SS433: a black hole candidate?

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Summary. Stewart et al. recently derived limits on the masses and dimensions of the components of the SS433 binary system. In this paper we show how their limits can be improved by using a better Roche lobe geometry and by taking account of the fact that the accretion disc in this system (which is geometrically thick according to optical observations by Wagner) may occupy a considerable fraction of the Roche lobe of the compact object. Our results are based on the minimum amount of information from X-ray and optical observations. We find that the mass of the compact object is \( \approx 10 \ M_\odot \) and that the length of the X-ray jet is \( L_1 \approx 1.4 \times 10^{12} \) cm.

1 Introduction

The discovery of Doppler-shifted moving lines in the optical spectrum of SS433 (Margon et al. 1979; Mammano, Ciatti & Vittone 1980) and the universally accepted interpretation in terms of the kinematical model (Milgrom 1979; Abell & Margon 1979), according to which two oppositely directed fast moving jets \( (\nu = 0.26 \, c) \) are ejected from a central source, gave rise to the hope that this galactic object could be a kind of Rosetta stone for the understanding of jets in extragalactic sources, in particular how they are accelerated and collimated. However, despite an enormous number of observations at various wavelengths and the efforts of many theoreticians, SS433 is still a puzzle in many respects (for recent review see e.g. Margon 1984; Sharp, Calvani & Turolla 1984; Katz 1986; Ogelman 1987). For instance, it is not yet clear what causes the 164-day precession of the jets or their acceleration (Rees 1988), or whether we are dealing with accretion on to a neutron star on to a black hole.

In this paper we show which limits can be placed on the mass of the compact object and on the system geometry by considering only the fact that the accretion disc must lie inside the Roche lobe of the compact object. The disc may be geometrically thick according to observations of the optical continuum spectrum (Wagner 1986; Antokhina & Cherepashchuk 1985) and as suggested by models of supercritical accretion discs (Calvani & Nobili 1981).

We take into account the observations of Stewart et al. (1987) with the EXOSAT satellite, according to which the X-ray emitting material is located in the relativistic jets, and of Watson et al. (1986), who found a 6.7 keV iron emission line which is Doppler-shifted (in accordance with the kinematical model) and which is sometimes obscured by a precessing accretion disc.

Our results are more stringent than those obtained by Stewart et al. (1987).
In the next section we discuss the assumptions and constraints on which we base our considerations. In Section 3 we describe the geometry of the system and then in Section 4 we derive limits on the sizes and masses of the system components. Some implications of our results are discussed in the concluding section.

2 Assumptions and constraints

Models of SS433 usually consider four separate sources of light: the normal star, the accretion disc surrounding the compact object and the two jets. The contributions by all of these sources to the light curve are important in the optical, while the situation is different in the soft X-ray band. Watson et al. (1986, hereafter WTS) have in fact shown that a large fraction of the total X-ray emission is thermal and fully consistent with that expected from the thermal plasma in the jets. We shall therefore assume that all of the X-ray luminosity comes from the two equal but oppositely aligned jets; the star and the disc only obscure them at certain orbital and precessional phases.

In this paper we use the following assumptions defining the geometry of the system:

(i) All of the $2-10$ keV band photons come from that part of each jet between the exit from the disc funnel and the end of the X-ray jet (which has length $L$).

(ii) The jets are exactly oppositely aligned. The axis of their precession cone is perpendicular to the orbital plane of the system. The cone opening angle $\alpha$ is $19^\circ8$ and the system inclination angle $i$ is $78^\circ2$ (Margon 1984). The precession is retrograde (Leibowitz 1984).

(iii) The rotation axis of the star is nearly perpendicular to the orbital plane. The star corotates with the orbital motion (Leibowitz 1984) and so the usual Roche lobe geometry is valid.

(iv) The star fills its critical lobe.

(v) The size and shape of the disc is arbitrary (we shall comment on this later) but the optically thick part of it is inside the critical lobe of the compact object.

We use the following constraints obtained from the measurements by WTS and Stewart et al. (1987, hereafter STW):

(a) Only the X-ray jet pointing towards the observer was seen at the particular precessional phase of their measurements; the redshifted jet was obscured by the disc (WTS).

<table>
<thead>
<tr>
<th>JD (mid-exp)</th>
<th>13-day orbital phase (b-g-exp)</th>
<th>(end-exp)</th>
<th>eclipse</th>
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<td>0.7592</td>
<td>0.7698</td>
<td>no</td>
</tr>
<tr>
<td>2 68.042</td>
<td>0.9759</td>
<td>0.9847</td>
<td>partial</td>
</tr>
<tr>
<td>3 69.010</td>
<td>0.0447</td>
<td>0.0641</td>
<td>partial</td>
</tr>
<tr>
<td>4 70.667</td>
<td>0.1739</td>
<td>0.1881</td>
<td></td>
</tr>
</tbody>
</table>

(b) At the times of measurements 2 and 3 (Table 1) the jet was partly eclipsed by the star. Therefore the partial eclipse lasted at least from the beginning of measurement 2 to the end of measurement 3.

(c) The system showed some X-ray brightness during all measurements (Table 1). Therefore, if the blueshifted jet was totally eclipsed, it happened between the end of measurement 2 and the beginning of 3.
3 System geometry

Here we adopt the assumptions (i–v) and introduce the geometrical description of the system.

We perform all calculations in the sky plane and so we first have to find the projection of all of the constituents of the SS433 system on to the sky plane. As all measurements were taken almost at the same time as the optical primary eclipse (when the star is in front of the compact object, STW and Table 1), we shall simplify our calculations by assuming that in the sky plane the shapes of the objects are fixed and only their relative position is changing with the orbital cycle. We choose the system separation $A$ as the unit of length.

![Relative orbit of the centre of the normal star with respect to the compact object.](image)

**Figure 1.** Relative orbit of the centre of the normal star with respect to the compact object.

**Table 2.** Size of the critical lobes of the star and of the compact object as a function of $q$. $R_{\text{eff}}$ refers to the normal star; it was evaluated using the appropriate Roche formulae (Paczynski 1971).

<table>
<thead>
<tr>
<th>$q$</th>
<th>$x_*$</th>
<th>$y_*$</th>
<th>$z_*$</th>
<th>$y_e$</th>
<th>$R_{\text{eff}}$</th>
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</tr>
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</table>

In the sky plane we choose the coordinate system $(x, y)$ with its origin at the compact object. The $x$ and $y$ axes are aligned with the major and minor axes of the apparent orbit of the centre of the normal star (Fig. 1). The projection of the star’s critical Roche lobe on to the sky plane at the moment of the primary eclipse can be well approximated by an ellipse; its $x_*$ and $y_*$ axes are parallel to the $(x, y)$ coordinates and can be calculated using standard Roche lobe formulae [Pringle & Wade 1985; assumptions (iii) and (iv)]. The values of $x_*$ and $y_*$ are given in Table 2 for several mass ratios between the compact object and the star ($q = M_*/M_\odot$). The projection of the critical lobe of the compact object on to the sky plane at the moment of the primary eclipse can be calculated in a similar way; the projection ellipse axes $x_e$ and $y_e$ are also given in Table 2. We stress here that the shape of the accretion disc is up to now arbitrary: the critical lobe of the compact object serves only as an upper limit for its size [assumption (v)].

Finally, we have to calculate the projection of the relativistic jets on to the sky plane. According to the kinematical model, the direction of each jet precesses around the normal to the sky plane with a period of 164 days. The residence time for the gas in the X-ray jets is much shorter (≈ 100 s) and we can therefore describe the X-ray jet as a thin pencil which starts at the...
exit of the disc funnels and extends up to a distance $L_j$ from the compact object [assumption (i)]. The direction of the jet is given by the precession cone opening angle $\alpha$ [assumption (ii)] and the precessional phase $\Psi$ (defined as in Margon 1984; $\Psi = 0$ at the moment of maximum blueshift of the relativistic jets). The blueshifted jet projection angle $\Theta$ (see Fig. 1) is given by:

$$\tan \Theta = \frac{\sin \alpha \cos \Psi - \cos \alpha \sin \Psi \sin \alpha}{\sin \Psi \sin \alpha}$$

(1)

and the projection of the jet length $L_j$ is

$$P_j = \frac{L_j \sin \alpha}{\cos \Theta}.$$

(2)

These formulae can be derived easily if one first writes the components of the jet direction vector in the coordinate system which has one axis along the jet cone axis and then rotates the coordinate system for $i = 78.2$. In all of our calculations we adopt $\Psi = 0.16 \times 2\pi$ (i.e. the precessional phase at the time of the primary eclipse) and then we get $\Theta = 73^\circ$ and $P_j = 0.923 L_j$. The redshifted jet will have the same length and the opposite direction [assumptions (i) and (ii)].

We have now derived the shapes and orientations of the system components; next we must fix the position of the centre of the star with respect to the compact object. This position changes due to the orbital motion with the period $P_{\text{orb}} = 13.081 \pm 0.003$ day (Kemp et al. 1986). The coordinates of the centre of the star in the $(x, y)$ coordinate system are

$$x = -A \sin \theta \quad y = -A \cos \alpha \cos \theta,$$

(3)

where the orbital phase angle $\theta$ is defined by

$$\theta = 2\pi(t - t_0)/P_{\text{orb}}$$

(4)

and $t_0$ is chosen in such a way that $\theta$ is zero at the moment of the primary optical eclipse.

The optical light curve, measured simultaneously with X-ray observations, shows primary and secondary minima centred at $2445 968.3$ JD and at $2445 974.8$ JD (STW). So we adopt $t_0 = 2445 968.3 \pm 0.1$ JD. Note that the X-ray eclipse is coincident with the deeper optical minimum (STW; Ögelman 1987).

4 Mass limits

Using the observational constraints (a)–(c) we can derive limits on the relative sizes of the disc and the star. The transition from the relative sizes to the mass ratio $q$ is then unique (Table 2). We want to stress that the use of accurate Roche lobe shapes is essential: observations were taken nearly at the time of eclipse and so the common simplification of using the effective radius of the Roche lobe makes the star look too 'fat' and therefore results in an overestimation of $q$. The use of two spherical lobes (STW) with radii $R_\ast$ and $(A - R_\ast)$ introduces even bigger errors. In Fig. 2 our results are shown in the $(L_j, q)$ plane in order that they may be compared with those obtained by STW (their fig. 2).

We first discuss the implications of constraint (b). The duration of the partial eclipse sets a lower limit on the size of the star. The projection of the jet on to the sky plane points away from the projection of the line connecting the mass centres during the eclipse (Fig. 1); therefore, even if the thickness of the disc is small, the star should be big enough to eclipse the compact object during measurements 2 and 3. It follows that the origin of the coordinate system $(x, y)$
must be inside the ellipse of the stellar disc:

\[(x_s/x_e)^2 + (y_s/y_e)^2 \leq 1.\]  \hspace{1cm} (5)

This inequality holds for every orbital phase angle \(\theta\) [defined in equations (3) and (4)] during partial eclipse. Now, if the eclipse lasted exactly from the beginning of measurement 2 to the end of measurement 3, we get \(|\theta| < (1.0641 - 0.9759) \times \pi = 0.088 \times \pi\) and the constraint \(q < 1.39\) would follow (using \(x_s\) and \(y_s\) given in Table 2). However, the eclipse could also partly fill the gaps between the first and the last pairs of measurements (Table 1). If we use the orbital ephemeris as in equation (4) and assume a symmetrical eclipse, we conclude that the jet was partly eclipsed between the orbital phases \((1 - 0.0641 + 0.0076)\) and \((0.0641 - 0.0076)\); the last figure in the brackets takes into account for the 0.1-day uncertainty in \(t_0\). Using equations (3), (5) and Table 2, we then get \(q < 0.74\). These limits are shown in Fig. 2 (the two vertical full and dashed lines).

Constraint (c) sets a lower limit for the jet length. The jet should be long enough to appear over the star disc during measurements 2 and 3; therefore, at this time the star’s elliptic disc should not cover the point \((P_j \cos \Theta, P_j \sin \Theta)\) in the \((x, y)\) coordinates:

\[\frac{(x_s - P_j \cos \Theta)^2}{x_s^2} + \frac{(y_s - P_j \sin \Theta)^2}{y_s^2} \geq 1.\]  \hspace{1cm} (6)

For every given \(q\) we get \(x_s\) and \(y_s\) from Table 2. The orbital phase angle \(\theta\) determines \(x_s\) and \(y_s\) (equation 3), while \(\Theta\) is given by equation (1). Finally, equation (2) connects \(P_j\) with the true length \(L_j\). Therefore, equation (6) gives the minimum jet length for every mass ratio. Note
that the choice of the orbital phase is important; the easiest way is to use the orbital ephemeris as given in equation (4). In this case equation (6) holds for $\theta < 0.9847 - 0.0076$ (measurement 2) and for $\theta > 0.0447 + 0.0076$ (measurement 3); we allowed for a 0.1 day uncertainty in $t_0$. The resulting dependence of the minimum jet length on $q$ is plotted in Fig. 2 (dashed ascending line).

On the other hand, one could claim that photometric orbital ephemeris as given in equation (4) cannot be used, since the epoch of the primary minimum of the mean V-band light curve is not known with sufficient accuracy. A similar problem also arises with the spectroscopic ephemeris (see Margon 1984). Therefore, we derive the minimum jet length using only differences between the orbital phases of the measurements and not their absolute values. For every $q$ we proceed as follows: we arbitrarily choose an orbital phase corresponding to the end of measurement 2 and calculate $L_j$ using equation (6). We then calculate the minimum $L_j$ for the orbital phase corresponding to the beginning of measurement 3 which is $(1.0447 - 0.9847) = 0.06$ greater than the previous one; we then vary the choice of the orbital phase until the pair of $L_j$ limits permits the shortest jet. The result of this procedure as a function of $q$ is shown in Fig. 2 (full ascending line).

Finally, constraint (a) limits the maximum jet length. In fact the redshifted jet should be obscured by the disc which can at most fill the critical lobe of the compact object. Therefore, the elliptic critical lobe covers the point $(-P_j \cos \Theta, -P_j \sin \Theta)$ in the $(x, y)$ coordinates:

$$\frac{(-P_j \cos \Theta)^2}{x^2} + \frac{(-P_j \sin \Theta)^2}{y^2} \leq 1. \tag{7}$$

Again, $\Theta$ is known from equation (1), and equation (2) connects $P_j$ with $L_j$. Table 2 gives the values of $x$ and $y$ as functions of $q$. Equation (7) therefore represents a relation between the maximum jet length and the mass ratio; this is shown in Fig. 2 (full descending line). Note that WTS measured the absence of the redshifted jet at an orbital phase close to (but not exactly at) the primary minimum. However, the assumption that the redshifted jet was obscured also at the primary minimum does not introduce any significant error in subsequent mass estimates.

Fig. 2 shows clearly what the constraints are on $L_j$ and $q$. The limits which we get are more stringent than those obtained by STW, which are also shown in Fig. 2 for comparison. Using the orbital ephemeris and allowing for a $+0.1$-day uncertainty in $t_0$ (dashed triangle in Fig. 2), we get as allowed ranges:

$$0.295 < q < 0.74, \quad 0.195 < L_j < 0.363, \tag{8a}$$

while if we use only time differences between the measurements (solid line triangle in Fig. 2) we get:

$$0.245 < q < 1.39, \quad 0.084 < L_j < 0.42. \tag{8b}$$

In order to translate the relative sizes and mass ratios into absolute values we use the mass function $f(M) = M_*/(M_* + M_j)^2 = 10.6 M_\odot$ (Crampton & Hutchings 1981; Margon 1984) derived from He II $\lambda 4686$ emission line velocities. Using equation (8a), we get:

$$5.2 M_\odot < M_\ast < 23.8 M_\odot, \quad 17.7 M_\odot < M_\ast < 32.9 M_\odot, \tag{9a}$$

$$4.6 \times 10^{12} \text{ cm} < A < 6.2 \times 10^{12} \text{ cm}, \quad 1.2 \times 10^{12} \text{ cm} < L_j < 2.3 \times 10^{12} \text{ cm},$$

while the more conservative limit from equation (8b) gives:

$$4.0 M_\odot < M_\ast < 84 M_\odot, \quad 16.4 M_\odot < M_\ast < 61 M_\odot, \tag{9b}$$

$$4.4 \times 10^{12} \text{ cm} < A < 8.6 \times 10^{12} \text{ cm}, \quad 7.1 \times 10^{11} \text{ cm} < L_j < 3.6 \times 10^{12} \text{ cm}.$$
Note that the mass function is calculated using $K = 195 \pm 19$ km s$^{-1}$. However, if one allows the possibility of $K = 157$ km s$^{-1}$, instead of the average value as in equation (9), the most conservative limit on $M_x$ turns out to be 2.1 $M_\odot$. We shall comment on this in the final discussion.

All of the assumptions (i)-(v), (a)-(c) described in Section 2 are necessary for deriving these mass limits. Assumption (i) is explained in STW; assumptions (ii)-(iv) are discussed in several papers (e.g. Margon 1984; Antokhina & Cherepashchuk 1984; Leibowitz, Mazeh & Mendelson 1984, STW). Assumption (v) is obvious (Pringle & Wade 1985), however, its relevance in limiting the disc size has often been overlooked; usually one assumes instead a certain disc shape, but the results thus derived are more model-dependent and sometimes also more vague. Assumption (iii) deserves more attention as no proof can be found for its validity: one must therefore consider also the misaligned and non-corotating Roche lobe models.

The slaved disc model (Whitmore & Mateos 1980) actually imposes that the angle between the star’s rotation axis and the normal to the orbital plane is approximately 20°. This effect would cause a periodical shrinking of the star’s critical lobe (Avni & Schiller 1982) but it would modify our results only slightly. Misalignment would also cause precession of the orbital plane. However, the opening angle of the orbital angular momentum vector cone is much smaller than that of the spin vector cone (van den Heuvel, Ostriker & Petterson 1980). The possibility of non-corotation was discussed by Whitmore & Mateos (1980); they found that the star’s rotation is slower than corotation. In this case the lower mass limit for the compact object would be increased.

5 Discussion and conclusions

The main result of this paper is the determination of allowed ranges of mass and dimension of the system components without any assumption on the disc shape: the values which we have derived for $L_q$ and $q$ are therefore the least stringent ones. One could of course choose a particular geometry for the disc shape (as in WTS); on the other hand, we know that the disc is geometrically thick (Wagner 1986; the thickness ratio is > 0.7, and the sizes of the star and the disc are comparable; see also Kemp et al. 1986 and Anderson, Margon & Grandi 1983) and therefore we believe that our results would not change much if we did this.

The lower mass limit for the compact object is, of course, the most interesting result. Causality arguments alone (Shapiro & Teukolsky 1983, p. 264) imply that such a massive compact object should be a black hole. The lower limit for the mass of the star is a refinement of the 10.6 $M_\odot$ value that follows from the mass function alone; it suggests that in contrast to many X-ray binaries (McClintock 1986) the (presumably) OB star is not considerably undermassive.

We used only a small quantity of X-ray data to build up our two-parameter model. Clearly one should consider all data in different bands of the spectrum in order to make a complete model of SS433. However, complicated models have many free parameters and the results are usually not unique (Margon 1984). An approach similar to ours was used for the optical part of the spectrum by Leibowitz et al. (1984); their results indicate that 0.43 < $q$ (note that they use a different definition of $q$). Using 10.6 $M_\odot$ for the mass function one then gets

\[ 9.4 \, M_\odot < M_x; \]

this range of masses overlaps with ours.

We conclude that the compact object in SS433 is very probably a black hole whose mass is of the order of $M_x = 10 \, M_\odot$. In this case the mass of the normal star is 23 $M_\odot$; the separation between the centres of mass is then one third of the astronomical unit, and the effective radius of the star is 45 per cent of the separation. The maximum length of the jets is $L_j = 1.5 \times 10^{12}$
This implies a mass flow rate of $10^{-6} \, M_\odot \, \text{yr}^{-1}$ and a kinematic luminosity in the jets of $2 \times 10^{39} \, \text{erg} \, \text{s}^{-1}$ (WT5; Ógelman 1987; Spencer 1984; Sarazin, Begelman & Hatchett 1980). Such an enormous kinematic luminosity requires an even larger radiative luminosity (see, however, Katz 1986); the accretion rate in the system is therefore supercritical and this implies, on theoretical grounds (Calvani & Nobili 1981), that the accretion disc must be geometrically thick, in agreement with the observations (Wagner 1986; Antokhina & Cherepashchuk 1985).

The fact that SS433 probably contains a black hole has previously been suggested in the literature (e.g. Margon 1984; Antokhina & Cherepashchuk 1985; Gomcharkii, Metlitskaya & Cherepashchuk 1984). However, our result is based on the minimum number of assumptions and conditions, and is therefore more convincing. Super critical accretion on to a black hole seems therefore to be the best explanation for this most unusual astronomical phenomenon.

Acknowledgments

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References