Superbroad Component in Emission Lines of SS 433

P. S. Medvedev1*, S. N. Fabrika2, V. V. Vasiliev3, V. P. Goranskij4, and E. A. Barsukova2

1Space Research Institute, ul. Profsoyuznaya 84/32, Moscow, 117997 Russia
2Special Astrophysical Observatory, Russian Academy of Sciences, Nizhniy Arkhyz, 369167 Karachai-Cherkessian Republic, Russia
3Moscow State University, Moscow, 199992 Russia
4Sternberg Astronomical Institute, Universitetskii pr. 13, Moscow, 119991 Russia

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Abstract—We have detected new components in stationary emission lines of SS 433; these are the superbroad components that are low-contrast substrates with a width of 2000–2500 km s⁻¹ in He I λ4922 and Hβ and 4000–5000 km s⁻¹ in He II λ4686. Based on 44 spectra taken during four years of observations from 2003 to 2007, we have found that these components in the He II and He I lines are eclipsed by the donor star; their behavior with precessional and orbital phases is regular and similar to the behavior of the optical brightness of SS 433. The same component in Hβ shows neither eclipses nor precessional variability. We conclude that the superbroad components in the helium and hydrogen lines are different in origin. Electron scattering is shown to reproduce well the superbroad component of Hβ at a gas temperature of 20–35 kK and an optical depth for Thomson scattering $\tau \approx 0.25$–0.35. The superbroad components of the helium lines are probably formed in the wind from the supercritical accretion disk. We have computed a wind model based on the concept of Shakura–Sunyaev supercritical disk accretion. The main patterns of the He II line profiles are well reproduced in this model: not only the appearance of the superbroad component but also the evolution of the central two-component part of the profile of this line during its eclipse by the donor star can be explained.

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INTRODUCTION

SS 433 is the only known supercritical accretor in our Galaxy. This object is a massive eclipsing close binary system with an orbital period of 13.1 days (for a review, see Fabrika et al. 2004). The donor star overfills its critical Roche lobe and transfers mass to the relativistic component (very likely a black hole) on the thermal time scale; the mass transfer rate from the donor to the accretion disk is $M \approx 10^{-4} M_\odot$ yr⁻¹.

The ultraluminous X-ray sources (Feng and Sofia 2011) observed in external galaxies can be other examples of supercritical accretion disks. It is very likely that these objects are supercritical accretors like SS 433 (Fabrika and Mescheryakov 2001), but their orientation is such that an observer can see the bottom of the supercritical disk funnel. Supercritical accretion is probably a necessary element for the growth of supermassive black holes (Volonteri and Rees 2005) at early stages of the increase in quasar mass. The supercritical regime can be of fundamental importance not only for the black hole growth efficiency but also for the feedback on the galaxies and the formation of galaxies and clusters of galaxies via jets and winds. Given the importance of these processes, detailed studies of SS 433 and the structure of gas flows in this system are needed, because no other bright and close examples of supercritical accretion disks have been found.

Despite the large number of studies devoted to SS 433, the mass of the relativistic star in this system has not been measured reliably; the spread in mass determinations for the compact object is from 2 to 15 $M_\odot$ (see Fabrika and Bychkova 1990; Hillwig et al. 2004; Blundell et al. 2008; Kuchota et al. 2010; see, however, Goranskij 2011). The system’s luminosity has been measured much more reliably (Cherepashchuk 2002; Fabrika and Sholukhova 2008), $L_{bol} \approx 10^{40}$ erg s⁻¹ with its peak in the ultraviolet. Since the observed luminosity would be too high for a neutron star, a black hole with a supercritical accretion disk is believed to be in SS 433. For a black hole with a mass of $\approx 10 M_\odot$, the
rate of gas accretion into the disk of SS 433 roughly corresponds to 300–500 Eddington accretion rates.

The main energy release in SS 433 is accounted for by the relativistic component or, more precisely, its supercritical accretion disk. The observational manifestations of this system are completely determined by the disk orientation. Almost all of the accretion energy must be released in the hard X-ray range, but the X-ray luminosity of SS 433 \( (L_x \sim 10^{36} \text{ erg s}^{-1}) \) is much lower than the bolometric one. The initial hard X-ray emission is thermalized in a powerful wind outflowing from the inner regions of the supercritical disk. The apparent size of the wind photosphere for an observer is \( \sim 10^{12} \text{ cm} \). The system’s orientation is such that we cannot see the funnel base even at the times of best funnel visibility during the precessional motion of the disk. If the funnel bottom were seen, then SS 433 would probably be the most luminous X-ray source in the Galaxy with \( L_x \gtrsim L_{\text{bol}} \). An increase in the X-ray luminosity is predicted through the geometric collimation of emission by the supercritical disk funnel.

SS 433 has precessing relativistic jets moving with a constant velocity \( v_J \approx 0.26c \) that are formed in the funnel of the supercritical accretion disk and closely follow the disk and funnel orientation. The so-called “moving” or “relativistic” hydrogen and He I lines are formed in the jets; these emission lines move over the spectrum in accordance with the orientation of the jets relative to the observer. The spectrum of SS 433 exhibits weak absorption lines from which the orbital motion of the donor star was measured (Gies et al. 2002; Hillwig et al. 2004; Cherepashchuk et al. 2005; Kubota et al. 2010). However, the extended gaseous envelope that outflows from the donor but is no longer gravitationally bound to it may make a noticeable contribution in the absorption line. Even at the times of the deepest (“total”) eclipses of the accretion disk by the donor, the contribution from the supercritical disk to the total brightness of the system is larger than the contribution from the donor (Gies et al. 2002; Hillwig and Gies 2008; Goranskij 2011). According to this contribution, the extended envelope of the donor will distort significantly the donor’s absorption lines.

The brightest emission lines in SS 433 are the hydrogen ones that originate in the wind outflowing from the accretion disk and in the gas lost by the system through the Lagrangian point behind the disk (Blundell et al. 2008). The He I and Fe II emission lines originate in the same medium. All these lines show orbital motion with different amplitudes and with a phase lag relative to the instantaneous position of the accretion disk (Crampton and Hutchings 1981; Kopylov et al. 1989). For this reason, it is difficult to measure the system’s mass using these lines.

The only line that reflects the motion of the relativistic component (in fact, the wind that is formed in the disk) is the He II line; it was used to measure the system’s mass function (Crampton and Hutchings 1981; Fabrika and Bychkova 1990). The width of the He II line is \( \text{FWHM} = 600–1000 \text{ km s}^{-1} \); obviously, it is formed in the hottest part of the wind, possibly closer to the disk axis. The orbital radial velocity curve depends on the precessional phase, i.e., on the disk inclination to the line of sight. Knowing the behavior of this line is very important for understanding the reliability of measuring the masses.

Here, we investigate the He II line profile based on our and archival best-quality spectra and find a new component in the profile of this line that we call a “superbroad” component (SBC). We find the same components in the He I and hydrogen lines. We investigate the behavior of these components using the H\( \beta \) and He I \( \lambda 4921 \) lines as an example. In the final part of the paper, we discuss the interpretation of the SBCs in these lines.

**OBSERVATIONAL DATA**

Our observational material consist of 44 optical spectra for SS 433 taken with different telescopes from 2003 to 2007. All spectra are only of good quality; these are the total spectra obtained during a single night. The dates of our spectroscopic observations, the precession and orbital phases, and the telescopes/instruments are given in Table I.

In 2003, observations were carried out at the 6-m BTA telescope with the UAGS spectrograph (Cherepashchuk et al. 2005); the spectral resolution was 4 \( \AA \). At the same telescope but with the SCORPIO spectrograph (Afanasiev and Moiseev 2005), spectra were taken in 2004–2007; the spectral resolution was 2 (2004), 2.5–3 (2005, 2006), and \( \approx 5 \) \( \AA \) (2007). In October 2007, simultaneously with BTA, spectroscopy for SS 433 was performed at the Subaru telescope with the FOCAS spectrograph (Kubota et al. 2010); the spectral resolution was 1.5 \( \AA \).

Our spectra were supplemented with archival data. These are the 2004 spectra from the 4.2-m WHT telescope taken with the ISIS spectrograph (Clegg 1991) with a resolution of 0.7 \( \AA \). Here, we selected a continuous set of observations consisting of six nights that covers the precessional phases when the line of sight was in the disk plane. We also used the archival data obtained in 2006 at the 8-m Gemini-North telescope with the GMOS spectrograph (Hillwig and Gies 2008); the spectral resolution in these data was \( \approx 1 \) \( \AA \). The difference in the spectral resolution of our data does not affect the identification and analysis of SBCs in the line profiles.