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Suzaku observations of the dwarf nova SS Cygni in quiescence and outburst

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Abstract. We present results from the Suzaku observations of the dwarf nova SS Cyg in quiescence and outburst in 2005 November. High sensitivity of the HXD PIN and high spectral resolution of the XIS enable us to determine plasma parameters with unprecedented precision. The maximum temperature of the plasma in quiescence $20.4^{+4.0}_{-2.6}$ keV is significantly higher than that in outburst $6.0^{+0.2}_{-1.3}$ keV. The elemental abundances of oxygen and iron are both subsolar ($0.46^{+0.04}_{-0.03}Z_{\odot}$ and $0.37^{+0.01}_{-0.03}Z_{\odot}$, respectively). The solid angle of cold reflecting matter subtending over an optically thin thermal plasma is $\Omega/2\pi = 1.7 \pm 0.2$ in quiescence. A 6.4 keV iron Kα line is resolved into narrow and broad components. These facts indicate that both the white dwarf and the accretion disk contribute to the reflection. We consider the standard optically thin boundary layer as the most plausible picture for the plasma configuration in quiescence. The solid angle of the reflector in outburst $\Omega/2\pi = 0.9^{+0.5}_{-0.4}$ and a broad 6.4 keV iron line indicate that the reflection in outburst occurs at the surface of the accretion disk. The broad 6.4 keV line suggests that the optically thin thermal plasma is distributed over the accretion disk like solar coronae.

Key words. accretion, accretion disks — plasmas — stars: dwarf novae — X-rays: individual (SS Cygni)

1. Introduction

SS Cygni is one of the best known dwarf novae with the primary and the secondary stars having mass of $1.19\pm0.02M_{\odot}$ and $0.704\pm0.002M_{\odot}$ (Friend et al. 1990) orbiting at a period of 6.60 h. It shows an optical outburst roughly every 50 days during which its visual magnitude changes from $m_{\rm V} \simeq 12$ to 8.

In order to fully understand multi-waveband behaviour of SS Cyg, the first systematic coordinated observation from optical to X-ray was conducted by Wheatley et al. (2003). Their light curves consist of optical (AAVSO V-band), EUVE (72–130Å), and RXTE (2–15 keV) which monitor an outer disk, the innermost part of the disk or optically thick boundary layer (hereafter referred to as BL), and the optically thin BL, respectively. The light curves show that the hard X-ray flux increases in the beginning of the outburst as the optical flux increases, but when the optical intensity exceeds $m_{\rm V} \simeq 10$, the hard X-ray intensity suddenly drops, and instead, the EUV intensity increases. This behavior can be explained by the optically thin to thick transition of BL (Patterson & Raymond 1985) as follows. In quiescence, where $\dot{M}$ is less

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than 10^{16} g s^{-1}, the optically thick to thin transition of the disk occurs at some radius due to increase of friction. The temperature of the optically thin part (optically thin BL) is $\sim 10^8$ K, emitting hard X-rays. In the outburst state, on the other hand, the density of the disk is high enough, and efficient cooling keeps the disk optically thick throughout, thereby emitting EUV and soft X-rays. Hence, the outburst is accompanied by an increase of the EUV flux in expense of the hard X-ray flux, as is observed. This picture, however, predicts that the hard X-ray emission in outburst should disappear in total, whereas in real there remains some flux in the hard X-ray band (Wheatley et al. 2003).

The aim of the Suzaku observations is to understand geometries of the hard X-ray emission region. In outburst, we try to identify the hard X-ray emission site and consider possible emission mechanism. In quiescence, we attempt to constrain physical parameters of the optically thin BL.

2. Observations

Figure 1 shows an AAVSO optical light curve of SS Cyg with the Suzaku observation windows overlaid. November 2 for 40 ks exposure. During the observation, m_{V} was in the range 11.5–12.1. SS Cyg then turned in an outburst state (normal outburst) on November 12. In order to firmly detect BL after the optically thin to thick transition, the outburst observation was performed on November 18. The exposure time was 60 ks.

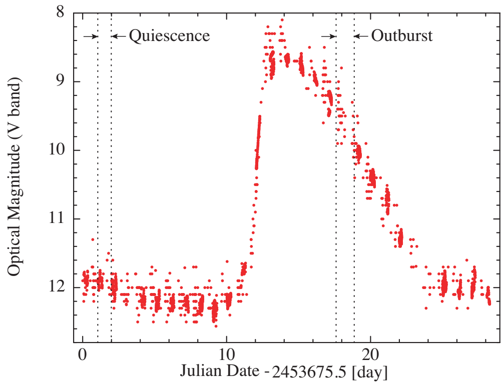

Fig. 1. AAVSO optical light curve of SS Cyg near the Suzaku observations.

3. Analysis and results

3.1. Suzaku spectra

In Fig. 2 shown are the Suzaku spectra of SS Cyg in quiescence and outburst. In quiescence, SS Cyg is detected with the HXD PIN at least up to 30 keV. The inset shows that iron emission lines are clearly resolved into 6.4, 6.7, and 7.0 keV components. Of them, the 6.7 and 7.0 keV lines are coronal emission from the optically thin hot plasma in BL,

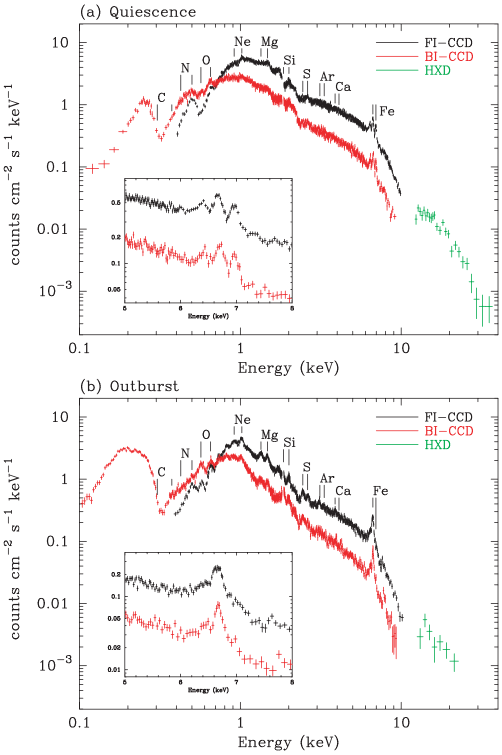

Fig. 2. Suzaku spectra of SS Cyg in (a) quiescence and (b) outburst. Spectra from the FI CCDs (XIS0, XIS2, and XIS3), from the BI CCD (XIS1) and the HXD PIN are shown in black, red, and green. The insets are blowup of the iron Kα line bands.

while the 6.4 keV line is emitted from cold matter surrounding BL via fluorescence. Close inspection of the 6.4 keV line profile indicates that this line is composed of narrow and broad tail components. They are interpreted as being from the white dwarf surface and the accretion disk, respectively.

In outburst, on the other hand, the spectra are softer than those in quiescence, and are characterized by H-like and He-like K-alpha lines from nitrogen to iron. This indicates that the plasma has a temperature distribution. From the inset, the 6.4 keV emission line is basically broad. In addition, there is an excess emission in the soft X-ray band below 0.4keV. From the light curve of this band (Ishida et al. 2009), this component monotonically declines from the beginning to the end of the observation. This fact undoubtedly indicates that this excess component is the high-energy end of the optically thick BL emission.

3.2. Spectral components

Figure 3 schematically shows spectral components of SS Cyg both in quiescence and outburst.. As explained above, the hard X-ray spectrum of SS Cyg is primarily composed of a multi-temperature plasma emission. We adopt a power-law type emission measure distribution described as,

$$d(EM) \propto \left(\frac{T}{T_{\rm max}}\right)^{\alpha-1} dT,$$

where $T_{\rm max}$ is the maximum temperature of the BL plasma. This temperature distribution is successful in explaining the spectra of 30 dwarf novae observed with ASCA as demonstrated by Baskill et al. (2005). In addition to this, there is a fluorescent iron line at 6.4keV. The matter responsible for the 6.4 keV line acts as a reflector also for the continuum emission. We thus should take into account a reflection continuum component of the original plasma emission spectrum.

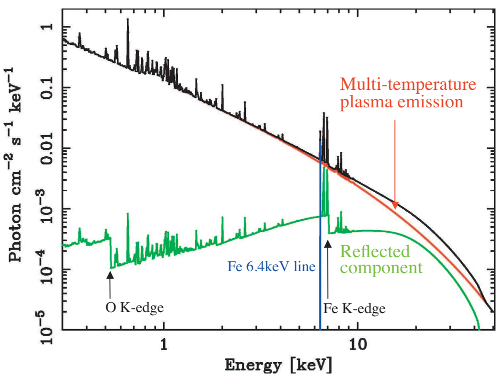

Fig. 3. Schematic view of the SS Cyg X-ray spectrum.

3.3. Spectral analysis

From the spectra of SS Cyg, we can obtain the equivalent width of the 6.4keV line, and the solid angle of the reflecting matter (Ω), and by using them we can deduce the geometry of the plasma. They are, however, coupled with some other parameters, such as $T_{\rm max}$, abundances of oxygen ($Z_{\rm O}$) and iron ($Z_{\rm Fe}$), in a complicated manner. We thus have decided to carry out a combined fit of the spectra relevant to all these parameters and tried to find self-consistent solution. They are the quiescence spectrum in the 4.2–40 keV band (sensitive to $T_{\rm max}$, α, Ω in quiescence and $Z_{\rm Fe}$), and the outburst spectra in the 4.2–10 keV (sensitive to $T_{\rm max}$, α, Ω in outburst and $Z_{\rm Fe}$) and 0.55–0.72 keV bands (sensitive to α in outburst, $Z_{\rm O}$ and $Z_{\rm Fe}$). The fit is acceptable at the 90% confidence level, and the best-fit parameters are listed in table 1. The maximum temperature of the plasma $T_{\rm max}$ is

Table 1. Best-fit parameters of the combined fit.

Parameter	Quiescence	Outburst
$T_{\rm max}$ (keV)	$20.4^{+4.0}_{-2.6}$	$6.0^{+0.2}_{-1.3}$
$\Omega/2\pi$	1.7 ± 0.2	$0.9^{+0.5}_{0.4}$
$Z_{\rm Fe}$ ($M_\odot$)	$0.37^{+0.01}_{-0.03}$	
$Z_{\rm O}$ ($M_\odot$)	$0.46^{+0.04}_{-0.03}$	

higher and the plasma is more covered by the reflector (Ω is larger) in quiescence. The metal abundances are subsolar.

4. Discussion

4.1. Plasma geometry in outburst

Based on the results above, we can discuss on the hard X-ray emission site in outburst. The 6.4 keV iron line is broad. Quantitatively, a Gaussian fit to the line results in a sigma of 70^{+80}_{-60} eV, which is equivalent to the line-of-sight velocity of 3300 km s^{-1}, although the error is large. This suggests that the main reflector in outburst is the accretion disk. If we attribute this width to the Kepler motion, the reflection site is ∼5000 km away from the WD (again the error range is 10^8–10^{10} cm), which is consistent with the size of the disk. The solid angle of the reflector is consistent with a plasma with small extent on a disk ($\Omega \simeq 2\pi$). All these facts indicate the plasma is located above the disk like coronae with their height small enough compared with the disk radius, as shown in Fig. 4.

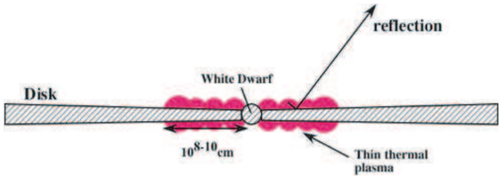

Fig. 4. Geometry of the hard X-ray emitting hot plasma in outburst.

4.2. Plasma geometry in quiescence

In quiescence, on the other hand, the solid angle of the reflector is as large as $\Omega/2\pi = 1.7 \pm 0.2$. Neither the white dwarf nor the accretion disk can cover more than 2π solely by themselves. The plasma should therefore be compact and covered both by the white dwarf and the accretion disk cooperatively. This is consistent with the standard picture of the optically thin BL in quiescence (Patterson & Raymond 1985). If the plasma is confined between the white dwarf and the accretion disk, as shown in Fig. 5, the solid angle can be as large as 3π at most. This is marginally consistent with the best-fit result.

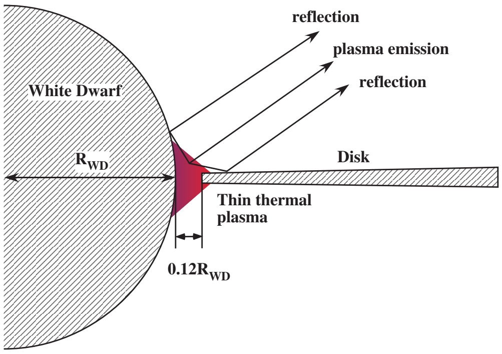

Fig. 5. Geometry of the hard X-ray emitting hot plasma in quiescence.

5. Conclusions

We have presented results of the Suzaku observations on the dwarf nova SS Cyg in quiescence and outburst in 2005 November. The X-ray spectra of SS Cyg are composed of a multi-temperature optically thin thermal plasma model with a maximum temperature of a few tens of keV, its reflection from the white dwarf surface and/or the accretion disk, and a 6.4 keV neutral iron Kα line from the reflectors via fluorescence. High sensitivity of the HXD PIN detector and the high spectral resolution of the XIS enable us to disentangle degeneracy between the maximum temperature and the reflection parameters, and to determine the emission parameters with unprecedented precision. The maximum temperature of the plasma in quiescence $kT_{\max} = 20.4^{+4.0}_{-2.6}$ keV is significantly higher than that in outburst $kT_{\max} = 6.0^{+0.2}_{-1.3}$ keV. The elemental abundances of iron and oxygen are $0.37^{+0.01}_{-0.03} Z_\odot$ and $0.46^{+0.04}_{-0.03} Z_\odot$, respectively. The solid angle of the reflector subtending over the optically thin thermal plasma is $\Omega/2\pi = 1.7 \pm 0.2$ in quiescence. Since even an infinite slab can subtend a solid angle of $\Omega/2\pi = 1$ over a radiation source above it, this large solid angle can be achieved only if the plasma views both the white dwarf and the accretion disk with substantial solid angles. We consider the standard optically thin BL formed between the inner edge of the accretion disk and the white dwarf surface (Patterson & Raymond 1985) as the most plausible model to explain the observed large solid angle.

The solid angle of the reflector in outburst $\Omega/2\pi = 0.9^{+0.5}_{-0.4}$, on the other hand, is significantly smaller than that in quiescence, and is consistent with an infinite slab. Since the 6.4 keV iron emission line is broad, and its velocity is consistent with the Keplerian motion of the accretion disk, we believe that the reflection occurs at the surface of the accretion disk. These facts lead us to conclude that the optically thin thermal plasma in outburst locates on the surface of the accretion disk, like solar coronae.

We refer the readers to Ishida et al. (2009) for the full detail of this work.

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