We present results of optical spectroscopic observations of the mass donor star in SS 433 with Subaru and Gemini, with an aim to best constrain the mass of the compact object. Subaru/Faint Object Camera and Spectrograph observations were performed on four nights of 2007 October 6–8 and 10, covering the orbital phase of \( \phi = 0.96 - 0.26 \). We first calculate the cross-correlation function (CCF) of these spectra with that of the reference star HD 9233 in the wavelength range of 4740–4840 Å. This region is selected to avoid “strong” absorption lines accompanied with contaminating emission components, which most probably originate from the surroundings of the donor star, such as the wind and gas stream. The same analysis is applied to archive data of Gemini/GMOS taken at \( \phi = 0.84 - 0.30 \) by Hillwig & Gies. From the Subaru and Gemini CCF results, the amplitude of the radial velocity curve of the donor star is determined to be \( 58.3 \pm 3.8 \text{ km s}^{-1} \) with a systemic velocity of \( 59.2 \pm 2.5 \text{ km s}^{-1} \). Together with the radial velocity curve of the compact object, we derive the mass of the donor star and compact object to be \( M_\alpha = 12.4 \pm 1.9 \, M_\odot \) and \( M_X = 4.3 \pm 0.6 \, M_\odot \), respectively. We conclude, however, that these values should be taken as upper limits. From the analysis of the averaged absorption line profiles of strong lines (mostly ions) and weak lines (mostly neutrals) observed with Subaru, we find evidence for heating effects from the compact object. Using a simple model, we find that the true radial velocity amplitude of the donor star could be as low as \( 40 \pm 5 \text{ km s}^{-1} \) in order to produce the observed absorption-line profiles. Taking into account the heating of the donor star may lower the derived masses to \( 1.9 \, M_\odot \leq M_X \leq 4.9 \, M_\odot \). Our final constraint, \( 1.9 \, M_\odot \leq M_X \leq 4.9 \, M_\odot \), indicates that the compact object in SS 433 is most likely a low mass black hole, although the possibility of a massive neutron star cannot be firmly excluded.

**Key words:** accretion, accretion disks – stars: individual (SS 433, V1343 Aquilae) – supergiants – techniques: spectroscopic – X-rays: binaries
at the Kitt Peak National Observatory (previously published in Hillwig et al. 2004) and the Gemini telescope. They derived a donor star semi-amplitude of $K_0 = 58.2 \pm 3.1$ km s$^{-1}$ and a systemic velocity of $v_0 = 73 \pm 2$ km s$^{-1}$. Combining their results with $K_X = 168 \pm 18$ km s$^{-1}$, the average value of Fabrika & Bychkova (1990) and Gies et al. (2002b), they conclude the mass of the donor and compact object to be $M_O = 12.3 \pm 3.3 M_\odot$ and $M_X = 4.3 \pm 0.8 M_\odot$, respectively. In the discussion below (Section 6.1), we review in detail the history of the radial velocity determinations of the compact object and the donor star.

The selection of absorption lines originating from the photosphere of the donor star is a key issue for a reliable determination of the radial velocity of the donor star. It is also important to observe SS 433 when the disk is oriented maximally toward the observer and the outflowing material does not intersect with the line of sight. Charles et al. (2004), Barnes et al. (2006), and Clark et al. (2007) suggested that the spectral type of the donor star is an A-type supergiant. However, the wavelengths of the lines they observed did not follow the expected orbital velocity curve. Barnes et al. (2006) and Clark et al. (2007) pointed out that some absorption lines originate from the mass accretion flow onto the compact object, and not from the surface of the donor star. More importantly, the heating of the donor surface by the compact object may significantly affect the accurate measurement of the radial velocity (Cherepashchuk et al. 2005).

The intensity of the absorption lines is maximum in the central phase of the accretion-disk eclipse and it rapidly decreases when the compact object moves out from the eclipse (Hillwig et al. 2004). There are at least two types of absorption lines in the SS 433 spectra: (1) absorption lines with emission components and (2) pure absorption lines. The former ones are usually stronger, showing typical “shell-type” line profiles, while the absorption line is located between two emission components. The pure absorption lines are weaker, and they are apparently not accompanied by emission features. Hereafter, we call these two types of absorption lines “strong” and “weak,” respectively.

The strong absorption lines have large oscillator strengths and are usually formed in the upper regions of a star’s atmosphere. In the case of SS 433, considering the heavy mass-loss rate of the donor of $M \sim 10^{-4} M_\odot$ yr$^{-1}$ (Fabrika 2004), and the underlying emission components, we expect that the strong absorption lines and associated emission lines may be formed in places not directly related to the donor photosphere. Hillwig et al. (2004) used a “highly rectified continuum” (see below) to smooth out the emission components of the strong absorption lines. Generally speaking, using the strong absorption lines without a detailed modeling of each spectral feature has to be considered risky.

The heating of the donor star by the strong UV radiation from the supercritical accretion disk is known to be important. For a disk UV luminosity of $\sim 10^{40}$ erg s$^{-1}$, the heated surface of the donor star in SS 433 is expected to have a temperature of $\sim 20,000$ K (Fabrika 2004), instead of only 9500 K in the absence of heating (Hillwig et al. 2004; Cherepashchuk et al. 2005). Such a strong heating effect can produce the emission components observed in the strong absorption lines. It can also distort the radial velocities measuring from the weak absorption lines (Cherepashchuk et al. 2005), since they are observed in the non-heated (or partly heated) regions of the donor surface, whose configuration changes with the orbital phase.

Here, we present the most recent determination of the radial velocities and mass of the donor star and the compact object. In our analysis, we consider various effects as discussed above. First, we carefully select absorption lines that originate from the donor’s photosphere with minimum contamination by emission components, such as those from the wind, the gas stream, and the heated surface of the donor star. For this purpose, we use high-quality optical spectroscopic data obtained with the Subaru/Faint Object Camera and Spectrograph (FOCAS) in 2007 October during four nights. Archival data taken at the Gemini telescope published by Hillwig & Gies (2008) are analyzed as well. We present our best constraints on the mass of the compact object in SS 433, based on a model that accounts for the averaged absorption line profiles with consideration of the heating effects from the compact object.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Subaru Data

We observed SS 433 with the FOCAS instrument (Kashikawa et al. 2002) on the Subaru telescope on 2007 October 6–8 and 10. The jet of this source is known to precess with a period of 162.15 days. This epoch was chosen to observe the system in a particular phase. First, the disk was oriented maximally toward us ($\psi \approx 0$, where $\psi$ is a precessional phase), which prevents the gas outflow from the accretion disk to intersect with the line of sight. Second, the orbital phase included the eclipse of the compact object by the donor star ($\phi \approx 0$, where $\phi$ is an orbital phase). The spectra cover the orbital phase of $0.96 \leq \phi \leq 0.26$ and precession phase of $0.02 \leq \psi \leq 0.04$, based on the orbital light curves presented below and the precession ephemeris given by Gies et al. (2002b).

FOCAS was operated with the 0′.4 slit, VPH450 Grism, and $3 \times 1$ binning for the CCD chip. The sky condition was mostly photometric, except for 2007 October 10, with a typical seeing of $\approx 1''$. The resulting spectra cover the wavelength range of 3750–5250 Å with a dispersion of 0.37 Å pixel$^{-1}$. Each night, we took 5–8 frames with 11–20 minutes exposure each. As reference stars we observed HD 9233 (spectral type A4 Iab), whose spectrum is similar to the donor star in SS 433 (Hillwig et al. 2004), HD 187982 (A1 Ia), and HD 332044 (B3 Ia).

All spectra are reduced by the IRAF package (Tody 1993) in the usual way. We first subtract the bias, using averaged data of 20 bias frames. Then, to correct for the individual difference of each frame, we further subtract the remaining offsets in the overscan region from the exposed region. For the data of SS 433 with long exposures, the cosmic ray particle traces are removed using the lacos_spec task (van Dokkum 2001). The averaged flat image is created from 13 frames taken each night, which is then corrected approximately for the wavelength dependence of the flux to give a “normalized” flat frame. Finally, we divide the object frames by the normalized flat frame. Any remaining cosmic ray traces are removed manually in this stage.

Accurate wavelength calibration is a critical point for our scientific goals. We utilize a thorium–argon lamp with the identify task on IRAF. The accuracy is confirmed to be better than 4 km s$^{-1}$ by checking the interstellar absorption feature of Ca ii λ3933.66. The flux calibration is made using the standard stars, BD+28D4211 (first night) and BD+40D4032 (second–fourth night). We ignore the effects of the slit loss, as we are mainly interested in the change of the relative flux. Finally, the atmospheric extinction is corrected. For the spectra of the fourth night, when the sky condition was not photometric, we correct the flux level relative to that of the third night by using the
Figure 1. Optical photometry of SS 433 during the Subaru observations. Crosses show data points interpolated to the time of the spectral observations. Variations larger than 0.01 in V and 0.02 in B represent real photometric activity in SS 433.

Table 1
Log of Observations

| Date          | HJD − 2,450,000 (Mid Time) | Total Exposure (s) | Frames |
|---------------|----------------------------|--------------------|--------|
| Subaru        |                            |                    |        |
| 2007 Oct 6    | 4379.76                    | 6000               | 5      |
| 2007 Oct 7    | 4380.78                    | 8400               | 7      |
| 2007 Oct 8    | 4381.84                    | 5484               | 5      |
| 2007 Oct 10   | 4383.77                    | 8400               | 7      |
| Gemini        |                            |                    |        |
| 2006 Jun 7    | 3893.99                    | 5400               | 3      |
| 2006 Jun 8    | 3895.04                    | 9000               | 5      |
| 2006 Jun 9    | 3895.96                    | 16200              | 9      |
| 2006 Jun 10   | 3897.02                    | 12600              | 7      |
| 2006 Jun 11   | 3898.01                    | 9000               | 5      |
| 2006 Jun 12   | 3899.03                    | 7200               | 4      |
| 2006 Jun 13   | 3900.03                    | 7200               | 4      |

B-band magnitudes reported in Section 2.3. To achieve the best signal-to-noise ratio, we add all the individual spectra produced in this way, except for those with low statistics or poor observing conditions, to obtain one spectrum for each night. We utilize 5, 7, 5, and 7 frames for the first, second, third, and fourth nights, respectively. We then produce “normalized” spectra, by dividing the original spectra by a smooth continuum.

2.2. Gemini Data

We analyze the archival data of SS 433 observed with the GMOS instrument on the Gemini telescope on 2007 June 7–13 (UT). These data were also used by Hillwig & Gies (2008). The observations cover the orbital phase of $\phi = 0.84 - 0.30$ at the precession phase of $\psi = 0.02 - 0.06$, when the accretion disk is oriented maximally toward us. In the epoch of the Gemini observations, SS 433 was found to be more active than during the Subaru observations. Starting from the original frames available from the Gemini Web site, we reduced the data using the ESO-MIDAS package (Warmels 1992), according to standard procedures. Like for the Subaru data, we produce an averaged spectrum for each night, “normalize” by a continuum fit, and apply a heliocentric correction to the wavelengths. Table 1 summarizes the observation dates and exposures of the Subaru and Gemini data analyzed in this paper.

2.3. Photometric Data

We obtained photometric data of SS 433 in the standard B and V bands at the 1 m telescope of the Special Astrophysical Observatory (SAO RAS) on 2007 October 2–11 with the CCD detector EEV 42-40. In addition, we obtained Subaru V-band images taken just before the spectral observation. To determine the B magnitudes of SS 433 during the Subaru spectroscopic observations, we used the V data and an interpolation of the $(B - V)$ versus $V$ relation, which is established very well in SS 433 (Goranskii et al. 1998). The final photometric accuracy is 0.01 and 0.02 mag in the V and B bands, respectively, in direct observations. For the B-band magnitudes interpolated to the Subaru observation time, we obtained an accuracy of 0.03 mag.

Figure 1 shows the V and B photometric light curves of SS 433. The SS 433 brightness out of eclipse is $V = 14.0$, indicating that the object was in “passive state” (Fabrika 2004). The middle eclipse took place between the first and the second night of the Subaru observations. The minimum is very well shaped and regular. Using these data and all previous photometric data of SS 433 we have, we update the orbital ephemeris. The main minimum is Min I = JD 2450023.76 ± 0.2 + (13.08227 ± 0.00008) × E. The new orbital period is slightly greater than the previous one (13.08211) published by Goranskii et al. (1998). This does not mean, however, that we detect a change of the period. The orbital ephemeris satisfies the previous photometric data as a solution with a constant period. The particular photometric eclipse displayed in Figure 1 has occurred 0.375 days after the predicted time from Goranskii et al. (1998) and 0.18 days after the time predicted by our new ephemeris. Such deviations are well known from the photometric behavior of SS 433. In the following, we assume JD 2454380.335 as the peak of the eclipse to calculate the orbital phase. For the analysis of the Gemini spectra, taken in 2006 June, we apply the new orbital ephemeris as presented above.

3. SPECTRAL FEATURES FROM THE DONOR STAR

Figure 2 shows the flux-calibrated spectra of SS 433 in the 3750–5250 Å range obtained with the Subaru/FOCAS instrument. Apparently, the continuum fluxes were small in the first and second nights, corresponding to orbital phases close to the eclipse ($\phi = 0.956$ and 0.034), and increased as the compact object move out of the eclipse. The most prominent features in these spectra are emission lines originating from the accretion

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5 http://www4.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/gsa/
disk and the gas stream (Fabrika 2004), including H\textsc{i} lines (from H\beta to H11), He\textsc{i} (the strongest are 5048 Å, 5015 Å, 4922 Å, 4713 Å, 4471 Å), He\textsc{ii} (4686 Å), Fe\textsc{ii} (the strongest is 5169 Å), and the C\textsc{iii}/N\textsc{iii} Bowen blend (∼4640 Å). The broad lines produced by relativistic jet were not strong during our Subaru observations. The H\beta line is detected close to H\gamma line, from λ ∼ 4400 Å to λ ∼ 4270 Å due to the jet nutation motion.

A large fraction of the optical emission of SS 433 originates from the compact object, i.e., from the accretion disk and the jet bases (Fabrika 2004). When the accretion disk move out from the eclipse, absorption lines from the donor star become very weak and hence careful analysis is required to study their features. To measure the orbital motion of the donor star (Section 4), we need to determine the cross-correlation function (CCF) with the spectrum of a reference star first. For this, we define three different spectral regions that are not affected by prominent emission lines from compact object: Region 1 (4490–4630 Å), Region 2 (4740–4840 Å), and Region 3 (4950–4990 Å).

The normalized spectra of Region 1 and Regions 2 and 3, taken during first night, are plotted in Figures 3 and 4, respectively. Region 1 contains many strong absorption lines of Fe\textsc{ii} and Ti\textsc{ii} surrounded by emission components. By contrast, Region 2 is practically void of strong absorption lines and contains the Cr\textsc{ii} λ 4824 line with a weak emission component. Region 3, the narrowest one, contains the Fe\textsc{i} λ 4957 line with a weak emission component. To make the absorption features clearly visible, we further divide the “normalized spectra” by a continuum function modeled by Legendre polynomials of order ∼15 in each region. We call the resultant spectra “highly rectified spectra.”

Figures 5 and 6 show the highly rectified spectra of SS 433 in Region 1 and Regions 2 and 3, respectively, together with the normalized spectrum of the standard star HD 9233. HD 9233, spectral-type A4 Iab, is known to show an absorption line spectrum similar to the donor star of SS 433 (Hillwig et al. 2004). For an easy comparison, all the spectra have been shifted into the rest frame by correcting for its radial velocity as determined by the CCF analysis in the following section. It is known that even during the eclipse, the surroundings of the
compact object (probably the accretion disk wind) contribute significantly to the total brightness of the system. The spectrum of HD 9233 is scaled to match the flux of the SS 433 spectra by multiplying with a factor of 0.36 (Hillwig et al. 2004). The deep absorption lines at 4500 Å, 4760 Å, 4780 Å, and 4980 Å are due to interstellar absorptions (Hobbs et al. 2008). Apart from these, the spectra of HD 9233 and SS 433 contain the same set of absorption lines. These absorption features in the SS 433 spectra become deeper as the donor star hides the compact object (Hillwig et al. 2004), providing evidence that they originate from the donor star.

The Gemini spectra observed for seven nights are analyzed with the same procedure. Figure 7 shows the resulting highly rectified spectra in Regions 2 and 3 obtained with the Gemini GMOS. For comparison, we also plot the Subaru HD 9233 spectrum in the same figure. The wavelengths are corrected for its radial velocity, except for that of the seventh night where the absorption-line features are found to be extremely faint. We do not analyze the Gemini spectra of Region 1, since the strong absorption lines in the region appear as pure emission lines. This is probably due to the higher activity during the Gemini observations than during the Subaru observations. This makes it impossible to use them for our CCF analysis.

4. THE RADIAL VELOCITY OF THE DONOR STAR

4.1. Cross-correlation Function Analysis

We derive the radial velocity of the donor star by cross-correlating the spectra of SS 433 with those of HD 9233 in each spectral region (Region 1, 2, or 3). Thereby, we assume the heating effects by the compact object at the surface of the donor star are negligible (see discussion in Section 4.3). We further ignore wavelengths with strong interstellar absorption. We pay special attention to the determination of the radial velocity of HD 9233, which is known to be a radial velocity variable star (Hillwig & Gies 2008). By measuring the Doppler shifts of 13 non-blended absorption lines (Chentsov & Sarkisyan 2007) from the A4 Iab supergiant, we derive a systemic velocity of HD 9233 of $V_{\text{HD9233}} = -44.2 \pm 1.3$ km s$^{-1}$. To verify our analysis, we also measure the radial velocity of another reference star HD 187982 (Type A1 Ia), which was observed on 2007 October 7 (i.e., during the second night of our Subaru observations). Our result is in good agreement with the literature value (Wilson 1953) within the error range.

Figure 8 shows the radial velocity curve of the donor star in SS 433 obtained by the CCF analysis of the Subaru data. Squares indicate the results from Region 1, filled circles from Region 2, and triangles from Region 3.

We have demonstrated that the selection of absorption lines does affect the estimate of the radial velocity within our simple analysis. The differences in the amplitudes are related to the strength of the spectral features; the absorption lines in Region 1 are the deepest and have underlying emission components, while those in Region 2 are the weakest and mainly
do not show emission components. We interpret that the strong absorption lines are more significantly affected by the emission from the wind, the gas stream, and the heated surface of the donor star, which decrease the amplitude of the radial velocity curve. From Region 1, we obtain \( K_O = 24 \pm 9 \text{ km s}^{-1} \) with a systemic velocity of \( \gamma_0 = 52 \pm 6 \text{ km s}^{-1} \). This value for \( K_O \) is even smaller than the result from Hillwig et al. (2004), \( K_O = 45 \pm 6 \text{ km s}^{-1} \), who studied the same spectral region. This is probably due to different conditions of the surroundings between the two epochs of observations.

In this context, the selection of “weak” lines is important to determine correctly the motion of the donor star, as the region responsible for the production of the absorption lines is constant over the orbital phase. Under this assumption, we can estimate the amplitude of the radial velocity curve by fitting the velocities with a Keplerian solution. Figure 10 shows the Subaru and Gemini results obtained from the CCF analysis of Region 2 together with the best-fit curve. We obtain a semi-amplitude of the radial velocity of \( K_O = 58.3 \pm 3.8 \text{ km s}^{-1} \) and a systemic velocity of \( \gamma_0 = 59.2 \pm 2.5 \text{ km s}^{-1} \). This value of \( K_O \) is consistent with the result of Hillwig & Gies (2008) within the error bars. We note that Figure 10 may indicate a distortion of the donor’s radial velocity curve in the orbital phases 0.0–0.15.

### Table 2

| Date (HJD–2,450,000) | Observatory | \( \psi \) | \( \phi \) | \( V_r \) (km s\(^{-1}\)) |
|----------------------|-------------|------------|------------|-----------------------------|
| 4379.76              | Subaru      | 0.018      | 0.956      | 52 \( \pm \) 7              |
| 4380.78              | Subaru      | 0.024      | 0.034      | 65 \( \pm \) 7              |
| 4381.84              | Subaru      | 0.031      | 0.115      | 84 \( \pm \) 7              |
| 4383.77              | Subaru      | 0.043      | 0.262      | 119 \( \pm \) 7             |
| 3893.99              | Gemini      | 0.022      | 0.838      | 9 \( \pm \) 8               |
| 3895.04              | Gemini      | 0.029      | 0.918      | 39 \( \pm \) 8              |
| 3895.96              | Gemini      | 0.034      | 0.988      | 47 \( \pm \) 8              |
| 3897.02              | Gemini      | 0.041      | 0.069      | 73 \( \pm \) 8              |
| 3898.01              | Gemini      | 0.047      | 0.145      | 106 \( \pm \) 9             |
| 3899.03              | Gemini      | 0.053      | 0.223      | 132 \( \pm \) 9             |
| 3900.03              | Gemini      | 0.060      | 0.300      | 128 \( \pm \) 8             |

**Note.** The errors are 1σ standard errors from the CCF analysis.

### 4.2. Average Absorption Line Profiles

The high quality of the Subaru spectra allows us to study individual absorption lines. In the case of CCF analysis (Section 4.1), one compares two stars (i.e., of SS 433 and reference stars) with almost identical spectra. Hence, the complex blending and crowding of the absorption lines is not critical for the study. The analysis of the individual lines, however, depends strongly on such line blending effects and requires knowledge of the “laboratory” wavelengths of the blends. We carefully check the whole spectrum of SS 433 for the first and second nights, when the system was in maximum eclipse. First, we select two groups of absorption lines: “strong” lines, which clearly show emission components, and “weak” lines with pure absorption line profiles. For the line identification, laboratory wavelengths and relative line strengths, we refer to the Atomic Spectra Database\(^6\) and to the Atomic Line List.\(^7\) We estimate the effective wavelengths of the blends by weighing the wavelengths of the individual lines according to their line strengths. We test each line or line blend to have the same radial velocity in the given Subaru night, allowing a difference of up to 20 km s\(^{-1}\). The set of strong lines as well as the set of weak lines is both formed from lines that have same radial velocities within the first and the second night. The data of the other nights are not considered at the line selection. Obvious or resolved line blends are not included in the two line groups.

Finally, we add the line profiles for each group in the normalized spectra in the radial-velocity space to create the strong and weak average line profiles. In the averaging procedure, we apply a weight of unity for a single line and a smaller weight for obvious (but non-resolved) blends. The line blending may distort the line profiles. The averaging procedure minimizes this distortion, because the line blending is only occasional, and because obvious and strong blends are excluded from the set of lines.

To derive the average line profiles, we do not use the “highly rectified” spectra. Instead, we apply a linear continuum

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\(^6\) National Institute of Standards and Technology; http://physics.nist.gov/PhysRefData/ASD/

\(^7\) Department of Physics and Astronomy, University of Kentucky; http://www.pa.uky.edu/~peter/atomic/
rectification to the final average line profiles in order to subtract the continuum levels near the lines. Both the “strong” and the “weak” absorption lines are considerably fainter than the strong emission lines in the SS 433 spectrum. Hence, in case where an absorption line is located near the wing of a strong and broad emission line, its local continuum does not become flat. Applying a linear function for the continuum rectification of the broad emission line, its local continuum does not become flat.

We include eight individual lines in the average strong line profile (Mg II λ4481.21, Ti II+Fe II λ4549.63, Ti II+Fe II λ4555.49, Fe II λ4576.39, Ti II+Fe II λ4583.41, P II+Cr II λ4823.84, Si II λ5041.03, Fe I λ5226.86) and eight individual lines in the average weak line profile (Cr I λ4161.42, Fe I λ4271.76, Ti II λ4290.22, Ti I λ4325.13, Fe I λ4528.87, λ4983.85, λ5125.11, Mg I λ5183.60). We find that nearly all strong absorption lines with emission components are generated by ions, while most of the weak, pure absorption lines are produced by neutral atoms. This implies that the ion absorption lines are partially formed in a more extended gas envelope of the donor star (i.e., the donor’s wind). This wind could be a low velocity wind, since the donor overfills its Roche lobe. The emission components in the strong absorption lines may be partly formed in the gas stream (probably the mass flow; see below), which is best observed in hydrogen and He I emission lines (Crampton & Hutchings 1981; Fabrika et al. 1997; Fabrika 2004).

The average strong and weak line profiles are shown in the right-hand panels of Figures 11 and 12, respectively. The strong lines show clear evolution of their emission components over the four nights of observations. The absorption components shift with time to positive velocities with an amplitude of $\approx 40$ km s$^{-1}$. The weak lines show the same systematic evolution with the orbital phase, although its orbital shift in radial velocity is notably larger than that of the strong lines. The final signal-to-noise ratio in the average line profiles is very high. We detect several features in the line profiles that change from night to night in ways that are difficult to interpret. They would be due to line-emitting and absorbing regions in the system having a complex structure. Additionally, emission components could partially fill the absorption profiles of the weak lines as well. In the following, we study the main features only, such as the line positions and intensities.

We measure the absorption line positions for the average weak and strong line profiles and compare them with the CCF results. Note that the CCF analysis and the study of the average absorption line profiles are independent. We find that the weak absorption lines show the same behavior as the lines in the CCF analysis of Region 2, which is free from strong lines. The total radial velocity amplitude measured between the first and fourth spectra is $\approx 63$ km s$^{-1}$, which is very close to $\approx 67$ km s$^{-1}$ derived from the CCF analysis (Table 2). The absolute velocities

Figure 11. Observed average absorption-line profiles for the “strong” lines with emission components (right) and its best-fit model (left). From the first to the fourth Subaru nights, the profiles are denoted by solid, dashed, dash-dotted, and dotted lines.

Figure 12. Observed average absorption-line profiles for the “weak” lines without notable emission components (right) and its best-fit model (left). From the first to the fourth Subaru nights, the profiles are denoted by solid, dashed, dash-dotted, and dotted lines.
are about the same as well, with the difference between the two methods being within 5 km s\(^{-1}\). We further compare the behavior of the strong absorption lines with the CCF results of Region I, which mainly contains strong lines with emission components. The difference is 10 km s\(^{-1}\) for the total radial velocity amplitude, although the systemic velocity is larger by 15 km s\(^{-1}\) for the average strong line profile than for the CCF analysis. Note that for the CCF analysis, we used the “highly rectified” spectra, where smoothing of the emission components may produce a systematic shift in the absorption line position. In the following, we study the average line profiles using a simple model of a close binary by taking into account the heating effects from the compact object.

### 4.3. Study with a Simple Model Including Heating Effects by the Compact Object

#### 4.3.1. Model Description

Figure 13 sketches the binary system with its main components. Since the UV luminosity of the compact object is as high as \(L_{UV} \sim 10^{40} \text{ erg s}^{-1}\) (Fabrika 2004), the compact object can heat the donor surface up to \(\sim 20,000 \text{ K}\) during the thirteen-day binary period. Although the detailed of geometry of the system is unknown, we know that the size of the optical continuum source is about the size of the donor star or slightly exceed it, because optical eclipses are never total (about half of the continuum light remains present always). The donor star has an extended and dense envelope, which is probably due to a strong, low-velocity wind. Studies of X-ray eclipses in SS 433 (Filippova et al. 2006) revealed that the radius of the envelope that is opaque to X-rays exceeds the donor radius (or its Roche lobe radius) by 10\%–20\%. This proves the existence of a gas envelope (“coat”) around the donor star, which can produce the emission components observed in the strong absorption line profiles. This gas envelope is also sketched in the figure.

We construct a simple toy model of the system to study the heating effect on the absorption lines. Heating effects increase the observed radial velocity amplitude of absorption lines (Antokhina et al. 2005; Cherepashchuk et al. 2005) because, due to the spin of the donor star, the non-heated side moves with a larger velocity than that of the center of mass. In our model, we consider three different regions of the donor surface (Figure 13): Region I, which is not heated and produces absorption lines only; Region II, which is heated and produces emission lines only; and Region III, which is overheated and therefore does not produce any emission or absorption lines of elements with low ionization potentials (such as, e.g., Ti\(^{2+}\) or Fe\(^{2+}\)).

We assume that the system is synchronized and the donor star is a sphere with a volume equal to that of the Roche lobe for a given mass ratio \(q = M_d/M_X\). The orbital inclination of the system is adopted as 79\° (Fabrika 2004). The semi-amplitude of the compact object is set to \(K_X = 160 \text{ km s}^{-1}\), as derived later in this paper (Section 5). The semi-amplitude of the donor star \(K_d\) (or the mass ratio \(q\)) is taken as free parameter in this model. The donor surface is divided into 100 grid cells both in longitude and latitude, with each grid cell producing a Gaussian absorption line profile in the non-heated region or an emission line profile in the heated region. A Gaussian line width of FWHM = 5 km s\(^{-1}\) is adopted. For absorption lines formed at the donor’s surface which is not exposed to the UV source (Region I in Figure 13), the Gaussian line intensity is normalized to unity. For emission lines formed in the heated region of the surface (Region II in Figure 13), we calculate the normalization depending on the heating parameters (see below). We adopt a quadratic limb-darkening law (Kalrath & Milone 1999) with \(x = y = 1\) for absorption lines only. Using this limb-darkening law, we can easily fit the observed absorption lines. Note, however, that determining the correct limb-darkening law for this supergiant with heavy mass loss and heating is a truly complex task. In the case of emission lines, we do not account for a limb-darkening effects, since one expects an inverse temperature gradient in the emission region.

The gas envelope is modeled in a similar way than the donor surface, with the difference that it produces emission lines in the heated region (Region II), but no emission or absorption lines in the other two regions. The radial extent is set to 10\% of the donor radius. It has ten individual segments in the radial direction. We assume that the emitting gas in the envelope rotates with the same velocity as the donor surface and moves in the radial direction with the escape velocity \(V_{esc}\).

The UV source is spherical and has the same size as the donor star in the model (Figure 13). Each point of the donor surface sees all the points of the extended source visible from it. We calculate the angle of incidence of the UV radiation in each point of the donor surface. Thus, we specify only geometrical properties of the source. We suggest that the donor’s regions exposed to the UV radiation of the source produce emission lines. This is expected if the temperature gradient in the donor’s atmosphere is inverse. Antokhina et al. (2005) confirmed this behavior in their X-ray heating model of a low-mass X-ray binary. UV radiation is subject to strong extinction and may therefore not penetrate deeply into the donor atmosphere. Considering the high luminosity \((L_{UV} \sim 10^{40} \text{ erg s}^{-1})\) of the accretion disk in SS 433; however, we suggest that the UV radiation can indeed produce the inverse temperature gradient in the atmosphere and that the gas in the donor’s wind may be ionized down to the photosphere.

We introduce two empirical parameters, the heating coefficients \(\gamma_{\text{phot}}\) and \(\gamma_{\text{env}}\), which define the intensities of the emission...
lines formed in the heated regions of the donor surface and in the envelope, respectively. From the relative fluxes of the incident radiation in each point exposed to the UV source, we calculate the expected emission-line components. We then determine the values of $\gamma_{\text{phot}}$ and $\gamma_{\text{env}}$ by comparing the line profiles between the model and the data observed in all four nights. The values are independent for the strong and the weak lines (in particular, $\gamma_{\text{env}} = 0$ for the weak lines). The obtained heating coefficients are relative ones only and cannot be used to estimate the heating effects physically. To produce a reasonable agreement between the observed and the modeled line profiles, $\gamma_{\text{phot}}$ has to be 2–3 times larger for the weak lines than for the strong lines. The weak lines do not require an additional emission component formed in the envelope. In the case of the strong lines, this component ($\gamma_{\text{env}}$) is necessary, since it produces emission line wings which are notably broader than the photospheric line profiles. By varying other parameters of the model, such as the mass ratio, we can infer the required amount of heating that is necessary to account for the observed line profiles.

Finally, we integrate the line profiles from individual regions of the donor surface and of the envelope which are visible from the observer during the orbital phases of the Subaru observations (indicated in Figure 13). The final line profiles are convolved with the instrumental response, which is derived from single line measurements in the comparison-lamp spectra. The normalization of the final absorption lines is determined from the data of the first night only. These normalization coefficients are kept constant for all four nights of the observations.

The final line profiles are notably broader ($\text{FWHM} \sim 100 \text{ km s}^{-1}$) than our Gaussian lines formed in the individual surface cells and they do not depend on the adopted line width of the individual lines (when it is less than $\sim 20 \text{ km s}^{-1}$). This simple approach is sufficient for the following study because we do not compare in detail the observed and calculated line profiles, but investigate the main features of the heating effects only.

Several effects are not taken into account here. In reality, heating by the UV radiation is a complex process. For example, the UV photons may not reach the donor surface because of strong absorption in the wind. The UV absorption can heat the gas deeply down to the surface, however. We further assume that the UV source radiates isotropically, which is probably an oversimplification. For instance, the thick outer rim of the disk (Filippova et al. 2006) may cast an extended shadow. This effect is most important in the fourth Subaru night, since, at precession phases $\psi \sim 0$, the donor star crosses the disk plane at $\phi \approx 0.25$ and 0.75. The assumption of isotropic UV radiation will lead to an overestimate of the heating effects in this case. Since the environment of the compact object (i.e., the wind, the jet bases, and the disk structure) is basically unknown, a complex modeling of the heating is problematic. Thus, in this paper, we illustrate how the heating distorts the radial velocities of the absorption lines in SS 433 for a better understanding of the principal difference between the strong and weak lines.

The gas stream is a strong source of hydrogen and He I emission lines. Crampton & Hutchings (1981) showed that the radial velocity curves have the largest redshifts at orbital phases $\sim 0$ close to the inferior conjunction of the donor star; their orbital phases lag behind the accretion-disk phase by 0.2–0.25. Later studies of the hydrogen and He I emission lines (Kopylov et al. 1989; Fabrika et al. 1997; Goranskii et al. 1997) revealed that H$\beta$ and He I radial velocities show the largest redshifts at orbital phases 0.9–0.95 and 0.85–0.9, respectively. These allow also the detection of a partial eclipse in the hydrogen emission lines at orbital phases 0.1–0.2. This indicates that the He I and hydrogen emission lines in the SS 433 spectra are formed in the gas stream onto the accretion disk.

Goranskii et al. (1997) and Gies et al. (2002b) also discussed whether the behavior of the hydrogen and He I radial velocity curves may result from an evacuation of the disk wind surrounding the donor star, which leads to anisotropic wind and the observed radial velocity curves. This cannot explain, however, both the partial eclipses and the differences between the hydrogen and He I radial velocity curves. If hydrogen and He I lines are formed in the anisotropic wind, their radial velocity amplitudes have to be greater than that of the accretion disk (traced by He II line), since the accretion disk powers the wind. This does not agree with the observed radial velocity amplitudes. We therefore conclude that the hydrogen and He I emission lines are formed in the gas stream, although a fraction of this emission may be formed in the disk wind as well. In any case, the emission region must be extended. A probable location of the gas stream region is shown in Figure 13. It is noteworthy that a fraction of the emission of the strong absorption lines (Figures 11) may be formed at the same location as the hydrogen and He I lines.

During all nights, we detected an additional red emission line component in the strong and even in the weak absorption lines, which we fail to reproduce with our model. We ascribe this component to the gas stream, which contributes more strongly to the red emission in the strong lines than in the weak lines. We do not model any probable eclipses of the gas stream (Kopylov et al. 1989; Fabrika et al. 1997; Goranskii et al. 1997), which may change the intensity of the red emission components. To model this additional red emission, we decided to follow the radial velocity curves of hydrogen and He I emission lines by Fabrika et al. (1997), where the lines show the largest redshifts (100–150 km s$^{-1}$) at the orbital phases $\sim 0.85–0.95$ and the velocity decreases gradually with the orbital phase. Finally, the gas stream is modeled to produce Gaussian emission lines, whose parameters are tuned to reproduce the observed line profiles.

4.3.2. Comparison with the Data

The left-hand panels of Figures 11 and 12 show the best-fit models of the strong and weak line profiles, respectively, to be compared with the observed ones in the right panels. These line profiles are modeled using a radial velocity amplitude of the compact object of $K_X = 160 \text{ km s}^{-1}$ and the real radial velocity amplitude of the donor star $K_O = 40 \text{ km s}^{-1}$ (i.e., $q = 0.25$). The relative heating coefficient $\gamma_{\text{phot}}$ for the weak lines is twice as large as that of the strong lines, and the wind velocity is set to $V_{\text{esc}} = 260 \text{ km s}^{-1}$ (for the strong lines only). We see that our model can reproduce the overall features of the observations. For the strong absorption lines, the emission components evolve in agreement with the idea that the gas envelope, which rotates with the same velocity as the donor star, is heated by the compact object.

For the weak absorption lines, emission lines originating from the heated donor surface are required, while those from the envelope are not. These emission lines are seen as a low intensity emission bump near the absorption line (as for the strong lines). This emission component alters the position and intensity of the absorption lines.

The absorption lines move in accordance with the orbital phase, and their velocity amplitudes are smaller for the strong
lines than for the weak lines. The absorption line intensities generally decrease with the orbital phase because of the heating (note that the observed spectra are scaled from the photometric data in order to keep the non-illuminated continuum radiation of the donor constant). Naturally, the observed absorption line profiles are more complex than those produced by our simple model. For example, the weak absorption line profile of the first night (solid line in Figure 12) shows either an additional absorption in its red wing or an additional emission component. Such a feature is not produced in our model, since we do not take into account a possible absorption of the continuum radiation from the compact object in the donor’s wind. This effect might be important during the first and second nights (see Figure 13). Additional absorption features may be present for the second and third nights in the blue wing of the strong and weak absorption lines (Figures 11 and 12). During these orbital phases, the speculated wind from the donor, which is seen projected onto the strong continuum source, is directed toward us because of the stellar rotation. This feature may also produce the distortion of the radial velocity curve observed in Figure 10.

We conclude that the model reproduces both the intensity and the radial velocity variations of the emission components and the absorption lines. The modeled line profiles are influenced mostly by the following parameters: the real velocity amplitude of the donor star $K_O$, and the heating efficiency coefficients $\gamma_{\text{phot}}$ and $\gamma_{\text{env}}$. As mentioned above, the best-fit value is $K_O \approx 40$ km s$^{-1}$ (i.e., $q \approx 0.25$ with $K_X \approx 160$ km s$^{-1}$). This is 18 km s$^{-1}$ or 30% less than that measured in our CCF analysis (58.3 ± 3.8 km s$^{-1}$). It is impossible to produce the average line profiles in our model for $K_O < 35$ km s$^{-1}$. Further, for velocity amplitude of the compact object between 170 and 150 km s$^{-1}$, we obtain values of $K_O$ between 35 and 45 km s$^{-1}$. We thus conclude that the donor’s real radial velocity amplitude is $K_O = 40 \pm 5$ km s$^{-1}$, based on our simple model.

From the set of models reproducing the observed averaged line profiles, we find that the size of the overheated region (Region III in Figure 13), modeled as a cone with origin at angle of the donor, has a half-opening angle of $\approx 15^\circ - 20^\circ$ for the strong lines and $\approx 20^\circ - 25^\circ$ for the weak lines, respectively. The wind velocity of the donor is $V_{\text{esc}} \sim 260$ km s$^{-1}$. The mass flow, which produces parts of the red emission components in the absorption lines, has a radial velocity decreasing from 160 km s$^{-1}$ in the first night to 90 km s$^{-1}$ in the last night for the strong absorption lines, and from 100 to 80 km s$^{-1}$ for the weak absorption lines, respectively. The emission line components formed in the gas stream are broad with a FWHM of 140–200 km s$^{-1}$. The intensity of this component is 2 times weaker in the weak absorption lines than in the strong absorption lines. The origin and formation of the gas stream (mainly observed in the hydrogen and He I emission lines) were discussed in previous papers (Crampton & Hutchings 1981; Fabrika et al. 1997; Fabrika 2004). It is important to note that the introduction of the red emission components in the modeled line profiles is necessary, although its formation remains unclear. All these parameters do not change, however, the modeled absorption line profiles so strongly as the real radial velocity amplitude of the donor and heating efficiency coefficients do.

Finally, in Figure 14, we present the radial velocity curves derived from the observed average line profiles, simply based on the position of the absorption line minimum. For comparison, the values from our best-fit models ($K_O = 40$ km s$^{-1}$ and $K_X = 160$ km s$^{-1}$) are displayed as well. Clearly, the heating model reproduces well the observed radial velocities. Note that these velocities are apparent ones and differ from the real radial velocities of the donor star considered in the model.

5. RADIAL VELOCITY OF THE COMPACT OBJECT

To constrain the radial velocity of the compact object, we analyze the He II $\lambda$4686 emission line, the brightest line known to originate from the compact object. Figure 15 shows the corresponding line profiles. The flux level is normalized to that of the first night ($\phi = 0.956$), calibrated using the B-band magnitudes (Figure 1). Although the line profile is complex, it is obvious that the line center moves from the red to the blue with increasing orbital phase.

To determine the radial velocity of the He II line, we calculate the center of gravity above a certain threshold in order to discard the broad wings. The line wings are stronger in the red than in the blue. We estimate the error of the so-derived radial velocities by changing the flux thresholds (upper and lower)
used in the calculation of the center of gravity. The results are summarized in Table 3.

In Figure 16, we show the radial velocities of the compact object as measured from the He \( \text{\textsc{ii}} \) line. A large velocity of \( \approx 150 \, \text{km s}^{-1} \) is required to fit them with a Keplerian velocity curve. This is unlikely and probably due to the fact that the He \( \text{\textsc{ii}} \) line was significantly affected by the eclipse during the first three nights, as observed in previous studies (Fabrika & Bychkova 1990). Indeed, the effects of the eclipse are clearly seen in Figure 15, where the He \( \text{\textsc{ii}} \) line profile changed notably across the eclipse of the line emitting region by the donor star. If we use the data of the fourth night only, together with a fixed value of \( \gamma_X \) for the donor star, we obtain \( K_X = 159 \pm 7 \, \text{km s}^{-1} \). This value is consistent with previous results.

Fabrika & Bychkova (1990) reported \( K_X = 175 \pm 20 \, \text{km s}^{-1} \), using the He \( \text{\textsc{ii}} \lambda 4686 \) line observed in the precession phase of \( 0.9 \leq \psi \leq 0.1 \), but outside of the eclipse. Fabrika et al. (1997) constructed precessional and orbital radial velocity curves of the He \( \text{\textsc{ii}} \) line using additional spectral data. They found \( K_X = 176 \pm 15 \, \text{km s}^{-1} \) for the same precessional phase of \( 0.9 \leq \psi \leq 0.1 \), while Gies et al. (2002b) used C \( \text{\textsc{ii}} \lambda 7231, 7236 \) blended lines and derived \( K_X = 162 \pm 29 \, \text{km s}^{-1} \). For consistency, we adopt \( K_X = 168 \pm 10 \, \text{km s}^{-1} \) in this paper, the average between these three studies and our own estimate of the \( K_X \). Note that Hillwig et al. (2004) and Hillwig & Gies (2008) adopted the same value, \( 168 \pm 18 \, \text{km s}^{-1} \), as the average between two studies, Gies et al. (2002b) and Fabrika & Bychkova (1990).

### Table 3

| Date (HJD−2,450,000) | Observatory | \( \psi \) | \( \phi \) | \( V_r \) (km s\(^{-1}\)) |
|----------------------|-------------|-------------|-------------|--------------------------|
| 4379.76              | Subaru      | 0.018       | 0.956       | 178 ± 2                  |
| 4380.78              | Subaru      | 0.024       | 0.034       | 120 ± 1                  |
| 4381.84              | Subaru      | 0.031       | 0.115       | 32 ± 10                  |
| 4383.77              | Subaru      | 0.043       | 0.262       | −96 ± 7                  |

**Note.** The errors are estimated systematic errors (see the text).

![Figure 16. Radial velocity curve of the compact object measured from the He \( \text{\textsc{ii}} \) line. The horizontal line corresponds to the systemic velocity of \( \gamma_0 = 59.2 \, \text{km s}^{-1} \) as determined from the CCF analysis for the donor star. The dotted, sinusoidal curve represents the best-fit obtained using the data of the fourth night (\( K_X = 159 \pm 7 \, \text{km s}^{-1} \)).](image)

6. DISCUSSION

6.1. Review of the Dynamical Mass Determination of SS 433

In this section, we review recent work on the dynamical determination of the mass function of SS 433 from measurements of \( K_X \) and \( K_O \), which we compare with our results.

1. Gies et al. (2002b) interpreted that an absorption feature in the strong emission line of He I \( \lambda 6678 \) may originate from the donor star, using the spectra taken at the KPNO 0.9 m telescope. They derived \( K_O = 126 \pm 26 \, \text{km s}^{-1} \). Combining these values with \( K_X = 175 \pm 20 \, \text{km s}^{-1} \) (Fabrika & Bychkova 1990), they determined \( M_X = 16 \pm 6 \, M_\odot \) and \( M_O = 23 \pm 8 \, M_\odot \).

2. Gies et al. (2002a) measured the radial velocity of the donor star using the CCF technique for the first time, based on data taken with the 2.7 m telescope of the University of Texas, McDonald. For the 4060–4750 Å range, they calculated CCFs between different SS 433 spectra. They obtained \( K_O = 100 \pm 15 \, \text{km s}^{-1} \) and \( \gamma_0 = −44 \pm 9 \, \text{km s}^{-1} \). Together with \( K_X = 175 \pm 20 \, \text{km s}^{-1} \) (Fabrika & Bychkova 1990), they concluded \( M_X = 11 \pm 5 \, M_\odot \) and \( M_O = 19 \pm 7 \, M_\odot \).

3. Hillwig et al. (2004) applied a CCF analysis of Region 1 (as defined in our paper) to spectra taken at the KPNO 4 m telescope (in this epoch, Region 1 did not contain strong emission lines, unlike in the case of Hillwig & Gies 2008). They used the same reference star HD 9233 (type A4 Iab) as we used in this paper, and derived \( K_O = 45 \pm 6 \, \text{km s}^{-1} \) and \( \gamma_0 = 65 \pm 3 \, \text{km s}^{-1} \). Together with \( K_X = 168 \pm 18 \, \text{km s}^{-1} \) (the average value of Fabrika & Bychkova 1990 and Gies et al. 2002b), they determined \( M_X = 2.9 \pm 0.7 \, M_\odot \) and \( M_O = 10.9 \pm 3.1 \, M_\odot \).

4. Cherepashchuk et al. (2005) examined Doppler shifts of 22 absorption lines in the 4200–5300 Å range relative to the laboratory frame, using spectra taken at the SAO 6 m telescope. They obtained \( K_O = 132 \pm 9 \, \text{km s}^{-1} \) and \( \gamma_0 = 14 \, \text{km s}^{-1} \). Combining these values with \( K_X = 175 \, \text{km s}^{-1} \) (Fabrika & Bychkova 1990), they determined \( M_X \approx 18 \, M_\odot \) and \( M_O \approx 24 \, M_\odot \). They noted that this radial velocity semi-amplitude is probably an upper limit, because the heating of the donor star increases the observed amplitude.

5. Barnes et al. (2006) observed SS 433 with the Calar Alto Observatory 3.5 m telescope and the Observatorio del Roque de Los Muchachos 2.5 m and 4.2 m telescopes. They cross-correlated the SS 433 spectra in the 4500–4630 Å range with those of HD 9233 using the radial velocity given in Hillwig et al. (2004). They obtained \( K_O = 69 \pm 4 \, \text{km s}^{-1} \) and \( \gamma_0 = −53 \pm 3 \, \text{km s}^{-1} \). But their observations were performed when the accretion disk was close to an edge-on orientation, where the outflowing material produces strong absorption lines. Note that they assumed a velocity for HD 9233 of \( −34 \, \text{km s}^{-1} \) (Hillwig et al. 2004). Since this star is velocity variable, its velocity might have been different at the time of the observations, and the systemic velocity \( \gamma_0 \) has an additional factor of uncertainty.

6. Hillwig & Gies (2008) made a CCF analysis in Regions 2 and 3 using the Gemini data. They obtained \( K_O = 58.2 \pm 3.1 \, \text{km s}^{-1} \) and \( \gamma_0 = 73 \pm 2 \, \text{km s}^{-1} \), which together with \( K_X = 168 \pm 18 \, \text{km s}^{-1} \) (the average of Fabrika & Bychkova 1990 and Gies et al. 2002b) leads to \( M_X = 4.3 \pm 0.8 \, M_\odot \) and \( M_O = 12.3 \pm 3.3 \, M_\odot \).
6.2. Constraints on the Mass of the Compact Object

Once the amplitudes of the radial velocity curves of both the donor star and the compact object are known, one can deduce the mass of each component. By fitting the radial velocity curve of the donor star obtained from the CCF analysis with a Keplerian curve (i.e., without consideration for the heating effects), we derived $M_D = 58.3 \pm 3.8$ km s$^{-1}$, which is consistent with the value obtained by Hillwig & Gies (2008). This is not surprising, since we use the same Gemini data for our analysis in addition to the Subaru data, although we restrict the wavelength range to Region 2 only, in order to avoid systematic effects from emission components in the absorption line profiles. We adopt the amplitude of the radial velocity of the compact object of $K_X = 168 \pm 10$ km s$^{-1}$ and conclude the mass of the donor star and compact object to be $M_D = 12.4 \pm 1.9$ $M_\odot$ and $M_X = 4.3 \pm 0.6$ $M_\odot$, respectively. The corresponding mass ratio is $q = 0.35$. Again, these values should be taken as upper limits only if we consider the heating effect, as discussed in Section 4.3.

By taking into account the heating effects, we derive lower limits on the masses, since we assumed a real radial velocity amplitude of the donor star of $K_D = 40 \pm 5$ km s$^{-1}$. This leads to lower masses of $M_D = 10.4^{+2.3}_{-1.9}$ $M_\odot$ and $M_X = 2.5^{+0.7}_{-0.4}$ $M_\odot$. We thus conclude that the compact object in SS 433 is most likely a low mass black hole. However, the possibility of a massive neutron star cannot be firmly ruled out at present, given the fact that neutron stars could have masses of up to $3 M_\odot$ as inferred from both theory (Lattimer & Prakash 2007) and observations (Freire et al. 2008).

7. CONCLUSIONS

1. To study the radial velocity curve of the mass donor star in SS 433, we obtained high-quality optical spectra with Subaru/FOCAS, covering the orbital phase of $\phi = 0.96 - 0.26$. We combine these observations with the Gemini data reported by Hillwig & Gies (2008) to analyze the largest set of the best quality spectra observed right now from this source. This allows us to study in detail the behavior of the “weak” absorption lines from the donor surface, which are least affected by the emission components from the surroundings of the donor star.

2. We demonstrate that the selection of the spectral region is critical for the CCF analysis. We adopt the 4740–4840 Å range (Region 2) for this study, where only “weak” absorption lines from the surface of the donor star are present. If we instead use the 4490–4630 Å range (Region 1), which contains many “strong” absorption lines associated with emission components, we obtain a significantly smaller velocity amplitude than Region 2.

3. From the Subaru and Gemini CCF results (Region 2), we determine the amplitude of the radial velocity curve of the donor star to be $58.3 \pm 3.8$ km s$^{-1}$. Together with the radial velocity of the compact object, $168 \pm 10$ km s$^{-1}$, we derive masses of the donor star and the compact object of $M_D = 12.4 \pm 1.9 M_\odot$ and $M_X = 4.3 \pm 0.6 M_\odot$, respectively. These values should be taken as upper limits, because of the heating of the donor star by the compact object.

4. We calculated average absorption line profiles for the strong and weak lines separately, each line using eight individual lines. The position of the line centers of the average absorption line agrees within our CCF results. Prominent emission components are observed in the strong lines, indicating that the heating effects are important for a proper interpretation.

5. We construct a simple model where we take into account the UV heating effects on the donor star surface and on its envelope, and where also consider the emission from the gas stream. The model reproduces well the emission components and absorption lines in the average line profiles, both in intensity and radial velocity variations. These results indicate that the heating could have a significant impact on the estimate of the real radial velocity of the donor star, which may be as low as $K_D = 40 \pm 5$ km s$^{-1}$. We then estimate the masses of the components as $M_D = 10.4_{-1.9}^{+2.3} M_\odot$ and $M_X = 2.5_{-0.4}^{+0.7} M_\odot$.

6. The final constraints for the compact object mass are $1.9 M_\odot \lesssim M_X \lesssim 4.9 M_\odot$, where the lower and upper limits are inferred from the modeling of the average absorption line profiles and from the CCF analysis, respectively. We conclude that the compact object in SS 433 is most likely a low mass black hole, although the possibility of a massive neutron star cannot be firmly excluded.

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