Spectroscopic observations of the mass donor star in SS 433

K. Kubota, Y. Ueda (Kyoto U.), S. Fabrika, E. Barsukova (Special Astrophysical Observatory)

ABSTRACT

The microquasar SS 433 is a target of great interest in modern astronomy as a unique Galactic source that shows steady relativistic jets. Although it has been studied for about 30 years since its discovery, the compact object has not been firmly identified yet. The best way to solve this problem is to determine its mass function by directly measuring the Doppler shifts of the stars due to the binary motion. We observed SS 433 using the FOCAS instrument on Subaru on 2007 October 5-9, and obtained good quarlity spectra over a one-third of the orbital period. We cross-correlate these spectra with that of the standard star HD 9233 in spectral regions where only "weak" absorption lines are present to avoid emission components not originating from the surface of the companion star. We made the same analysis using archive data of Gemini. From the Subaru and Gemini results, the amplitude of radial velocity curve of the companion star is found to be 60.5 +/- 4.0 km/s with a gamma velocity of 53.8 +/- 2.7 km/s. Combining our results with the radial velocity of the compact star previously studied, we determine the mass of the companion star and the compact star to be M_o=12.6(+4.2/-3.4) M_sun and M_x=4.5(+1.3/-1.1) M_sun, respectively. Our results establish that the compact star of the SS 433 is a black hole.

1. Microquasar SS 433

- SS 433 is the only one source that has continuous relativistic jets in our Galaxy.
- The nature of the compact object is unknown.
- **The best way to solve this problem is to determine its mass function by directly measuring the Doppler shifts of both stars due to the binary motion.**

Fig1: The image of the microquasar SS 433. The jets speed is 26 % of the light velocity. The jet axis shows precession with a period of 164 days. The orbital period is 13.1 days.

2. Subaru observations of SS 433

We observed SS433 using the Subaru FOCAS on 2007 October

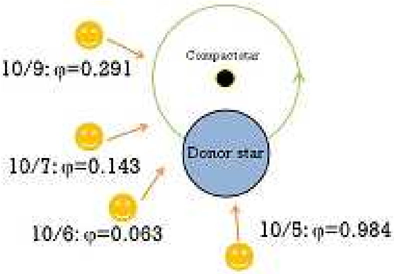

Fig2: The arrows show the line of sight at each observation epoch (ϕ: orbital phase). We observed SS 433 covering a period when the compact star recovered from an eclipse.

3. Spectra of the mass donor star of SS433

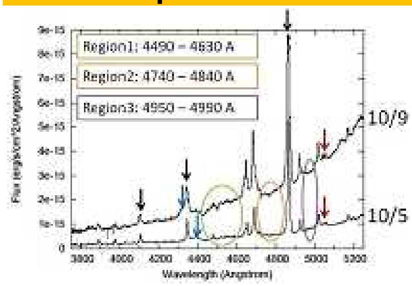

Fig3: The spectra of SS 433 obtained with FOCAS/Subaru on 2007 Oct 5 and Oct 9. Remarkable features are emission lines from the jets (↓,↓) and those from the accretion disk (↓). To find very weak absorption lines from the donor star, we make highly rectified spectra of Region 1 – 3 (Color circles region in the figure).

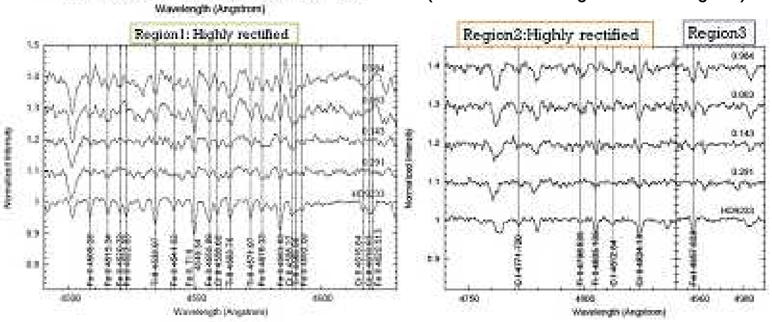

Fig4: Highly rectified spectra of SS 433 in Region 1 – 3 and the normalized spectrum of the standard star (HD 9233, A4 Iab) are shown in these figures. The numbers on the right side of the spectrum are the corresponding orbital phase ϕ of each spectrum. All spectra have been shifted into the rest frame. The spectrum of HD 9233 is scaled to match the SS 433 spectra (multiply by 0.36). Deep absorption lines near 4500 Å, 4760 Å, 4780 Å and 4980 Å are due to inter-stellar absorption (Hobbs et al. 2008). The spectra of HD 9233 and SS 433 contain the same weak absorption lines. The absorption-lines features in the SS 433 spectra become deeper as the donor star hides the compact star. This is evidence that they are originated from the donor star.

4. Radial velocity of the donor star

- By cross-correlating the spectra of SS 433 with that of HD 9233, we derived the radial velocity of the donor star.
- The obtained amplitude of the radial velocity curve is different between spectral regions used in the analysis (Region 2>Region 3> Region1).
- The difference in the amplitude is related to the "deepness" of the absorption lines; the absorption lines in Region 1 are the deep, while those in Region 2 are the weakest.
- We interpret that the deep absorption lines are affected by emission component from circumstellar medium, making the amplitude of the radial velocity curve apparently smaller in cross-correlation analysis.
- **To select "weak" lines are very important to trace the real moving of the donor star.** We conclude that the results of Region 2 is the most reliable.
- From the average line profiles of the "deep" and "weak" absorption lines, we confirmed that the position of the absorption-line center in the deep absorption features show the same velocity as in the weak ones, although there are emission components containing the feature in the former.

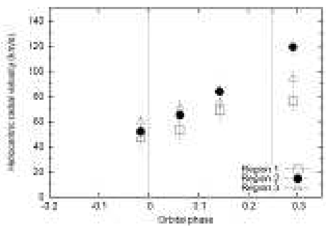

Fig5: The radial velocity curve of the donor star of SS 433.

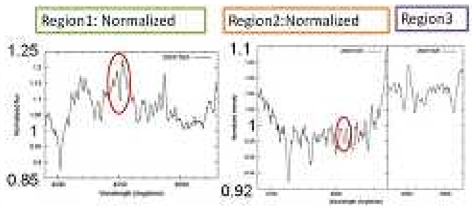

Fig 6: Normalized spectra of SS 433 in Region 1 – 3. The absorption lines in Region 1 are deep and show complex feature, while the absorption lines in Region 2 are weak and simple (See the lines in red circles).

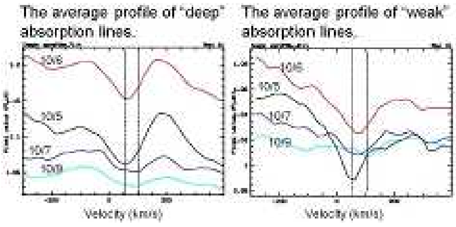

Fig7: The average profiles of "deep" and "weak" absorption lines. It is seen that the "deep" absorption lines have "wing" in emission. The shifts of the line center from Oct 5 to Oct 9 in both average line profiles are almost same as the results of Region 2.

- We analyzed Gemini archive data (Hillwig & Gies 2008) as well.
- SS 433 was active in the radio band in this observational period.

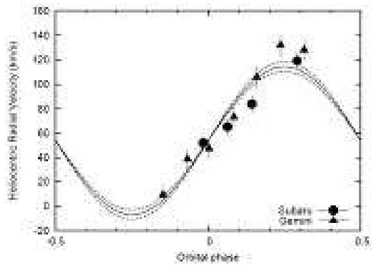

Fig 8: The radial velocity curve of the donor star measured from Subaru and Gemini, both using Region 2.

Amplitude of the radial velocity curve:
$$K_{\rm o} = 60.52 \pm 3.98 \text{ km/s}$$
Gamma velocity:
$$\gamma_{\rm o} = 53.82 \pm 2.7 \text{ km/s}$$

5. Radial velocity of the compact star

To measure the radial velocity of the compact star, we use He II (4685.71 Å) emission line originating from the accretion disk.

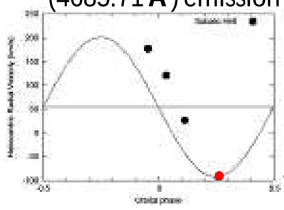

Fig 9: The radial velocity curve of the compact star measured from the He II line. Since the He II line in 1st – 3rd nights spectra are affected by eclipse effects (Fabrika & bychkova 1990), we utilize only 4th night data, with a fixed gamma velocity of 53.8 km/s, to determine the radial velocity amplitude. We obtain Kx = 146.9 km/s, which is consistent with previous works (Fabrika & bychkova 1990, Geis et al. 2008).

6. An estimate for the mass of the compact star in SS 433

$$M_{\rm O}\sin^3 i = \frac{1}{G}K_{\rm X}(K_{\rm X}+K_{\rm O})^2\frac{P}{2\pi} \qquad M_{\rm X}\sin^3 i = \frac{1}{G}K_{\rm O}(K_{\rm X}+K_{\rm O})^2\frac{P}{2\pi}$$

- Inclination angle: i = 78.8 ° (Margon & Anderson 1989)
- The amplitude of the radial velocity curve of the compact star:
  K_X = 168 +/- 18 km/s
  (The average of Fabrika & bychkova 1990 and Geis et al. 2008)
- Orbital period: P = 13.08 days(Goranskii et al. 1998)

$$M_{\rm O} = 12.6^{+4.2}_{-3.4}\, M_\odot \qquad M_{\rm X} = 4.5^{+1.3}_{-1.1}\, M_\odot$$

We conclude that the compact star of SS 433 is a ∼5 solar mass black hole !