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SS 433 as an eclipsing binary

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Summary. New photoelectric B, V observations carried out in 1980 February–June have shown that SS 433 appears to be an eclipsing binary system with orbital period 13.09 ± 0.04 day, which agrees well with the spectroscopic period 13.08 ± 0.07 day reported by Crampton, Cowley & Hutchings. The maximum of positive low-amplitude radial velocity corresponds to the primary minimum which is presumably connected with the eclipse by the normal star of the accretion disc surrounding a collapsed object. Strong variability from period to period is observed. The average brightness of SS 433 both in 1979 and 1980 correlates with the phase of the precession period of the moving emission features, and the maximum of the average brightness occurs at the time of largest separation of these features. This correlation may be explained by the variable contribution of the accretion disc to the total optical luminosity of the system, due to its precession. At the maximum of the average brightness, the accretion disc contributes at least 60 per cent of the total optical luminosity of the system. The average brightness-temperature of the disc is about twice that of the normal star which is presumably a later O or early B star filling its Roche lobe. The bolometric luminosity of the disc is $\sim 10^{39}$ erg s^{-1}.

1 Introduction

The remarkable object SS 433, associated with X-ray and radio sources (Clark & Murdin 1978; Seward *et al.* 1976; Clark & Crawford 1974; Ryle *et al.* 1978; Seaquist, Gregory & Crane 1978) and located in the peculiar supernova remnant W50 (Geldzahler, Pauls & Salter 1980; van den Bergh 1980; Sealey, Dopita & Martin 1980), reveals enormous periodic red- and blue-shifts of two strong satellite emissions of the Balmer and He I lines (Margon *et al.* 1979; Margon, Grandi & Downes 1980; Ciatti, Mammano & Vittone 1980). This peculiarity of SS 433 is consistent with the precession of two oppositely directed collimated beams from a central source, with the velocity of streaming close to $0.27c$ (see, e.g. Milgrom

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1979; Fabian & Rees 1979; Martin & Rees 1979; Terlevich & Pringle 1979; Thompson *et al.* 1979). Crampton, Cowley & Hutchings (1980) have discovered 13.08-day periodic low-amplitude variations of radial velocities in the 'stationary' line spectrum, which imply a probable binary nature for SS433. Such a binary nature has been supported recently by the discovery by Margon *et al.* (1980) of a 13.1-day periodicity of the strength of the low-velocity 'stationary' Hα, Hβ emission, and was suggested also in several theoretical models of SS433 (see, e.g. van den Heuvel, Ostriker & Petterson 1980; Shklovsky 1979; Martin & Rees 1979).

The photometric variability has been investigated by Kemp & Arbabi (1979), Gottlieb & Liller (1979), Giles *et al.* (1979) and Gladyshev *et al.* (1979). Photometric binary star modulation of SS433 appears to be related (Gladyshev *et al.* 1979) to the precession period of the moving emission features.

In this paper we report new photoelectric observations which support the binary nature of SS433.

2 Photometric observations

Photoelectric *B*, *V* observations of SS433 have been carried out during 1980 February–June with the 24-inch reflector of Siding Spring Observatory and are presented in Table 1 and Figs 1 and 2. The rms errors are ~ 0.02 and ~ 0.04 mag for individual observations through *V* and

Table 1. Photoelectric observations of SS433.

JD	*V*	*B*	JD	*V*	*B*
2444296.2751	14.06	—	2444330.2465	13.96	15.56
2444298.2727	13.84	—	30.2821	13.77	15.56
2444302.2564	13.81	—	2444332.2300	14.37	—
02.2719	13.82	—	32.2459	14.27	—
2444320.2871	14.38	—	32.2609	14.43	—
2444322.2648	13.91	16.09	2444334.2643	14.24	—
22.2765	13.87	16.07	34.2115	14.02	—
22.2874	13.93	—	34.2308	13.96	—
2444323.2407	13.91	16.24	34.2415	14.07	—
23.2527	13.97	15.85	34.2529	14.16	—
23.2682	13.87	15.94	34.2643	14.21	—
23.2804	13.90	—	34.2909	14.07	—
2444324.2796	13.85	16.17	2444335.2340	13.94	15.89
24.2898	13.88	—	35.2459	13.94	15.89
2444325.2443	13.95	16.11	35.2592	13.91	15.94
25.2547	13.96	16.05	35.3010	13.89	—
25.2758	14.07	16.24	2444365.2975	14.47	16.55
25.2868	14.01	16.17	65.3106	14.60	—
2444326.2224	13.98	16.17	2444383.2324	14.47	16.55
26.2590	14.09	16.02	83.2433	14.49	16.59
26.2711	14.11	16.31	83.2542	14.50	16.64
26.2816	14.16	—	83.2802	14.52	16.70
2444327.2400	13.92	—	83.2909	14.50	16.60
27.2744	14.07	16.06	83.3016	14.48	16.54
27.2853	14.10	—	2444393.0399	14.27	—
2444328.2717	13.70	—	93.0536	14.42	—
28.2841	13.80	—	93.0649	14.28	15.97
28.2946	13.86	—	93.0774	14.44	—
2444329.2733	13.72	—	93.0895	14.47	16.32
29.2925	13.74	—	93.1014	14.40	16.07
2444330.2342	13.88	15.52	93.1194	14.48	15.91

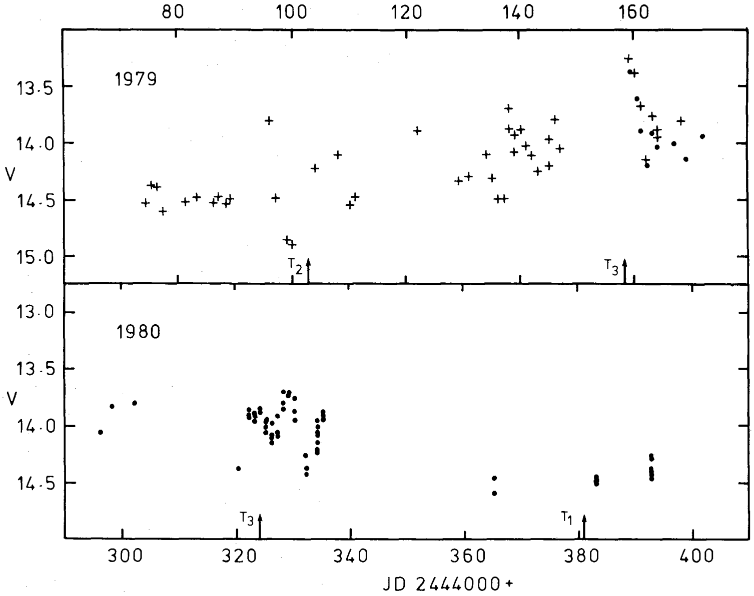

Figure 1. Individual photometric V observations of SS 433. Top – observations 1979 (Gladyshev *et al.* 1979), crosses – photographic observations, full circles – photoelectric data. Bottom – new photoelectric observations 1980. The arrows denote the times of largest separation of the moving emission features (T_3) and 'cross-over' dates (T_1, T_2).

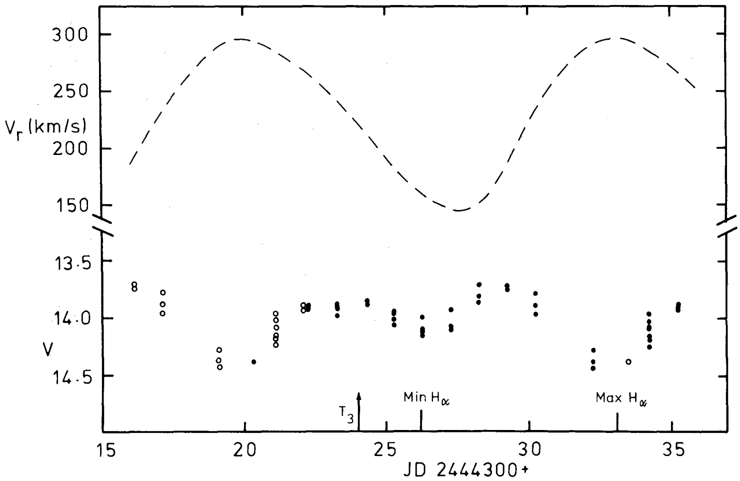

Figure 2. New individual photoelectric V observations of SS 433 obtained in the interval JD 2444320–36. Some data have been plotted twice, the second time (open circles) being one period earlier or later. On the top the average low-amplitude radial-velocity curve obtained by Crampton *et al.* (1980) is presented. Left and right vertical lines denote the times of the minimum and maximum of the strengths of the low-velocity 'stationary' Hα emission reported by Margon *et al.* (1980). The time of the largest separation of the moving emission features T_3 = JD 2444324.0 is denoted by an arrow.

B filters respectively. B observations were made only on dark nights and their number is small so, in the analysis, we used mainly our V observations together with B and V observations by Gladyshev *et al.* (1979).

2.1 CORRELATION WITH THE PRECESSION PERIOD

For our analysis we use a value of the precession period of 165.5 day (Ciatti *et al.* 1980) and the following characteristic dates: T_1, T_2 – first and second 'cross-over' dates, and T_3 – the time of largest separation of the moving emission features.

The mean light $\bar{B}$, $\bar{V}$ of SS433 both in 1979 and 1980 appears to be correlated with the relative position of the moving emission features (see Fig. 1), with the maximum of the mean light corresponding to the largest separation of the moving emission features. In 1980 at the date $T_3 \simeq$ JD 2444324, $\bar{V} \simeq 14.0$ mag and $\bar{B} \simeq 16.0$ mag, and for $T_1 =$ JD 2444383, $\bar{V} \simeq 14.5$ mag and $\bar{B} \simeq 16.5$ mag. In 1979 (Gladyshev *et al.* 1979) at the time $T_3 =$ JD 2444158.5, $\bar{V} \simeq 13.8$ mag and $\bar{B} \simeq 15.9$ mag, and for $T_1 = 2444052$, $\bar{V} \simeq 14.5$ mag and $\bar{B} \simeq 16.8$ mag. An accurate value of the precession period cannot be derived from our data. Estimates of this, according to recent spectroscopic results (Ciatti *et al.* 1980; Margon *et al.* 1980), range from 164.0 to 165.5 days.

Note that variability connected with the transition of the moving emission features through the V and B passbands is negligible (less than 0.1 mag), because the equivalent widths of such emissions are less than 100 Å (Murdin, Clark & Martin 1980).

The mean light of SS433 is modulated by the ~13-day periodicity. The amplitude and character of this modulation seem to be dependent on the phase of the 165.5-day periodicity (see Fig. 1), but this dependence is not unique. Observations in 1979 and 1980 imply that the ~13-day binary modulation is superposed on the high-amplitude irregular variability (at least ~0.5 mag through the V filter) which is statistically related to the phase of the 165.5-day period.

2.2 BINARY LIGHT-CURVE

Fig. 2 represents the new 1980 observations carried out in the interval JD 2444320–36, including the moment of largest separation of the moving emission features, $T_3 =$ JD 2444324. This light curve is quite similar to that of an eclipsing binary system. The depths of the primary and secondary minima in the V band are ~0.5 and ~0.3 mag respectively. The difference of ~0.15 mag between the maxima is conspicuous. These characteristics of the V light curve are due mainly to the variability of the continuum of SS433, because the strongly variable 'stationary' Hα and Hβ emissions (Margon *et al.* 1980) lie near the edges of the V passband. Variability of SS433 during the night with an amplitude ~0.1 mag and a characteristic time of several hours was observed. Such a variability was reported by Gladyshev *et al.* (1979).

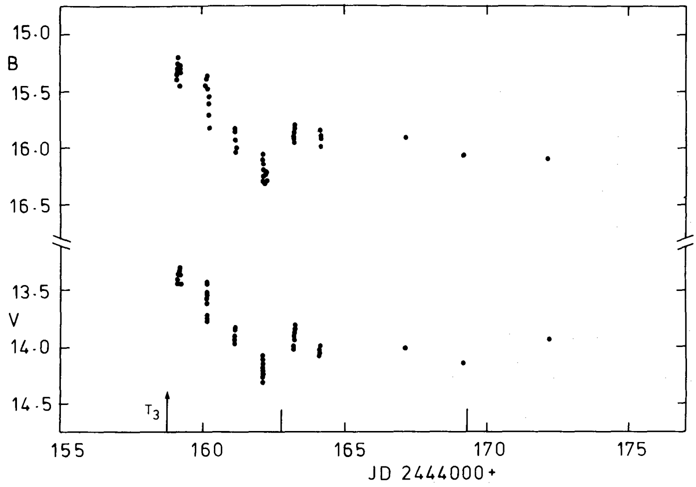

Figure 3. Individual photoelectric B, V observations of SS433 carried out in 1979 (Gladyshev *et al.* 1979). The time of largest separation of the moving emission features $T_3 =$ JD 2444158.5 is denoted by an arrow. Left and right vertical lines denote the times at the primary and secondary minima of 13.09-day periodicity. This figure should be compared with Figs 2 and 4.

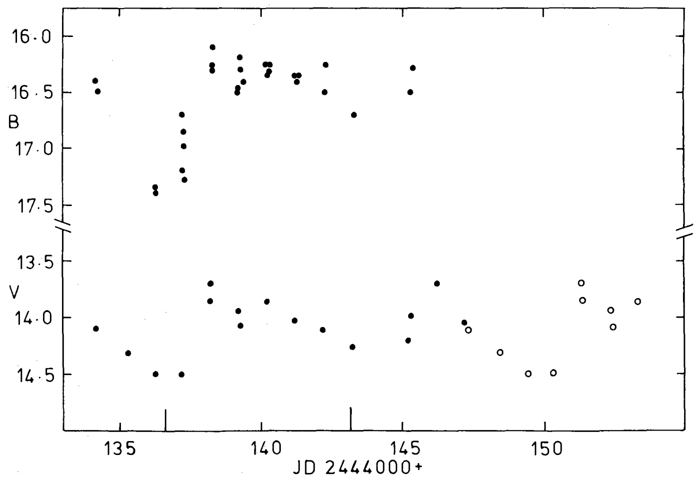

Figure 4. Individual photographic B, V observations of SS 433 carried out in 1979 (Gladyshev *et al.* 1979). Some data have been plotted twice, the second time (open circles) being one period later. The closest time of largest separation of the moving emission feature is T_3 = JD 2444158.5. Left and right vertical lines denote the times of the primary and secondary minima of 13.09-day periodicity.

In Fig. 3 the photoelectric B, V light curves of SS 433 obtained in 1979 (Gladyshev *et al.* 1979) in the interval JD 2444158–173 including the time T_3 = JD 2444158.5 are presented. Figs 2 and 3 both represent observations carried out at practically the same phases of the 165.5-day period, but the light curves are radically different! Fig. 4 represents photographic B, V light curves (Gladyshev *et al.* 1979) obtained in the interval JD 2444133–148 (~ 20 days earlier than for those in Fig. 3). These light curves are quite similar to the light curves obtained in 1980 (Fig. 2). The B-light of SS 433 may be contaminated by the contribution of the strong variable 'stationary' Hβ-emission, which can explain some of the difference between the V and B light curves during the 13.09 and 165.5 day periods.

The results presented in Figs 1–4 lead to the suggestion that SS 433 is an eclipsing binary system. Eclipses of both components in this system are taking place (see Fig. 5), but the regular eclipsing variability is mixed with the strong irregular physical variability with characteristic time less than ~ 15 days and with the long-term 165.5-day periodicity of the mean brightness of the system.

2.3 ORBITAL PERIOD

The following times of the minima were determined from observations during 1979–80 (see Figs 2–4): primary minima, JD 2444136.7, 162.2, 332.9; secondary minima, JD 2444143.4,

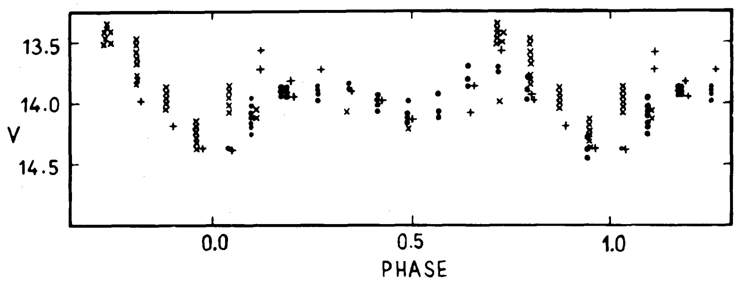

Figure 5. Amalgamated V-light curve of SS 433 obtained by convolution of the observations presented in Figs 2–4 with the period p = 13.09 day. Some shift along the magnitude axis is allowed. Different symbols correspond to the different periods.

326.4. From these times of minima we derived a value of the orbital period of $p = 13.09 \pm 0.04$ day. All the observations during 1979–80 agree with this period if we take into account the physical variability of the system mentioned above. This value of the period agrees well with the spectroscopic orbital period of $p = 13.08 \pm 0.07$ day reported by Crampton *et al.* (1980).

2.4 CORRELATION WITH LOW-AMPLITUDE RADIAL VELOCITIES

Fig. 2 shows that the primary minimum of the binary light-curve corresponds to the maximum of positive low-amplitude radial velocity (Crampton *et al.* 1980) and to the maximum of the strengths of the low-velocity 'stationary' Hα emission measured by Margon *et al.* (1980) in the form of its equivalent width and peak-to continuum ratio. Correction of the results of Margon *et al.* for the 13.09-day variability of the continuum, using our V light-curve (see Fig. 2), implies that, at the phases of the primary minimum of the V light-curve, the absolute Hα intensity is, on average, about twice as strong as at other phases of the binary 13.09-day period. There is strong physical variability of the strength of Hα (Margon *et al.* 1980) which may be related both to 'proper' variability of the absolute intensity Hα, and to the variability of the continuum of SS433 caused both by physical variability in the system and by the 165.5-day periodicity.

3 Discussion

In the framework of the model of an eclipsing binary system, two observational facts are to be explained:

1. The primary minimum of the 13.09-day light curve corresponds to the maximum of radial velocity.
2. The mean brightness of SS433 and the amplitude of the 13.09-day periodicity are different in different phases of the 165.5-day precession period.

In connection with the first fact, there is an analogy between SS433 and old novae and cataclysmic variables. Spectroscopic evidence for such an analogy was pointed out by Crampton *et al.* (1980) and Margon *et al.* (1980), although Margon *et al.* note that the analogy breaks down when the luminosity of SS433 is considered. According to Murdin *et al.* (1980), the colour temperature for the total continuum of SS433 is ~ 40 000 K and the bolometric luminosity is $\sim 3 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. In the case of SS433 as an eclipsing binary system, it is natural to relate these values to the total radiation from the system. The total optical luminosity is $\sim 10^{38}\,\mathrm{erg\,s^{-1}}$. Because both primary and secondary minima are well observed, the optical luminosities of both components are comparable. Therefore, neither component can be a red dwarf.

The low-amplitude radial-velocity curve was measured by Crampton *et al.* (1980) using principally the narrow emission peaks, but also absorption features. Similar narrow components of emission lines, called S-components, are observed in the spectra of cataclysmic variable stars (Smak 1979). But the analogy between SS433 and cataclysmic variables in this case is also not quite complete because, as was pointed out by Crampton *et al.* (1980), the absorption radial velocities of SS433 obtained from He I and Fe II apparently exhibited the same variations as the emission lines, which suggests that variations of low-amplitude radial velocities are orbital rather than the outgrowth of motion within a stream or hot spot on a disc. However, according to the results of Margon *et al.* (1980) concerning the variability of the strength of the low-velocity 'stationary' Hα (see above), it seems more likely that the low-amplitude radial velocity curve, obtained from Hα, Hβ emission peaks, is related to the gaseous stream or hot spot. The increase in the intensity of Hα near the phase of the primary minimum may be explained by the effects of the hot spot and absorption in the gaseous streams (Kraft 1962; Warner 1976). Effects of the eclipse of the hot spot by the normal star may be mixed with the effect of the precession of the accretion disc, leading to variability in the relative positions of the gaseous stream, hot spot and normal star. The strong scattering of the observational points on the Hα-intensity curve (Margon *et al.* 1980) may also be due to this effect. Because the optical luminosity of SS 433 is $\sim 10^{38}\,\mathrm{erg\,s^{-1}}$, the kinetic energy of the gaseous streams $\dot{M}V^2/2$ should be at least $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$ to produce observable effects in the hot spot. This fact implies that the value of the mass loss by the normal star through the inner Lagrangian point should be at least $\sim 10^{-4}$–$10^{-5}\,M_\odot\,\mathrm{yr^{-1}}$. In this case the gaseous stream may be optically thick in the frequency of the continuum and produce some additional eclipsing effects. This estimate can be compared with the value 10^{-5}–$10^{-6}\,M_\odot\,\mathrm{yr^{-1}}$ estimated for the relativistic beams from the effect they have on the interstellar medium (Zealey *et al.* 1980). Such a large value for $\dot{M} \simeq 10^{-5}$–$10^{-4}\,M_\odot\,\mathrm{yr^{-1}}$ indicates that the normal star loses its mass in the thermal time-scale (Paczynski 1967; van den Heuvel 1976; Tutukov & Yungelson 1979). The absorption features, similar to those observed and measured by Crampton *et al.* (1980), may be formed in such an optically thick gaseous stream. Despite a great difference in energy and luminosity, there is thus some similarity between the kinematics of SS 433 and cataclysmic variables. The low-amplitude radial velocity curve for SS 433 (Crampton *et al.* 1980) may be considered as an analogy of an S-wave component of radial velocity connected mainly with a gaseous stream from a normal star to the second component, presumably an accretion disc surrounding a collapsed object. If the low-amplitude radial velocity curve is an 'S-wave', the primary minimum of our light curve (Fig. 2) corresponds to the eclipse of the accretion disc by the normal star. In the secondary miminum, the normal star is eclipsed by an optically thick accretion disc.

The shape and amplitude of the light curves imply that the contribution of the ellipticity and reflection effects have total amplitude ~0.1 mag. Interaction of the relativistic beams with the expanding atmosphere of a normal star can produce, in certain phases of the 165.5-day period, optical appearances similar to a reflection effect (Gladyshev *et al.* 1979). This mechanism may be responsible for the irregular variability of the system.

The model of SS 433 as an eclipsing binary system seems to be very attractive. Although the observational data are not yet complete, we can estimate some of the physical parameters. From the depths of the minima of the V and B light curves (Figs 2 and 4), we derive the ratio of the average surface brightness of the accretion disc (I_d) and the normal star (I_s) as $I_\mathrm{d}/I_\mathrm{s} \simeq 2.5$ for the B filter and 2.1 for the V filter. The relatively low accuracy of the photographic B light curve does not allow us to consider the difference between these values as significant. Therefore, we conclude that the average brightness temperature of the disc is about twice that of the normal star in the Rayleigh–Jeans part of the spectrum, a result independent of the interstellar reddening. The shapes of the minima of the light curves imply that the radii of the normal star and accretion disc are comparable. The bolometric luminosity of the disc should be $L_\mathrm{d} \sim 10^{39}\,\mathrm{erg\,s^{-1}}$, because the total bolometric luminosity of the system is $\sim 10^{39}\,\mathrm{erg\,s^{-1}}$.

The depths of the minima of the light curves also indicate that the contribution of the accretion disc to the total optical luminosity of the system at the maximum mean light of the system is at least 60 per cent. The photospheric absorption spectrum of the normal star may be thus masked by the strong optical radiation of the accretion disc.

The 'normal' star, filling its Roche lobe, should be of type later O or early B. The dimension of the relative orbit $a \sim 1.6 \times 10^{12}\ (M_\mathrm{tot}/M_\odot)^{1/3} \simeq 4 \times 10^{12}$ cm for $m_\mathrm{tot} \simeq 20 M_\odot$. Similar B-stars are observed among the classical X-ray binary systems; for example, in the system HD 77581 = 4U 0900 − 403, the period is ~ 8.97 day and the optical star is B0.5Ib (Bradt, Doxsey & Jernigan 1979).

Because both minima of the light curve are well observed, the parameters of the kinematical model of the precessing relativistic beams (Ciatti *et al.* 1980; Margon *et al.* 1980), which give a value for the inclination of the orbital plane $i \simeq 79°$, are to be preferred.

The excitation of the matter in the relativistic beams cannot arise from photo-ionization by the UV radiation of a normal star (as was suggested by van den Heuvel *et al.* 1980), but may be provided by the large UV flux of the accretion disc. The matter in the beams may be accelerated by radiation pressure up to relativistic velocities as was pointed out by Jaroszynski, Abramowicz & Paczynski (1980).

The dependence of the mean light and the amplitude of the 13.09-day periodicity of SS 433 on the phase of the 165.5-day precession period (see Fig. 1) may be explained as a result of the variable orientation of the accretion disc due to its precession. The red- or blue-shift z of the moving emission features arising in the beams are described by the well-known relativistic relation (see, e.g. Ciatti *et al.* 1980):

$$Z = \gamma(1 \pm \beta \cos \psi) - 1,$$

where $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$ and ψ is the angle formed by the direction of the beam with the line-of-sight. The 'cross-over' dates correspond to $\psi = 90°$, and the time of largest separation of the moving emission features corresponds to the maximum deviation of the value of ψ from 90°. Let us assume that the relativistic beams are perpendicular to the plane of the accretion disc. There are grounds for such an assumption (see e.g. van den Heuvel *et al.* 1980), although the alternative possibility, of the relativistic beams having been ejected in the plane of the accretion disc, has also been considered (Bisnovaty-Kogan *et al.* 1980; Gladyshev *et al.* 1979). In the former case, the 'cross-over' dates correspond to the line-of-sight being coincident with the plane of the accretion disc. The projected area of the disc is a minimum and its visible luminosity is relatively small. At the time of largest separation of the moving emission features, the projected area of the accretion disc is a maximum and its luminosity is large. This variable contribution of the accretion disc to the total luminosity of the system seems to be the main cause of the observed 165.5-day periodicity of the mean light of SS433. Such a periodicity is mixed with irregular variability in the system. It can explain the relatively poor representation of the different cycles of 165.5-day photometric periodicity, which disturbs the accurate determination of the precession period from the photometric data.

At the 'cross-over' dates, the optical radiation of the normal star in the system SS 433 is least contaminated by the contribution of the accretion disc. It would be very interesting to search for the ellipticity effect of the normal star in the photometric variability of SS 433, and the appearance of the 'proper' absorption spectrum of this star at these phases of the 165.5-day period.

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