Bull. Spec. Astrophys. Obs., 1996, 41, 134–139

SS Cygni — an intermediate polar or a dwarf nova?

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Received May 16, 1996; accepted July 23, 1996.

Abstract. The cause of discrepancies in the estimates of the inclination angle of the system, which have been obtained from radial velocity curves and from orbital light curves is considered. An analysis of properties of SS Cyg has shown that the system inclination angle is small and more than likely the system is a dwarf nova.

Key words: cataclysmic variable stars: individual: SS Cygni – variability problems

1. Introduction

SS Cygni is the brightest among the known dwarf novae, that is why it has been extensively observed. It is a low–mass close binary system consisting of a white dwarf and a red dwarf. Two outbursts of amplitude up to $4^{\rm m}$, which recur on the average every 50 days, are distinguished on the long–term light curve. Between the outbursts the system light fluctuates with an amplitude up to $0.2^{\rm m}$. Since it has been a failure to isolate a component varying with the orbital period phase the opinion has been confirmed that the inclination of the SS Cyg orbital plane to the line of sight is small. From spectral observations it equals $35^\circ - 40^\circ$. Thorough ten–year observations made by Voloshina and Lyutyj (1983; 1993); and Voloshin (1986) and allowed them to obtain light curves of the system and study their properties depending on the outburst period. Each curve has two maxima and two minima, and their shape varies markedly with wavelength. In Fig.1 are represented the light curves in the U filter from Voloshina and Lyutyj (1993). The most remarkable feature of the average curve (Fig. 1a) is a dip at phase $\varphi = 0.54$ lasting approximately 0.1P. As Voloshina and Lyutyj (1993) claim it appears just before the outburst and immediately after it. Comparing the light curves from Voloshina and Lyutyj (1993) with the curves of the same authors from Voloshina (1986), one can notice their difference. The former were obtained by averaging the results of measurements for 10 years, the latter, for 2 years. On the curves from Voloshina (1986) different details can be seen, whereas the dip is absent. The curves from Voloshina and Lyutyj (1993) are rather smooth with the dip pronounced. It is obvious that the curves are time–variable, and the variability is likely to be random since they are smoothed in long–term averaging. The dip, if it is real, is not constant either. The random character of the variability is clearly seen on the light curves obtained on different nights in Voloshina (1986). There is no dip on these curves, however short–time small light increase with an amplitude $\geq 0.1^m$ are visible. Voloshina and Lyutyj (1993) examine separately the light curves in the middle of the quiet state (between the outbursts), just before the outburst and soon after it (Fig. 1b–d). These three types of outbursts differ from each other and from the average curves. In all the cases the curves vary with wavelength, and new details are especially marked in the U filter. Voloshina and Lyutyj (1993) explain their result by a decrease in the disk size before the outburst and estimate the system inclination angle to be $i \approx 70^\circ$, which is much larger than the one agreed–upon.

As regards the value of i and the causes of orbital light variability, they are directly related to the nature of SS Cyg: whether the system is a dwarf nova with disk accretion or an intermediate polar with disruption of the internal disk and accretion channelling to the magnetic poles of the white dwarf. In order to answer this question we have analyzed the properties of the system and came to the conclusion that SS Cyg is a dwarf nova with a small angle of inclination of the orbital plane to the line of sight.

2. Minimum light

The light curves of the quiet state of the system (Fig. 1b) differs from the average curves: the dip is absent, and a sharp light increase is observed at phase $\varphi = 0.58$, whose maximum falls at $\varphi = 0.65$.

In Vojkhanskaya (1973a) the intensity variation of emission Balmer lines during the orbital period at minimum light is obtained. As an example, in Fig. 1e is represented the intensity variation of H_β from Vojkhanskaya (1973a). The phases are recalculated using the ephemerides from Voloshina and Lyutyj

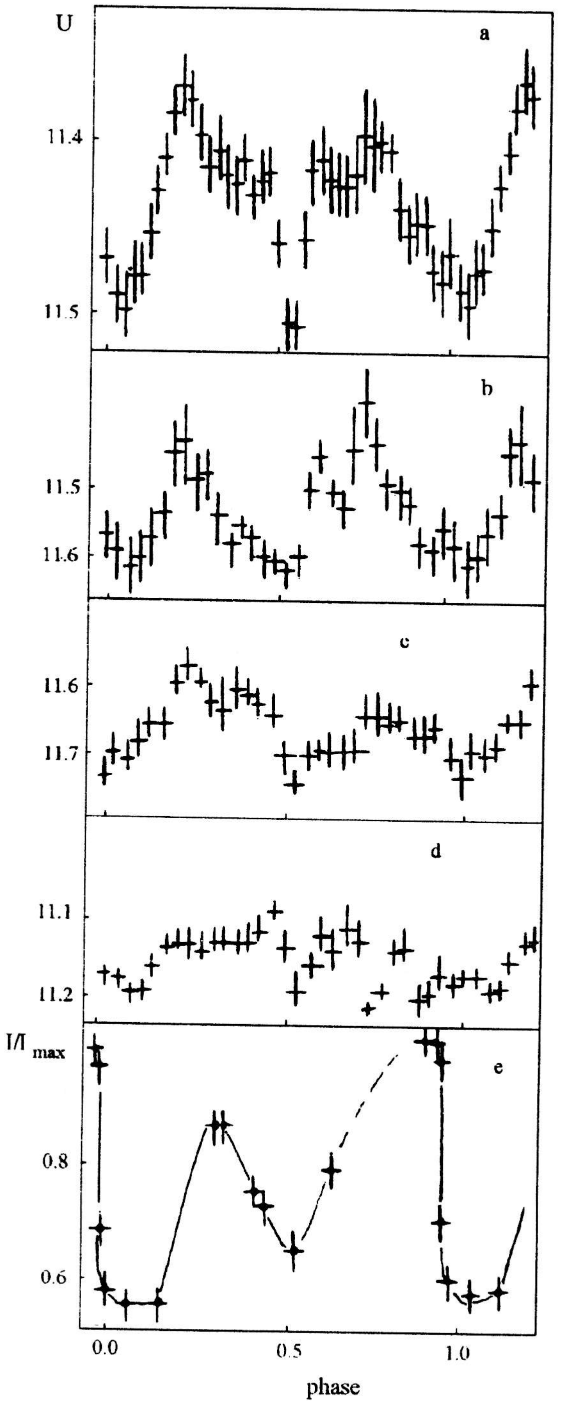

Figure 1: *Light curves in the U band from (Voloshina and Lyuty, 1993) and* H_β *emission line intensity from Vojkhanskaya (1973) (a — average curve, b — minimum light between the outbursts, c — short before the outburst, d — shortly after the outburst).*

(1993). It is seen that the extrema of the H_β curve are generally in phase with the extrema of the light curve. One point of the H_β curve falls within the region of the narrow dip. The point does not respond to the abrupt change of light.

The intensity of high–excitation emission lines in the ultraviolet region also vary during the period. Within a long time interval no phase dependence is detected (Mansperger et al., 1994), whereas individual observations show phase variations inconsistent with each other. However, as in optics too, not a single paper has noted a violet change in intensity of ultraviolet lines, which could be associated with eclipse of the spot.

In Fig. 2 is displayed a schematic of SS Cyg with the phases computed from ephemerides of Voloshina and Lyutyj (1993) and some observed peculiarities are indicated. As is seen in this figure, the appearance of the lines HeII is associated with the visibility of the spot. When the spot is invisible they are very weak and are practically absent. According to Hack and la Dous (1993) in the interval of phases 0.12–0.15, besides the line HeII λ 1640 Å the strong line $\lambda 1619 \pm 2$ Å is present. If this is the shifted HeII line, then the shift corresponds to the velocity -3800 km/s. Such a high velocity can be ascribed to polar ejection if it exists. Possibly, this is a blend of several weak lines of SiI and CIII from the overheated side of the secondary companion. In this case the shift corresponds to the velocity $\simeq 200 - 300$ km/s, which is higher than the orbital velocity of the companions. this line may be caused by some moving matter in the vicinity of the white dwarf or at the base of the stream. A comparison of the light curves with the H_β curve and Fig. 2 shows that the main minimum near phase $\varphi = 0.0$ is most likely due to eclipse of the hot spot by the disk. However it is not clear why coming in eclipse on the H_β curve is so steep. Selfeclipse by the disk causes a smooth flux variation 0.5P long. A possible reason may be eclipse of the disk by the flux from the outer Lagrangian point L_2. The existence of fluxes from the Lagrangian points is shown by the calculations of Sawada et al. (1986). This assumption is supported by the following two points:

- the onset of eclipse coincides with the position of the point L_2 and
- the strongest absorption lines fall at the moment of eclipse, while they are weak when the secondary component is best visible (Giovannelli et al., 1983).

The second, less deep, minimum on the H_β curve ($\varphi = 0.55$) is caused, in our opinion, by eclipse of emission regions near the white dwarf by the secondary companion and, possibly, by matter outflowing from the point L_3. The fact that the H_β curve minima are separated not exactly by 0.5P may result

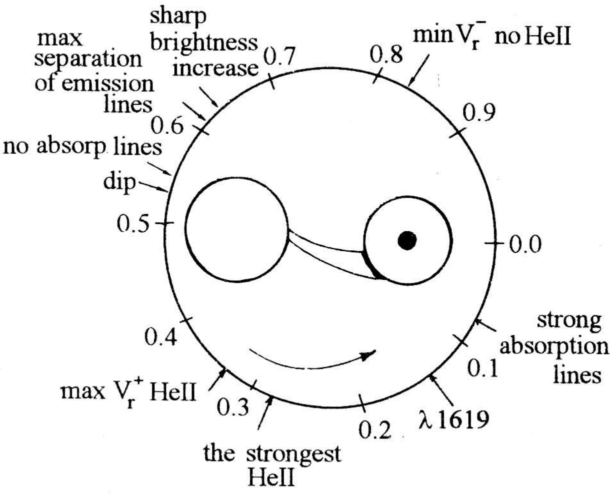

Figure 2: *A schematic of SS Cyg with indication of some observational peculiarities. Phases are computed using the ephemerides from (Voloshina and Lyutyj, 1993).*

from inaccurate determination of extrema position, however may be the case since strict symmetry in the system can hardly be expected. The different height of the H_β curve maxima may be the consequence of asymmetry of the disk, when the rim visible in the first half of the period is thicker than the opposite one, but this may also result from partial screening the disk by matter outflowing from L_2.

Attention is claimed by one distinguishing feature of the light curves: within the errors their maxima are the same in B and U, and only in V the main maximum is higher than the secondary. That is, the spot has a minor effect, which is seen only in the V region. The sharp increase in brightness at $\varphi = 0.58$ with the maximum at $\varphi = 0.65$ implies that the spot is out of eclipse and well visible for a short time. With further rotation of the system the visibility of the spot decreases again.

Thus, all the data suggest that at minimum light the spot is not a significant contributor to the radiation from SS Cyg. This may be due either to its faintness or to its poor visibility because of the small inclination of the system.

3. Before and after the outburst

The shape of the light curves changed over several days preceding the outburst: firstly, they lowered by $0^{m}.1$ as compared to the quiet state, and their amplitude became somewhat smaller, secondly, the additional radiation at phase 0.65 strongly decreased and is seen clearly only on the U curve, however a new additional radiation appeared at phases 0.35–0.47 with a maximum at $\varphi \simeq 0.4$. At minimum light it was hardly observed.

Multiple observations have shown the outburst to be rather a complex process, which begins before the optical outburst and the consequences of which are noticeable some time after the outburst.

It is shown in (Clarke et al., 1984) that for 3–5 days prior to the rapid increase the light rises very slowly. At this time the Balmer decrement, which turned out to be highly responsive to the processes taking place in the system, changes dramatically (Vojkhanskaya, 1977). At minimum light the decrement is partly inverse ($I_\gamma/I_\beta \simeq 1.5 - 2$). Before the onset of the outburst the inverse degree begins to decrease and at the onset it disappears ($I_\gamma/I_\beta < 1$). The faster increases the light of the outburst the stronger varies the decrement and the sooner it shows itself. A outburst with rapidly rising light can be detected from the decrement variation 2–3 days before the onset.

Approximately in the middle of the increasing branch of the outburst emission lines are replaced by absorption lines and a spectrum of type A is observed for a short time. The energy distribution in the continuum becomes less steep as compared to the minimum of light. With further increase in brightness the slope of the spectrum increases again (Szkody, 1976; Vojkhanskaya, 1973c; Polidan and Holberg, 1984), while the absorption features become weaker and gradually disappear.

On the two–colour diagram the star describes a loop during the outburst: first it goes down and moves to the left, to the supergiant branch, then it goes up along this branch to the initial U–B colour and after the outburst regains its original position on the diagram. The steeper the increasing branch of the outburst the lower SS Cyg moves on the two–colour diagram. The moment the star appears on the supergiant branch approximately coincides with the development of the absorption spectrum in it (Vojkhanskaya, 1974).

From the above–said it follows that a rarefied gaseous medium with a steep decrement appears (or manifest itself) initially in the system, then other phenomena associated with the outburst follow. This is consistent with the agreed–upon opinion that the outburst is initiated upon increasing the rate of mass loss $\dot{M}$ by the secondary companion. With a small delay from initiation of the optical outburst the hard X–ray flux increases rapidly. A little later it drops to zero as fast, while the soft X–ray flux increases sharply. The soft X–ray outburst lags behind the optical outburst by about 1 day. On termination of the outburst the opposite takes place (Jones and Watson, 1992). Neither at minimum nor at maximum light the X–ray flux variations with phase of the orbital period have been found, which most likely points to the small inclination angle of the system.

If SS Cyg is a dwarf nova, the most probable region of hard X–ray radiation origination is the boundary layer (Patterson and Raymond, 1985). Systems with strong emission lines, SS Cyg belongs to, must have optically thin disks and an intensive hard X–ray flux. Using the empirical relationship from (Patterson and Raymond, 1985) and the mean equivalent width of H_β, $\overline{W_\beta} = 70$ Å, obtain the hard X–ray and optical flux ratio $F_X/F_V = 2.7$, which corresponds to the rate of mass transfer $\dot{M} \simeq 3 \cdot 10^{14}$ g/s. With the initiation of the outburst the ratio F_X/F_V may somewhat increase, because of increasing $\dot{M}$, as long as the boundary layer remains optically thin ($\dot{M} \leq 6 \cdot 10^{15}$ g/s (Patterson and Raymond, 1985)). With further increase of $\dot{M}$ the ratio F_X/F_V decreases rapidly, as well as the disk, and the boundary layer becomes optically thick, their temperature drops, and they begin to emit soft X–rays. If the inclination angle of the system was large, it was difficult to notice the hard X–ray increase at the beginning of the outburst because the baundary layer was obscured by the disk. For instance, in U Gem this variation is faint (Swank et al., 1979).

If SS Cyg is an intermediate polar (Giovannelli and Martinez–Pais, 1991), in this case hard X–rays are emitted by the accretion column. With increasing $\dot{M}$ the hard X–ray flux must increase continuously and can not stop ubruptly, which is inconsistent with the observations. Besides, from the estimates of Gnedin at al. (1995) the magnetic field of the white dwarf in SS Cyg is 1.5–2 orders smaller as compared to intermediate polars.

The line spectrum variations with development of the outburst, which are observed in SS Cyg, are typical of dwarf novae. Radial velocity curves change too (phasing, amplitude, γ velocity). In particular, the velocity curve amplitude of the secondary companion strongly increases during the outburst (Hessman et al., 1984). Robinson et al. (1986) suggest a possible explanation of this: the overheating of the secondary component's side by radiation of the primary displaces the center of gravity of the radiation of the late–type spectrum to the far rim of the red star. It is shown with our estimates that the displacement of the center of gravity by half the radius can explain the observed increase in the amplitude of the secondary companion radial velocity.

It is shown by Deng et al. (1994) that in the quiet state of the system there is a correlation between the equivalent width W of high–excitation lines in the ultraviolet region of the spectrum and the inclination angle i of the orbital plane: the smaller i the larger W. For example, the equivalent width of the CIV line $\lambda 1550$ Å in systems with a large inclination angle (U Gem, HT Cas, Z Cha) is 0–4 Å, while in systems with a small inclination it is by 1–1.5 orders larger. In SS Cyg it is ≈83 Å. During the outburst all high–excitation lines are in absorption, while the strongest of them have the P Cyg–type profile. The velocity of the absorption component is close to the escape velocity of the white dwarf. This means that during the outburst high–velocity wind is created. The existence of the wind is confirmed by the calculations of Sulejmanov (1995). A comparison of different systems have shown that the profiles of the P Cyg type is observed only in systems with a small inclination angle (Cordova and Mason, 1982).

After the outburst the light curve changed dramatically (Fig.1d): the average brightness increased by $0.3^m - 0.4^m$, the main eclipse depth reduced and the eclipse is clearly seen only on the B and V, in the second half of the period a few eclipse–like fluctuations at phases 0.52, 0.72 and 0.87 with a sharp light drop and a fair rise are seen. These fluctuations make the secondary maximum and minimum practically indiscernible, especially on the U curve. Only the first of these fluctuations at $\varphi = 0.52$ can be attributed to the spot. The location of the other two does not allow them to be associated with the spot. The very steep forefront of the three fluctuations suggests that in this case we may be dealing with a structure of the type of shock–wave. Multiple calculations of flow of matter in binary systems show a very complicated pattern where shock waves and tangential breaks are necessarily to be created. The number of these features and their locations with respect to the system components depend on the original bounder conditions, the degree of filling the Roche lobe, the type of flow of matter and its quantity. In the case, which is the closest to the one under consideration (the secondary component fills the lobe Roche), spiral–like waves are formed in a disk–like structure and detached shock–wave originates between the components (Sawada et al., 1986; Bisikalo et al., 1994). Besides, considerable flows of matter through the outer Lagrangian points L_2 and L_3 develop, which strongly increase during the outburst. Stellar wind from the disk and overheated secondary companion may bring about flows through the points L_4 and L_5 as well. In any case, the Balmer decrement change prior to and during the outburst, the movement of the star on the two–colour diagram, and the appearance of the strong absorption spectrum as well as P Cyg–type profiles, point to the appearance of a great quantity of rarefied gaseous matter. The interaction of wind flows with each other and with the system components has been treated in paper of Bisikalo et al. (1994) and shown that this causes a very complex system of shock–waves and discontinuities to arise, predominantly in the flow directed opposite to the motion of the accreting companion. In our case (Fig. 2) this is the second half of the period. If the inclination of the system were great, one would fail to see the structure of the internal regions, especially after the outburst, when there is still much matter out of the disk. Neither could it be seen with a zero inclination of the system. To see the structure of the internal regions, the inclination angle must be small, but such that the orbital motion would have an effect.

So, the abrupt light fluctuations observed in the second half–period after the outburst are most likely the effect of shock–waves arising during the outburst. The hot spot manifests itself at phases 0.65 at minimum light and 0.4 before the outburst.

It follows from the above–said that the outburst is accompanied by quite a number of intricate phenomena. All of them are consistent with the agreed–upon concept that before the outburst is initiated the rate of mass transfer from the secondary component increases sharply and the size of the disk grows. But it is not a simple increase of the disk sizes. The distinctions of the light curves, the behaviour of the X–ray flux, the emission line properties etc. indicate that the system orbital plane inclination angle to the line of sight is small and SS Cyg is likely to be a dwarf nova rather than an intermediate polar.

4. Discussion and conclusions

Using the light curves from Voloshina and Lyutyj (1993) it is possible to estimate the brightness and colour of the spot at $\varphi = 0.65$ at minimum light between the outbursts: $U = 13.6^{m}, B = 14.8^{m}, V = 14.7^{m}$, $U - B = -1.2^{m}$, $B - V = +0.1^{m}$. Out of the spot $U - B = -0.9^{m}, B - V = +0.5^{m}$, which corresponds to the mean value from the catalogue of Echevarria (1984). If the difference in the maxima is caused by the hot spot effect, then the brightness of the spot at the minimum is $V = 14.8^{m}$, which is in a good agreement with the value at $\varphi = 0.65$ within the errors. However, in the B and U filters the maxima are equal, i.e. the influence of the spot is not perceptible. Probably the conditions for this to be visible at $\varphi = 0.65$are more favourable. The equal depth of the two minima suggests that the conditions of spot visibility are the same at these moments. It means that at $\varphi = 0.5$ the disk is slightly eclipsed by the secondary companion, consequently the system inclination angle can not be large.

It has already been mentioned about the changes of the light curves before the outburst. If the detail that became visible at $\varphi = 0.4$ is the spot, then it became low–contrast and blurred. The colours are practically unaffected during the whole period and are $U - B \simeq -0.9^{m}, B - V \simeq +0.5^{m}$. The difference in the maxima corresponds to a faint source, $B = 15.4^{m}$, which is equal in light to the spot at $\varphi = 0.4$. The proportion of the spot contribution to the light of the system reduced: the flux ratio E_{spot}/E_{disk} is 0.16 in U, 0.12 in B and 0.08 in V, while before the outburst the ratio was as low as $\simeq 0.06$ in all the bands. For comparison, in the eclipsing binary U Gem the spot accounts for 40–50% of the system total light in different bands, and with initiation of the outburst the contribution of the spot also decreases, and it ceases to be visible. The colours of SS Cyg at minimum light are more blue ($U - B = -1^{m}.2, B - V = +0^{m}.1$) than in U Gem ($U - B = 0^{m}.6, B - V = 0$) as is the case for the small inclination of the system.

The structure of the sky field in the direction of SS Cyg has been studied in Vojkhanskaya (1973b), where it is shown at a distance of 52 pc a weak absorbing region with the total absorption $A_V = 0.1^{m}$ begins, which extends up to 140 pc. The distance to SS Cyg is 72 ± 10 pc. Subsequent estimates of the distance to SS Cyg (Kiplinger, 1979; Bailey, 1981; Warner, 1987) are consistent with the results of Vojkhanskaya (1973b), however they depend strongly on the models adopted and therefore differ considerably from each other. In further estimates the distance from Vojkhanskaya (1973b) will be used since it has been obtained by direct sounding of the appropriate sky area.

With the distance 72 pc the absolute magnitude of SS Cyg is $M_V = 7.5^{m}$ and luminosity is $L_V = 0.3 \cdot 10^{33}$ erg/s at minimum and $L_V = 12 \cdot 10^{33}$ erg/s at maximum light. Since $L \sim \dot{M}$, then having adopted $\dot{M}_{min} = 3 \cdot 10^{14}$ g/s obtained above, derive $\dot{M}_{max} = 1.2 \cdot 10^{16}$ g/s. This flux is sufficient to make the boundary layer optically thick which results in termination of hard X–ray radiation and soft X–rays begin to be radiated.

The phase shift of the radial velocity curve obtained from emission lines, which has been detected in the last years with respect to the curve from absorption lines, is of great interest. The phase lag of the curve plotted using emission lines is $9 - 10°$ (Stover et al., 1980). The most simple explanation of this phenomena is the asymmetrical distribution of line emission over the disk, which may be caused by the hot spot influence. The different heights of the maxima on the H_β curve (Fig. 1) confirms the different brightness of the disk in different directions.

Numerous investigations of the line spectrum of SS Cyg have shown that sometimes certain spectral lines have slightly double peaked profile. The split is observed at different time, at different phases, in different lines. That is the split is a random phenomenon caused by some accidental processes that control distribution of the luminous in lines matter over the disk, but not by inclination of the system. What is the dip on the 10–year averaged light curves at phase $\varphi = 0.54$ (Voloshina and Lyutyj, 1993) due to? In our opinion this is the result of random combination of rises in light at $\varphi = 0.65$ at minimum and at $\varphi = 0.4$ before the outburst and sudden drop at $\varphi = 0.52$ after the outburst. That is detail is unreal, it results from random combination of the features of the variable light curve.

The analysis of the results of observations together with the results of investigation of SS Cyg using other techniques led to the conclusion that the angle of inclination of the system to the line of sight is small, and the system itself is most likely a dwarf nova. The narrow dip on the average light curves is a result of random combination of variable features of the light curves. Moreover the light curves (Voloshina and Lyutyj, 1993) that have been first obtained allow the properties of SS Cyg and the accretion process features during the outburst to be revised.

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