SS 433: OBSERVATION OF THE CIRCUMBINARY DISK AND EXTRACTION OF THE SYSTEM MASS

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ABSTRACT

The so-called stationary Hα line of SS 433 is shown to consist of three components. A broad component is identified as emitted in that wind from the accretion disk that grows in speed with elevation above the plane of the disk. There are two narrow components, one permanently redshifted and the other permanently shifted to the blue. These are remarkably steady in wavelength and must be emitted from a circumbinary ring, orbiting the center of mass of the system rather than orbiting either the compact object or its companion: perhaps the inner rim of an excretion disk. The orbiting speed (approximately 200 km s⁻¹) of this ring material strongly favors a large mass for the enclosed system (around 40 M☉), a large mass ratio for SS 433, a mass for the compact object plus accretion disk of ∼16 M☉, and hence the identity of the compact object as a rather massive stellar black hole.

Subject headings: binaries; close — stars: individual (SS 433)

1. INTRODUCTION

SS 433 is famous for the moving emission lines from its relativistic precessing jets, but the stationary lines in the spectrum have enlightened, intrigued, and frustrated a generation of astronomers (Crampton et al. 1980; Crampton & Hutchings 1981; Fabrika & Bychkova 1990; D’Odorico et al. 1991; Gies et al. 2002). Its binary nature was first indicated by periodic variations in the redshift of stationary Hβ and He i lines (Crampton et al. 1980), but the redshifts were found to be phased incorrectly, relative to eclipses, for these periodic shifts to yield reliably the orbital speed. Rather, these variations were attributed to H and He i lines being formed in a wind or in gas streams within the system. A blue He ii line may be formed at the base of the jets, providing a measure of the orbital speed of the compact object (Fabrika & Bychkova 1990; Fabrika 1997; see also Fabrika 2004).

We obtained a sequence of nightly spectra over some 30 days (see Blundell et al. 2007). Our spectra did not extend into the blue, but we have studied in detail the brilliant stationary Balmer Hα emission, and the daily sampling made obvious properties that had escaped earlier observation. Over the period JD 2,453,000 +245.5 to +274.5 only one observation is missing (+252.5), and in addition SS 433 was quiescent and very well behaved during this period. After JD +274.5 observations were more intermittent and at the same time SS 433 was becoming restive, culminating in flaring episodes around JD +294.5. This Letter is restricted to the period terminating on JD +274.5.

The stationary Hα lines possess a profile more complicated than a single Gaussian and so were fitted, spectrum by spectrum, with a number of Gaussian components. In almost every case three components were required. Where wavelengths or redshifts are quoted in this Letter, they refer to the centroids of the fitted Gaussians.

2. RESULTS

2.1. The Wind from the Accretion Disk

Figure 1 shows the components of the stationary Hα line as a function of time. The horizontal scale is wavelength, time increases upward, and the height of each tick is proportional to the standard deviation of the fitted Gaussian. The nightly observations have created a striking pattern in this figure: the central component (whose fitted Gaussians have standard deviations as much as 20 Å) varies in redshift periodically, between two narrow components (having standard deviations of only a few Å) that display no significant motion. The broad component is very symmetric, which implies that it is formed in a fairly transparent wind; Figure 2 establishes unambiguously that this is so. This figure displays the variation with time of the center of the wind component (Fig. 2a) and of its width, measured by the fitted standard deviation (Fig. 2b). The variation of the central redshift exhibits a periodicity of approximately 13 days, but the width—a measure of the speed of the wind along the line of sight—reveals a distinctive pattern with approximately half that periodicity, which matches the nodding period seen in the jets. Figure 2b also shows that the projected wind speed drops as the precessional phase advances (as the jet axes lie more in the plane of the sky and the line of sight lies closer to the plane of the disk). In other data the speed of the wind measured primarily in absorption is slow for a dense equatorial component but otherwise varies as the square of the cosine of the angle between the jets and the line of sight (Fabrika 1997; see also Fabrika 2004, p. 114). For this reason Figure 2c shows the cosine of the angle between the jets of SS 433 and the line of sight in these same data (Blundell et al. 2007), and the ratio of the width of the wind line to the square of this cosine is shown in Figure 2d. In this ratio the 6.5 day periodicity has disappeared and the ratio is almost flat, apart from a possible 13 day period effect (having maxima at orbital phase 0.55, as for the 13 day jet-speed periodicity [Blundell et al. 2007]). Thus, the wind increases in speed with elevation above the plane of the accretion disk. The dependence of the projected speed of the wind (Fig. 2b) on both the precessional phase and the nodding of the disk establishes unambiguously that the broad component of the stationary Hα line is formed in the wind from the accretion disk.

The amplitude of the 13 day oscillation of the center of the wind (Fig. 2a) is ∼130 km s⁻¹, and the maximum redshift occurs just before orbital phase 0 (eclipse by the companion) and certainly after orbital phase 0.75, where the compact object is receding most rapidly. It would be dangerous to identify this with the speed at which the disk is carried around the system,
Fig. 2.—Properties of the wind from the accretion disk. Panel a displays the redshift of the wind centroid (gray in Fig. 1) as a function of time. A 13 day periodicity is apparent, but the redshift does not display a clean sinusoidal variation. In panel b is displayed the standard deviation of the Gaussian fitted to the wind: a measure of the speed along the line of sight for a transparent wind. There is a clear 6.5 day periodicity that matches the nodding of the disk. The latter is shown in panel c, where \( \cos \chi \) (the cosine of the angle the jet axis makes with our line of sight) is plotted, extracted from the nodding of the relativistic jets. Finally, panel d displays the result of dividing the wind speed by the square of the cosine of the angle displayed in panel c. There may be a residual 13 day oscillation but otherwise the wind speed so corrected is flat (but see text), demonstrating that the wind is rooted in the accretion disk. The subtle gray lines indicate orbital phases of 0 and 0.5; phase 0 occurs at day \( +254.9 \).

2.2. The Circumbinary Ring

The redshifts of the two narrow components of H\( \alpha \) are remarkably constant. The natural interpretation is that we are looking more or less edge-on to an orbiting ring of glowing material and the narrow peaks are contributed by the two regions tangential to the line of sight. There is no significant 13 day period in the sum of the redshifts (Fig. 3a): the source must be circumbinary.

This structure cannot be part of the accretion disk. First, the current estimate of the orbital speed of the compact object is 175 km s\(^{-1}\) (Fabrika & Bychkova 1990; Fabrika 1997). Second, the core of the wind oscillates with a redshift amplitude of about 130 km s\(^{-1}\) and that wind is rooted in the accretion disk (§ 2.1). Finally, in our data after day +274 the accretion disk is unveiled and observed to orbit the binary center of mass at...
of 0.25 and 0.75, rather than approximately 0.5 and 1. (See also Rudak & Paczynski 1981.) The observed effect is not a real change in local disk velocity but is caused by alternating intensities in the red and blue components, discussed below, and would conceal the tidal effects.

The systemic velocity is about 70 km s$^{-1}$, but there is no indication of whether this is the real recession velocity of SS 433 or an effect of reddening on the blue edges of the lines. A systemic velocity of about 70 km s$^{-1}$ is consistent with the H$\text{i}$ velocity of the environment (see recent H$\text{i}$ data of Lockman et al. 2007), but He$\text{ii}$ emission data apparently prefer a systemic velocity close to 0 (Fabrika & Bychkova 1990; Fabrika 1997). An exotic system such as SS 433 may be possessed of a peculiar velocity, and the true systemic velocity is hard to establish through optical spectroscopy in a filthy environment. VLBI astrometry reported in Lockman et al. (2007) has yielded a radial peculiar velocity relative to the local standard of rest of SS 433 of roughly $-17$ km s$^{-1}$.

Although these narrow stationary H$\alpha$ lines stay put, their intensities oscillate with a 13 day period. The oscillations of the two are out of phase, such that when the redshifted line is most intense, the blue is least intense. This phenomenon is clear in the raw spectra (Schmidtobreick & Blundell 2006) and quantified in Figure 3b, where the difference in areas of the Gaussians fitted to the red and blue lines is plotted as a function of time. The inference is that ejected hot gas, cooling and fading with time as the source and ejected gas follow their respective orbits. This circumbinary structure may feed the large-scale feature known as the ruff (Blundell et al. 2001).

Stationary lines from He$\text{ii}$ and the Paschen H series are in order of magnitude less intense than the brilliant Balmer H$\alpha$. They too contain narrow components that are radiated by material in the inner circumbinary ring, and the intensities of the red and blue components alternate as the components of H$\alpha$. These lines fade faster than the H$\alpha$ components and do not present as simple a picture as Figure 1. We intend to discuss these at a later date but here simply mention that both He$\text{ii}$ and the Paschen lines are formed in regions orbiting with speeds of approximately 190 km s$^{-1}$. The alternating intensities of the Paschen lines have been observed passing through the configuration captured over a few days only by Filippenko et al. (1988). Both the He$\text{ii}$ and Paschen lines exhibit much more marked 6.5 day periodicities in the difference velocities than H$\alpha$, because of their stronger alternation in intensities. (H$\alpha$ and He$\text{ii}$ can be directly compared in Schmidtobreick & Blundell 2006.)

### 3. DISCUSSION AND CONCLUSIONS

The oscillating redshift of the overall Balmer H$\alpha$ line (Gies et al. 2002) is due to the wind component oscillating in redshift and the red and blue narrow components alternating in intensity. There may be emissions from gas streams within the binary system itself, but the dominant sources of the Balmer H$\alpha$ emission have now been elucidated.

The glowing ring contributing the narrow lines is orbiting the system as a whole, rather than either the compact object or the donor, and the emission fades with time, the hottest spot matching the rotation of the binary system and the tail fading, like a katherine wheel. The glowing ring is most likely to be located at or close to the inner regions of a circumbinary annulus, because the activity requires continual refreshment and is linked to the orbital period of the binary. The radiating material might be either spilling out piping hot or perhaps disk
material excited by X-rays from the accreting system. A further possibility is that the hot spot migrating around the disk is produced where excreta hit the inner radius of the circumbinary ring. Filippenko et al. (1988) suggested as a possible interpretation of their split Paschen series lines an excretion disk fed by overflow of gas from the L2 point in the binary system, with the implication that the system is greater than 40 $M_\odot$. Fabrika (1993) remarked that such an excretion disk should be visible in Hα and the intensities of the two lines should vary with the phase of the orbit; our observations are in excellent agreement with these qualitative predictions.

The masses of the system and the compact object can be extracted from these observations of the circumbinary ring and the orbital speed of the compact object. The radiating material must be orbiting close to the inner stable radius for test particles (or gas) outside a binary system. This critical distance, $r_c$, from the binary center of mass has been investigated analytically and also using numerical techniques (Szebehely 1980; Rudak & Paczynski 1981; Holman & Wiegert 1999; Artymowicz & Lubow 1994). For binaries with essentially circular orbits the critical radius is

$$r_c \approx f(q)a_q = f(q)r(1 + q),$$

where $a_q$ is the distance between the components of the binary, $q$ is the mass ratio $m/M$ of the components, and $r$ is the radius at which the less massive component orbits the center of mass. The value of $f(q)$ is approximately 2; more precisely, if $f(q) = 2$ at $q = 0.1$, it has risen to 2.2 at $q = 0.2$ and to 2.3 beyond $q \sim 0.3$ (Holman & Wiegert 1999). For comparison, the ratio of the critical radius to the L2 radius is approximately 1.6, roughly independent of the mass ratio $q$ for $q > 0.1$.

The speed $v_c$ of Keplerian orbits close to the inner radius of the circumbinary ring is given by the relation

$$v_c = (1 + q)v_x/f(q),$$

where $v_x$ is the orbital speed of the compact object.

Thus, if $f(q)$ is 2 and $v_c \approx v_x$, it follows that the mass ratio $q > 0.4$. The mass of the system is given (for an orbital period of 13.08 days) by

$$M(1 + q) = 1.35f(q)^{3/2}(v_c/100)^3$$

in $M_\odot$, $v_c$ in km s$^{-1}$.

If the Hα radiation from the circumbinary ring is coming from material orbiting at the critical radius or greater, then $v_c$ is greater than or approximately equal to 200 km s$^{-1}$. The orbital speed $v_x$ is probably 175 km s$^{-1}$ (Fabrika & Bychkova 1990; Fabrika 1997). Thus, it seems that $q > 0.4$ and the mass of the system is greater than $16 M_\odot$ and of the compact object greater than $6 M_\odot$, including the mass of the accretion disk. These are conservative estimates; Table 1, constructed from equations (2) and (3), gives the mass $m$ of the compact object and its disk as a function of the orbital speed $v_x$ of the compact object and the speed of the inner circumbinary disk $v_c$. The smart money is on the compact object being a rather massive stellar black hole. For $v_x = 175$ km s$^{-1}$ and $v_c = 200$ km s$^{-1}$, the mass of the compact object is $16 M_\odot$ and of the companion $22 M_\odot$.

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### TABLE 1

| $v_c$ | 150 | 175 | 200 |
|-------|-----|-----|-----|
| 150   | 5.4 | 3.7 | ... |
| 175   | 11  | 8.6 | 6.2 |
| 200   | 18.8| 15.9| 12.8|
| 225   | 30  | 26.1| 22.2|

Note: Masses are in units of $M_\odot$, and speeds in units of km s$^{-1}$. 

The value of $f(q)$ is approximately 2; more precisely, if $f(q) = 2$ at $q = 0.1$, it has risen to 2.2 at $q = 0.2$ and to 2.3 beyond $q \sim 0.3$ (Holman & Wiegert 1999). For comparison, the ratio of the critical radius to the L2 radius is approximately 1.6, roughly independent of the mass ratio $q$ for $q > 0.1$.