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Structure of the Accretion Disk of the Dwarf Nova WZ Sagittae

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Abstract—The spectroscopic observations of the dwarf nova WZ Sge in May 1994 are presented. An analysis of the dependence of the degree of asymmetry of the H_α emission profile on orbital phase has revealed two bright spots on the accretion disk in the system. Their positions are determined. We obtain the accretion-disk parameters and the phase dependence of the spot luminosities by modeling the H_α profiles. The size of the H_α emission region is estimated. Its comparison with other data indicates that the radius of the accretion disk in WZ Sge decreases during the outburst cycle (32.5 years) by about 15%. Doppler tomography was used to ascertain the structure of the accretion disk and show that the secondary component also contributes to the H_α emission.

1. INTRODUCTION

The cataclysmic variable WZ Sagittae is a unique eclipsing binary system with an extremely short orbital period (81 min 38 s). WZ Sge has been known since 1913, when it flared up as a nova. After the 1946 outburst, it was classified as a recurrent nova with an outburst quasi-periodicity of about 33 years. Later, based on the system's spectroscopic properties, Warner [1] showed that WZ Sge is a dwarf nova. After the 1978 outburst, the light curve of WZ Sge exhibited superhumps which are characteristic of the subclass of SU UMa stars. At the same time, the light curve of WZ Sge differs greatly from the light curves of other stars of this subclass; its shape changes rapidly. On the other hand, the observational data for WZ Sge show evidence of its belonging to the subclass of DQ Her stars [2].

Although WZ Sge has been repeatedly studied spectroscopically and photometrically [3–10], many observed properties of this system remain incomprehensible. For example, difficulties in interpreting the light curve of this system persist up to now. Its distinctive feature is phase variability of the secondary minimum and of an occasionally observed third minimum. In addition, the explanation of the primary minimum by eclipses of a bright spot is also inconsistent with some observational data.

In this paper, our goal is to study the spot structure of the accretion disk of WZ Sge. Our interest in this system was aroused by the studies of Gilliland *et al.* [8], who showed that the spot lies on the far side of the accretion disk relative to the normal component. This conclusion is inconsistent with classical views of the interaction between the accretion disk and the stream of matter in cataclysmic variables. On the other hand, the latest study of Spruit and Rutten [10] has yielded an opposite result. They showed that, in this system, the spot lies in the region of interaction of the stream with the accretion disk.

Our observations of WZ Sge with the 6-m BTA telescope are described in Section 2. In Section 3, we analyze the spectroscopic variability and model the observed H_α profiles of WZ Sge. In Section 4, we use Doppler tomography to ascertain the disk structure. The results of our modeling are discussed in Section 5.

2. OBSERVATIONS

We carried out the spectroscopic observations of WZ Sge on May 30, 1994 with a 1000-channel television scanner attached to the SP-124 spectrograph at the Nasmyth-1 focus of the 6-m Special Astrophysical Observatory telescope. A total of 27 spectra were taken in the wavelength range 5500–7200 Å with a dispersion of 1.9 Å channel^{-1}.The weather conditions were good for the observations, and the seeing was ~1.5″–2″. The duration of individual exposures was 300 s, and the interval between them was no longer than 30 s.

We reduced all our spectroscopic data by using the procedure described in [11]. Since the total duration of the observations was almost twice the orbital period, we averaged some of the data by using the ephemerides of Robinson *et al.* [5]:

$$\mathrm{HJD} = 2\,437\,547.72845 + 0\overset{\mathrm{d}}{.}0566878455E. \qquad (1)$$

The zero phase corresponds to the primary minimum. According to the universally accepted model, the bright spot is eclipsed at this time. Based on spectroscopic data, Spruit and Rutten [10] found the correction $\Delta\varphi = -0.041$ which makes it possible to pass from the photometric minimum to the time of inferior conjunction of

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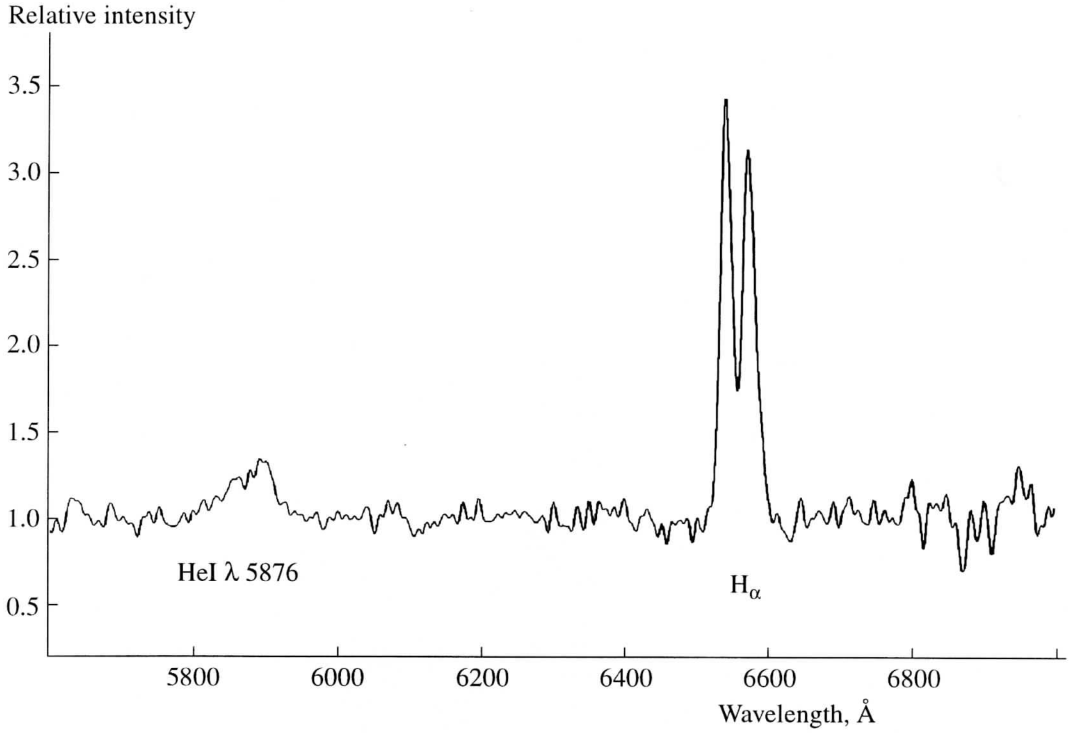

Fig. 1. The overall normalized spectrum of WZ Sge.

the red dwarf. We applied this correction when calculating the phases. After the separation in phase, we obtained 18 spectra covering the orbital period.

The overall spectrum of WZ Sge is shown in Fig. 1. This spectrum exhibits broad double-peaked H_α and He I λ 5876 emission lines. No other emission and absorption features are observed in this wavelength range.

3. MODELING

We studied the structure of the accretion disk by using the procedure for computing emission-line profiles of an inhomogeneous accretion disk from [12]. In our computations, we used a two-component model with a flat geometrically thin Keplerian accretion disk and a bright spot whose position was fixed relative to the binary's components. We began the line modeling with the computation of a double-peaked symmetric component that is formed in a homogeneous axisymmetric disk to which we then added a perturbing component formed in the bright spot. The profiles were computed by the method described in [13]; this method takes into account anisotropy of the observed surface brightness of the disk which depends on the gradient of Doppler shifts and on the finite disk thickness. The model parameters are briefly described below:

(1) the radial dependence of the surface brightness of an axisymmetric disk is described by the function $f(r) \propto r^{-\alpha}$, where $\alpha \sim 1.0–2.5$;

(2) $R = R_{in}/R_{out}$ is the ratio of the inner and outer radii of the disk ($R_{out} = 1$);

(3) V is the line-of-sight velocity component of the accretion disk's rim (in km s^{-1});

(4) ϑ is the phase angle of the spot, which is defined as the angle between the directions from the accreting component to the secondary and to the spot center. The phase angle is related to the spot azimuth by $A = \vartheta + 2\pi\varphi$, where φ is the orbital phase (the azimuth is the angle between the directions from the accreting component to the observer and to the spot center);

(5) ψ is the azimuthal extent of the spot;

(6) R_s is the radial position of the spot center in fractions of the disk outer radius;

(7) L is the relative dimensionless luminosity of the spot, which is given by

$$L = \int_{R_S - \Delta R_S/2}^{R_S + \Delta R_S/2} SBf(r)dr$$

$$= \frac{\pi}{180}\frac{\psi \Delta R_S B}{2-\alpha}\left(\left(R_S + \frac{\Delta R_S}{2}\right)^{(2-\alpha)} - \left(R_S - \frac{\Delta R_S}{2}\right)^{(2-\alpha)}\right),$$

where ΔR_S is the radial extent of the spot, S is the spot area, and B is the spot contrast (the spot-to-disk brightness ratio at the same distance from the accreting component).

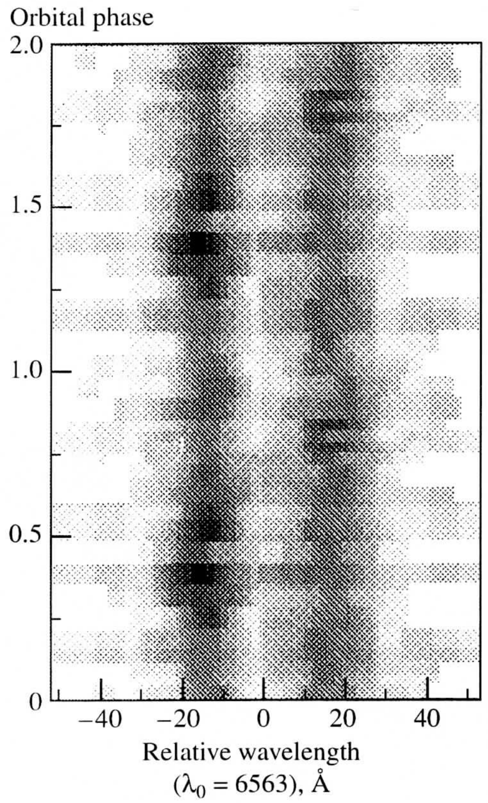

Fig. 2. Variations of the H_α profile with orbital phase.

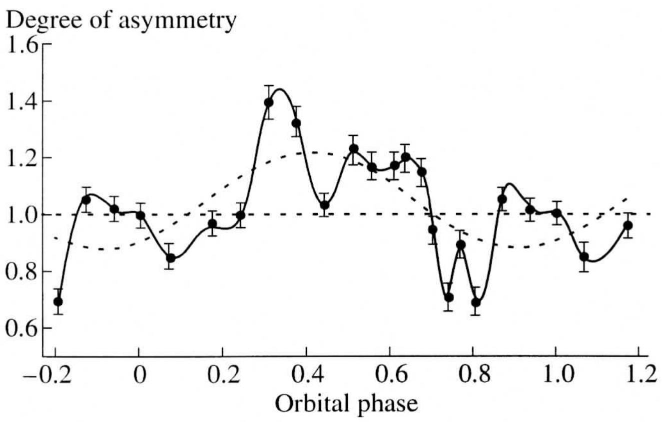

Fig. 3. The degree of asymmetry of the H_α profile versus orbital phase.

Note that, since the shape of the line profile is essentially independent of variations in the radial extent of the spot, its value can be taken arbitrarily in the computations (for example, we can specify a typical radial extent of the bright spot) [12]. We set $\Delta R_S = 0.1$.

Application of this procedure to the cataclysmic variable U Gem is detailed in [14].

We used the H_α emission line to study the structure of the accretion disk of WZ Sge. Figure 2 shows how it changed over the orbital period. We began our analysis of the spectroscopic data by plotting the degree of asymmetry of the line profile against orbital phase (below, we call it the S wave). This plot enables us to determine the phase angle of the spot and to draw some conclusions regarding the spot optical depth [12]. Let us highlight the principal features of the resulting curve (Fig. 3). Note first that its shape deviates appreciably from a sine wave, although it must be nearly sinusoidal [12]. Moreover, during much of the orbital period, the blue hump of the line is larger in area than its red hump; i.e., the degree of asymmetry is $S > 1$ (this is one reason why the profile is asymmetric in the overall spectrum in Fig. 1). Next, a comparison of our curve for the degree of asymmetry of the profiles with the same curves of Gilliland *et al.* [8] and Spruit and Rutten [10] reveals a mismatch of all the three curves. For example, Gilliland *et al.* [8] found the ratio of the H_α blue and red peaks to be at a maximum at phase 0.34. (Interestingly, in the same set of observations, the curve for the degree of asymmetry of the H_β profiles had a maximum at phase 0.58.) Let us now consider our data. If the curve for the degree of asymmetry were fitted by a sine wave without regard to significant residuals, then its maximum would occur at phase 0.40. Finally, according to Spruit and Rutten [10], this curve had a maximum at phase ~0.7. Note also that the ranges of degrees of asymmetry of the profiles also differed markedly: from 0.87 to 1.18 for the curve of Gilliland *et al.* [8] and from 0.7 to 1.4 for our curve.

Although this appreciable change in the spectroscopic behavior of WZ Sge is difficult to explain, it comes as no surprise. Indeed, the photometric data also suggest a frequent change in the photometric behavior. The light curve of WZ Sge, which is typical of dwarf novae, is known to occasionally become similar to the light curve of W UMa contacting binary systems. A transition from one type of variability to the other can occur during one (!) orbital period [15]. This transition is probably also accompanied by a change in the spectroscopic behavior. In conclusion, note that, during the spectroscopic observations immediately after the last outburst in 1978, the degree of asymmetry of the H_α profiles was greater than 1 over the entire orbital period (!) [6].

Let us return to our curve for the degree of asymmetry of the H_α profiles. A similar distortion of the S wave was also observed in other cataclysmic variables (for example, in TU Men [16] and DQ Her [17]) and was commonly explained by the presence of an additional emission region on the accretion disk [16]. We developed the procedure described in [12] for the standard model of an accretion disk with a single bright spot. Adding a second spot considerably complicates our model: the number of free parameters increases, while the parameters of the individual spots are even more difficult to determine. Nevertheless, the procedure remains qualitatively the same, and the problem is quite solvable if there is a sufficient number of spectra. As usual, it is first necessary to determine the phase angles of the spots from the S wave. Below, we analyze the shape of its curve for the single- and two-spot accretion-disk models.

3.1. Modeling the S Wave

Let us first consider the accretion disk with a single bright spot. Calculations show that, at a constant spot luminosity, the shape of the curve for the degree of asymmetry of the profiles is nearly sinusoidal and depends only slightly on the spot parameters during the orbital period [12]. However, it is known from photometric and spectroscopic studies [4, 18] that the spot luminosity is generally variable. The spot contribution to the system's total flux is normally at a minimum at those orbital phases when the spot lies on the far side of the accretion disk relative to the observer and at a maximum on its near side. This is mainly attributable to an eclipse of the spot by the outer opaque parts of the disk and to variations in the visible spot area with orbital period. For simplicity, we assume that the spot on the far side of the accretion disk relative to the observer has a constant luminosity, while that on the near side has a luminosity that is a quadratic function of the orbital phase. This "photometric" curve is described by only three parameters: the minimum and maximum luminosities and the phase of maximum luminosity.

We computed the phase dependences of the degree of asymmetry of the H_α profiles for some values of these parameters; some of our results are shown in Fig. 4. We see that the shape of the curve remains qualitatively constant, and it is satisfactorily fitted by simple functions with a small number of parameters. Of interest among them is only φ_0, the phase at which the S wave passes through unity as the degree of asymmetry decreases, which allows the phase angle of the spot to be determined: $\vartheta = 1 - 2\pi\varphi_0$.

Let us now consider how the phase dependence of the degree of asymmetry will be distorted when adding a second spot. It is easy to show that the degree of asymmetry of the line profile formed in the accretion disk with two spots can be assumed, with a small error, to be equal to

$$S = (S_1 - 1) + (S_2 - 1) + 1, \quad (2)$$

where S_1 and S_2 are the degrees of asymmetry of the profile in the presence of only the first or the second spot on the accretion disk, respectively.

Our method enables us to qualitatively describe the observed S wave and to determine the phase angles of the spots. We did this for WZ Sge. The observed and computed S waves are shown in Fig. 5a. The individual S waves for both spots are displayed in Fig. 5b. In Fig. 5c, the relative spot luminosities are plotted against phase. The discrepancy (although not very large) between the computed and observed degrees of asymmetry appears to be attributable to a difference of the actual phase dependence of the spot luminosity. Nevertheless, we determined their phase angles: $\vartheta_1 = 128°$ and $\vartheta_2 = 216°$. Note that the phase angle of spot 1 essentially matches the value obtained for a single-spot model (see above) and is close to that of Gilliland *et al.* [8].

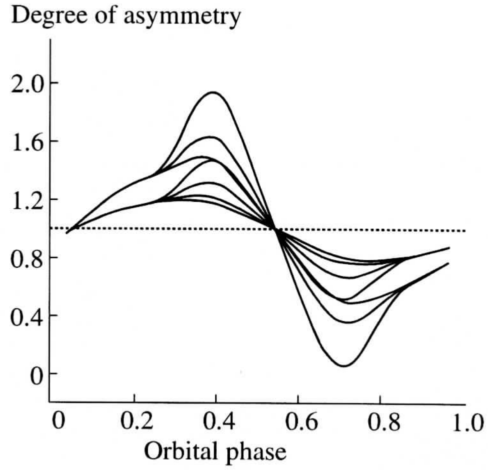

Fig. 4. Examples of computed S waves for various phase dependences of the spot luminosity.

Unfortunately, we can say nothing about the optical depth of the spots (its indicator is doubling of the maximum and the minimum of the "normal" sinusoidal S wave [12]) because of the difficulty in interpreting the S wave in the first place. In our computations, however, we nevertheless use the model of an optically thin spot by analogy to U Gem [14].

3.2. Modeling the Line Profiles

It was shown in [12] that, in order to correctly determine the spot parameters, it is important to follow a certain sequence of their determination. For the two-spot model, an additional constraint is imposed on this condition: one cannot model the spectra accumulated at the time when the line components formed in the spots are superimposed on the same hump of the line. For this reason, we selected eleven of the available spectra that were not subject to this constraint and determined the spot parameters only from these spectra. Once we obtained their values, we modeled the remaining seven spectra to establish the disk parameters.

The average parameters of the disk and the bright spots are all summarized in the table.

4. DOPPLER TOMOGRAPHY

We used Doppler tomography [19] to independently confirm the conclusion about the complex spot structure of the accretion disk of WZ Sge. Doppler tomography is a powerful method of analyzing the orbital variability

Average parameters of the accretion disk and the bright spots

Accretion disk		Spot 1	Spot 2
$V = 747 \pm 40$ km s^{-1}	$\vartheta =$	128°	216°
$\alpha = 1.66 \pm 0.19$	ψ	44° ± 8°	75° ± 19°
$R = 0.08 \pm 0.04$	$R_S =$	0.80 ± 0.07	0.96 ± 0.05
	$L =$	3.1 ± 4.8	2.8 ± 3.2
	$\Delta R_S =$	0.1*	0.1*

* The value of 0.1 for ΔR_S was taken by default.

of emission lines in the spectra of close binary systems. It allows the emission to be mapped in two-dimensional velocity space; the intensity of each pixel with coordinates V_x, V_y is related to the intensity of the corresponding sinusoidal component in the spectra with a radial velocity:

$$V = \gamma - V_x \cos(2\pi\varphi) + V_y \sin(2\pi\varphi). \quad (3)$$

The semiamplitude of the radial velocity for each sinusoidal component and its phase are determined by the distance from the system's center of mass and the azimuth on the Doppler map, respectively. For example, the radial velocity of the secondary component is $V_R = K_R \sin(2\pi\varphi)$, and its coordinates on the map are $(0, K_R)$. A detailed description of the method can be found in [19], and its application to some cataclysmic variables is detailed in [20–22].

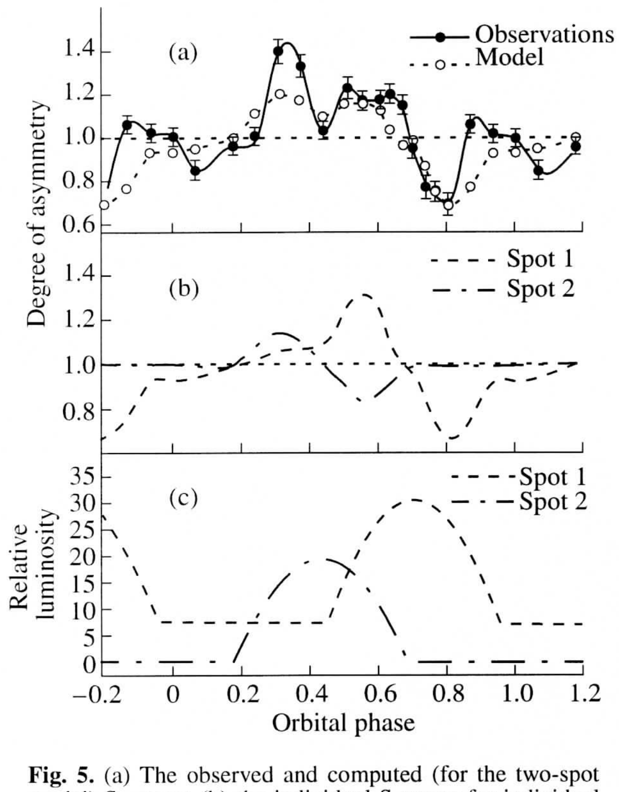

Fig. 5. (a) The observed and computed (for the two-spot model) S waves; (b) the individual S waves for individual spots; and (c) variations in the spot relative luminosities with orbital phase.

In this paper, we used the method of Robinson *et al.* [23] to construct a tomogram. An advantage of this method is a high space resolution of the Doppler map, although we cannot analyze variations in the intensity of its different parts with orbital phase.

The resulting Doppler map is shown in Fig. 6a. A ring structure associated with the axisymmetric disk and several regions of enhanced luminosity can be identified on this map. A version of this map with the axisymmetric part subtracted is shown in Fig. 6b. On both maps, the positions of the white dwarf, the secondary component, the inner Lagrangian point, and the system's center of mass are marked. In addition, we also marked the path of matter moving from the secondary through the inner Lagrangian point. In this case, we used the system's parameters determined by Smak [9].

The Doppler map is discussed in detail below.

5. DISCUSSION

5.1. Accretion Disk

While studying the accretion disk of U Gem [14], we detected sinusoidal variations in the parameters of the disk (particularly the velocity of its outer edge *V*) with a double wave in the orbital period. We explained these variations by the presence of spiral shock waves in the disk of U Gem [24]. Naturally, we also tried to find a similar effect in WZ Sge. It turned out, however, that there were no such variations in the parameters of the accretion disk of WZ Sge at a confidence level higher than 99%.

Assuming that the outer edge of the accretion disk had a Keplerian velocity, we determined the size of the H_α emission region. The computed size of this region is 1.14×10^{10} cm, which corresponds to 0.34a or 0.48 R_{L1}, where $a = 3.4 \times 10^{10}$ cm is the size of the system, and $R_{L1} = 2.36 \times 10^{10}$ cm is the separation between the white dwarf's center of mass and the inner Lagrangian point [9].

Our velocity of the outer edge of the accretion disk in WZ Sge is close to its values obtained previously by other authors. Nevertheless, we constructed a plot (Fig. 7) of the disk radius determined from spectroscopic data versus phase of the outburst cycle (32.5 years) on which we plotted our and all the published disk radii [3, 4, 6–8, 25]. There are data among them that refer both to the past outburst cycle (before the 1978 outburst) and to the current cycle. We did not use the disk radius that was determined from the spectra taken between December 1 and 29, 1978, because the accretion disk was apparently not the only H_α formation region at these dates. Otherwise, its radius would exceed the size of the entire system. The graph clearly shows a smooth decrease in the radius of the accretion disk between the outbursts, similar to that found in U Gem [26], Z Cha [27], and IP Peg [28]. Thus, WZ Sge

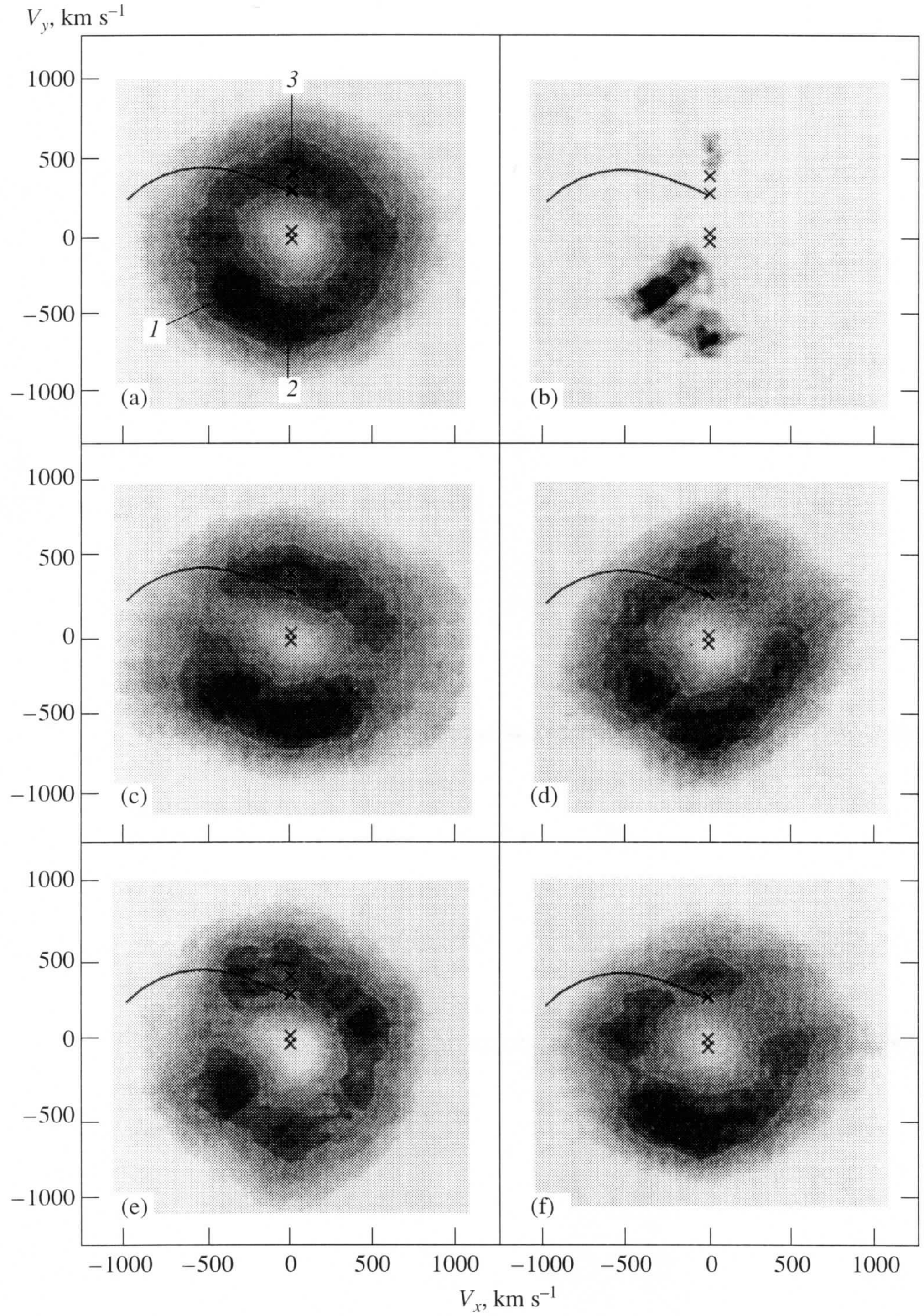

Fig. 6. Doppler maps constructed from different sets of spectroscopic data for WZ Sge. The crosses mark the positions (from top to bottom) of the white dwarf, the system's center of mass, the inner Lagrangian point, and the secondary component. The path of the stream is indicated by the curve. The numbers denote the regions of enhanced luminosity (see the text for details). (a) The Doppler map constructed from all spectra. (b) The same map with the axisymmetric part centered on the white dwarf subtracted. (c) and (d) The maps constructed from those spectra which were obtained at maximum spot luminosities. We see that the spot brightness ratios are different for them. (e) and (f) The maps constructed by using only half of the spectra centered at phases 0.0 and 0.5, respectively. This enabled us to identify the secondary component on the second map.

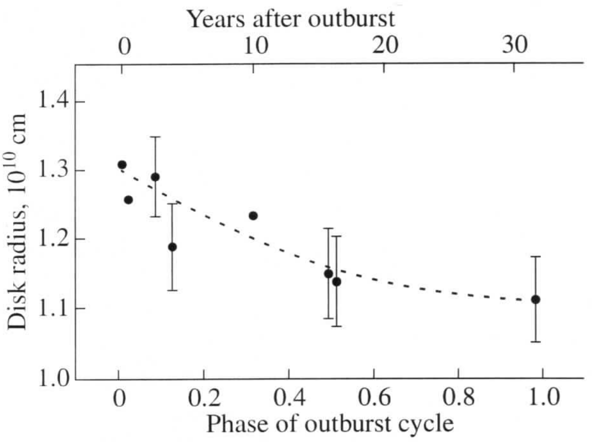

Fig. 7. The radius of the accretion disk of WZ Sge versus phase of the outburst cycle (32.5 years). In addition to our data, we used those of Greenstein [3], Krzeminsky and Kraft [4], Gilliland and Kemper [6], Voikhanskaya [7], Gilliland *et al.* [8], and Honeycutt *et al.* [25].

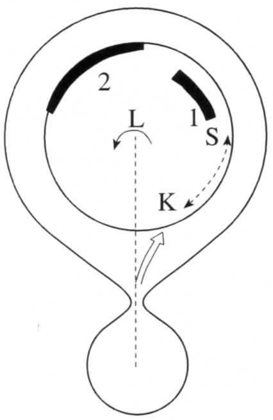

Fig. 8. A schematic representation of the accretion disk of WZ Sge. The following notation is used: 1 and 2 for the model spots; K and S for the theoretical "classical" positions of the spots with the Keplerian and stream velocities, respectively; L is the region of secondary disk-stream interaction [33].

is the fourth dwarf nova in which such a decrease in the radius has been detected.

According to [29], the lower limit on the mass of the outer part of the accretion disk in WZ Sge is

$$M_d = \frac{1-(R_c/R_{\min})^{1/2}}{(R_{\max}/R_{\min})^{1/2}-1}\dot{M}\Delta t, \quad (4)$$

where $R_{\max}$ and $R_{\min}$ are the maximum and minimum observed radii of the disk, Δt is the outburst quasi-period, and R_c is the radius of a circular orbit with the same angular momentum as that of the matter at the inner Lagrangian point. If $\dot{M} = 2 \times 10^{15}$ g s^{-1} [9] and $\Delta t = 10^9$ s, then the lower limit on the mass of the outer part of the disk is 5.5×10^{24} g or $2.8 \times 10^{-9} M_\odot$. This value matches the mass of the disk around U Gem in order of magnitude and is greater than that for IP Peg and Z Cha by one order of magnitude [28, 29].

5.2. Bright Spot

Knowing the binary's parameters, we can compute the path of the stream of matter and determine the expected position of the spot on the accretion disk [30, 31]. Figure 8 shows where the spot must be on the disk of WZ Sge. Since the direction of the velocity vector of the matter in the spot can be between the directions of the disk's Keplerian velocity vector (in the case of complete dissipation of the stream's radial velocity component) and the stream's velocity vector, the observed phase angle of the spot ϑ can also lie within some range. For WZ Sge, it lies between 35° and 99°. If part of the matter is reflected when the stream is interacted with the disk, as in U Gem [14], then the lower limit of this range decreases. Figure 8 also shows where the spot with the stream velocity could be seen. We now see that the computed spot positions do not coincide with any of the predicted "classical" positions.

This conclusion is also confirmed by Doppler tomography. As was already noted above, several regions of enhanced luminosity can be identified on the Doppler map (Figs. 6a and 6b). The two brightest spots with numbers 1 and 2 correspond to the model spots. We estimated their phase angles and azimuthal extents, which proved to be in satisfactory agreement with their computed values ($\vartheta_1 \approx 130°$, $\vartheta_2 \approx 180°$, $\psi_{1,2} \approx 45°$). The map clearly shows that both spots lie at some distance from the stream path.

Some theoretical studies indicate that, under certain conditions, part of the matter of the gas stream may continue its motion after a collision with the disk at some height above its plane [32, 33]. After a time, this stream must again fall onto the accretion disk. In this case, the phase angle of the region of secondary interaction must be about 140°–150° for a wide range of the system's parameters, while the distance from the accreting component will change from 0.02 to 0.18 of the system's size, depending on the mass ratio [33]. For WZ Sge, the values of these quantities must be 145° and 0.123, respectively. In addition, the most recent numerical hydrodynamic calculations point to a possible difference in the thickness of the outer edge of the accretion disk in a close binary system. For example, Meglicki *et al.* [34] identified three regions of disk thickening at phases 0.2, 0.5, and 0.8 (the phase angles are ~–72°, 180°, and 72°, respectively). Armitage and Livio [35] also pointed to a possible transfer of the stream matter above the plane of the accretion disk and an increase in the number of atoms along the line of sight relative to the average level at phases 0.1–0.2 and 0.7–1.0.

Thus, the first bright spot is probably formed in the region of secondary interaction of the gas stream. Its phase angle and distance from the white dwarf do not differ significantly from their predicted values. The second spot is more difficult to identify with a particular region of the accretion disk. Although its phase angle is close to the phase angle of one of the accretion disk's thickening regions found by Meglicki *et al.* [34], the mechanism of the increase in its luminosity is not quite clear. This is probably attributable to ionization by emission from the inner disk region. In this case, this spot must have maximum and minimum (at the expected large optical depth of this region) luminosities at those orbital phases at which it lies on the far and near sides of the disk, respectively. Indeed, the light curve of this spot (Fig. 9) exhibits a maximum at phases 0.8–1.0 and a minimum at phases 0.4–0.8. In addition, if this thickening region does exist, it may be responsible for a third minimum in the light curve which is occasionally observed at $\varphi \approx 0.2$–0.4, eclipsing the bright spot at the place of primary collision of the stream with the disk.

Given the region of secondary stream-disk interaction with enhanced luminosity, the absence of a bright spot at the place of primary interaction is incomprehensible. This spot was clearly identified by Spruit and Rutten [10]. It is probable that the matter flying above the disk plane occasionally eclipses this region, thus considerably reducing its luminosity in the line.

While modeling the orbital phase curve for the degree of asymmetry of the line profile, we assumed that the spot had maximum and minimum luminosities at those orbital phases at which the spot lay on the near and far side of the accretion disk relative to the observer, respectively. Once we have modeled the line profiles, we can now construct a real plot of the spot luminosity versus phase (Fig. 9). In general, our assumption has been confirmed. The light curve of the first (brighter at maximum) spot actually has a hump of width $\Delta\varphi = 0.4$–0.5 at those phases at which the spot lies on the near side of the disk relative to the observer. On the far side, the spot luminosity is nearly zero. The observed luminosity of the second spot varies irregularly, with the light curve exhibiting two maxima. Figures 6c and 6d show two Doppler maps that we constructed by using only those spectra which were obtained at maximum spot luminosities. We see that the spot brightness ratios on them are different, which also lends support to our conclusion about variability of the spot luminosities.

Note that the latest studies of the structure of accretion disks in cataclysmic variables by using models and Doppler tomography suggest that the disk structure is fairly complex. For example, Marsh [36] showed that the spot position on the disk of the dwarf nova Z Cha roughly coincides with our position of the first spot in WZ Sge. By contrast, the spot on the disk of SW UMa lies at the same position where the secondary spot in WZ Sge does [37]. The disk of IP Peg exhibits an even

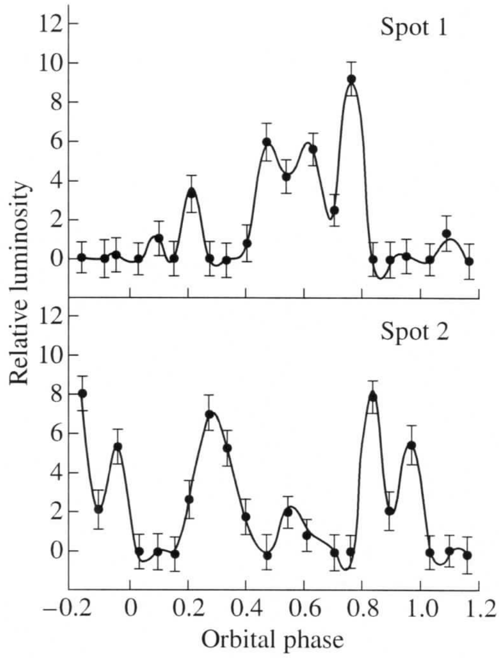

Fig. 9. The relative spot luminosity versus orbital phase.

more complex structure. Marsh and Horne [20] identified three regions of enhanced luminosity on the accretion disk of this system, with the positions of two of them being again coincident with the spot positions on the disk of WZ Sge.

5.3. Secondary Component

The position of spot 3 in the upper part of the Doppler map (Figs. 6a and 6b) coincides with the marked position of the secondary component. We again constructed two Doppler maps for which we used only half of the spectra centered at phases 0.0 and 0.5 (Figs. 6e and 6f). We see that spot *3* is clearly identified on the second map and is virtually absent on the first map. Consequently, we have every reason to conclude that spot *3* is formed on the surface of the red dwarf facing the accreting component. Meanwhile, the Doppler map of Spruit and Rutten [10] exhibits no secondary component.

Line emission from the secondary components is also seen in some other cataclysmic variables (IP Peg [20], U Gem [21], OY Car [38]). It is commonly observed during outbursts or within a short period after them, although there are exceptions (U Gem [21]). WZ Sge constitutes one of such exceptions.

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REFERENCES

1. Warner, B., *The Structure and Evolution of Close Binary Systems, IAU Symp. no. 73*, Eggleton P., Mitton S., and Whelan J., Eds., Dordrecht: Reidel, 1976, p. 85.
2. Patterson, J., *Publ. Astron. Soc. Pac.*, 1994, vol. 106, p. 209.
3. Greenstein, J.L., *Astrophys. J.*, 1957, vol. 126, p. 23.
4. Krzeminsky, W. and Kraft, R.P., *Astrophys. J.*, 1964, vol. 140, p. 921.
5. Robinson, E.L., Nather, R.E., and Patterson, J., *Astrophys. J.*, 1978, vol. 219, p. 168.
6. Gilliland, R. and Kemper, E., *Astrophys. J.*, 1980, vol. 236, p. 854.
7. Voikhanskaya, N.F., *Astron. Zh.*, 1983, vol. 60, p. 938.
8. Gilliland, R., Kemper, E., and Suntzeff, N., *Astrophys. J.*, 1986, vol. 301, p. 252.
9. Smak, J., *Acta Astron.*, 1993, vol. 43, p. 101.
10. Spruit, H.C. and Rutten, R.G.M, *Preprint Max-Planck-Institut fuer Astrophysik MPA*, 1996, no. 982.
11. Knyazev, A.Yu., *Sistema upravleniya i sbora dannykh spektrofotometra v Nesmit-1 BTA: IV. Reduktsiya skanernykh dannykh v MIDAS, Otchet SAO* (The Control and Data Acquisition System of the Spectrophotometer at the BTA Nasmyth-1 Focus: IV. Reduction of Scanner Data in MIDAS, SAO Report), 1994.
12. Borisov, N.V. and Neustroev, V.V., *Bull. Spec. Astrophys. Obs., Izv. SAO*, 1998, vol. 44, p. 10.
13. Horne, K. and Marsh, T.R., *Mon. Not. R. Astron. Soc.*, 1986, vol. 218, p. 761.
14. Borisov, N.V. and Neustroev, V.V., *Astron. Zh.*, 1998, vol. 75, (in print).
15. La Dous, C., *Cataclysmic Variables and Related Objects*, NASA/CNRS 29, Monograph Series on Non-Thermal Phenomena in Stellar Atmospheres, Hack, M., Ed., 1989.
16. Mennickent, R.E., *Astron. Astrophys.*, 1995, vol. 294, p. 126.
17. Hutchings, J.B., Cowley, A.P., and Crampton, D., *Astrophys. J.*, 1979, vol. 232, p. 500.
18. Livio, M., *Accretion Disks in Compact Stellar Systems*, Wheeler, J.C., Ed., Singapore: World Sci. Publ., 1993, p. 243.
19. Marsh, T.R. and Horne, K., *Mon. Not. R. Astron. Soc.*, 1988, vol. 235, p. 269.
20. Marsh, T.R. and Horne, K., *Astrophys. J.*, 1990, vol. 349, p. 593.
21. Marsh, T.R., Horne, K., Schlegel, E.M., *et al.*, *Astrophys. J.*, 1990, vol. 364, p. 637.
22. Ratering, C., Bruch, A., and Diaz, M., *Astron. Astrophys.*, 1993, vol. 268, p. 694.
23. Robinson, E.L., Marsh, T.R., and Smak, J.L., *Accretion Disks in Compact Stellar Systems*, Wheeler, J.C., Ed., World Sci. Publ., 1993, p. 75.
24. Chakrabarti, S.K. and Wiita, P.J., *Astron. Astropys.*, 1993, vol. 271, p. 216.
25. Honeycutt, R.K., Kaitchuck, R.H., and Schlegel, E.M., *Astrophys. J., Suppl. Ser.*, 1987, vol. 65, p. 451.
26. Smak, J., *Acta Astron.*, 1984, vol. 34, p. 93.
27. O'Donoghue, D., *Mon. Not. R. Astron. Soc.*, 1986, vol. 220, p. 23.
28. Wolf, S., Mantel, K.H., and Horne, K., *Astron. Astrophys.*, 1993, vol. 273, p. 160.
29. Anderson, N., *Astrophys. J.*, 1988, vol. 325, p. 266.
30. Lubow, S. and Shu, F., *Astrophys. J.*, 1975, vol. 198, p. 383.
31. Flannery, R.K., *Mon. Not. R. Astron. Soc.*, 1975, vol. 170, p. 325.
32. Lubow, S.H. and Shu, F.H., *Astrophys. J.*, 1976, vol. 207, p. 53.
33. Lubow, S.H., *Astrophys. J.*, 1989, vol. 340, p. 1064.
34. Meglicki, Z., Wickramasinghe, D., and Bicknell, G.V., *Mon. Not. R. Astron. Soc.*, 1993, vol. 264, p. 691.
35. Armitage, P.J. and Livio, M., *Astrophys. J.*, 1996, vol. 470, p. 1024.
36. Marsh, T.R., *Ph. D. Thesis*, Cambridge Univ. Press, 1985.
37. Shafter, A.W., Szkody, P., and Thorstensen, J.R., *Astrophys. J.*, 1986, vol. 308, p. 765.
38. Harlaftis, E.T. and Marsh, T.R., *Astron. Astrophys.*, 1996, vol. 308, p. 97.

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