Suzaku and Optical Spectroscopic Observations of SS 433 in the 2006 April Multiwavelength Campaign

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Abstract

We report results of the 2006 April multi-wavelengths campaign of SS 433, focusing on X-ray data observed with Suzaku at two orbital phases (in- and out-of- eclipse) and simultaneous optical spectroscopic observations. By analyzing the FeXXV Kα lines originating from the jets, we detect rapid variability of the Doppler shifts, \( dz/dt \approx 0.019/0.33 \) day\(^{-1}\), which is larger than those expected from the precession and/or nodding motion. This phenomenon probably corresponding to “jitter” motions observed for the first time in X-rays, for which significant variability both in the jet angle and intrinsic speed is required. From the time lag of optical Doppler curves from those of X-rays, we estimate the distance of the optical jets from the base to be \( (3 - 4) \times 10^{14} \) cm. Based on the radiatively cooling jet model, we determine the innermost temperature of the jets to be \( T_0 = 13 \pm 2 \) keV and \( 16 \pm 3 \) keV (the average of the blue and red jets) for the out-of-eclipse and in-eclipse phase, respectively, from the line intensity ratio of FeXXV Kα and FeXXV Kα. While the broad band continuum spectra over the 5–40 keV band in eclipse is consistent with a multi-temperature bremsstrahlung emission expected from the jets, and its reflection component from cold matter, the out-of-eclipse spectrum is harder than the jet emission with the base temperature determined above, implying the presence of an additional hard component.

Key words: stars: individual (SS433) — binaries — accretion discs — ISM: jets and outflows — X-rays: individual (SS433)

1. Introduction

SS 433 is a unique Galactic binary system that exhibits continuous relativistic jets, and hence is an ideal target to study fundamental problems of astrophysical jets, including the acceleration/collimation mechanism, structure, and influence on the environment (for a review, refer to e.g., Margon 1984; Fabrika 2004). The intrinsic speed of the jets is \( 0.26c \) (\( c \) is the light speed), and the jet axis precesses with a period of 162 days. The optical and X-ray spectra show several pairs of Doppler shifted lines from the bipolar jets. The strong emission lines, such as Hα and lines from ionized heavy elements, give direct evidence that the jets mainly contain baryonic plasmas. Most recently, Kubota et al. (2010) constrains the mass of the compact object to be \( 1.9 - 4.9 \) M⊙, indicating that the supercritical accretion star is most likely a low mass black hole, although a possibility of a massive neutron star cannot be ruled out. The inclination angle and orbital period are accurately measured to be \( i = 78.8° \) (Margon & Anderson 1989) and \( P=13.082 \) days (Goranskii et al. 1998), respectively.

Soon after the discovery of SS 433, many efforts were done to determine the kinematic model and parameters of the jets, by tracing the Doppler shifts of emission lines in the optical spectra. Margon et al. (1979) for the first time proposed a kinetic model, where the jets of about 1/4 the light speed make precession, with a period of 162±15 days, according to the latest value obtained by Gies et al. (2002). In superposition to the “precession” motion, another regular periodicity of the Doppler shifts is observed as a “nodding” motions with an amplitude of \( \Delta z \sim 0.01 \) and a period of 6.28 days. They are caused by the tidal torques from the companion star. Furthermore, faster random variability of Doppler shifts were sometimes reported (see e.g., Ciatti et al. 1981; Katz & Piran 1982; Iijima 1993; Collins & Garasi 1994). These phenomena are called as “jitter”, which contains an important clue to understand the collimation mechanism of the jets. The origins of “jitter” have not been understood,
2. Observations and Data Reduction

2.1. Suzaku

We observed SS 433 with Suzaku on two occasions, on 2006 April 4–5 and April 8–9 for a net exposure of \( \approx 40 \) ks each. Suzaku (Mitsuda et al. 2007) carries the four X-ray Imaging Spectrometers (XIS-0, 1, 2 and 3) coupled with the X-ray Telescopes (XRTs) and the Hard X-ray Detector (HXD), which covers the 0.2–10 keV and 10–600 keV bands, respectively. The XIS-0, 2, and 3 are front-side illuminated CCDs (XIS-FI), while the XIS-1 is a back-side illuminated one (XIS-BI). The energy resolution of the XISs is \( \approx 130 \) eV (FWHM) at 6 keV. The first observation was performed at the orbital phase of \( \phi = 0.97 \) (as calculated from the ephemeris by Goranskii et al. 1998), during the midst of an eclipse by the companion star, while the second was at \( \phi = 0.26 \) after the source recovered from the eclipse. From our optical observations, the precession phase is found to be \( \psi \approx 0.6 \) (as calculated from the ephemeris by Gies et al. 2002), when we see the accretion disk in almost an edge-on view. At this precession phase, the directions of the twin jets with respect to the line-of-sight are inverted from those observed at most of the precession phases, and both show redshifts. In this paper, we call the jet with a larger redshift as “red” jet and the other as “blue” jet. The XIS was operated in the normal clock/editing mode without an window option. The target was observed at the XIS nominal position. Table 1 gives the log of the X-ray observations.

2.1.1. XIS data

We analyze the XIS data in a standard manner with the HEASoft\(^1\) version 6.6.2 software package. Photon events are extracted from a circular region centered at the target with a radius of 6 mm (4′.35). The background is taken from the surrounding annulus region. For spectral analysis, we make the response matrix file (RMF) and ancillary response file (ARF) using \texttt{xisrmfgen} and \texttt{xisimarfgen} (Ishisaki et al. 2007), respectively. The spectra of all the XIS sensors are combined to improve the statistics, together with the corresponding responses. We screen out events suffering from telemetry saturation, using GTI filters provided by the Suzaku team\(^2\).

2.1.2. HXD/PIN data

The HXD is a non-imaging collimated X-ray sensor consisting of two main detection parts; silicon \( \delta \)-intrinsic-\( n \) diodes (hereafter PIN) and gadolinium silicate crystals (Ce-doped \( \text{Gd}_2\text{SiO}_5 \); GSO). They cover the energy range of 10 – 70 keV (PIN) and 40 – 600 keV (GSO) with low

\(^{1}\) http://heasarc.nasa.gov/heasoft

\(^{2}\) http://www-cr.scphys.kyoto-u.ac.jp/member/hiroya/xis/gtifile.html
background levels (Takahashi et al. 2007). In the present study, we concentrate on the PIN data, since the signals from SS 433 above 40 keV is below the sensitivity of the GSO. Since the observations were performed in the normal mode of the HXD, we simply extract the spectra from the PIN event data, following the standard analysis procedure. We subtract the non X-ray background (NXB) from the data, utilizing the modeled NXB distributed by the Suzaku team. The version keyword of the NXB files is METHOD=LCFITDT (i.e., so-called the “tuned background”), which gives the best reproductivity of the PIN NXB (0.34% systematic error in the 15–40 keV for a 40 ksec exposure; Fukazawa et al. 2009).

In addition to the NXB, two kinds of diffuse/extended background should be subtracted before the spectral analysis; the cosmic X-ray background (CXB) and the Galactic X-ray background (GXB). The GXB is particularly important because a target source is close to the Galactic plane. Since the surface brightness of the GXB varies field to field, we estimate its spectrum using the Galactic plane. Since the surface brightness of the GXB is particularly important because a target source is close to the Galactic plane. Since the surface brightness of the GXB varies field to field, we estimate its spectrum using the Galactic plane.

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variability, we divide the one day data into eight parts (data number 1 to 8) with an equal interval, and perform spectral fitting to each spectrum. To focus on the iron-K band by making the best use of the energy resolution of the XIS, we only analyze the 5.0–10 keV band.

The fitting model consists of a bremsstrahlung continuum and 11 emission lines, modified by the interstellar absorption. It is expressed as a function of energy $E$:

$$e^{-\sigma(E)N_H \times \left[\text{Brems}(kT) + \text{Fe}_1 K\alpha_{z=0} + \left(\text{Fe}_{XXV} K\alpha + \text{Fe}_{XVI} K\alpha + \text{Ni}_{XXVII} K\alpha + \text{Fe}_{XXV} K\beta + \text{Fe}_{XVI} K\beta\right)_{z=2,\text{red}} + \left(\text{Fe}_{XXV} K\alpha + \text{Fe}_{XVI} K\alpha + \text{Ni}_{XXVII} K\alpha + \text{Fe}_{XXV} K\beta + \text{Fe}_{XVI} K\beta\right)_{z=2,\text{blue}}\right]}$$

where $\sigma(E)$ is the photo-electric cross section and $N_H$ is the hydrogen column density toward the source. We fix $N_H$ at $1.5 \times 10^{22}$ cm$^{-2}$, which is converted with the formula by Predel & Schmitt (1995) from $A_V=8$, a typical extinction for SS 433 (Fabrika 2004). In this study, for simplicity, we adopt a single temperature bremsstrahlung model for the continuum, considering the limited energy band; although a more complicated model is applied for the continuum and line emission by self-consistent calculation. Instead, we only consider a continuum model, over which the 11 emission lines are superposed as independent parameters.

We adopt a multi-temperature bremsstrahlung model for the continuum; assuming a power law dependence of the temperature of the jet $T$ on the distance from the jet base $r$, we can compute a model spectrum according to the expected relation between the differential emission measure and temperature. Here we consider a stationary jet model consisting of radiatively cooling, expanding plasmas (e.g., Kotani et al. 1996). The jets are assumed to move in a truncated cone with a constant velocity. Hence, the density changes as $n(r) \propto r^{-2}$. This model predicts approximately $T \propto r^{-2(\gamma-1)}$, where $\gamma$ is the adiabatic index ($5/3$ for non relativistic particles). Since we cannot well constrain the power law index from our data, we assume $T \propto r^{-4/3}$ according to this model. The free parameters are the innermost temperature $T_0$ and its normalization.

We also consider a reflection component from cold matter, which is indicated by the presence of the fluorescence 6.4 keV iron K emission line, although it has been neglected in most of previous studies. For this we adopt the reflection code by Magdziarz & Zdziarski (1995), available as reflect model on XSPEC applicable for any incident spectrum. The free parameter is the reflection strength $R=\Omega/2\pi$, where $\Omega$ is the solid angle seen by the X-ray emitter (i.e., the jets). We fix solar metal abundances and an inclination angle of 79°, assuming that the reflection mainly takes place in outer parts of the accretion disk.

The fitting results for the epoch A spectra are shown in Figures 6 and 7. The best-fit parameters are summarized in Table 3. In the analysis, the relative normalization between the XIS and HXD/PIN is fixed at 0.923, based on the calibration using the Crab Nebula (Ishida et al. 2007). We obtain the innermost jet temperature of $T_0 = 27 \pm 2$ keV. To make the reflection parameter physically meaningful, we limit $R \leq 1$ in the fitting and finally obtain $R = 1.0^{+0.41}_{-0.40}$. The equivalent width of the 6.4 keV line with respect to the reflection component turns out to be 1.0 keV at the best-fit value, well consistent with theoretical calculations (Matt et al. 1991) within a possible range of viewing angle and an iron abundance.

4. Suzaku Results II. (in Eclipse)

The same analysis as in the previous section is applied for the data of the first Suzaku observation (in-eclipse). Figure 8 shows the X-ray light curves on 2006 April 4–5 in the three energy bands. A long term variability is clearly seen, as expected from the eclipse of the jets by the companion star. Similarly to the out-of-eclipse data, we make 8 time-sliced spectra and perform spectral fitting to each one, using the same spectral model described in § 3.

In this period, since the spectra around 6.4 keV are very crowded and hence the intensity of the Fe Kα line can-
not be determined, we fix it at $3.7 \times 10^{-5}$ photons$^{-1}$ cm$^{-2}$, a value that is estimated from the analysis of the broad-band spectra with a reflection component, as described below. Figure 9 shows the evolution of the line center energies of the FeKα line. We do not detect significant variability of the reflection component as described in the previous subsection. We use the same multi-temperature jet model with a reflection component to constrain the continuum model, using the HXD/PIN spectra to constrain the continuum model, as described in the previous subsection. We limit $R \leq 1$ and fix the equivalent width of the fluorescence FeKα line with respect to the reflection component at 1.0 keV, based on the result of the out-of-eclipse data, since it is difficult to constrain the absolute intensity from the data. We obtain $T_0 = 21 \pm 1$ keV and $R = 1.0^{+0.13}_{-0.004}$.

Figures 10 and 11 show the data and best-fit model. The best-fit parameters are summarized in Table 3.

5. Discussion

5.1. X-ray and Optical Doppler Shift Curves

Figure 12 shows the Doppler shifts of the SS 433 jets measured with the Suzaku XIS (circles) and optical spectroscopy (crosses). The two dot lines correspond to the 162.15 days period sinusoidal curves for the blue and red jets expected from the precession motion (Gies et al. 2002), which is shifted by $-5.5$ days to fit the observational points. From this figure, it is confirmed that the Suzaku observations were performed at a precession phase when the jets axis are almost perpendicular to the line of sight.

Figure 13 is a blow-up of Figure 12 around the Suzaku observation epoch. It is clearly seen that the observed Doppler shift curves both from the X-ray and optical data show strong deviation from the precession curve with a 162.15 days period. Except for the data around 2006 April 8 (MJD 53834), both amplitude and periodicity of this deviation are consistent with the nodding motion of the jets, expressed as a sinusoidal curve with a 0.28 days period and a semi-amplitude of $\Delta z \approx 0.012$ at our precession phase (Fabrika 2004).

As mentioned above, in the Suzaku XIS data on 2006 April 8, we detect rapid variability of the Doppler shifts, $dz/dt \approx 0.019/0.33$ day$^{-1}$. This is larger than those expected from the precession and/or nodding motion of the jets; the maximum variability from the nodding motion is $dz/dt \approx 0.004/0.33$ day$^{-1}$ (Fabrika 2004). Hence, we interpret that our Suzaku result corresponds to a jitter which was previously reported only from the optical spectroscopy (e.g., Iijima 1993), observed for the first time in X-rays. The origin of these phenomena will be discussed in the next subsection.

Utilizing our quasi simultaneous X-ray and optical spectroscopic data, we can determine a time lag between the epochs when same jet material emits X-rays and optical lights, assuming that the Doppler shift remains constant in traveling along the jet. Based on the optical data points on MJD 53834.8 and previous X-ray curves, the lag in the red and blue jet is estimated to be $0.64 \pm 0.08$ day and $0.38 \pm 0.08$ day, respectively. Assuming that the jets speed is constant at 0.26c, we estimate the distance of the optical jets measured from the X-ray jets to be $l_{\text{opt}} = (4.3 \pm 0.6) \times 10^{14}$ cm (red) and $l_{\text{opt}} = (2.6 \pm 0.6) \times 10^{14}$ cm (blue). Thus, the Hα emitting region may not be at the symmetric location between the twin jets, depending on the efficiency of the cooling determined by the plasma density. The order of the jet size is well consistent with previous estimates (Fabrika 2004).

The jitter observed in X-rays on 2006 April 8–9 is confirmed in the optical spectra taken after this event. Since the length of the optical jets is 1000 times larger than that of the X-ray jets, fast time variability observed in X-rays is significantly smeared out in the optical band. Thus, soon after a rapid change of Doppler shifts is observed in X-rays, the optical emission lines become broad (if unresolved), by including the contribution from jet material ejected at different epochs. This is called a “projection effect”, previously observed from nodding motions (Borisov & Fabrika 1987). Thus, we investigate the change of the width of Hα lines originating from the jets before and after the second Suzaku observation (out-of-eclipse). The optical spectra observed at the GAO are plotted in Figure 14. We find that while the Hα line width of the blue and red jets was 40 Å (FWHM) and 58 Å on April 7, the lines became significantly broader with a FWHM of 188 Å and 315 Å, respectively, on April 9. This change of the Hα line width corresponds to $\Delta z = 0.023$ (blue jet) and $\Delta z = 0.039$ (red jet), which is larger only by $\Delta z = 0.005$ than the total observed change of the Doppler shifts of X-ray lines. Thus, the broadening of the Hα lines seen in the April 9 spectrum is mainly attributable to the rapid change of the Doppler shifts occurring close to the jet base.

5.2. Origin of the X-ray Jitter

We have detected the fastest variability of Doppler shifts of X-ray emission lines ever observed from SS 433, which can be interpreted as jitter motions of the jets, not the nodding motions where much slower change of red-shifts is expected. Assuming that the twin jets are always symmetric, we can estimate the orientation and intrinsic speed of the jets from the observed Doppler shifts of blue and red components. The results are plotted in Figure 15. As noticed from the figure, we detect a significant change in both angle and speed of the jets during the latter interval. From the former half toward the end of the observation, the jet speed increased by a factor of $(8 \pm 2)\%$. Recall that in the same epoch, the X-ray spectra became softer and hence the temperature of the jet decreased. This anti-correlation between the jet speed and temperature must be explained in theoretical models of jets.

Considering the smooth evolution of flux and line center energy, we infer that the X-ray jitter originates from a continuous change of the jet kinetic parameters, not reflecting the production of discrete jets with largely different Doppler shifts. Since the length of the X-ray jets is $\sim 10^{12}$ cm corresponding to a traveling time of only $\sim 100$ sec, we simply measure the flux-weighted average of Doppler shifts of jets emitted during the integration time ($\sim 10^4$...
sec) of each spectrum. If jets with very different Doppler shifts are emitted within each exposure, we would expect broadening of the emission lines. We check the line widths of the Fe_{XXV} Kα emission lines from the 8 time-sliced spectra on 2006 April 8–9. The same fitting model as in § 3 is used, by making the width of Gaussian lines free. We find that the width is almost constant over the observation at 34 ± 6 eV (the average from the blue jet) and 36 ± 7 eV (red jet), which are comparable to the observed line width resolved with Chandra/HETGS (Namiki et al. 2003; Lopez et al. 2006). No significant line broadening is observed in epoch B. Thus, we favor the continuously changing jet model, although we cannot exclude the possibility of many discrete jets with slightly different kinetic parameters. In the optical jets, by contrast, the evolution of emission lines from discrete plasmoids were sometimes observed on a time scale of ~0.1–0.3 days (Panferov & Fabrika 1993). The relation of these phenomena to the X-ray jitter is not clear.

5.3. Broad Band X-ray Spectra

We obtain for the first time simultaneous broad band spectra of SS 433 covering up to ~40 keV including those observed with CCD resolution below 10 keV with Suzaku. This gives us a unique opportunity to investigate the origin of the spectra not only from the emission lines but also from the continuum shape. We find that the spectrum in eclipse is consistent with the emission from optically thin plasmas in the twin jets as reported in previous works (Brinkmann et al. 1991; Kotani et al. 1996), although the out-of-eclipse spectrum may need an additional hard component to self-consistently explain both emission lines and continuum.

From the line intensities, we can estimate the innermost temperature of the jets based on the radiatively cooling jet model, as done in Kotani et al. (1996). The innermost temperature derived from the ratio of the Fe_{XXV} and Fe_{XXVI} Kα emission lines are summarized in Table 3 as “Jet Temperature” $T_0^{\text{line}}$. The averaged temperature of the blue and red jets is found to be $\approx 15$ keV and $\approx 16$ keV, respectively. Due to the confusion with the 6.4 keV line under the limited energy resolution, these could be a systematic uncertainty in the line intensity of Fe_{XXV}. We conservatively estimate the possible systematic errors in the line ratio of Fe_{XXV} and Fe_{XXVI} to be $\approx 10\%$, which corresponds to $\approx 15\%$ (2–3 keV) in the innermost temperature. If we take into account this uncertainty, the averaged innermost temperature is consistent with each other between the out-of-eclipse and in-eclipse phase. In our precession phase (edge-on), the region size obscured by the outer rim of the accretion disk and that by the companion star is similar, and hence there is no large difference in $T_0^{\text{line}}$ between the two Suzaku observations.

Independently, we are able to constrain the innermost temperature $T_0$, listed in Table 3, directly from the continuum shape based on the same jet model, thanks to the high quality hard X-ray spectra obtained with the HXD/PIN. We find that in the eclipse phase, this $T_0$ value (21 ± 1 keV) is close to $T_0^{\text{line}}$ (16 ± 3 keV, the average of the blue and red jets). In the out-of-eclipse phase, however, $T_0$ determined from the continuum (27 ± 2 keV) is significantly higher than that determined from the Fe line ratio (13 ± 2 keV). These facts suggest that the out-of-eclipse spectrum may be contaminated by an additional hard X-ray component that is hidden in eclipse. The spectrum must be very hard and/or heavily absorbed since its contribution should not be large below ~7 keV, where the ratio of the continuum intensity between the out-of-eclipse and in-eclipse phases is similar to that of the iron emission lines originating from the jets. The presence of such a hard component not directly related to the jets was suggested by the comparison of in- and out-of-eclipse spectra observed with Ginga (Brinkmann et al. 1991; Yuan et al. 1995). This may be related to the extended corona around the accretion disk discussed in Krivosheyev et al. (2009) or a reflection feature of the emission from the inner disk by the outer wall of the funnel (Medvedev & Fabrika 2009). To constrain its origin, analysis of broad band data utilizing a fully self-consistent model for the thermal jets (including both continuum and emission lines) would be required, which we leave for future studies.

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Fig. 1. The PIN spectra of SS 433 on 2006 April 8–9 (upper, out-of-eclipse) and April 4–5 (lower, in-eclipse). From upper to lower, the total spectrum, the NXB, the source spectrum after background subtraction, and the GXB+CXB.

Fig. 2. The PIN light curves of SS 433 in the 12–40 keV band on 2006 April 8–9 (upper, out-of-eclipse) and April 4–5 (lower, in-eclipse). From upper to lower, the total spectrum, the NXB, the source spectrum after background subtraction, and the GXB+CXB.
Fig. 3. The XIS light curves of SS 433 on 2006 April 8–9 (out of eclipse) in three bands, 0.5–2 keV (upper), 2–5 keV (middle), and 5–10 keV (lower). The bin size is 180 sec. The arrows define epochs A and B for the spectral analysis.

Fig. 4. The 5.0–10 keV spectra of SS 433 in epoch A (upper) and B (bottom). The four XISs are summed. See Figure 3 for the definition of the epochs.

Fig. 5. Time variability of the line center energy of FeXXV Kα determined from the Suzaku spectra on 2008 April 8 (out-of-eclipse). The horizontal lines show the average values determined from the time averaged spectra.

Fig. 6. The XIS spectrum in the 5–10 keV band on 2006 April 8–9 (data number 1–4 only; out of eclipse). The best-fit model is over-plotted with separate contribution of the reflection component (lower curve, green) and Gaussians (blue: those from the blue jet, red: those from the red jet, green: the fluorescence iron-K line at 6.4 keV). The fitting residuals in units of χ are plotted in the lower panel. The best fit parameters are given in Table 3.

Fig. 7. The simultaneous fit to the XIS and HXD/PIN spectra of 2006 April 8–9 (out-of-eclipse), using a multi-temperature jet model for the continuum (see text). The best-fit models are over-plotted with separate contribution from the reflection component and fluorescence iron-K line (green). Residuals in units of χ are shown in the lower panel. See Table 3 for the best-fit parameters of the continuum.
Fig. 8. The XIS light curves of SS 433 on 2006 April 4–5 (in eclipse) in three bands, 0.5–2 keV (upper), 2–5 keV (middle), and 5–10 keV (lower). The bin size is 180 sec.

Fig. 9. Time variability of the line center energy of FeXXV Kα determined from the Suzaku spectra on 2008 April 4–5 (in eclipse). The horizontal lines show the average values determined from the time averaged spectra.

Fig. 10. The XIS spectrum in the 5–10 keV band on 2006 April 4–5 (in eclipse). The best-fit model is over-plotted with separate contribution of the reflection component (lower curve, green) and Gaussians (blue: those from the blue jet, red: those from the red jet, green: the fluorescence iron-K line at 6.4 keV). The fitting residuals in units of $\chi$ are plotted in the lower panel. The best fit parameters are given in Table 3.

Fig. 11. The simultaneous fit to the XIS and HXD/PIN spectra of 2006 April 4–5 (in eclipse), using a multi-temperature jet model for the continuum (see text). The best-fit models are over-plotted with separate contribution from the reflection component and fluorescence iron-K line (green). Residuals in units of $\chi$ are shown in the lower panel. See Table 3 for the best-fit parameters of the continuum.
Fig. 12. A summary of Doppler shifts of the jets observed around the observation campaign epoch. The results determined from the optical (Hα) and X-ray (FeXXV Kα) are shown by the crosses and circles, respectively. The dotted lines correspond to the 162.15-days sinusoidal curves due to the precession motions.

Fig. 13. A blow up of Figure 12 around the epoch of the Suzaku observations.

Fig. 14. The optical spectra of SS 433 observed at the GAO on 2006 April 7 (solid line) and April 9 (dashed line). The vertical lines denote the line center positions of Hα originating from the red and blue jets. There are two HeI lines (λ6678, λ7065) in the figure.

Fig. 15. The change of the jet parameters observed on 2006 April 8–9, in terms of the cosine of angle between the line-of-sight and jet axis (upper) and intrinsic velocity (lower).
### Table 1. X-Ray Observation Log.

| Start (MJD) | End (MJD) | Exposure (ks) | Remark |
|-------------|-----------|---------------|--------|
| 2006/04/04 14:40 (53829.6108) | 2006/04/05 12:47 (53830.5326) | 38.68 | Eclipse |
| 2006/04/08 11:04 (53833.4610) | 2006/04/09 10:59 (53834.4578) | 40.20 |

### Table 2. Log of Optical Spectroscopic Observations

| Start (MJD) | Exposure (s) | Remark |
|-------------|--------------|--------|
| 2006/04/06 00:45:35 (53831.0317) | 590 | |
| 2006/04/07 19:57:47 (53801.8297) | 590 (the sum of 120×5) | |
| 2006/04/05 19:15:28 (53830.8024) | 900 (the sum of 180×5) | |
| 2006/04/06 18:39:53 (53831.7777) | 900 (the sum of 180×5) | |
| 2006/04/07 18:40:42 (53832.7783) | 900 (the sum of 180×5) | |
| 2006/04/09 18:38:27 (53834.7783) | 1080 (the sum of 180×6) | |
| 2006/05/03 18:16:07 (53858.7612) | 720 (the sum of 180×4) | |
| 2006/05/20 17:35:43 (53875.7441) | 900 (the sum of 180×5) | |
| 2006/04/06 18:04:52 (53828.7534) | 1800 | |
| 2006/04/05 17:55:00 (53830.7465) | 1800×2 | |
| 2006/04/07 17:48:03 (53832.7417) | 592, 540 | |
| 2006/04/12 08:07:16 (53837.3384) | 1800 | |
| 2006/04/03 18:04:52 (53828.7534) | 1800 | |
| 2006/04/05 17:55:00 (53830.7465) | 1800×2 | |
| 2006/04/07 17:48:03 (53832.7417) | 592, 540 | |
| 2006/04/12 08:07:16 (53837.3384) | 1800 | |
| 2006/04/03 18:04:52 (53828.7534) | 1800 | |
| 2006/04/05 17:55:00 (53830.7465) | 1800×2 | |
| 2006/04/07 17:48:03 (53832.7417) | 592, 540 | |
| 2006/04/12 08:07:16 (53837.3384) | 1800 | |

**Telescope:** BTA 6 m. **Observatory:** SAO. **PI:** S. Fabrika.
**Telescope:** 150 cm. **Observatory:** Gunma. **PI:** K. Kinugasa.
**Telescope:** Nayuta 2 m. **Observatory:** Nishi-Harima. **PI:** S. Ozaki.
**Telescope:** 122 cm. **Observatory:** Padova-Asiago. **PI:** T. Iijima.
Table 3. The best fit parameters of the continuum emission obtained by a simultaneous fit to the XIS+HXD spectra. The uncertainties refer to statistical errors at 90% confidence limits for a single parameter (but 1σ for Jet Temperature $T_{0}^{\text{line}}$).

| Parameter                  | April 8–9          | April 4–5          |
|----------------------------|---------------------|---------------------|
| **Continuum**              |                     |                     |
| $T_0$ (keV)                | 27.0$^{+2.1}_{-1.6}$| 21.1$^{+1.1}_{-0.9}$|
| R*                        | 1.00$^{−0.41}_{+0.40}$ | 1.00$^{−0.13}_{+0.16}$ |
| EW**                      | 1.00$^{+0.32}_{−0.28}$ | 1.00 (fixed)        |
| **Line Flux:** 10$^{-8}$photons$^{-1}$cm$^{-2}$ (rest-frame line energy) |                     |                     |
| Fe$^{\text{XXV}}\alpha$ (6.698keV) | 40.5$^{+1.8}_{−1.7}$ | 45.8$^{+2.2}_{−2.6}$ | 17.90$^{+0.68}_{−0.63}$ | 19.61$^{+0.67}_{−0.66}$ |
| Fe$^{\text{XXVI}}\alpha$ (6.965keV) | 13.9$^{+3.4}_{−2.9}$ | 12.8$^{+1.1}_{−0.85}$ | 5.96 $^{+0.61}_{−0.58}$ | 8.11$^{+0.50}_{−0.59}$ |
| Ni$^{\text{XXVII}}\alpha$ (7.798keV) | 10.8$^{+1.5}_{−1.8}$ | 14.8$^{+3.4}_{−2.6}$ | 4.95$^{+0.47}_{−0.58}$ | 5.04$^{+0.57}_{−0.73}$ |
| Fe$^{\text{XXV}}\beta$ (7.897keV) | 4.7$^{+1.6}_{−1.8}$ | 3.8$^{+2.3}_{−1.9}$ | 2.8$^{+0.54}_{−1.1}$ | 2.2$^{+0.56}_{−0.62}$ |
| Fe$^{\text{XXVI}}\beta$ (8.210keV) | 1.7$^{+1.8}_{−1.8}$ | 3.64 $^{+0.94}_{−0.94}$ | 1.90$^{+0.53}_{−0.50}$ | 1.38$^{+0.47}_{−0.45}$ |
| Fe$^{\text{I}}\alpha$ (6.399keV) | 6.9$^{+2.2}_{−2.7}$ | 3.7 (fixed)         |                     |                     |
| **Jet Temperature**$^{***}$ $T_0^{\text{line}}$ (keV) | 14.5$^{+1.4}_{−1.0}$ | 12.23$^{+0.34}_{−0.47}$ | 14.14$^{+0.23}_{−0.50}$ | 17.10$^{+0.83}_{−0.87}$ |
| Redshift                  | 0.0661$^{+0.0038}_{−0.0000}$ | 0.0064$^{+0.0012}_{−0.0009}$ | 0.0559$^{+0.0046}_{−0.0009}$ | 0.0318$^{+0.0066}_{−0.0005}$ |
| $\chi^2$/d.o.f           | 810 / 749           | 704 / 698           |

*: $R \equiv \Omega/2\pi$, where $\Omega$ is the solid angle of the reflector seen from the emitter (i.e., jets).

**: The equivalent width of an Fe$^{\text{I}}\alpha$ line with respect to the reflection component.

**: Determined from the line intensity ratio between Fe$^{\text{XXV}}\alpha$ and Fe$^{\text{XXVI}}\alpha$ based on a multi-temperature jet model (see text).