly suggests that they can be evolutionary progenitors of polars (Haberl & Motch, 1995). This property of the IP was important for our choice of the object of the current study.

2. Observations and data reduction

RXJ0558.0+5353 was observed at the Special Astrophysical Observatory (Nizhnij Arkhyz, Russia) between March 1996 and December 1998. Dynamic spectropolarimetric observations were performed using the spectrograph SP–124 placed at the Nasmyth secondary focus of the 6 m Big Telescope Azimuthal (BTA) (Ioannisiani et al., 1982). The spectrograph was equipped with a 1200 lines/mm grating giving a dispersion of 50 Å/mm. A television scanner with two lines of 1024 channels recorded two spectra simultaneously in a photon–counting mode (Somova et al., 1982; Drabek et al., 1986; Afanasiev et al., 1991). Most of our observations were carried out with the analyzer of circular and linear polarization (Najdenov & Panchuk, 1996). The latter was installed in front of the slit of the spectrograph and two spectra were acquired in the circular or linear polarizations simultaneously. The sky was observed between the exposures. A 2–arcsecond slit was used. The spectra were obtained in the wavelength passband $\approx$ 1000 Å within the range 3900–5100 ÅÅ with a dispersion of 1 Å/channel and a temporal resolution of 32 ms. The spectra were recorded continuously (3000–5200 s), and a He–Ne–Ar lamp spectrum was measured between the exposures for the wavelength calibration. The log of our observations is presented in Table 1.

The data reduction was performed with the help of a special algorithm. Its mathematical justification is presented in Appendix of Somov et al. (1998a). To study the oscillations, the range of periods for investigation was chosen to be between 100 s and 666.66 s to allow detection of QPOs around the periods corresponding to the spin frequency and its first and second harmonics. The resolution over the period was 1.66 s in the range from 100 s to 200 s, 3.33 s in the range from 200 s to 400 s and 16.66 s in the range from 400 s to 666.66 s. For every period the power, amplitude and phase of the oscillations for every channel (wavelength) were calculated in the two polarized spectra. All measurements were made in relative units, the level of the continuous spectrum is equal to 1. To estimate the time of coherence of the QPOs, an additional temporal resolution for the power spectra was introduced in the current study. We have separated the long exposures (3200–5200 s) in several subexposures with a duration of 2000 s. The shorter (2000 s) subexposures were extracted from all available exposures, and computations of the power spectra for all exposures and subexposures were made. The wavelengths were calibrated (Kopylov et al., 1986) with the help of a He–Ne–Ar lamp. Our observations of other IPs (one of them is PQ Gem (Somov et al., 1998a,b)), which were made on the same nights with the RXJ0558.0+5353 ones, revealed MQPOs with significantly different periods corresponding to the known spin periods of white dwarfs or their first harmonics. To check possible instrumental effects, we observed standard stars (Feig 25, HD217086, BD+82015) and other magnetic CVs with similar spectra. No significant features in the power spectra of the standard stars were found.

3. Results

3.1. QPOs in the spectrum

To search for the QPOs in the spectrum, we have made a relatively long exposure (5023 s, recording the wavelength and the time of detection of every photoelectron in a file) without the analyzer of polarization (12/27/98–11, see Table 1) and calculated the power spectrum. The grey–scale image of the power spectrum is shown in Fig. 1. The level of the grey intensity is proportional to the power of spectral oscillations in arbitrary units. Black features in the power spectrum are seen in the periods around the period (273 s) corresponding to the first harmonic of the white dwarf spin frequency. The wavelengths of the features are inside the profiles of the Balmer and HeII 4686 Å emission lines.

This property can be seen better in Fig. 2, where the section of the power spectrum along the wavelength corresponding to the 273 s period (lower) and

Table 1: *Log of the observations of RX J0558.0+5353.*

Date	Number of the exposure	Start (UT time)	Exposure (s)	Mode
03/15/96	3	16:54:12	4209	circular polarization
03/16/96	1	16:36:12	3584	circular polarization
11/18/96	8	22:01:58	4056	linear polarization
	9	23:15:20	2920	linear polarization
11/19/96	9	21:47:50	4168	linear polarization
12/26/98	3	21:22:10	4924	circular polarization
	4	22:53:16	4815	linear polarization
12/27/98	9	21:39:51	4033	circular polarization
	11	00:34:52	5023	spectrum
12/28/98	4	18:26:20	5024	circular polarization
	5	19:57:17	4020	linear polarization

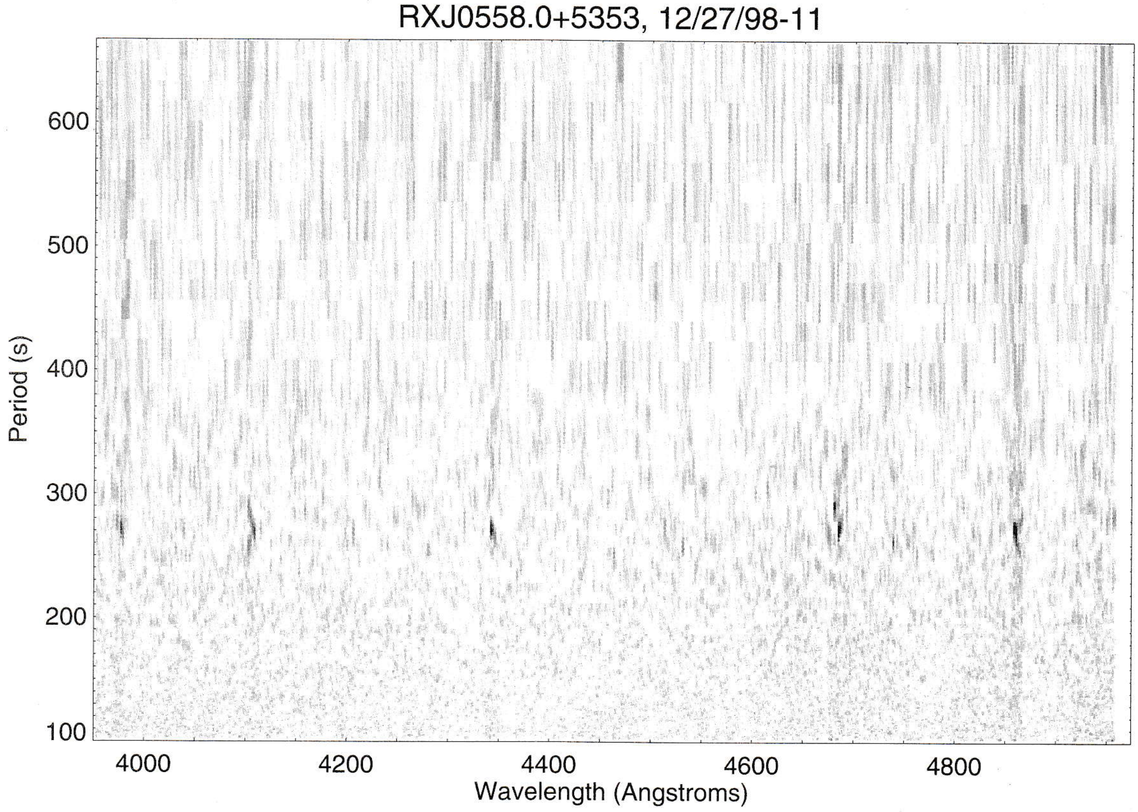

Figure 1: *A grey–scale image of a power spectrum. The level of grey intensity is proportional to the power of spectral oscillations in arbitrary units.*

relative intensity (normalized to the continuum) spectrum (upper) are presented. The scales of the power and relative intensity are expressed in arbitrary units, but zero for the upper spectrum is shifted and corresponds to 75 units. Considering the values of the power at adjacent wavelengths as independent random values, it is possible to estimate the statistical significance of the detected oscillations by the method used for the classical power spectra (Foster, 1996). The typical values of statistical significance or the probability that the signal is random are in the range $10^{-7} - 10^{-11}$ for the oscillations presented in Fig. 1 and in other figures of this paper.

To estimate correspondence between the period of the feature and the 273 s period, an example of monochromatic power spectrum, i.e. the section of the power spectrum over the period corresponding to the wavelength 4340 Å in the profile of the Hγ emission line is displayed in Fig. 3. The coincidence of the position of the strong feature in the monochromatic power spectrum with the 273 s period (upper arrow) is readily seen.

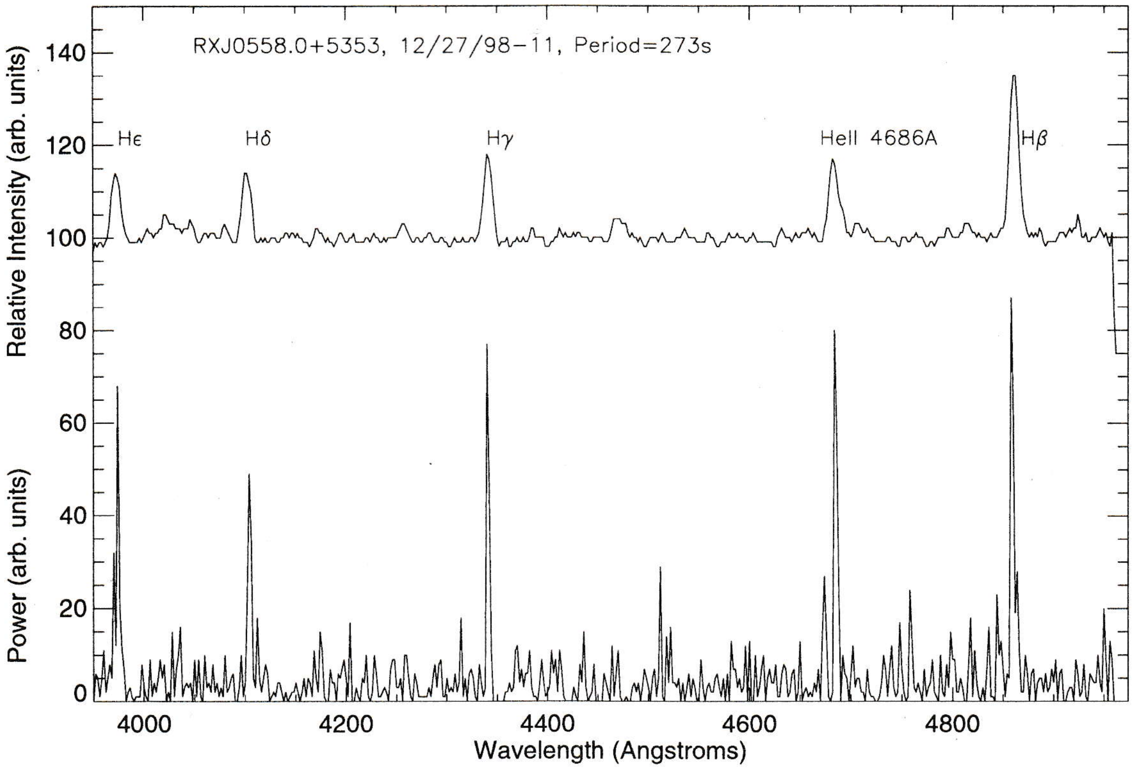

Figure 2: *The section of the power spectrum along wavelength corresponding to the 273 s period of the first harmonic of the white dwarf spin frequency (lower) and the relative intensity spectrum (upper).*

However, it has to be noted that small deviations of features along the period in other lines exist, and we explain them in terms of the quasi–periodicity of the oscillations. As in our previous study of the monochromatic oscillations in PQ Gem, the QPOs at different wavelengths are independent. It is possible to observe the presence of the QPOs in the profile of an emission line simultaneously with their absence in another one. The phases of the QPOs at different wavelengths showed a significant difference and as a result we find it impossible to predict a definitive phase. Another important property of the oscillations, which is visible in Fig. 2, is the absence in the integral spectrum of features which could be associated with the features in the power spectrum, or the oscillations do not cause statistically significant changes in the integral spectrum. In other words, the features in the power spectrum do not affect the integral spectrum in the way any other noise features do. The narrow wavelength passband (2–3 Å) in which the oscillations can be observed is the reason for naming them Monochromatic Quasi–Periodic Oscillations (MQPOs). Figs. 1–3 demonstrate the fact of existence of the oscillations at the wavelengths corresponding to the profiles of the emission lines and in the periods close to the 273 s period.

3.2. Polarization of the MQPOs

One of the principal physical characteristics of the electromagnetic radiation causing the MQPOs is the polarization, and most of our observations, as can be seen in Table 2, were carried out with the analyzer of circular or linear polarization. The objective of the observations was the polarization properties of the radiation which is responsible for the MQPOs but not the classical polarization in the integral spectra.

Examples of monochromatic power spectra for the wavelengths inside the profiles of the emission lines Hβ in the two circular polarizations and Hγ in the two linear polarizations are presented in Figs. 4–5, respectively.

For a quantitative description of the polarization properties of the radiation causing the MQPOs we subsequently use a formal measure of dynamic polarization P_d which characterizes the observed oscillations as

$$P_d = (P_1 - P_2)/(P_1 + P_2) \cdot 100\%, \qquad (1)$$

where P_1 and P_2 are the powers of the oscillations in the left and right or in the orthogonal linear polarizations in the same period and at the same wavelength. P_d characterizes the polarization properties of the radiation causing the MQPOs. A typical value

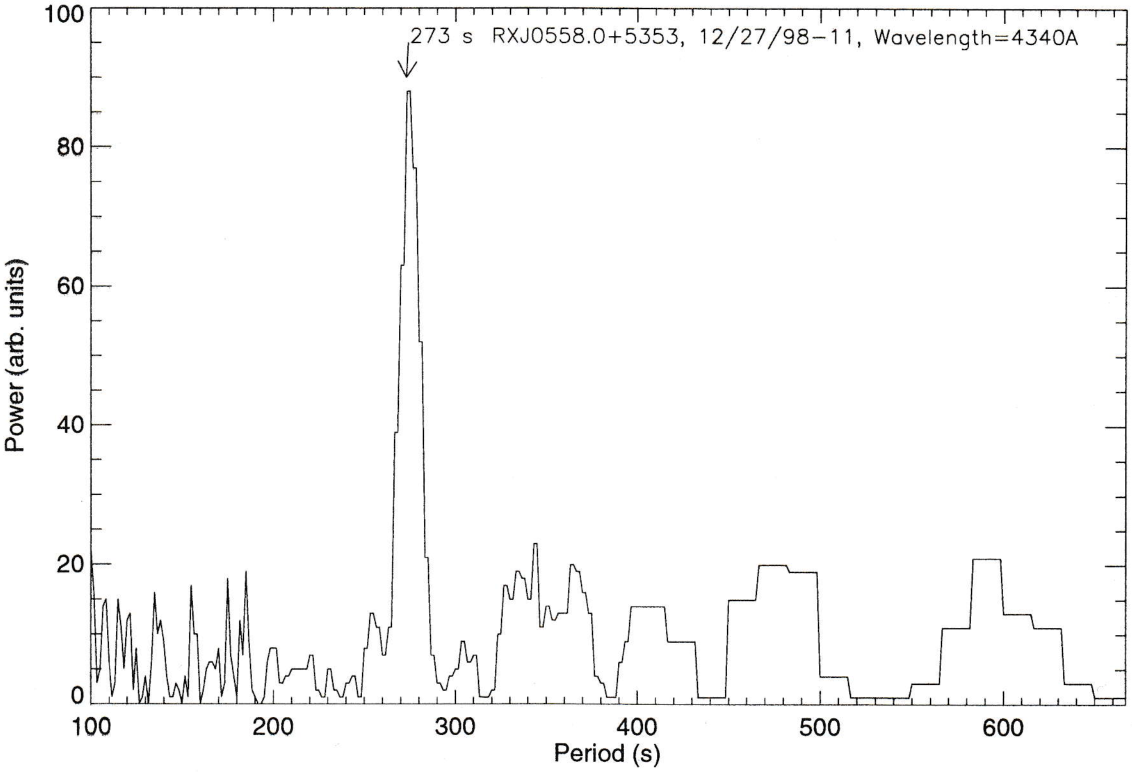

Figure 3: *The section of the power spectrum, presented in Fig. 1, along period corresponding to the wavelength 4340 Å.*

Table 2: *Parameters of the MQPOs*

Parameter	Value	Comments
Amplitude	up to 60%	relatively the continuum and during ~ 2000 *s*
Period	273 ± 6 *s*	the first harmonic of the spin frequency
Time of coherence	1500–2000 s	
Dynamic circular polarization	60–90%	formula (1)
Dynamic linear polarization	60–90%	formula (1)
Wavelengths	in profiles of emission lines	more rarely outside
FWHM(Å)	2–3 Å	in power spectra
Confidence level	$10^{-7} - 10^{-11}$	probability of the random signal

of the dynamic circular and linear polarization of the MQPOs ranges from 60 to 90%. In the qualitative description the MQPOs can be detected alternatively in one of the two circularly or linearly polarized spectra. The last property of the MQPOs is a law which finds confirmation in all our data. We have recorded several cases where the MQPOs were seen in two polarization channels in relatively long exposures, but every time it was possible to resolve them along wavelength or time into shorter subexposures.

It is very important to note that the MQPOs were detected not only inside the profiles of the Balmer and HeII 4686 Å emission lines but in spectral bands without emission or absorption features at the wavelengths of the $\sigma-$ transitions in strong magnetic fields. Evidence of the MQPOs at the wavelength 4038.2 Å which corresponds to the calculated wavelength 4039.8 Å of the strongest $\sigma-$ transition of Hδ in a magnetic field of ≈ 4 MG (Somov et al., 1998a) is given in Fig. 6. The MQPOs in the continuum have the similar properties as the MQPOs in the profiles of emission lines, but the probability to detect them in a 4000 s exposure is less than in emission lines. We have already discussed the probable reason (Somov et al., 1998a).

For instance, we have only three good cases of de-

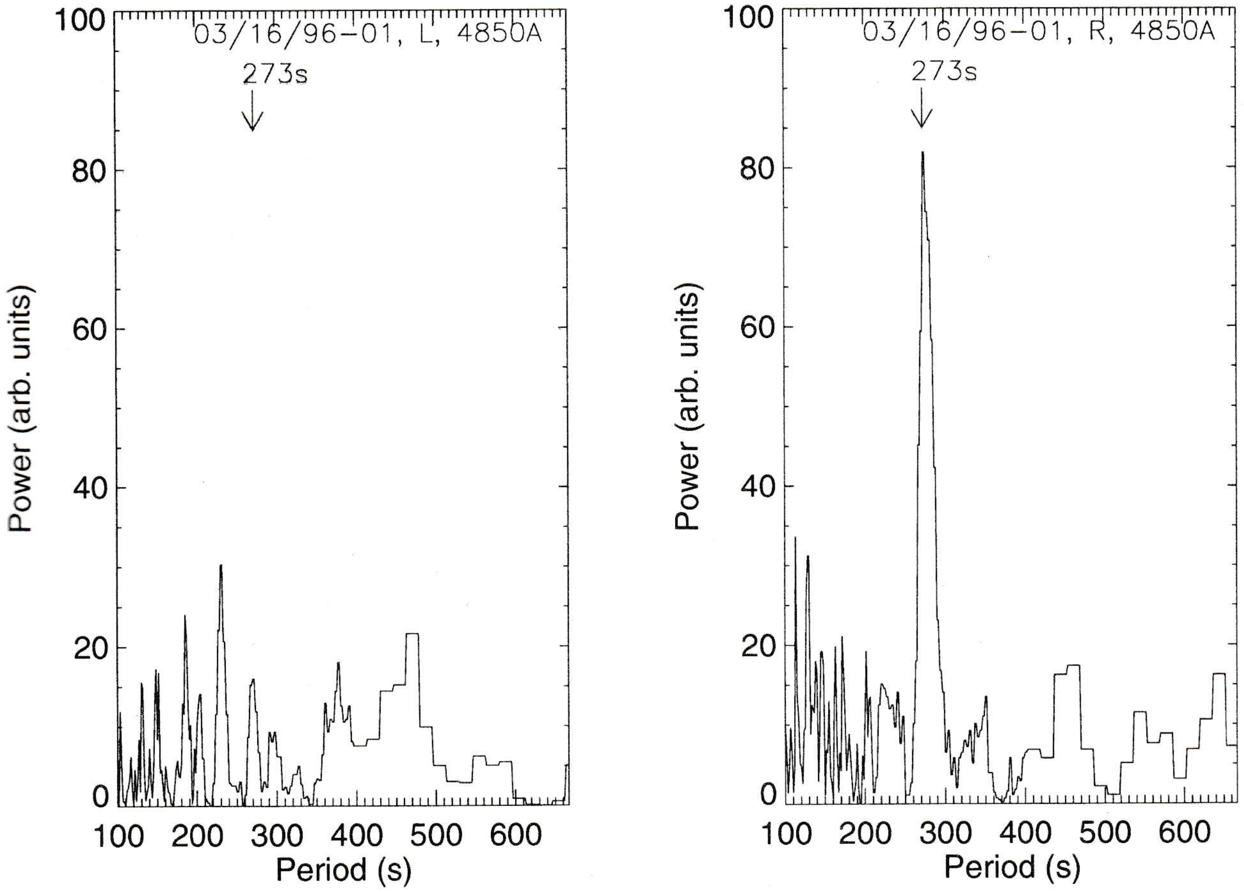

Figure 4: *The sections of the power spectra along period corresponding to the wavelength 4850 Å in the two circular polarizations.*

tection of the MQPOs at the wavelength 4039 Å in all our data or this probability is ~ 0.3, in contrast to the oscillations inside the profiles, which can be revealed in one randomly taken exposure during 4000 s with a probability of ~ 0.6 – 0.8. It has to be noted that our statistics of the MQPOs is too poor and consequently these probabilities should be considered with caution mainly as preliminary estimates. The polarization properties and the presence of the oscillations outside of the profiles of emission lines are arguments in favor of the magnetic origin of the MQPOs.

3.3. The time of coherence of the MQPOs

Another principal parameter of the MQPOs is the time of coherence of the oscillations. To estimate this time we have modified our method of data reduction as follows. We have divided a long exposure (for example, longer than 4000 s) into four small subexposures with times of 2000 s which correspond to the time intervals of 0-2000 s, 1000–3000 s, 2000–4000 s and 0–4000 s within the long exposure, respectively. The computations of the power spectra for all available exposures and the subexposures therein were made. A typical result of the computations for the MQPOs in the HeII 4686Å emission line is presented in Figs. 7–8. The figures show monochromatic power spectra only in the right circular polarization for the 0–2000 s, 1000–2000 s, 2000–4000 s and 0–4000 s intervals. The scales of the power are equal for these figures, and the powers of the oscillations can be compared. It is seen that the power of the oscillations in the 1000–2000 s interval is about 4 times that in the 0–4000 s interval. Analysis of the power spectra as in Figs. 7–8 gives an estimate of the time of coherence of about 1500–2000 s. It should be noted that the time of life and the time of coherence of the MQPOs are not the same. We have examples of the MQPOs in shorter subexposures which disappear in the long one. This fact confirms the short time of coherence of the MQPOs.

3.4. Parameters of the MQPOs

To describe quantitatively the MQPOs observed in the power spectra, we collect the principal observ-

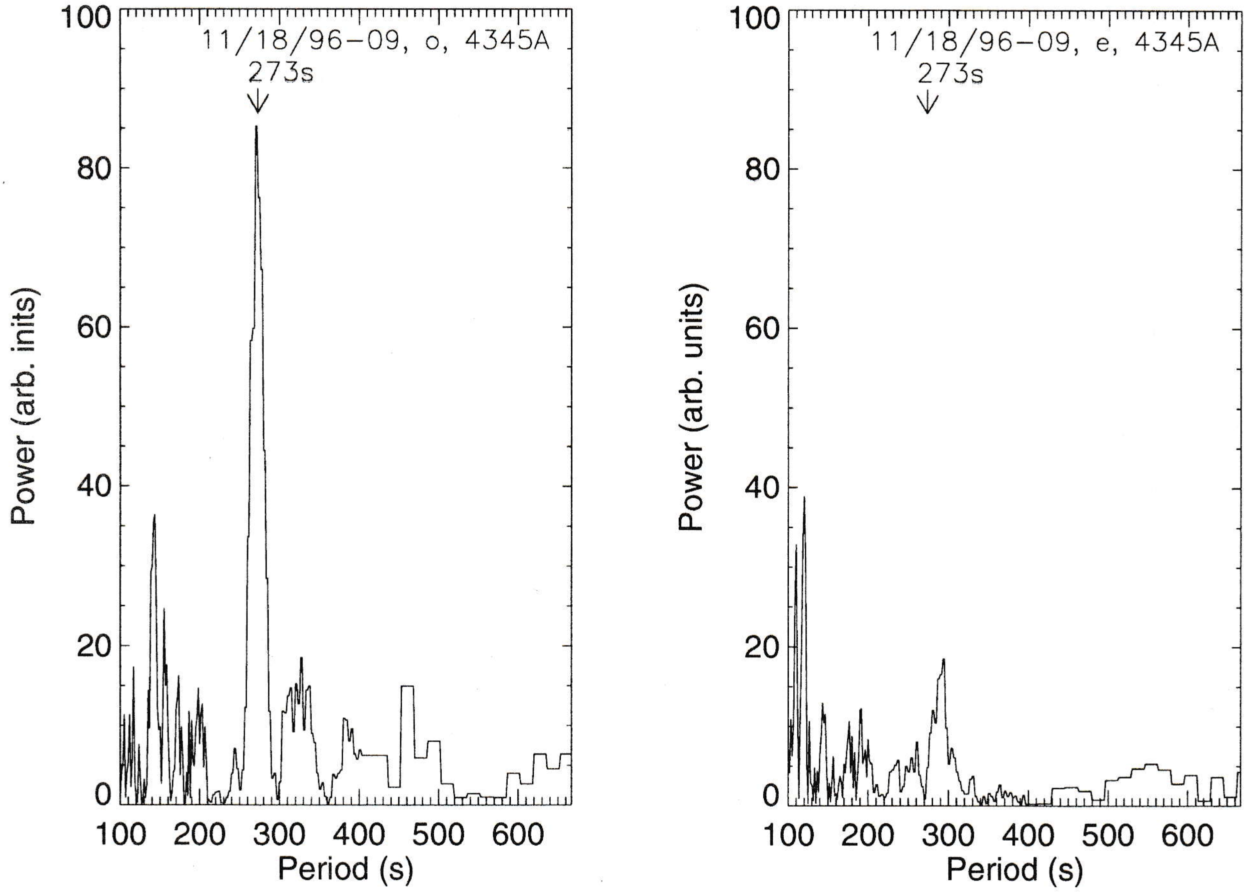

Figure 5: *The sections of the power spectra along period corresponding to the wavelength 4345 Å in the two orthogonal linear polarizations.*

able parameters of the MQPOs in Table 2. For most parameters the range of variations is given because the poor statistics of the MQPOs makes it impossible to draw more definite conclusions. In addition to the quantitative parameters of the MQPOs we summarize principal qualitative properties of the MQPOs:
(1) the presence of statistically significant features in the power spectra in the narrow wavelength bands;
(2) the features in the power spectra do not significantly affect the integral spectra as other noise or statistically nonsignificant features do;
(3) the features appear alternatively in one of the two circularly or linearly polarized power spectra on a time-scale of ~ 2000 s;
(4) the oscillations show a short time of coherence and are independent at different wavelengths.

In addition to the coherent periodic oscillations which have been detected in X–ray and optical data using a large number of different instruments and analysis techniques, and the known MQPOs in PQ Gem, we have presented evidence of existence of the MQPOs in the optical spectrum of the second IP.

4. Discussion

4.1. Monochromatic oscillations

In our previous study of the MQPOs in PQ Gem we discussed the radiation from the accretion column as the most probable reason for the MQPOs and in this case one can expect the modulation of the radiation at the spin frequency and its harmonic (Somov et al., 1998a). It was found in the same study of the MQPOs that the wavelengths of the oscillations correspond to those of radiation from strong magnetic fields. The equation for calculations of the magnetic fields for σ transitions is the equality of the wavelength shifts due to the linear and quadratic Zeeman effect. The detection (Fig. 6) of the oscillations corresponding to the strongest $\sigma-$ transition of Hδ in a magnetic field of $\approx$ 4 MG is additional evidence of the magnetic nature of the radiation causing the MQPOs. In the current study of the MQPOs we confirm our previous conclusion and suggest that the spectral composition of the MQPOs along the optical wavelength should point to the presence of strong magnetic field of the

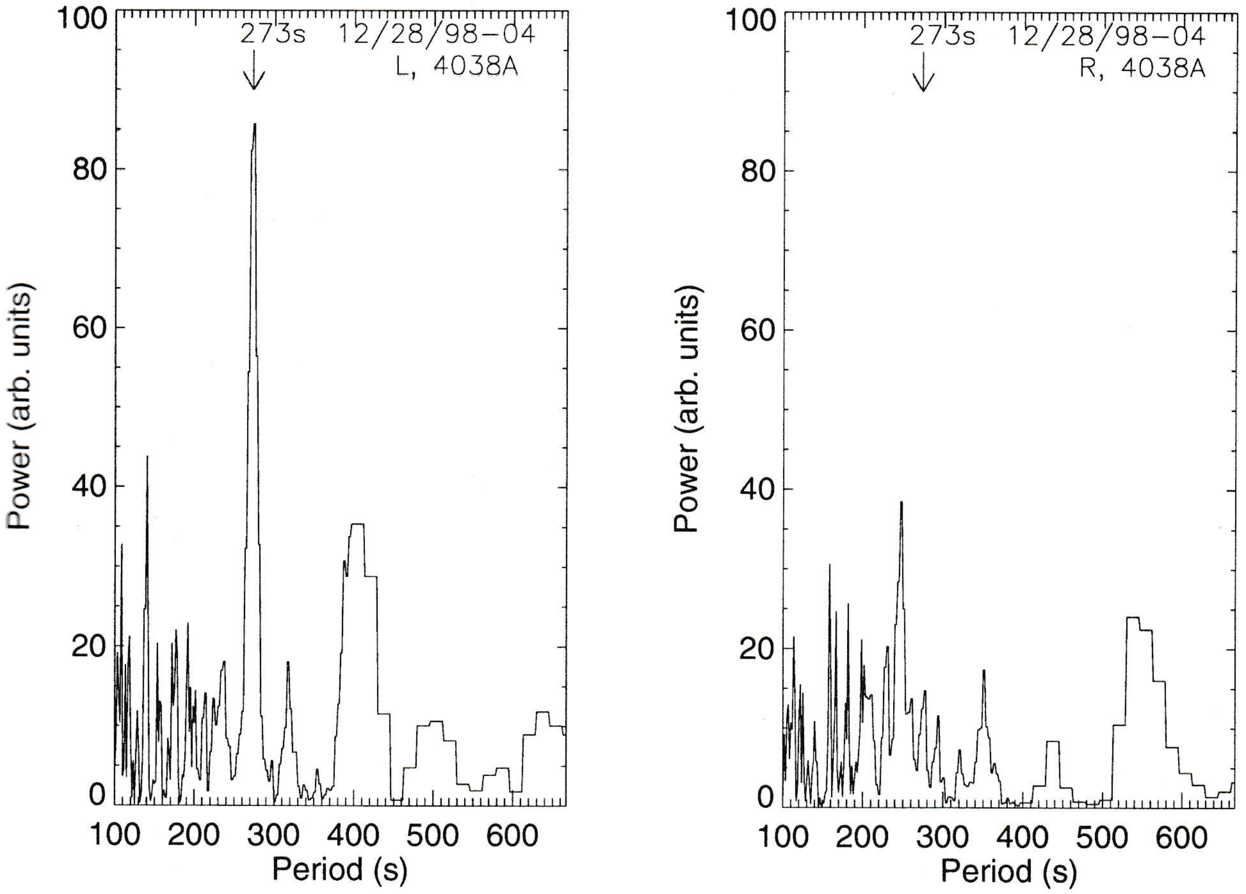

Figure 6: *The sections of the power spectra along period corresponding to the wavelength 4038 Å in the two circular polarizations.*

white dwarf in the IP.

It is evident (Figs. 4–5) that the MQPOs are strongly polarized (60–90%) in dynamic sense (formula 1). Polarization does not depend on whether the linear or circular polarization analyzer is used, neither does it on the small instrumental polarization in the integral spectra. We believe that the measure of the dynamic polarization of the oscillations in the theoretical consideration should be taken as ±100% for the linear and circular polarizations. The ±100% polarization means that the MQPO appears alternatively in one of the two polarization channels. We confirm our previous conclusions drawn from the polarization observations of PQ Gem and strongly suggest that the ±100% dynamic polarization is a fundamental property of the MQPOs.

Comparison of the estimates of the times of coherence of the MQPOs in the PQ Gem (3000–5000 s) and in the RX J0558.0+53 (1500–2000 s) shows that the ratio of these times to the periods of the MQPOs is about the same (4–7).

In our previous discussion (Somov et al., 1998a,b) of the nature of radiation causing the oscillations we couldn't find a satisfactory interpretation. From the observations of the two IPs (RE0751+14, RX J0558+53) it is seen that the MQPOs give us information, at least, about the value of the spin period and the magnetic field of the white dwarf, and it has been shown that this information is consistent with other observations. We have already put forward a hypothesis (Somov et al., 1997,1998a,b) which is able to explain the properties of the MQPOs. Here we propose for discussion to consider the MQPOs as signatures of elementary particles. In this case these particles manifest their wave properties inside the spectrograph or in the optical wavelength range and the energy of these particles or their corpuscular properties exhibit themselves as the features in power spectra with a period of 273 s.

4.2. Comparison with other observations

Comparing the results of our observations with the spectral observations of the same object at other tele-

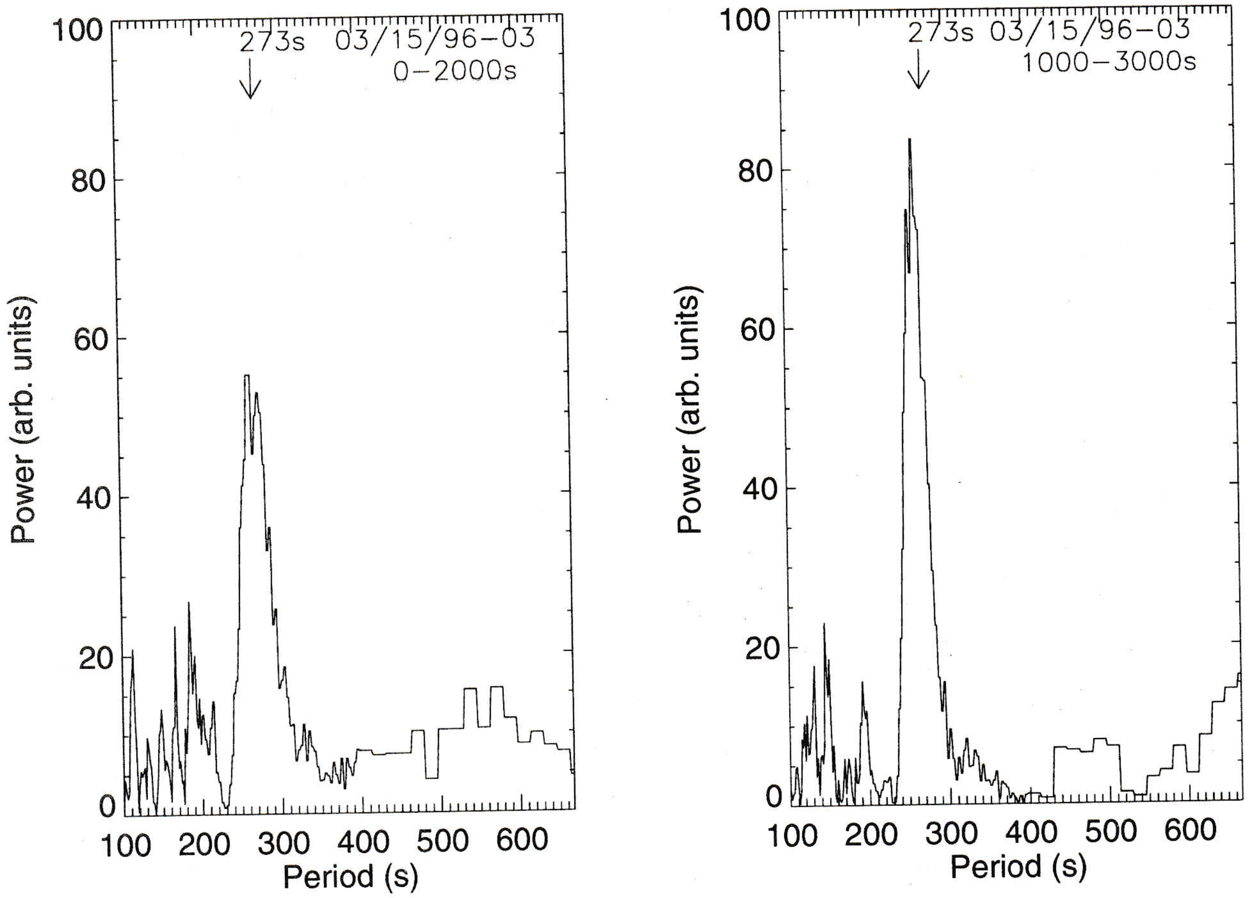

Figure 7: *The sections of the power spectra along period corresponding to the wavelength 4690 Å in the right circular polarization calculated for the subexposures 0–2000 s and 1000–3000 s.*

scopes using other instrumentation and data reduction (Harlaftis & Horne, 1999), one can see either similarity in the observational results or a principal difference in methods and conclusions. This difference is that of the time-scales used for data analysis. On the one hand, the phase of the MQPOs looks like random on the time-scales of 2000–5000 s in our observations and large variability between spin cycles was visible in many cases on very short time-scales. The most clear pulses in emission lines were recorded in HeII 4686 Å and they were not in phase with the continuum pulses and some were even in antiphase (Harlaftis & Horne, 1999). On the other hand, on the time–scale of 3 hours, which is comparable with the orbital period (4.15 hours), one can expect an influence of the effects of orbital motion such as orbital trends in light curves and the orbital variation of wavelengths of the MQPOs due to the Doppler effect. As evidence of these effects it is possible to observe the side–band features in the Fourier periodogram which correspond to the beat frequency between the orbital and spin ones. The best way to decrease the influence of these effects is to shorten the time interval for data analysis and normalize spectra to continuous ones. On the shorter time-scale (5000 s, Figs. 1–2) the regular patterns in pulsed lines are absent or in other words the MQPOs do not fill the profiles of emission lines and are presented only in their blue wings. Our approach is based on the analysis of normalized spectral data in the narrow wavelength passbands during the short time intervals. On the other hand, in the approach of Harlaftis & Horne (1999) they used the spectra without the normalization and the long time intervals with integration over the profiles of emission lines for detection of the pulsations, ignores the MQPOs and reflects the pulsations caused by the optical photons. In this case the pulsations in continuous spectrum are mixed with the pulsations in the emission lines.

5. Conclusion

We have presented the results of optical dynamic spectropolarimetry and spectroscopy of the interme-

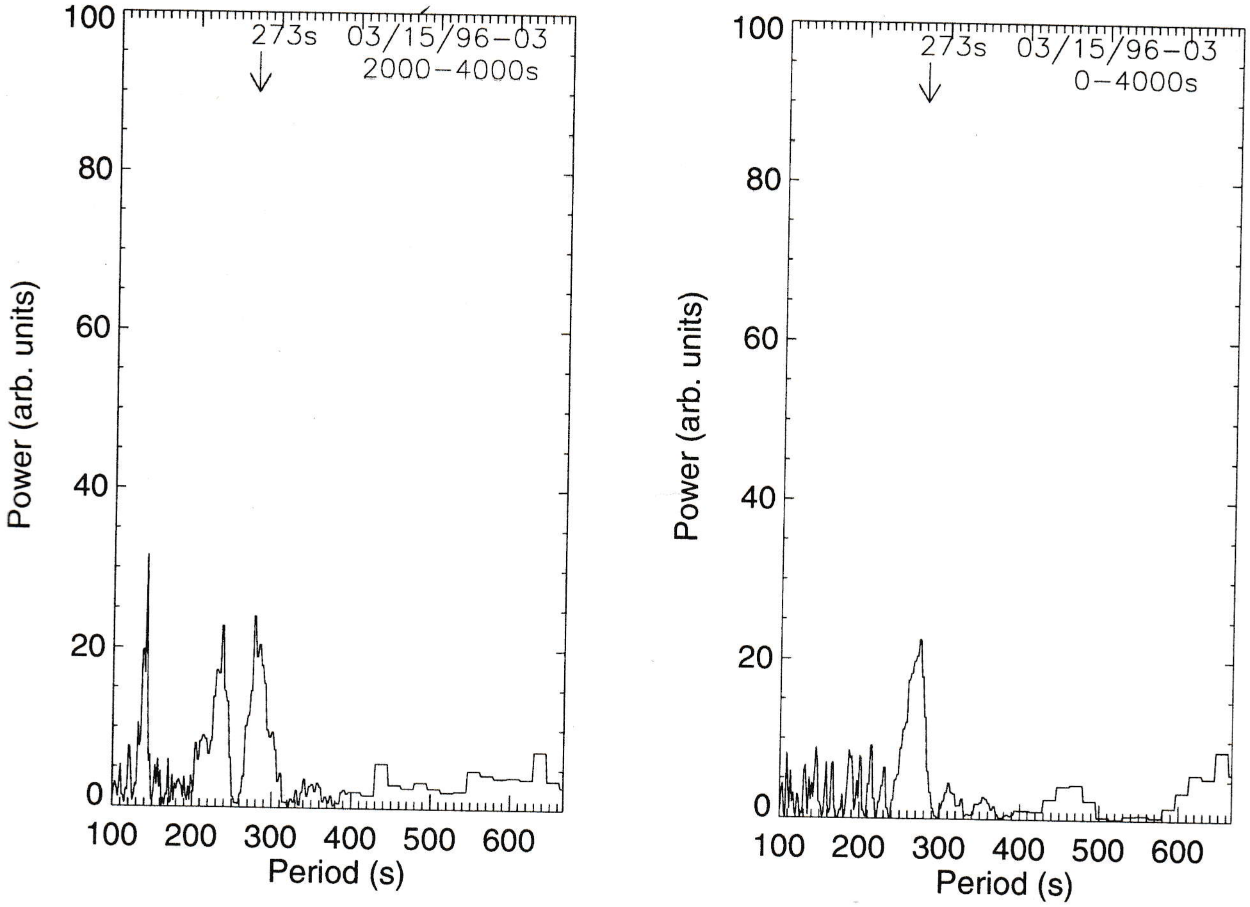

Figure 8: *The sections of the power spectra along period corresponding to the wavelength 4690 Å in the right circular polarization calculated for the subexposures 2000–4000 s and 0–4000 s.*

diate polar RXJ0558.0+5353 obtained at the 6 m telescope with the BTA scanner in the high time resolution mode from March 1996 to December 1998. Analysis of the photoelectron events tagged by polarization, wavelength and time, revealed oscillations or the statistically significant features in the spectral composition of photoelectron noise in the narrow wavelength passbands (1 Å). The strong (amplitude up to 60%), polarized (predominant alternatively in one of the two circularly or linearly polarized spectra), monochromatic (FWHM in power spectra 2–3 Å) oscillations at the periods of 273 ± 6 s corresponding to the vicinity of the first harmonic of the spin frequency of the white dwarf at the wavelengths mainly in the profiles of emission lines with the time of coherence of 1500–2000 s have been discovered. All properties of monochromatic oscillations, which were detected in the spectra of PQ Gem, have found confirmation in the observations of the second IP.

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