The mass of SS 433: a conflict resolved?

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ABSTRACT

Context. The Galactic microquasar SS 433 is very luminous and launches oppositely-directed jets of cool hydrogen at a quarter of the speed of light. Observations of emission lines from the circumbinary disk imply a system mass exceeding \(40 M_\odot\), with the compact object exceeding 16 \(M_\odot\). The most recent attempts to establish a mass via observation of absorption lines in the spectrum of the companion imply a system mass of less than 20 \(M_\odot\), and a compact object of perhaps 4 \(M_\odot\).

Aims. To examine these conflicting data and present a possible resolution of this conflict.

Methods. Interpretation of data through the application of simple trigonometry to the configuration of the SS 433 system.

Results. The absorption spectra which, attributed to the atmosphere of the companion, yield an orbital speed of \(\sim 60 \text{ km s}^{-1}\) could well be attributable to absorption of light from the companion in material of the circumbinary disk. Then the absorption spectra predict an orbital speed for the circumbinary disk material of \(\sim 240 \text{ km s}^{-1}\), in agreement with the emission line data.

Conclusions. If continuum light from the companion is absorbed in passage through the circumbinary disk material rather than in the atmosphere of the companion itself, the periodic Doppler shifts in the absorption spectra are entirely consistent with observations of the circumbinary disk and a system mass exceeding \(40 M_\odot\). The consistency is striking and the implication is that the compact object is a rather massive stellar black hole.

Key words. Stars: individual: SS 433 - stars: binaries: close - black holes

1. Introduction

The microquasar SS 433 is remarkable for its luminosity and its jets of cool hydrogen ejected almost continuously with a mean speed of about 0.26 \(c\). The system is binary and while there is evidence that the compact object orbits the centre of mass of the binary at \(\sim 175 \text{ km s}^{-1}\) the companion has proved elusive. (The system is reviewed in Fabrika 2004). It is important to establish whether the compact object is a neutron star (unlikely), a black hole of a few solar masses or a much more massive stellar black hole. Observations of emission spectra, interpreted as originating in a circumbinary disk (Blundell, Bowler & Schmidtobreick 2008, Bowler 2010b), imply a massive black hole; the most recent observations of absorption spectra (Hillwig & Giess 2008, Kubota et al 2010), when attributed to absorption in the atmosphere of the companion, imply a low mass black hole and the authors are wary of dismissing the possibility of a neutron star. These delicate absorption spectra in the blue show Doppler shifts consistent in phase with an origin in the companion and an orbital speed of \(\sim 60 \text{ km s}^{-1}\). The inferred mass for the compact object is \(\sim 4 M_\odot\), for the companion \(\sim 12 M_\odot\) and for the system \(\sim 16 M_\odot\). My recent analyses of the data on the circumbinary disk (Bowler 2010b) yield an orbital speed for the disk material of \(\sim 250 \text{ km s}^{-1}\) and hence a mass for the system in excess of 40 \(M_\odot\). These two measures are not consistent. It can be argued on the one hand that attempts over the years to determine the orbital speed of the companion have yielded little consistency (see the summary in section 6.1 of Kubota et al 2010) and so the absorption spectra can be dismissed as coming from something else; on the other hand that maybe the data interpreted as revealing the circumbinary disk do not in fact yield a reliable estimate of the system mass because the system is full of gas streams. Neither argument is satisfactory in the absence of additional evidence or alternative explanations. In this note I point out that there is a case to be made for the absorption spectra of Hillwig & Giess (2008) and Kubota et al (2010) originating as the continuum from the companion is absorbed in circumbinary disk material; the phasing is correct and the orbital speed of the disk then predicted to be \(\sim 240 \text{ km s}^{-1}\), just as obtained from the wholly independent H\alpha and He I emission spectra (Bowler 2010b). This suggestion, if correct, would resolve the conflict, in favour of the companion being a rather massive stellar black hole, as originally argued in Blundell, Bowler & Schmidtobreick (2008).

2. The relevant data

In the work of Hillwig & Giess (2008) (see also Hillwig et al 2004) and Kubota et al (2010) weak absorption lines appearing the blue part of the spectrum of SS 433 at precession phase \(\sim 0\), where the accretion disk is most open to the observer, were cross correlated with spectra of mid A type stars. The results were Doppler shifts from shortly before orbital phase 0 (when the companion eclipses the environs of the compact object) over about a quarter of an orbital period. The extracted recessional velocities have a sinusoidal variation with (semi-)amplitude of \(\sim 60 \text{ km s}^{-1}\) and phase appropriate to an origin in the companion. Furthermore, the visibility of these absorption lines is greatest near eclipse and grows feeble near extreme elongation. These data were interpreted as yielding the orbital velocity of the companion about the binary centre of mass, the assumption being that continuum light from the photosphere of the companion is absorbed in the atmosphere of the companion itself. The systemic speed of these absorption lines is \(\sim 70 \text{ km s}^{-1}\); the widths
were interpreted in terms of the companion rotating at \( \sim 80 \text{ km s}^{-1} \) (Hillwig et al. 2004).

The stationary emission spectra of SS 433 in both H\( \alpha \) and He I are displayed in raw form in Fig. 2 of Schmitzobreick & Blundell (2006) and in terms of the Doppler shifts of fitted Gaussian components in Blundell, Bowler & Schmitzobreick (2008) and Bowler (2010b). The H\( \alpha \) line displays two horns which scarcely change their spacing over more than two orbital periods (but their relative intensity oscillates slightly with the period of the binary orbit). The He I lines correspond to much the same two horns, but with greater variation of intensity. Both H\( \alpha \) and He I are consistent with material orbiting in a circumbinary ring and stimulated by some hot spot rotating with the compact object and its accretion disk. The primary evidence for a circumbinary ring is the extreme stability of the H\( \alpha \) ring and the Doppler shifts of fitted Gaussian components in Blundell, Bowler & Schmitzobreick (2006) and in terms of the Doppler shifts of fitted line displays two horns.

The systemic speed of the circumbinary ring as revealed in emission is \( \sim 70 \text{ km s}^{-1} \). The discussion in Bowler (2010b) contains references to the most recent data and a critique of supposedly alternative explanations.

Both the absorption line data and the emission spectra attributed to the circumbinary disk are separately convincing but apparently contradictory. A little trigonometry suggests that the contradiction may be only apparent.

3. A little trigonometry

The trigonometry is illustrated in Fig. 1, for the particularly simple case of equal mass components. The radius at which the companion orbits is \( r \) and the angle \( \phi \) is the orbital phase, defined to be zero when the companion eclipses the compact object. The companion presents an orbital radius projected on the sky \( r \sin \phi \) as a function of time; the orbit is almost edge on to our line of sight. Thus the companion moves back and forth in the usual projection of circular motion.

The line of sight intersects absorbing material further out in the circumbinary disk, of radius \( R \), and that point of intersection moves back and forth across the sky in the same way. When \( \phi \) is zero, the companion is viewed (in the centre of mass frame of the binary) through material moving transverse to the line of sight. More generally, for phase \( \phi \) the companion is viewed through material with recessional velocity \( V_r \) given by

\[
V_r = \frac{r}{R} V \sin \phi
\]  

(1)

where \( V \) is the speed with which the circumbinary material orbits (\( \sim 250 \text{ km s}^{-1} \)) at a radius \( R = \alpha A \), \( A \) being the separation of the members of the binary. The binary radius \( r \) is \( \sim \alpha/2 \), for mass ratios implied by the orbital speed of the circumbinary ring and \( \alpha \) is about 2. Thus \( V_r \) oscillates sinusoidally with an amplitude \( \sim V/4 \) so that, if continuum light from the companion is absorbed in the circumbinary disk, the emission line data from the circumbinary disk predict that the absorption lines oscillate with an amplitude of \( \sim 60 \text{ km s}^{-1} \) and the phase of the companion, exactly as observed.

Essentially the same trigonometric argument can be applied to the contribution of the companion size to the width of the absorption lines. The effect matches that for absorption in a companion rotating with speed \( \alpha V / R \), where \( \alpha \) is the radius of the companion. The radius \( \alpha \) is not well determined; if the companion fills its Roche lobe then \( a \approx 0.4A \), but one sequence of observations suggests it did not then exceed 0.3A (Bowler 2010a). Thus the contribution to the line width caused by the size of the companion seen through the circumbinary material matches that for absorption in a companion rotating at 50 km s\(^{-1}\) at most; more likely \( \sim 30 \text{ km s}^{-1} \). From observations close to full eclipse Hillwig et al (2004) extracted a rotational velocity for the companion of 80 km s\(^{-1}\).

If the argument is inverted, the observed amplitude of the absorption lines, 60 km s\(^{-1}\), can be used to predict the orbital speed of the absorbing circumbinary material, as a function of the ratio of the mass of the compact object to that of the companion, \( q \). For a fixed value of the orbital velocity of the compact object (I took 175 km s\(^{-1}\)) \( q \) and \( \alpha \) cannot be chosen independently; thus choosing \( q \) determines both \( \alpha \) and \( \alpha \). The results for \( V \) are insensitive to the mass ratio, ranging from a value of 235 km s\(^{-1}\) (\( f = 1.69 \)) for \( q \) of 0.75 to 250 km s\(^{-1}\) (\( f = 2.2 \)) for \( q \) as large as 1.1. These values are in agreement with the speed of the circumbinary disk as extracted from the H\( \alpha \) and He I stationary emission lines.

Fig. 1. This diagram shows a plan view of the binary and circumbinary orbits in the SS 433 system. The companion is located at radius \( r \) and an azimuthal angle \( \phi \), here 0.15 of a period or 54\(^{\circ} \). The companion is viewed through circumbinary material located at \( R, \theta \) and moving with velocity \( V \). The recessional velocity of this material is \( V \sin \phi \) and the projections \( r \sin \phi \) and \( R \sin \theta \) are equal, for all values of \( \phi \). The radius of the companion orbit has been taken as \( A/2 \) and of the circumbinary ring 2\( A \), where \( A \) is the separation of the two binary components.
4. Discussion - successes

The observations interpreted as implying an orbital speed for the companion of 60 km s\(^{-1}\) were all made for a precession phase within ~0.05 of phase zero. In this configuration the plane of the accretion disk is tilted maximally toward the observer and for orbital phase near 0 the companion appears above the disk and clear of outflowing material in its plane (Hillwig et al 2004). Scattered observations of absorption lines in the blue were presented in Barnes et al (2006); their data were taken with the disk much more edge on and differ in two important respects from those of Hillwig et al (2004), Hillwig & Gies (2008) and Kubota et al (2010). The scattered data do show approximately sinusoidal variation with orbital phase, but with maximum redshift near orbital phase 0 and the whole pattern shifted to the blue by ~ 100 km s\(^{-1}\). These features are attributed to the absorption lines being formed in an equatorial outflow from the accretion disk (Barnes et al 2006, Hillwig & Gies 2008), for which there is independent evidence (see Fabrika 2004). When the accretion disk is maximally tilted toward the observer, such an outflow is least likely to interfere with observation of absorption lines in the atmosphere of the companion (for orbital phase near 0) and equally is least likely to interfere with observation of absorption in the circumbinary disk.

Hillwig & Gies (2008) set out three criteria that must be met if their absorption line pattern is to be associated directly with the companion. These criteria may be necessary but they are not sufficient, since the first is met by the completely different origin proposed in this note and the other two may be:

1) The observation of absorption lines in the spectrum of SS 433 oscillating sinusoidally with a period of 13 days and phased to the companion naturally invited interpretation in terms of absorption of continuum light from the photosphere in the atmosphere of the companion. My simple calculations above have shown that if light from the companion is rather being absorbed in material of the circumbinary disk, the lines will oscillate with a period of 13 days, phased to the companion and the numbers work out in remarkable agreement. The systemic radial speeds also agree. Thus the first criterion is met.

2) A number of arguments against these absorption line spectra having a shell like origin are set out in Hillwig et al (2004). It is far from obvious that they apply to the particular case of an orbiting circumbinary shell. Hillwig et al (2004) remark that a shell like spectrum would likely be seen through a region shadowed by the companion from the high flux from the inner accretion disk. This condition is most realised at orbital phase zero and as the phase advances toward extreme elongation irradiation of the relevant region of the circumbinary disk is increasing. Eclipse of the intense source of radiation near the compact object by the companion would relatively enhance absorption lines formed from the companion in the circumbinary disk, just as for formation in the atmosphere of the companion. Thus absorption by the circumbinary disk may not be inconsistent with the variation of absorption amplitude with phase (Fig.3 of Hillwig & Gies 2008) and the second criterion is likely met.

3) The line broadening due to absorption of light emitted across the diameter of the companion in slightly differently moving parts of the orbiting circumbinary material matches that expected for a synchronously rotating giant companion if absorption takes place in the atmosphere of that giant, for a rotational speed not exceeding 50 km s\(^{-1}\). There could be a problem matching the line widths, because Hillwig et al (2004) inferred a rotational speed of 80 km s\(^{-1}\). This potential mismatch might be alleviated by a modest range of outflow velocities of ring material, the ring being fed by excretion through the L2 point, but this suggestion is highly speculative.

![Fig. 2. This cartoon depicts the extended SS 433 system, looking down at an angle of 12° to the plane of the binary orbit, as observed from Earth. As in Fig.1, a mass ratio of 1 has been assumed and the radius of the binary orbit here seen in projection is A/2. The centre of mass of the companion, here denoted by C, is located at r and the compact object X at \(\odot\) on the opposite side of the orbit. The equator of the circumbinary ring or the core of a torus, of radius 2A, is shown on both the near and far sides of the system. The shallow curve passing through the origin denotes the latitude of material orbiting 0.4A above the orbital plane. The circle illustrates the companion for a radius of 0.3A; the limb of the companion is peeking over a cloud deck in the circumbinary ring at latitude 12°. The companion is otherwise viewed through the circumbinary material.](image-url)
condition for material being in the right place. It also has to be capable of producing absorption lines in the continuum from the companion, at least for orbital phase 0.85 to 0.25. This is a function of the density of the material, the depth and the temperature, which in turn is likely to depend on the degree of irradiation by X, the accretion disk source. Near orbital phase 0 X is furthest away from material through which the companion is viewed; in addition X is eclipsed for roughly 1 day about phase zero and the material through which C is viewed is in shadow for about 1 day before and 1 day after orbital phase 0. By orbital phase 0.15, C is viewed through material freshly exposed to X. There may thus be an additional reason for the relative amplitude of absorption lines from the continuum of the companion to be feeble out of eclipse.

The second question is whether it is possible to see absorption lines formed from the companion by circumbinary material and not see such lines in the continuum from X. Since X and C are never viewed simultaneously through the same patch of material, it is not necessarily impossible and the question becomes one of plausibility. There is no problem during eclipse but it becomes potentially more troublesome as X emerges from eclipse by C. It can be seen from Fig. 2 that if the circumbinary material is too thin to absorb above latitude 10° it can be seen from Fig. 2 that if the circumbinary material is too thin to absorb above latitude 10°. Yielding a mass for the compact object of 18 $M_\odot$. The absorption spectra which are phased with the companion and imply an orbital speed of ~60 km s$^{-1}$ were only observed for precession phases where the accretion disk is most open. The same is true of the spectra analysed by Cherepashchuk et al. (2005), where the Doppler shifts are also phased with the companion and match a sine curve with period 13 days. The spectral resolution is inferior to the later observations but if absorption was in the atmosphere of the companion an orbital speed of 132 km s$^{-1}$ is implied, with an error of 9 km s$^{-1}$. Yielding a mass for the compact object of 18 $M_\odot$, this would not conflict with inferences from the circumbinary disk. There is agreement that not all the absorption features in the spectrum of SS 433 form in the photosphere of the mass donor companion (Barnes et al. 2006, Hillwig & Gies 2008); the environment in the outer reaches of the system is complicated and it might be that there are absorptive regions more closely associated with the companion, perhaps even within its atmosphere. Different absorptive regions evidently dominate at different times. It might be that a serendipitous sequence of spectra could be companion dominated and it might even be that the data of Cherepashchuk et al. (2005) constitute such a sequence.

6. Conclusions

The evidence, to my mind compelling, for a circumbinary disk provides an alternative explanation for those absorption spectra hitherto attributed to the atmosphere of a companion orbiting at

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