

# Spectroscopic Observations of the Mass Donor Star in SS 433<sup>1</sup>

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## ABSTRACT

The microquasar SS 433 is an interacting massive binary consisting of an evolved mass donor and a compact companion that ejects relativistic jets. The mass donor was previously identified through spectroscopic observations of absorption lines in the blue part of the spectrum that showed Doppler shifts associated with orbital motion and strength variations related to the orbital modulation of the star-to-disk flux ratio and to disk obscuration. However, subsequent observations revealed other absorption features that lacked these properties and that were probably formed in the disk gas outflow. We present here follow-up observations of SS 433 at orbital and precession phases identical to those from several previous studies with the goals of confirming the detection of the mass donor spectrum and providing more reliable masses for the two system components. We show that the absorption features present as well as those previously observed almost certainly belong to the mass donor star, and we find revised masses of  $12.3 \pm 3.3$  and  $4.3 \pm 0.8M_{\odot}$  for the mass donor and compact object, respectively.

*Subject headings:* stars: individual (SS 433, V1343 Aquilae) — X-rays: binaries — star: winds, outflows — stars: individual (HD 9233) — supergiants

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## 1. INTRODUCTION

The unique system SS 433 is an X-ray binary star that falls in the class of microquasars (Fabrika 2004). The system exhibits relativistic jets originating from a compact object surrounded by an accretion disk. The companion star in the system contributes only a small fraction of the total light and is thus difficult to detect. Because the accretion disk and its wind are the dominant source of light in the system, reasonable measurements have been made of the radial velocity amplitude of the compact object (e.g. Fabrika & Bychkova 1990; Gies et al. 2002a). Models of the precessing jets and eclipses have also provided a very accurate system inclination ( $78^\circ 8'$ , Margon & Anderson 1989). Therefore, identifying the mass donor and accurately determining its radial velocity amplitude will lead to direct kinematical masses for both components.

The first potential observations of the mass donor star were reported by Gies, Huang, & McSwain (2002b) with additional observations published later by Cherepashchuk et al. (2005). These studies detected faint absorption lines present in blue spectra of SS 433 that exhibited the Doppler shifts expected for the donor star. Finding these lines is difficult, not only due to the small relative flux contribution of the A-star, but also to the active emission spectrum from the accretion disk, jets, and strong disk wind in the system. The most convincing observations to date of the mass donor spectrum were obtained by Hillwig et al. (2004). Their spectra suggested that the donor star has a spectral classification of A3–7 I, and their radial velocity measurements led to component masses of  $M_O = 10.9 \pm 3.1 M_\odot$  and  $M_X = 2.9 \pm 0.7 M_\odot$  (where the subscripts represent the optical companion star  $O$  and the X-ray emitting compact object  $X$ ).

This identification of the mass donor star was challenged by Charles et al. (2004), Barnes et al. (2006), and Clark, Barnes, & Charles (2007). These authors present spectra of SS 433 that show features found in an A-supergiant, but that do not follow a coherent orbital radial velocity curve. Their observations show a larger scatter, were performed over a greater variety of orbital and precessional phases, and have a much lower average velocity than those presented by Hillwig et al. (2004). Barnes et al. (2006) and Clark et al. (2007) suggest that these A-supergiant absorption lines arise in an accretion-driven outflow. Thus, their work demonstrates that not all the absorption features in the spectrum of SS 433 form in the photosphere of the mass donor star.

Some of the differences between these investigations are due to the timing of the observations and the inherent time variability of the spectrum. Given the relative faintness of the mass donor star compared to the super-Eddington disk in the system, Hillwig et al. (2004) planned observations for orbital phases when the disk is partially eclipsed and for precessional phases when the donor star appears above the disk plane at orbital inferior

conjunction. This strategy maximizes the opportunity to reduce the glare of the disk and avoid obscuration by the extensive disk gas. On the other hand, Barnes et al. (2006) made observations at a variety of other orbital and precessional phases and made plausibility arguments that the donor star spectrum might appear at some of these (but was not in fact detected).

Given the need to resolve the differing interpretations in the papers of Hillwig et al. (2004) and Barnes et al. (2006), we undertook follow-up observations to repeat the observations of Hillwig et al. (2004). If the absorption features identified do originate in a disk outflow, then the highly variable nature of the outflow in SS 433 suggests that repeat observations will show significant scatter from prior observations, if in fact the absorption features are still present. However, if the absorption lines originate from the mass donor star, then the highly stable and periodic nature of the orbit should produce observations consistent with the data of Hillwig et al. (2004).

## 2. Observations and Reductions

Observations were acquired with GMOS on the Gemini North Telescope on UT 2006 June 7–13. The resulting spectra cover the wavelength range 3767–5227 Å with a dispersion of 0.235 Å pixel<sup>-1</sup> and resolution  $R(\lambda/\Delta\lambda) = 9580$ . Observations were made for approximately four hours each night, and all the individual spectra from each night were coadded to improve the S/N. The coadded spectra were shifted to a heliocentric frame and continuum normalized by fitting regions free of strong emission lines.

The observations were timed to correspond to mid-eclipse and greatest disk opening angle, as with the data from Hillwig et al. (2004). The spectra cover orbital phase  $0.85 \leq \phi \leq 0.32$  and precessional phase  $0.02 \leq \psi \leq 0.06$ , according to the orbital ephemeris of Goranskii et al. (1998),

$$\text{HJD } 2, 450, 023.62 + 13.08211E$$

and, for disk precession, the model ephemeris of Gies et al. (2002a),

$$\text{HJD } 2, 451, 458.12 + 162.15E.$$

The orbital phase coverage overlaps with and extends that of Hillwig et al. (2004).

### 3. Spectral Appearance and Radial Velocity Analysis

The resulting spectra from seven consecutive nights around mid-eclipse show the expected broad “stationary” emission lines. The brightest emission lines of hydrogen and helium all showed strong P Cygni absorption components every night except on the fourth and last nights of the run. The  $H\beta^-$  jet line was present in the spectra, but weak.

The new series of spectra appear to show considerably more emission contamination in the range  $\lambda\lambda 4500\text{--}4625 \text{ \AA}$  than seen at the time of the investigation by Hillwig et al. (2004), and consequently, it was not possible to measure unambiguously the same set of absorption lines they analyzed. The only clearly problem free regions larger than  $\sim 25 \text{ \AA}$  in the observed spectral range are the intervals of  $\lambda\lambda 4750\text{--}4830 \text{ \AA}$  and  $\lambda\lambda 4950\text{--}4985 \text{ \AA}$ . These regions show clear absorption features in the spectra. An interesting case is that of night seven, in which the only visible absorption features are interstellar in origin. Their clear appearance in that spectrum allowed us to subtract the interstellar absorption from the spectra obtained on the first six nights. This was especially helpful near 4762 and 4780  $\text{\AA}$  where interstellar lines overlapped apparent stellar absorption features.

The resulting, interstellar-subtracted, and normalized spectra of SS 433 in the wavelength region described above are shown in Figure 1 along with a spectrum of an A-supergiant, HD 9233 (A4 Iab). The HD 9233 spectrum was obtained in 2005 August with the medium resolution spectrograph (MRS) on the University of Texas Hobby-Eberly Telescope (HET). It has been smoothed to match the resolution of the SS 433 spectra and intensity scaled to match the mid-eclipse line depth as described below. A comparison of the interstellar spectrum of SS 433 from night seven with that of HD 9233 shows that the latter has no appreciable interstellar absorption. We confirm that the the lines of an A-type supergiant absorption spectrum are once again present in the spectrum of SS 433.

Line identifications for major absorption lines are also shown in Figure 1. All the spectra in the figure are Doppler-shifted to the heliocentric rest frame. The SS 433 spectra were shifted using the radial velocity values discussed below. The HD 9233 spectrum was shifted using a measured heliocentric radial velocity of  $-69.5 \pm 1.0 \text{ km s}^{-1}$ , significantly different than the value of  $-34 \pm 2 \text{ km s}^{-1}$  given by Hillwig et al. (2004). It is likely that HD 9233 is a radial velocity variable.

We measured radial velocities for the absorption lines in the SS 433 spectra using the same method applied by Hillwig et al. (2004), i.e., by calculating cross-correlating functions (CCFs) of the absorption line regions in each SS 433 spectrum with those in the spectrum of HD 9233. The spectrum of HD 9233 was first rescaled in intensity to match the absorption features of the mid-eclipse spectrum of SS 433. The scaling factor found in Hillwig et al.

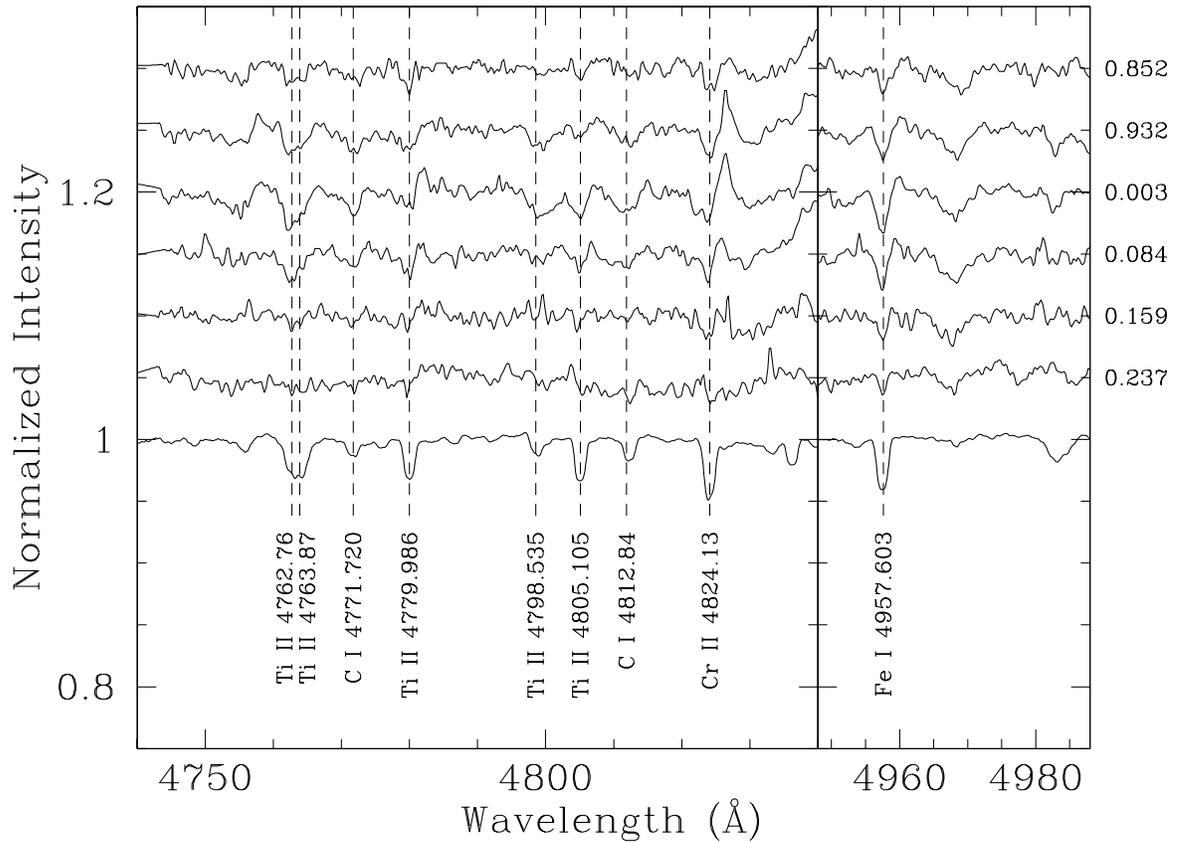


Fig. 1.— SS 433 spectra obtained with GMOS at Gemini North in 2006 June along with a spectrum of the A4 Iab star HD 9233 (*bottom*) obtained with the MRS on HET in 2005 August. The HD 9233 spectrum has been smoothed and scaled to match the SS 433 spectra (see text). Spectra have been offset for clarity. The corresponding orbital phase for each spectrum is shown on the right side of the plot.

(2004) of  $0.36 \pm 0.07$  was also found to be appropriate for this data. We then added the radial velocity of HD 9233 to the relative velocities from cross-correlation to transform them to an absolute scale. The resulting heliocentric radial velocities for SS 433 are given in Table 1 and are plotted as a function of orbital phase in Figure 2 (together with the radial velocity measurements from Hillwig et al. 2004 for comparison).

The CCF fitting was adversely affected by the emission near the Cr II  $\lambda 4824$  line so that line was removed from the CCF fitting region. Also, the fit on night six is clearly dominated by the strongest line (Fe I  $\lambda 4957$ ). To determine if this line might be consistently offset from the full sample CCF values, and thus offset the night six radial velocity value, a CCF fit was run using just this line. The resulting radial velocity and CCF amplitude results for nights 1–6 were well within the individual error ranges of the full CCF fits and there were no apparent systematic differences.

The absorption lines shown in Figure 1 appear to be strongest near mid-eclipse (phase 0.0) when the flux dilution from the disk light is minimized. This variation in strength is represented in Figure 3 by the relative CCF amplitudes for the 2006 June Gemini North data, along with those from Hillwig et al. (2004). The solid line in this figure shows the predicted variation in strength for a constant flux component that is diluted by the phase-variable flux contribution from the disk. This function was derived from the schematic *B*-band light curve of Goranskii et al. (1997, 1998) as described in Hillwig et al. (2004). Since the disk flux varies stochastically, the actual eclipse light curve during the time of the 2006 June observations may have differed from this prediction. Nevertheless, it appears that the absorption lines did strengthen and weaken as expected during this particular eclipse.

Table 1. Absorption Line Radial Velocities

| Date<br>(HJD - 2,450,000) | $\psi$ | $\phi$ | $V_r$<br>(km s <sup>-1</sup> ) | $\sigma(V_r)$<br>(km s <sup>-1</sup> ) |
|---------------------------|--------|--------|--------------------------------|--|
| 3893.99 .....             | 0.022  | 0.852  | 25                             | 4                                      |
| 3895.04 .....             | 0.029  | 0.932  | 57                             | 4                                      |
| 3895.96 .....             | 0.034  | 0.003  | 77                             | 4                                      |
| 3897.02 .....             | 0.041  | 0.084  | 96                             | 4                                      |
| 3898.01 .....             | 0.047  | 0.159  | 125                            | 6                                      |
| 3899.03 .....             | 0.053  | 0.237  | 135                            | 6                                      |
| 3900.03 .....             | 0.060  | 0.314  | ...                            | ...                                    |

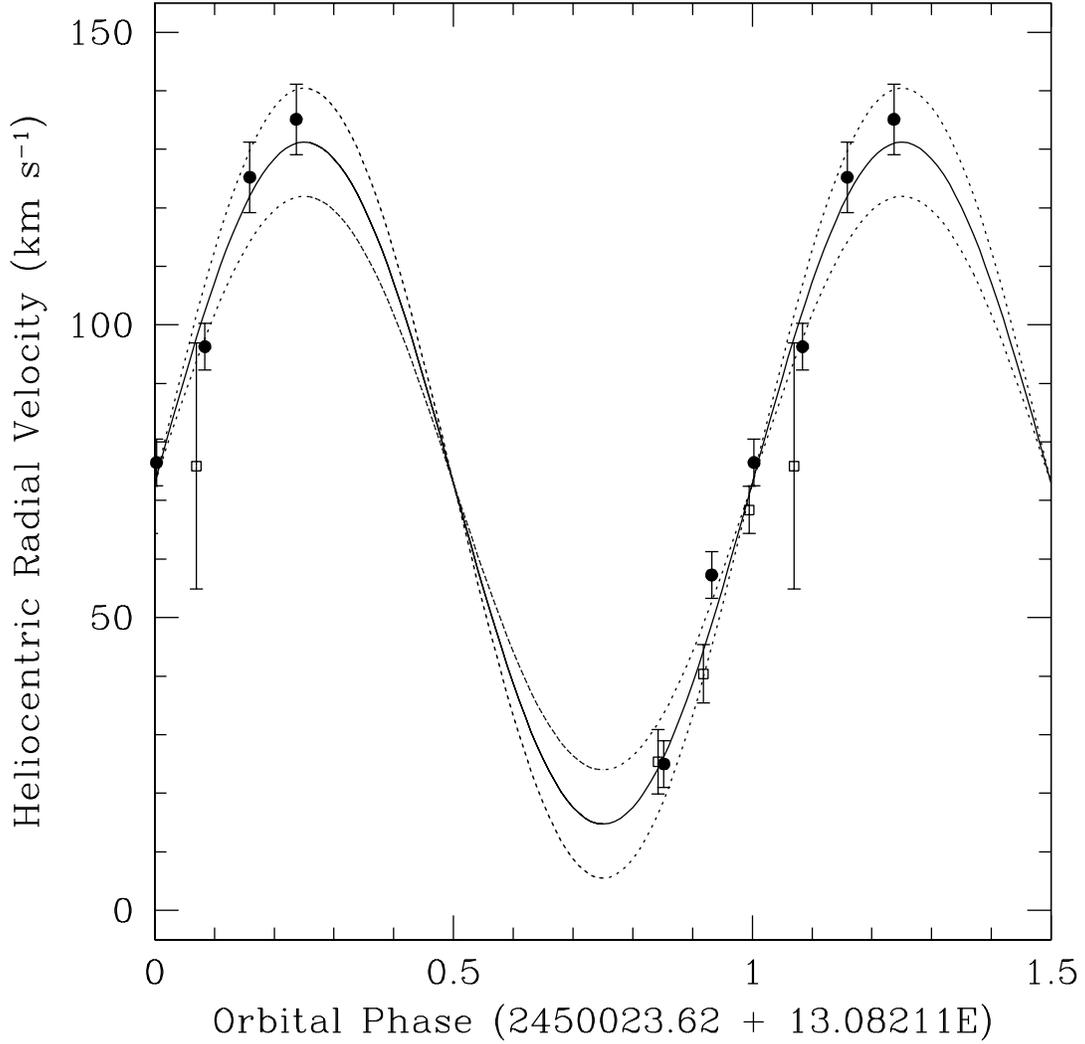


Fig. 2.— The phase-folded radial velocity curve for the absorption spectrum in SS 433. Shown are the Gemini North data from 2006 June (*filled circles*) and the data from Hillwig et al. (2004) (*hollow squares*). The dashed lines show the  $\pm 2\sigma$  semi-amplitude solutions relative to the calculated best fit.

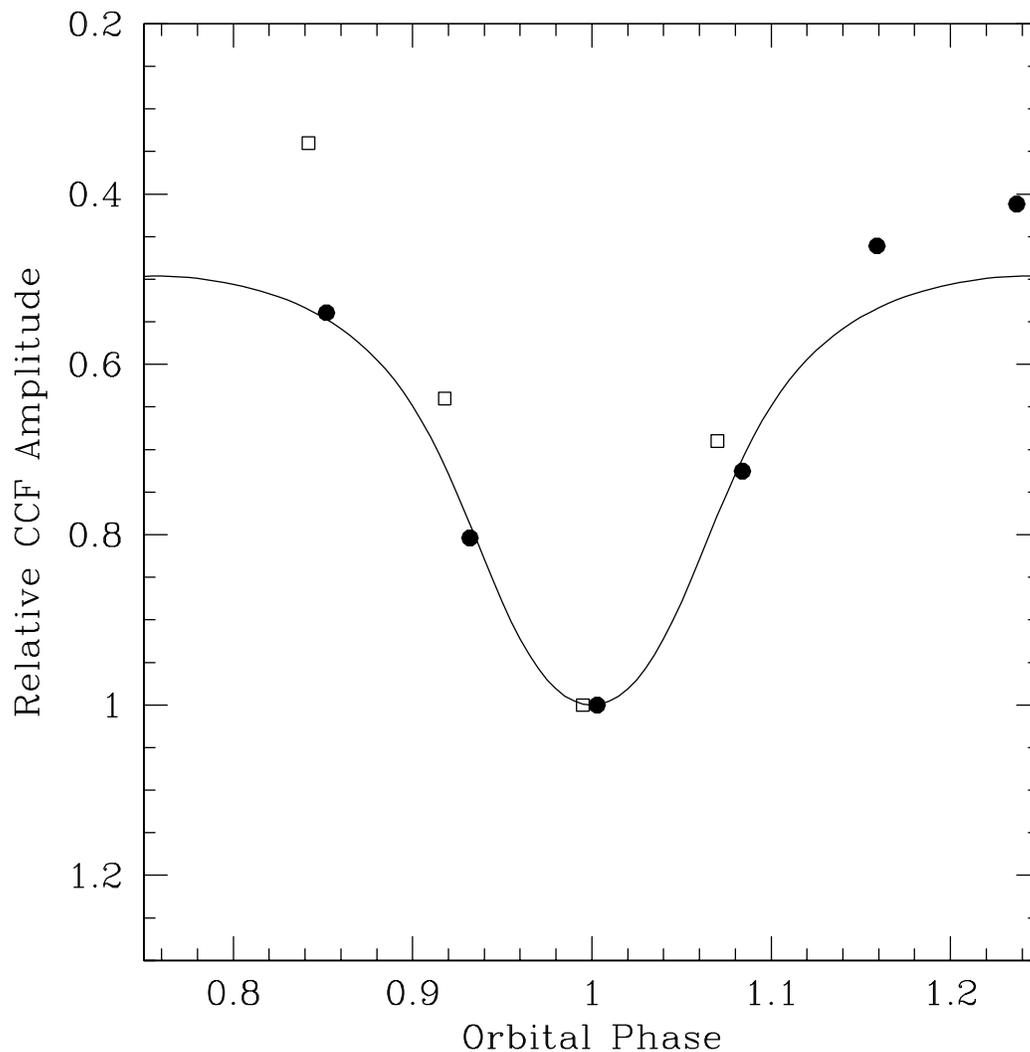


Fig. 3.— The normalized CCF amplitude vs. orbital phase curve for the SS 433 absorption spectrum. Shown are the results from the Gemini North data from 2006 June (*filled circles*), the CCF data from Hillwig et al. (2004) (*hollow squares*), and the prediction (*solid line*) for a constant flux photospheric spectrum diluted by the variable flux from the accretion disk (according to the mean *B*-band light curve).

#### 4. Discussion

Hillwig et al. (2004) discuss three criteria that must be met if the absorption line pattern is to be reliably associated with the supergiant: (1) The radial velocity variation with orbital phase should appear with the ascending branch centered at orbital phase 0.0 (i.e., at inferior conjunction at the time of the optical and X-ray mid-eclipse). Furthermore, the systemic velocity should be approximately the same as that of the nebula (+56 to +75 km s<sup>-1</sup>; Boumis et al. 2007; Lockman, Blundell, & Goss 2007). The new radial velocity data (Fig. 2) agree with these predictions and with the earlier radial velocity measurements. (2) The absorption line depths will usually be weak and modulated in strength by the orbital curve and precessional phase. The observed spectrum is a composite of disk and stellar light, so that the stellar lines will always be diluted by the continuum flux from the disk. Furthermore, the accretion disk is probably optically thick and vertically extended, so the supergiant will often be hidden when the star is behind the disk plane from our line of sight. The new spectra show the same variation in absorption line strength (Fig. 3) as found previously by Hillwig et al. (2004), consistent with our expectations for the varying supergiant to disk flux ratio. (3) The presence of a super-Eddington disk in SS 433 implies that the system is undergoing rapid mass transfer from an evolved and Roche-filling mass donor. The fact that the absorption line spectrum resembles that of an A-supergiant with a projected rotational line broadening that matches expectations for a Roche-filling star in synchronous rotation (Hillwig et al. 2004) is fully consistent with the mass transfer picture.

All three criteria are met in the new observations, and the remarkably consistent agreement between the new results and those of Hillwig et al. (2004) strongly support the conclusion that the absorption pattern in the spectrum of SS 433 observed near mid-eclipse and precessional phase zero is that of the mass donor star. On the other hand, the behavior of an absorption spectral component associated with a disk or disk wind will be highly time variable, and we suspect that the kind of absorption features described by Barnes et al. (2006) and Clark et al. (2007) do originate in a disk outflow as they propose.

The radial velocity curve also provides us with the opportunity to revise the kinematical mass calculations for each component. The best-fit radial velocity curve for the combined sets of data shown in Figure 2 gives a semiamplitude for the mass donor star of  $K_O = 58.2 \pm 3.1$  km s<sup>-1</sup> and a systemic velocity of  $\gamma = 73 \pm 2$  km s<sup>-1</sup>. Adopting a compact object semiamplitude of  $K_X = 168 \pm 18$  km s<sup>-1</sup> (see Hillwig et al. 2004) and system inclination of 78°8 (Margon & Anderson 1989) gives component masses of  $M_O = 12.3 \pm 3.3 M_\odot$  and  $M_X = 4.3 \pm 0.8 M_\odot$ . The larger revised mass for the compact object establishes it much more firmly as a black hole candidate. The derived mass ratio  $M_X/M_O = 0.35$  is consistent with limits from the optical (Antokhina & Cherepashchuk 1987) and X-ray

(Antokhina, Seifina, & Cherepashchuk 1992; Filippova et al. 2006) light curves.

We caution that our estimate of  $K_O$  may differ from the actual geometric value if the inner hemisphere of the A-supergiant is significantly heated by flux from the disk (Cherepashchuk et al. 2005). The amount of irradiation present is very uncertain since the disk vertical extensions may be sufficient to block most of the high energy radiation from the central accretion zone from reaching the facing hemisphere of the supergiant. Furthermore, the effects of such heating on line formation are complicated. For example, a hotter, brighter inner hemisphere will have a center of light that is shifted towards the companion (so that the measured radial velocity shifts would be less than actual). On the other hand, if the temperature is high enough in the irradiated hemisphere to shift the plasma to higher ionization stages or to reduce the temperature gradient in the atmosphere, then the lines we observe would be weaker or absent in the surface elements of the inner hemisphere (shifting the measured radial velocities to larger than actual). The clues from the available spectra suggest that irradiation probably plays a minor role since the decline in CCF strength following mid-eclipse follows approximately the expected curve for flux dilution alone (Fig. 3). However, the absorption lines do weaken and disappear in the final spectrum obtained near orbital quadrature phase, and this behavior may be due to some contribution of irradiation or the disappearance of the supergiant behind an optically thick accretion disk. If irradiation of the inner hemisphere were to change the ionization stage, however, then at quadrature the absorption lines would be visible from only half of the projected stellar surface, meaning the line strengths should be no greater than half that predicted by the eclipse model (*solid line*) in Figure 3.

## 5. Conclusions

We have shown that the behavior of the A-supergiant absorption spectrum observed in SS 433 during eclipse and near precessional phase zero is repeatable. This suggests that the origin of the spectrum is a consistent, well-behaved source. We suggest that the source is the mass donor star in the system rather than the disk or a disk wind. It is interesting that SS 433 would show such similar spectra from both the mass donor star and the disk/disk wind. However, the appearance of such absorption might be anticipated if the disk outflow material is clumpy and has a temperature in the line forming region comparable to that of the supergiant.

The radial velocity curve resulting from observations of the mass donor star then allow calculations of the kinematical masses of the two components. We find masses of  $M_O = 12.3 \pm 3.3 M_\odot$  and  $M_X = 4.3 \pm 0.8 M_\odot$  for the mass donor and compact object. It is possible

that the inner hemisphere of the mass donor is irradiated, which would change the mass of both components, potentially reducing the compact object mass to below the neutron star limit. The behavior of the CCF amplitude suggests that a strong irradiation effect is not present in the data presented here. If this is the case, then the compact object in SS 433 can be firmly identified as a black hole candidate.

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