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Letter to the Editor

Spiral shocks in the accretion disk of the dwarf nova U Geminorum

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Abstract. We present a study of the observable spectral manifestations associated with spiral shocks within quiescent accretion disks and compare them with observations of the dwarf nova U Geminorum. Our results indicate that the orbital behaviour of the hydrogen emission line profile in the spectrum of U Gem can be reproduced via a simple model of the accretion disk with two symmetrically located spiral shocks with the spiral angle θ about 60°. This provides for the first time convincing evidence for the existence of spiral shocks in the accretion disk of a cataclysmic variable in quiescence.

Key words: accretion, accretion disks – line: profiles – line: formation – novae, cataclysmic variables – stars: individual: U Gem

1. Introduction

Although the understanding of accretion disk physics has made much progress in recent years, a viable angular momentum transfer mechanism still remains the main unresolved problem. At present there are two main standpoints on this problem. According to first one, angular momentum is transported due to the presence of turbulent or magnetic viscosity in the disk (Shakura & Sunyaev 1973). On the other hand, hydrodynamical numerical calculations have shown that tidal forces from the secondary will induce spiral shock waves in the accretion disk (Sawada et al. 1986), which may provide an efficient transfer mechanism. It should be noted, that these two mechanisms are mutually exclusive, as shock waves in the presence of viscosity will be smeared out (Bunk et al. 1990; Chakrabarti 1990).

Up till now, there were no proof for spiral structure within quiescent accretion disk. Only Steeghs et al. (1997) have found evidence for spiral structure in the accretion disk of the dwarf nova IP Pegasi, observed during outburst.

The importance regarding the determination of this angular momentum transfer mechanism for accretion disk theory determines rigourous observational efforts to confirm such spiral shock phenomena. Preliminary work by Bunk et al. (1990) investigated the distribution of energy in a continuum spectrum, and the eclipsing light curve in the presence of spiral shocks on the disk. It has been shown that the direct photometric detection of spiral shocks is problematic.

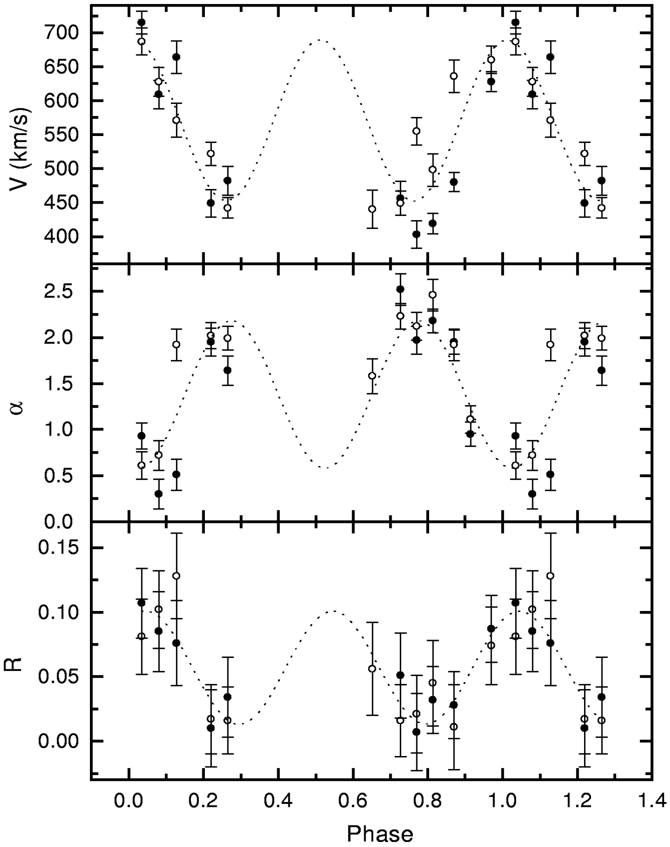

Fig. 1. The orbital phase dependence of the accretion disk parameters, obtained from modelling H_β (closed circles) and H_γ (open circles) emission lines (for details see Borisov & Neustroev, 1998a)

On the other hand, Chakrabarti & Wiita (1993) have shown that the spiral shocks in an accretion disk could have significant effects upon observable emission lines, namely that the double peak separation in emission lines will vary with the binary's phase. In our recent study of the accretion disk structure of the dwarf nova U Geminorum in quiescence (Borisov & Neustroev 1998a), we have detected a change of the double peak sepa-

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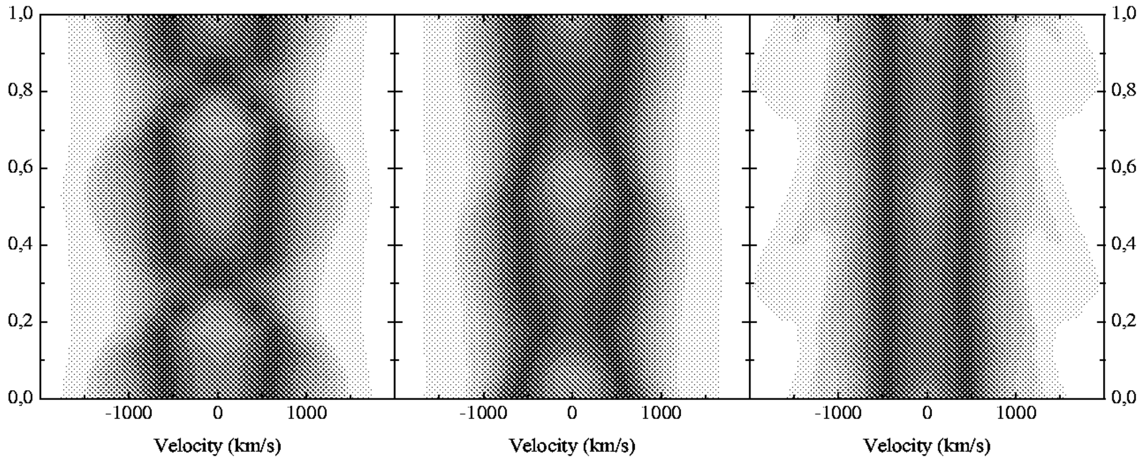

Fig. 2. The predicted trailed spectra of the emission lines arising in the accretion disk with 2 spiral shocks. The spiral angle θ is 40° (left), 60° (middle) and 80° (right)

ration in all investigated emission lines (H_β, H_γ and H_δ) with amplitudes 136, 108 and 60 km/s respectively in agreement with this hypothesis. It is important to note, that such changes consistent with the shock model were observed during two separate observation runs.

In this paper we present a more detailed study of the observable spectral manifestations of spiral shocks than was previously done (Chakrabarti & Wiita 1993) and we compare our conclusions with observational data of the U Gem system.

2. U Gem: observations and results

U Gem is one of the best studied cataclysmic variables, being the prototype of the dwarf nova class. The optical spectrum of U Gem types are dominated by broad double-peaked emission lines of H I, He I and Ca II, having their origin in the accretion disk.

The spectral data of U Gem we present here were obtained during January 21, 1994 and December 5-6, 1994 with the 1000-channel television scanner and the spectrograph SP-124 of the 6-m telescope of the SAO. We would like to point out that our January observations were obtained after U Gem returned to the minimum light. This happened 30 days after U Gem's outburst began which finished 7 days prior to our observations i.e. around January 14th. December data was collected after the outburst has finished, which was about 85 days before the observations. After analysis and modelling of the emission lines we obtained all the basic parameters of the accretion disk and the bright spot (see Borisov & Neustroev 1998a).

In Fig. 1 we show the orbital phase dependence of the disk parameters. Here, R is the ratio of the inner and the outer radius of the disk, V is the projection of velocity of outer rim of accretion disk on the line of the sight, α is the emissivity parameter (the line surface brightness of the disk is assumed to scale as $R^{-\alpha}$). For details see Borisov & Neustroev (1998a,b). In case of moving substance in the disk on keplerian circular orbits, the peak separation in emission lines (which mostly affects on the definition of parameter V) should remain constant during an orbital period. However, it can be seen that all parameters, including V, vary sinusoidally as $\sin 2\varphi$ (the hypothesis of constant parameters can be rejected with a confidence probability of more than 99%). Moreover, the explicit correlation between change of V, R and α is observed. The multiple correlation coefficient between V and parameters R and α for all lines is more than 0.72 with a confidence probability more than 96%. Such variability of parameters is present in both data sets and the phases of their modification are almost identical. Please note, that the marked variations of parameters were not revealed on the other objects observed with the same devices and in similar conditions (for example, WZ Sge - Neustroev 1998). Of particular interest is the behaviour of the parameter V as it's variation with the binary's phase reveals a deviation of the velocity field in the disk from the standard circular Keplerian model. The possible cause of such a deviation is the non-circular form of the outer edge of the accretion disk.

Research into the dynamics and stabilities of Keplerian elliptical accretion disks has shown (Lyubarskij et al. 1994), that such disks should be stable formations. However, modelling has indicated that the peak separation in emission lines, formed in the Keplerian elliptic accretion disk, will remain constant during an orbital period. Therefore, to sustain the Keplerian velocity field hypothesis in the disk, the phase variability of the peak separation can only be explained by a deviation in the emission line source region from a circle in the circular disk. For the elliptic disk the source region should have at least an eccentricity different from the disk.

Paczynski (1977) investigated the tidal effect of the secondary star upon the disk by integrating the orbits of test particles in the restricted three-body problem to determine the departures from a Keplerian velocity field in a pressureless disk. He found an elliptical distortion of the outer disk. The peak separation in emission lines, formed in such a disk, will vary as

$$V = V_0 - \Delta V \cos 2\varphi \qquad (1)$$

where φ is a phase of an orbital period. The dependence of parameters which is obtained (Fig. 1), however, does not agree

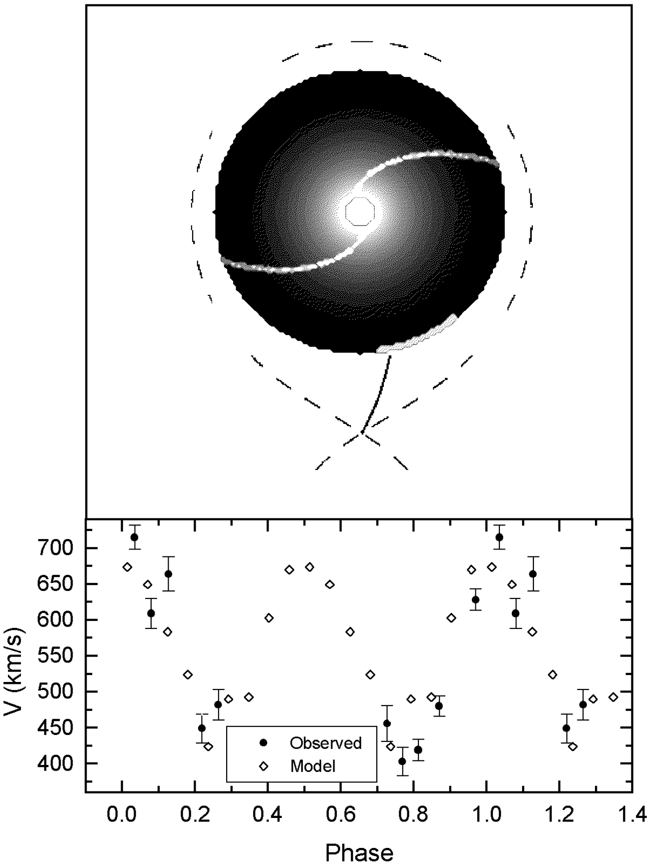

Fig. 3. Possible spatial image of the accretion disk emissivity model (top) and the predicted orbital phase dependence of the double peak separation along with actual observed data (bottom)

with Eq. (1) because of a shift of phases which is about 90°, and therefore cannot be explained by the model of Paczynski.

Such variations of the peak separation in lines could be caused by spiral shock in the accretion disk, obtained in many numerical hydrodynamic calculations (for example, Sawada et al. 1986). An earlier analysis of the influence of spiral shock on emission lines (Chakrabarti & Wiita 1993) has shown that the peak separation in such lines under certain conditions should vary with orbital phase.

3. Modelling

Emission line profiles arising in the accretion disk with or without spiral shocks can be calculated theoretically and by comparing them, the observed effects of spiral shocks can be derived. For this purpose we used the following technique. We decided to apply a model which includes a flat Keplerian geometrically thin accretion disk with spiral shocks, the position of which is constant regarding to the components of a double system. First of all a set of line profiles arising in an accretion disk with spiral shocks was calculated. Profiles were calculated for various orbital phases. After this shock-free model parameters were fitted to a minimum of a residual deviation of a "new" shock-free model profile from an "old" spiral one.

Self-similar accretion flow solutions for logarithmic spiral waves were obtained analytically by Chakrabarti (1990). For calculations of line profiles arising in an accretion disk with spiral shocks we used the method of Chakrabarti & Wiita (1993). It should be noted, that for a given number of spiral shocks, a model is uniquely determined by providing the pitch angle of the logarithmic spirals θ and the adiabatic index of the flow γ. The free parameters which we varied for this analysis of line profiles are the number of spiral shocks, spiral angle θ and azimuthal velocity component at the sonic surface q_{2c} (Chakrabarti & Wiita 1993). We would like to point that the model parameters (first of all, brightness of shocks) were optimised to reproduce the real observational emission line profiles in the spectra of dwarf novae.

To compute the shock-free model profile we used the method of Horne & Marsh (1986). Main free model parameters are α, R and V. For details see Horne & Marsh (1986).

4. Analysis and comparison with observations

As calculations have shown, the choice of spiral shocks parameters allows one to obtain amplitudes of the variation of the double peak separation from zero up to hundreds km/s. In this study, least deformed line profiles were obtained at the value of the spiral angle θ of about $50^\circ\div60^\circ$. In this case the line parameters depend on the phase of orbital period as $\sin n\varphi$ for an even number of shocks, and as $\sin 3\varphi/2$ for an odd number, where n is a number of the shocks

For the spiral angle θ less than 50° in certain phases the line profile becomes the one-peak for strong waves, or additional peak(s) appears between the original two, and the amplitude of the variation of the double peak separation will increase. For the spiral angle θ more than 60° additional peaks on the line wings are formed and the amplitude of the variation of the double peak separation will sharply reduce (Fig. 2). Parameter q_{2c} does not affect the behaviour of the line profiles during the orbital period (but not on profiles themselves). Once again note that we tended to examine the line profiles close to those observed.

One can reproduce the detected variability of the line parameters of U Gem (Borisov & Neustroev 1998a) using the model of the accretion disk with two symmetrically located spiral shocks with the spiral angle θ about 60°, q_{2c}=0.025 and γ=1.5. In Fig. 3, we present a possible spatial image of the accretion disk emissivity model and the predicted orbital phase dependence of the double peak separation along with actual observed data. Note that we obtained an extremely similar pattern with one for IP Peg (Steeghs et al. 1997). Fig. 4 shows the predicted without the influence of hot spot and the observed H_β line profiles of U Gem.

5. Conclusion

In this paper we present a study of the observable spectral manifestations of spiral shocks and compare them with results of spectroscopic observations of U Gem. The primary result of this study is that the orbital behaviour of the hydrogen emis-

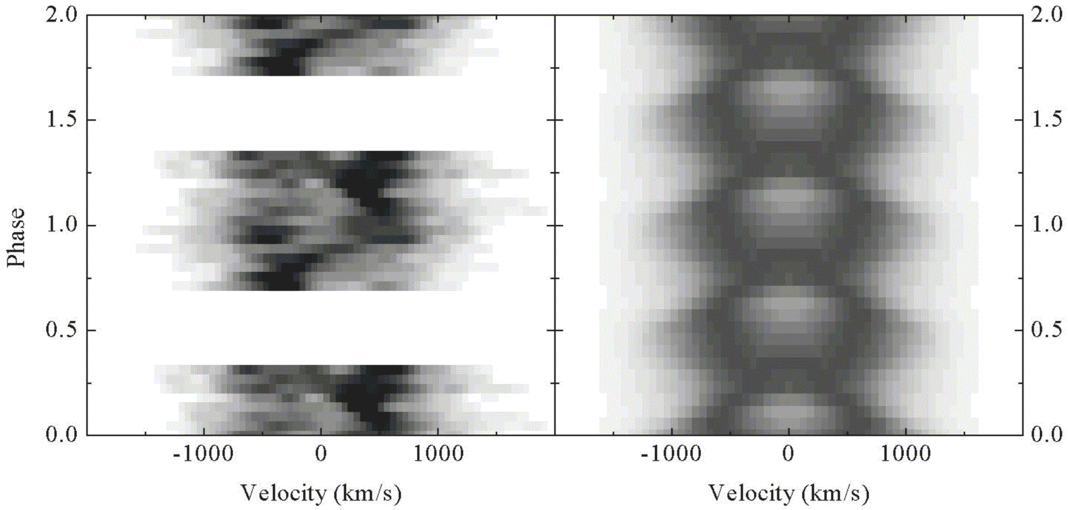

Fig. 4. The observed (left panel) and the predicted without the influence of hot spot (right panel) H_β line profiles of U Gem

sion line profile in the spectrum of U Gem can be reproduced by the simple model of the accretion disk with two symmetrically located spiral shocks with the spiral angle θ of about 60°. The best evidence of the presence of shocks is the orbital phase dependence of the separation of the double peak emission line. Furthermore, even weak shocks may be expected to be detected from analysis of the double peak emission line. Finally, the choice of the spiral shocks parameters allows one to obtain amplitudes in the variation of the double peak separation from zero up to hundreds km/s. This is perhaps the first conclusive evidence for spiral shocks in the accretion disk of cataclysmic variables in quiescence.

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