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Doppler tomography of the pre-outburst disk in SS Cygni

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Abstract. We present results of Doppler tomography of the pre-outburst accretion disk in SS Cygni. Analysis of Doppler tomograms shows that the the following gas dynamic details exist in the disk: "hot line"; spiral tidal shock; and a bow shock. Comparison of tomograms constructed using results obtained in different epochs shows that by the outburst the density of the disk increases and its radius becomes larger.

Key words. Stars: cataclysmic variables – Stars: accretion disks – Stars: Doppler tomography

1. Introduction

SS Cygni is a very well known representative of dwarf novae, close binary stars demonstrating quasi-periodic outbursts. There are several models proposed to describe physical mechanisms leading to outbursts: the secondary instability model (SIM) Bath (1973) and disk instability model (DIM) Abramowicz (1995). Another mechanism was proposed in Bisikalo et al. (2004).

These models can explain some aspects of outbursts in cataclysmic variables but can not give a complete picture. Thus the question about physical mechanisms leading to outbursts still remain open. Since it is known that the outburst is caused by the increased accretion rate, to answer this question, it is necessary to investigate the flow structure in the system.

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One of the observational methods to investigate the flow structure is Doppler tomography. In this paper we propose new spectroscopic data of SS Cygni acquired three days before a long outburst and Doppler tomograms constructed from these data. Using them we aim to investigate the structure of the pre-outburst disk in SS Cygni. Besides, we use spectroscopic data acquired in the beginning of the quiescent state right after a short outburst, tomograms and results of gas dynamic simulations from Bisikalo et al. (2008). Comparing these results with the new ones we attempt to derive conclusions about changes happening in the disk during the quiescent state.

2. Observations

The observations we report were performed on June 18th, 2009 at the Bologna Astronomical

Observatory with the 1.52 m 'Cassini' Telescope. The telescope was equipped with the Bologna Faint Object Spectrometer and Camera (BFOSC) Merighi et al. (1994) mounted in the Cassegrain focus. After the reduction we obtained series of 53 spectral line profiles of the H_β, H_γ and H_δ lines for the June 18, 2009 night. The profiles cover a binary phase interval from 0.75 to 0.25.

The observational data we compare with the material of June, 2009 were obtained on August, 2006 using the 2-meter telescope of the observatory located at the Terskol peak (Caucasus, Russia) Bisikalo et al. (2008). These data were acquired right after a short outburst.

3. Doppler tomograms in the H_β, H_γ and H_δ lines

Using the obtained spectra we constructed H_β, H_γ and H_δ Doppler tomograms of SS Cygni. Doppler tomography was performed using our own implementation of a maximum entropy algorithm proposed in Lucy (1994). The tomograms are shown in Fig. 1. According to the used restoration algorithm the total intensity of each map is normalized to the unity. The root-mean-square (rms) error of the tomogram restoration was approximately the same for all the tomograms ($\sim 7\%$).

All the tomograms demonstrate a ring-like structure. It may be a sign of an accretion disk existing in the system. In all the tomograms one can see an asymmetric region in the right quadrants. In the H_β and H_γ tomograms there are spots in the upper- and lower-left quadrants ($V_x < 0$). In the H_δ the bright region in the lower-left quadrant ($V_x, V_y < 0$) looks like a spot, but the bright region in the upper-left quadrant extends to both the right quadrants and finishes in the asymmetric region.

Since in accretion disks of CVs the temperature increases inwards, spectral lines with the higher excitation energy should originate closer to the accretor. In the Keplerian disks the velocity also increases inwards. It means that the lines with the higher excitation energy should be broader and correspondingly Doppler tomograms constructed from the high

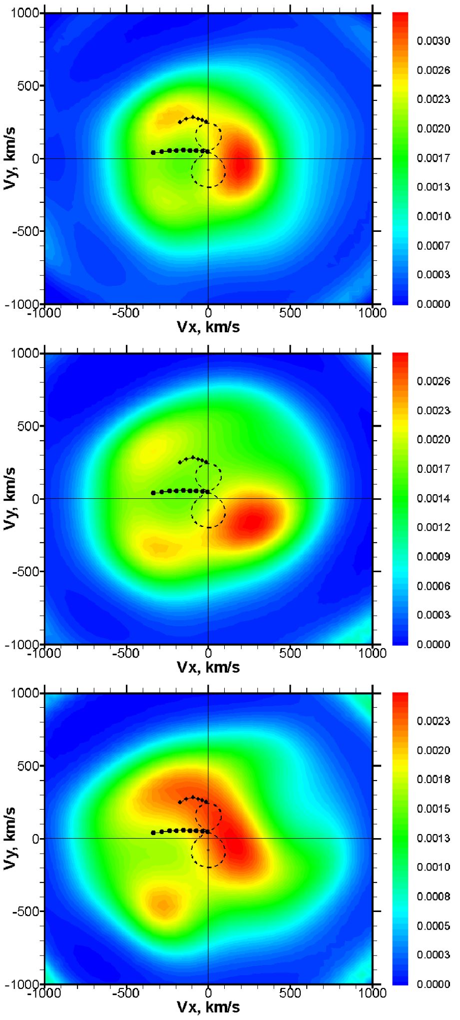

Fig. 1. H_β, H_γ, and H_δ Doppler tomograms of June 18, 2009 (top-down). The dashed line denotes the Roche lobe of the donor and accretor stars. The asterisk denotes the accretor. The line with the circles is a part of the ballistic trajectory of a particle moving from the L_1 point. The line with the diamonds traces disk velocities along the stream.

exitation energy lines should be larger. Indeed, looking at Figure 1 one can clearly see that for the lines with the higher excitation energy the tomograms have larger sizes (from H_β to H_δ).

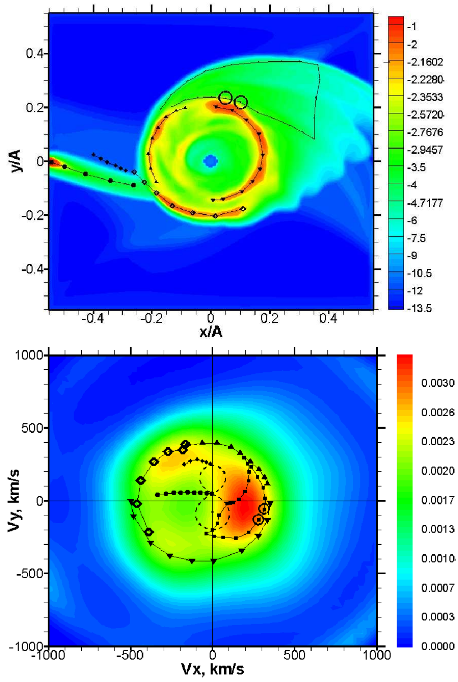

Fig. 2. Intensity distribution in the spatial coordinates Bisikalo et al. (2008) (upper panel) and H_β Doppler map with the markers denoting main gas dynamic features. The markers in the upper panel denote the following gas dynamic features: lines with the triangles correspond to the arms of the spiral tidal shock; line with hollow diamonds denotes the "hot line"; line with filled diamonds lies in the region along the stream from the L_1 point; and line with small squares encloses the region of the matter near the bow shock. In the lower panel the same markers transferred into the velocity field are plotted.

4. Results and discussion

To explain the observed details of the tomograms we follow the approach presented in Bisikalo et al. (2008). In accordance with the idea of this paper we compare the observed Doppler tomogram with results of gas dynamic simulations. In Fig. 2 an intensity distribution in the spatial coordinates and the H_β Doppler map are shown. The intensity distribution shown in Fig. 2 is calculated using results of gas dynamic simulations described in Bisikalo et al. (2008). It corresponds to the quiescent state of the system.

Since in gas dynamic simulations we calculate distributions of the density, pressure and velocity we can associate a particalar pair of V_x, V_y components of the velocity to a certain point in spatial coordinates. Thus, each (x, y) point of the markers can be associated to a particular point in the (V_x, V_y) space. It allows us to transfer the markers into the Doppler map to see what gas dynamic details exist in the pre-outburst disk. In the lower panel of Fig.2 the H_β Doppler map is shown. One can see that there is some correspondence between locations of the markers and bright regions in the tomogram. The "hot line" lies near the bright region in the upper-left quadrant of the tomogram. The bright region in the lower-left quadrant is produced by the radiation of one arm of the tidal shock. Another arm of the spiral shock is not visible as a distinct detail. However, its radiation can overlap with the radiation of the bow shock.

Presence of the bow shock is proved by the asymmetry of the tomogram. A mechanism that is responsible for the asymmetry and a role of the bow shock in this mechanism are described in Bisikalo et al. (2008)

To investigate what changes happen in the disk during the quiescent state we compare results of the observations and Doppler tomograms reported in Bisikalo et al. (2008) with those of June 18, 2009. We should remind that observational material of Bisikalo et al. (2008) was obtained right after a short outburst and that of June 18, 2009 - three days before a long outburst.

Making comparison of the data we, first of all, analyzed profiles of the spectral lines. Our measurements show that the mean EW of the H_γ line observed on June 18, 2009 exceeds the same parameter of the H_γ line observed on August 14, 2006 by factor of approximately 2.5. This effect may be explained in two ways. Since we normalize our data using the continuum level, the differences in this level may cause the differences in the EWs. The second reason is that the disk density before the outburst increases. If we suppose that the emission lines, we observe, are of the re-

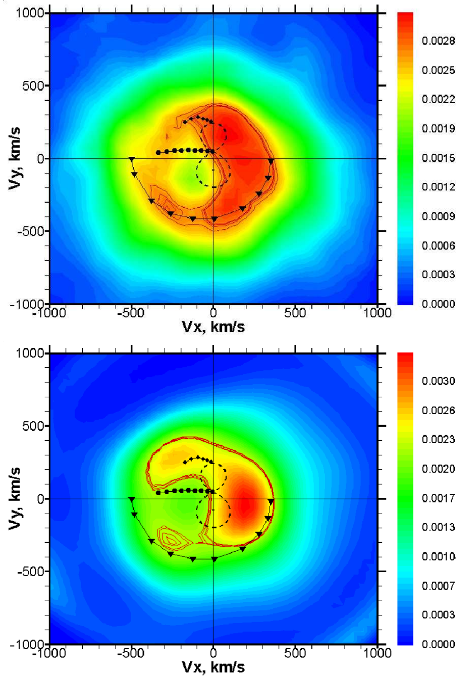

Fig. 3. Doppler tomograms in the H_{β} line. The upper panel is computed using the data of August 2006, the lower panel is computed using the new data. Markers are the same as in Fig. 1 and 2. Certain isolines are plotted to pick out regions of tidal shock (lower left quadrants of the tomograms)

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combination type their intensity should be proportional to the squared density (ρ^2) Storey & Hummer (1995). So, providing the same level of the continuum, the EW increase may be explained by the increased density of the disk. Unfortunately, we performed neither absolute measurements of the flux nor simultaneous photometry in the B band to make quantitative conclusions. However, there are arguments supporting this hypotheses. These arguments arise from analysis of the Doppler tomograms. In Fig.3 we plotted two tomograms in the H_{β} line of August 2006 (upper panel) and June, 2009 (lower panel). The first remarkable difference of the two tomograms is their sizes. The tomogram of August 2006 is larger than that of June 2009. It may happen, since in the tomogram of August 2006 we see the disk down to more inner regions having higher Keplerian velocities, while in the tomogram of 2009 these regions are not visible due to increased density and, hence, optical depth of the disk matter. There is a new work of Sanad (2011) based on spectral UV observations of SS Cygni, where the author also proposes the idea that during quiescence the disk accumulates mass.

In Fig.3 we again plot the markers, corresponding to one of the arms of the tidal shock wave. Besides, we have marked the bright regions of the tomograms that are believed to be due to this shock with isolines. We see that the region on the tidal shock of the tomogram of 2006 is located at slightly higher velocities. Then it must be located closer to the accretor than the same region of the tomogram of 2009. The observed difference between the tomograms may mean that in June 2009 we observed a larger disk.

There is a distinct detail in the new tomogram. This detail is denoted by the filled diamonds in Fig.2. The filled diamonds lie in the region along the stream. If the disk increases as we said above, the "hot line" starts closer to the donor-star and produces the detail noted above. Thus, the presence of this detail is an additional evidence of the disk size increase.

The regions of the asymmetry marked in Fig. 2 by thin solid lines with squares are different in the tomograms, too. The outer boundary of the asymmetric region in the tomogram corresponds to its inner boundary in the spatial coordinates, i.e. to the outer edge of the accretion disk. To illustrate this we put two points enclosed by circles in Fig. 2. As we can see in Fig. 3 in the tomogram of August 2006 (upper panel) the region of the asymmetry extends to ~ 500 km s^{-1} along the V_x−axis, while in the tomogram of June 2009 its edge has V_x− velocity smaller than 400 km s^{-1}. It means that the disk had different sizes at these two moments. On August 14, 2006 we observed the system right after the outburst when the significant portion of the disk matter was accreted, and we can guess that the disk was smaller at that time. Three days before the outburst, on June 18, 2009, the disk having accumulated material during the quiescent period became larger, thus its outer edge and the region of the asymmetry had lower velocities, as it is seen in the lower panel of Fig. 3.

5. Conclusions

In June 2009 we performed spectral observations of SS Cygni three days before an outburst. As a result we obtained series of 53 H_{β}, H_{γ} and H_{δ} line profiles. It allowed us to calculate Doppler tomograms of SS Cygni in these lines and investigate the structure of the pre-outburst disk. Analyzing the new Doppler tomograms and results of gas dynamic simulations we see that the main gas dynamic elements as shocks ("hot line", tidal spirals, bow shock) and the region of matter behind the bow shock found in previous works remain in the disk and are located almost at the same positions.

The obtained spectra and Doppler tomograms were compared with data acquired in August 2006 Bisikalo et al. (2008) right after an outburst. Comparison of the post- and pre-outburst tomograms shows that by the outburst the density of the disk increases and its radius becomes larger.

6. Discussion

M.MONTGOMERY How did you select a marker point in the disk to be a point in the tomogram?

D.KONONOV In gas dynamic simulations we calculate distributions of the density, pressure and velocity. So we can associate a particalar pair of V_x, V_y components of the velocity to a certain point in spatial coordinates. Thus, each (x, y) point of the markers can be associated to a particular point in the (V_x, V_y) space. It allows us to transfer the markers into the Doppler map

V.NEUSTROEV How would your conclusion change if the system's parameters used for Doppler tomography and simulations are not completely correct?

D.KONONOV I believe that the system with a very long history of observations should have good parameters. Anyway my main conclusions do not directly depend on the system's parameters

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