Suzaku X-Ray Observation of the Dwarf Nova Z Camelopardalis at the Onset of an Optical Outburst

Kei Saitou,1,2 Masahiro Tsuimoto,1 Ken Ebisawa,1,2 and Manabu Ishida1

1Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara 252-5210
2Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033

(Received 2011 December 2; accepted 2012 February 27)

Abstract

We present the result of a Suzaku X-ray spectroscopic observation of the dwarf nova Z Cam, which was conducted by chance at the onset of an optical outburst. We used the X-ray Imaging Spectrometer (a 38 ks exposure) and the Hard X-ray Detector (34 ks) to obtain a 0.35–40 keV spectrum simultaneously. Spectral characteristics suggest that the source was in the X-ray quiescent state, despite being in the rising phase of an outburst in the optical band. The spectrum shows a clear signature of circumstellar absorption in excess of interstellar absorption and the reprocessed-emission features of Fe fluorescence and Compton scattering. The extra absorption is explained as being due to partial covering by either neutral or ionized matter. We found a spectral change during the observation, which is attributable only to a change in the circumstellar absorption. Such an X-ray spectral variation was reported for the first time in the case of dwarf novae. We speculate that the variation in the circumstellar absorption is interpreted as a time-varying disk wind, or geometrically flaring disk around the white dwarf during the propagation of a heat wave along inward the accretion disk at the beginning of the outburst, in which optical outburst and X-ray quiescent states co-exist.

Key words: stars: binaries: close — stars: dwarf novae — stars: individual (Z Camelopardalis) — stars: novae, cataclysmic variables — X-rays: stars

1. Introduction

Dwarf novae (DNe) are a subclass of non-magnetic cataclysmic variable stars, which are close binary systems consisting of a white dwarf (WD) and a late-type companion star (Warner 1995; Hellier 2001). The defining characteristic of DNe is repeated optical outbursts, in which the optical brightness increases by 2–5 mag. Thermal-viscous instability in the accretion disk is considered to be the cause (e.g., Smak 1984; Osaki 1996; Lasota 2001). The cycle repeats between two distinctive stable disk states: a quiescent state with the disk mostly made of neutral hydrogen, and an outburst state mostly made of ionized hydrogen. The viscosity, surface density, and the mass-accretion rate are higher in the latter state. DNe are known to be X-ray emitters. The X-ray features typically show a dichotomy between the quiescent and outburst states. In the quiescent state, X-rays are from the hot, optically thin thermal plasma, which is produced in the boundary layer between the inner edge of the accretion disk rotating at a Keplerian velocity and the WD surface rotating at a slower spin period. The plasma is localized within a height of \( \sim 0.1 R_{\text{WD}} \) from the surface of the WD with a radius of \( R_{\text{WD}} \) (Mukai et al. 1997). The X-ray spectrum is very hard and has a temperature beyond 10 keV and strong Fe K emission features. In the outburst state, the other hand, the hard emission is suppressed with two or three times the firmness, and is replaced by extreme ultraviolet (EUV) plasma emission having a much lower temperature. This is because the plasma in the boundary layer becomes optically thicker and more efficient in radiative cooling due to the increased-accretion rate to the WD.

One of the features often seen in the X-ray spectra of DNe is a complex extinction structure in the soft band (< 2 keV). The extinction cannot be explained by interstellar absorption alone, which indicates the presence of circumstellar absorption. In eclipsing systems with high inclination angles (e.g., OY Car: Ramsay et al. 2001; V893 Sco: Mukai et al. 2009), the complex extinction can be naturally interpreted as being partial absorption by a part of the accretion disk. However, the extra extinction is also seen in some non-eclipsing systems with lower inclination angles (e.g., SS Cyg: Done & Osborne 1997; Z Cam: Baskill et al. 2001). There is an idea that such extinction is due to the disk wind, which is ionized to some extent, and intervenes partially or fully in the line of sight.

The disk wind is a phenomenon seen in any type of compact object with an accretion disk (e.g., Ueda et al. 2001; Boirin & Parmar 2003; Kubota et al. 2007; Tombesi et al. 2010). They may play an important role in the feedback process of energy and matter from compact objects to the interstellar space, and also to the intergalactic space in the case of active galactic nuclei (e.g., Elvis 2006; Fabian 2010). In nearby DNe, which are accessible with optical and ultraviolet (UV) spectroscopic observations, the disk wind is observable in such systems as P Cyg profiles (Robinson 1973; Córdova & Mason 1982; Klare et al. 1982; Szkody & Mateo 1986), motivating progress in the spectral synthesis modeling of disk winds (Shlosman & Vitello 1993; Knigge et al. 1995; Feldmeier & Shlosman 1999; Long & Knigge 2002). If we can trace features of disk wind in X-ray spectra of DNe, which is yet to be established, it will broaden...
the application to the constraint of wind parameters in a large number of objects in a variety of phases in the quiescent and outburst cycles. Of particular interest is the transition phase between the two states, in which we may be able to distinguish the extinction brought about by disk wind from that by other causes, since we expect a change of disk wind in strength and structure during the transition to happen.

In this paper, we present the result of a Suzaku X-ray observation of Z Cam, which was conducted by chance at the onset of an optical outburst. As we discuss in subsection 5.2, the source was in the X-ray quiescent phase, despite being in the outburst phase in the optical region, suggesting that the heat wave had not reached the boundary layer. We utilize this opportunity to investigate the presence of circumstellar absorption in the X-ray spectrum, and examine any changes in the feature. Only a few X-ray observations to date are carried out in this particular phase of DN outbursts (e.g., Z Cam: Baskill et al. 2001; SS Cyg: Wheatley et al. 2003).

The plan of this paper is as follows. In section 2, we briefly summarize the basic properties of Z Cam with an emphasis on disk winds. In sections 3 and 4, we describe our observation and results of temporal and spectral analysis, where we present the presence of the circumstellar absorption and its time variation. We discuss some possible interpretations of our findings in section 5, and make conclusions in section 6.

2. Object: Z Cam

Z Cam is the archetype of the Z Cam subgroup of DNe. It is one of the brightest DNe in the optical band (V = 10.5–13.0 mag), and thus is a well-studied object. Major parameters are summarized in table 1.

Sources in the Z Cam subgroup show an optical outburst at about every few months (on average ~ 26 d for Z Cam: Oppenheimer et al. 1998). The defining characteristic of this subgroup is the “stand-still” phase after some outbursts. For a certain period of time, the brightness remains in the middle of the outburst peak and the quiescence level, rather than decreasing monotonically to the quiescence level. The stand-still phase continues for periods ranging from several days to even years (e.g., Oppenheimer et al. 1998).

There is ample evidence that Z Cam has a mass loss in the form of wind. The object is thus used as a test bed for constructing UV spectral synthesis models of disk wind. The spatial structure of the wind has been investigated by various authors (Knigge et al. 1997; Long & Knigge 2002; Hartley et al. 2005), in which the rotating biconical wind was found to explain various observed features very well. It is known that the disk wind appears and disappears depending on the phase of the outburst and quiescent cycle. The P Cyg profile of the C IV feature, which is the most prominent feature of the disk wind, was seen in the decline phase from an outburst and for one month from the start of a stand-still phase, but not seen in six months and at quiescence (Szkody & Mateo 1986; Knigge et al. 1997; Hartley et al. 2005). With poor sampling only with UV observations, a picture of the temporal behavior of the wind is not yet clear; indeed, the wind starts and stops emanating from the disk.

Z Cam was observed in the X-ray band several times with the EXOSAT (Mukai & Shiokawa 1993), ROSAT (Wheatley et al. 1996), and ASCA (Baskill et al. 2001) observatories. A hint of X-ray absorption by wind was seen in two ASCA observations (Baskill et al. 2001), in which extra absorption occurred upon interstellar absorption was required to explain the X-ray spectra. The amount of the extra absorption, which was successfully modeled by ionized absorber, was larger than the interstellar absorption by two orders of magnitude in two observations taken during an optical outburst and a transition phase from the quiescence to the outburst. However, due to limited statistics and resolution in the soft energy band, a possible time variation in the circumstellar absorption was not detected between the two observations and during each observation.

3. Observation and Data Reduction

We observed Z Cam with the Suzaku satellite (Mitsuda et al. 2007) on 2009 April 10. Figure 1 shows the optical light curve covering our X-ray observation taken from the American Association of Variable Star Observers (AAVSO). The X-ray observation was carried out during the onset of an optical outburst for a total duration of 65 ks, corresponding to 2.6 orbits of Z Cam.

Suzaku has two operating instruments covering different energy ranges. One is the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007) sensitive at an energy range of 0.2–12 keV. XIS is equipped with four X-ray CCD cameras, three of which (XIS 0, 2, and 3) are front-illuminated (FI) devices, and the remaining one (XIS 1) is a back-illuminated (BI) device. The FI and BI devices are superior in response to the hard and soft bands, respectively, to each other. XIS 2 has been dysfunctional since 2009 November, and we thus used the remaining devices for the work described in this paper. In combination with four X-ray telescopes (Serlemitsos et al. 2007) co-aligned with each other, the XIS has an imaging capability to cover a field of view (FoV) of 17.8 × 17.8 with a pixel scale of 0.104 pixel−1 and a telescope half-power diameter of ~2.0. The total effective area for the remaining three CCDs is 1030 cm2 at 1.5 keV. The energy resolution in the full width at half maximum (FWHM) is 170–220 eV at 5.9 keV as of the observation date.

The other instrument is the Hard X-ray Detector (HXD: Takahashi et al. 2007; Kokubun et al. 2007; Yamada et al. 2011), which is sensitive to an energy range of 10–600 keV. HXD consists of PIN diodes and GSO scintillators, which compose a non-imaging detector. We concentrate on the PIN data at 10–70 keV in this paper. The effective area of the PIN is ~160 cm2 at 20 keV. The passive fine collimators restrict the FoV to ~34′ square in FWHM and to ~70′ square in the full width at zero intensity (FWZI). The narrow FoV, the surrounding anti-coincidence detectors, and the low and stable instrumental background enable us to achieve unprecedented sensitivity to this energy band.

In our observation, the target was placed at the center of the XIS FoV. The XIS was operated in the normal clocking mode with a frame time of 8 s.

The data were screened by the standard pipeline processing

1 For details see [http://www.aavso.org/].
Throughout this paper, we used the HEASoft (version 6.8) for a net exposure time of 38 ks for the XIS and 34 ks for the PIN. Of less than 6 GV were removed. As a result, we obtained angles below 5°. For the PIN, events taken at the cut-off-rigidity: 0.13 (180 pixels), which maximizes the signal-to-noise ratio. The background events were extracted from an annulus with radii ranging 4–7°, having the source region as its center. The encircled energy fraction of the background region is approximately 3% of the source region.

For the PIN, which is a non-imaging detector, the background consists of the instrumental non-X-ray background (NXB), the cosmic X-ray background (CXB), and possible contaminating sources within the FoV. We used NXB events provided by the instrument team (Fukazawa et al. 2009) and simulated CXB events on the assumption of a model obtained with the HEAO-1 satellite (Boldt 1987). We checked the latest INTEGRAL IBIS (Bird et al. 2010) and Swift BAT (Cusumano et al. 2010) catalogues, and found no contaminating source within the FWZI FoV of the PIN.

### 4. Analysis

#### 4.1. Event Extraction

In the XIS image, we can see no source besides Z Cam. We accumulated the source events from a circular region with a radius of 3.13 (180 pixels), which maximizes the signal-to-noise ratio. The background events were extracted from an annulus with radii ranging 4–7°, having the source region as its center. The encircled energy fraction of the background region is approximately 3% of the source region.

For the PIN, which is a non-imaging detector, the background consists of the instrumental non-X-ray background.

#### 4.2. Temporal Analysis

Using the XIS (0.2–12 keV) and PIN (14–40 keV) data, we constructed light curves of the background-subtracted count rate (figure 2). We constructed curves with several different time bins to find any changes within a wide range of time scales. As a result, we found two apparent changes of different time scales.

One is a fluctuation in the XIS count rate on a short time scale of ~100 s, which was found most prominently in the light curve binned with 16 s. The count rate changes by ~50% in a range of 2–8 s⁻¹ with a mean of 4.1 s⁻¹ in this bin size.

The other is an increase in the XIS count rate at around the ~30–50 ks interval from the start of the observation (figure 2a). In order to investigate this change further, we also constructed band-limited curves in the soft (0.2–2 keV) and hard (2–12 keV) bands of the XIS (figures 2b and 2c), as well as the hardness ratio (figure 2a, blue curve), defined as \((H - S)/(H + S)\), where \(H\) and \(S\) are the count rates in the hard and soft bands, respectively. The change in the ~30–50 ks interval is significantly seen only in the soft band, which is confirmed both by the count-rate curve and by the hardness-ratio curve. No similar change is seen in the PIN light curve (figure 2d). For time-sliced spectroscopy in subsection 4.4, we divided the observation time into three phases: phase 2 being the interval with a significant decrease in the hardness ratio, and phases 1 and 3 being the intervals prior and posterior to phase 2, respectively (figure 2).

We also investigated changes associated with the orbital period of \(P_{\text{orb}} = 25.0\) ks. Figure 3 shows a count-rate curve folded by the period, in which no apparent variation was found, except for the short time fluctuation seen also in the light curve before folding (figure 2). To quantify this claim, we made two comparisons between the folded and unfolded curves: the mean count rate and its standard deviation. And we found

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### Table 1. Parameters of the Z Cam system.

| Parameter               | Value     | Units   | Methods                      | References |
|-------------------------|-----------|---------|------------------------------|------------|
| Distance \((d)\)        | 163\(^{+68}_{-38}\) | pc      | Trigonometric parallax      | [1]        |
| Interstellar absorption \((N_{\text{ISM}})\) | \(4 \times 10^{19}\) | cm⁻²    | UV spectroscopy              | [2–5]      |
| Inclination angle \((i)\) | 68\(^\circ\) |         | Far-UV spectroscopy         | [6]        |
| Orbital period \((P_{\text{orb}})\) | 6.96 | hr      | Optical photometry and spectroscopy | [7]        |
| WD mass \((M_{\text{WD}})\) | 0.99 ± 0.15 | \(M_\odot\) | Radial velocity             | [8]        |
| WD radius \((R_{\text{WD}})\) | 5.8\(^{+1.1}_{-0.2}\) \times 10\(^8\) | cm      | Mass–radius relation        | [6, 9]     |
| Companion mass \((M_2)\) | 0.70 ± 0.15 | \(M_\odot\) | Radial velocity             | [4, 8]     |
| Companion spectral type | K7        |         | Optical spectroscopy        | [10]       |

\(^*\) References are — [1] Thorstensen (2003); [2] Mauche, Raymond, and Córdova (1988); [3] Wheatley et al. (1996); [4] Knigge et al. (1997); [5] Baskill, Wheatley, and Osborne (2001); [6] Hartley et al. (2005); [7] Thorstensen and Ringwald (1995); [8] Shafter (1983); [9] Anderson (1988); [10] Ritter and Kolb (2003).
Fig. 2. Light curves of background-subtracted count rates in the (a) 0.2–12.0 keV, (b) 0.2–2.0 keV, and (c) 2.0–12.0 keV bands using the XIS and (d) 14–40 keV band using the PIN. The light curve of the hardness ratio in the XIS band is overlaid in (a). The curves are binned with 128 s for the XIS count rate curves, and with 512 s for the PIN count rate curve and the XIS hardness ratio curve. The discontinuities are due to Earth occultation of the object. A 1σ Poisson statistical uncertainty is given. The three phases are divided by the dotted vertical lines. The dotted horizontal lines indicate the mean count rate and the mean hardness ratio derived from phase 1. The origin of the abscissa is the time of the observation start at MJD = 54931.147.

Fig. 3. Light curve folded by the orbital period in 0.2–12 keV with a bin size of ~500 s bin⁻¹. A 1σ Poisson statistical uncertainty is given for the data. Two orbital phases are shown for clarity. The orbital phase 0.0 corresponds to the observation start. The vertical ticks on the left-hand side represent the count rate, while those on the right-hand side represent the count rate normalized by the mean count rate. The standard deviation of the count rate is shown by the horizontal dotted lines for the folded light curve and by the gray bands for the unfolded light curve.

that they are consistent with each other in both cases. In fact, similar fluctuation was seen in light curves folded by any other arbitrarily chosen periods. Also, the above-mentioned feature of the hardness change in the 30–50 ks interval was seen only once, and did not repeat itself. We thus conclude that there is no X-ray change associated with the orbital period.

4.3. Spectral Analysis (1): Time-Averaged Spectrum

We first present the spectral fitting for the time-averaged spectrum. We constructed a background-subtracted spectrum using the XIS and the PIN. For the XIS, we generated the detector- and telescope-response files using the xisrmfgen and xissimarfgen (Ishisaki et al. 2007) tools. The two FI spectra were merged for their nearly identical response, while the BI spectrum was treated separately. The 1.8–2.0 keV band was removed for the known calibration uncertainty at the Si K edge. At the soft-band end of the response, which is affected by accumulating contamination material on the surface of the CCDs, the recent introduction of the time variability in the chemical composition of contaminants has brought some progress in its calibration. We examined the spectra of two calibration sources, 1E 0102.2–7219 and RX J1856.5–3754, the observation dates of which are close to that of Z Cam, and found that the systematic uncertainty in the lowest end of
the response is <20% at 0.35 keV from the deviation of the response-convolved model to the data. For the PIN, we used the standard detector-response file distributed by the instrument team.

Figure 4 shows the 0.35–40 keV spectrum using both the XIS and the PIN. The most prominent feature in the entire spectrum is intense emission lines at 6.7 and 7.0 keV, respectively, from the n = 2→1 lines by Fe XXV and the Lyα line by Fe XXVI, which indicates an optically thin thermal plasma. Other features can also be noticed.

In order to characterize the spectrum, we began with a simple model; i.e., a multitemperature thin-thermal plasma model (\(\text{mekal}\)) attenuated by photoelectric absorption (\(\text{tabs}\): Wilms et al. 2000) of a column fixed to the interstellar value (table 1). The multitemperature model is an integral of a single-temperature plasma model (\(\text{mekal}\)) with a differential emission measure (\(EM\)) as a function of the plasma temperature \(T\) in a power-law form of \(d(EM)/dT \propto (T/T_{\text{max}})^\alpha\). Such a model is widely used for deriving X-ray spectra from CVs (e.g., Done & Osborne 1997; Baskill et al. 2005). Free parameters were the maximum temperature \(T_{\text{max}}\), the power \(\alpha\), the distribution, and the abundance \(Z\) changed collectively for all metals relative to hydrogen with respect to the solar value. We employed the solar abundance by Wilms, Allen, and McCray (2000) and the photo-ionization cross-section by Verner et al. (1996). The 4–10 keV data were used for the fitting, and the best-fit model was extrapolated to both the lower and the upper energy ranges (figure 4). We multiplied the PIN normalization against the interstellar value. The 4–10 keV data were used for the fitting. The data (crosses) and the best-fit model (solid lines) are shown in the upper panel, while the ratio of the data to the best-fit model is shown in the lower panel.

An enlarged view at the Fe Kα complex band is shown in the inset.

The residual of the fiducial model (figure 4) indicates that the spectral model requires other components to account for the following features: (1) excess-emission line at 6.4 keV, presumably from Fe Kα fluorescent emission, (2) extra attenuation below \(\sim 2\) keV, which is attributable to extinction by circumstellar medium (CSM), and (3) excess emission above \(\sim 20\) keV, which is a signature of Compton-scattered continuum emission. In the given spectrum, we found that these multiple spectral components are coupled to each other. Therefore, we started inspecting individual components separated into carefully selected-energy bands by local fitting (sub-sections 4.3.1–4.3.3), and then conducted the entire fitting with a synthesized model (sub-section 4.3.4).

**4.3.1. Fe fluorescent line**

First, we constrained the emission line at 6.4 keV. We fitted a fiducial model plus a Gaussian line component to the 4–10 keV spectrum. The center energy and intensity of the line were the free parameters, while the intrinsic width was fixed to 0 eV in the fitting. We obtained a best-fit center energy of 6.40 \pm 0.02 keV, which is consistent with the Kα fluorescence line from Fe I. We fixed the center energy at this value in the following steps.

**4.3.2. Reflection component**

Second, we constrained the excess-continuum emission by Compton scattering in the PIN band. The fluorescence and Compton scattering were coupled physically under the same geometry with a common parameter \(\Omega/2\pi\); that is, the solid angle subtended by the reflector viewed from the plasma (figure 5). However, since no spectral model accounts for both processes in \(X_{\alpha}\), we iterated the fitting procedure until we had obtained a converged result between the two processes. The relation between the equivalent width \(EW_{\text{FeI}}\) of the Fe fluorescence line and the viewing angle \(\Omega/2\pi\) was taken from George and Fabian (1991). The inclination angle \(i\) was fixed at the value given in table 1.

We fitted a fiducial model plus a Gaussian line component, which is modified by the Compton reflection model (reflect: Magdziarz & Zdziarski 1995), to the 4–40 keV spectrum. We started with \(\Omega/2\pi = 1\) as an input parameter of the Compton-reflection model. The derived \(EW_{\text{FeI}}\) was compared with the value expected to constrain the viewing angle, \(\Omega/2\pi\). In George and Fabian (1991), it is assumed

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3 An X-Ray Spectral Code for Optically Thin Plasmas (Internal SRON-Leiden Report, updated version 2.0).
4 For details see a Suzaku memo (http://www.astro.isas.jaxa.jp/suzaku/doc/suzakumemo/suzakumemo-2008-06.pdf).
that the photo-ionization continuum emission has a power-law spectrum. We approximated the best-fit thermal model with a power-law slope. We also made correction for the Fe abundance [Fe/H] = 2.69 × 10⁻⁵, while George and Fabian (1991) assumed 3.3 × 10⁻⁵. The derived Ω/2π value was used as an input parameter of the Compton-reflection model in the next iteration. This process was repeated until we had obtained a converged value of Ω/2π = 0.484. The parameter is fixed at this value in the following steps.

### 4.3.3. Additional absorber

Third, we constrained an additional extinction prominent below ~2 keV (figure 4). We convolved the above-mentioned model with several additional absorption models, and compared their reduced χ² values (χ²_red) in the 0.35–1.8 keV band (figure 6).

For additional model, we started with photoelectric absorption by neutral matter using the same model as the interstellar absorption (tbabs). This model was unsuccessful in our attempts because of χ²_red = 1.90 for 309 degrees of freedom (dof).

The residual (figure 6b) indicates that the observed spectrum remains less attenuated than the model predicts, despite the fact that the deviation from the fiducial model (figures 4 and 6a) starts at an energy as high as ~3 keV. This is a signature of either the partial coverage by the absorber, or the partial coverage by the absorber being ionized, or both. We thus employed a partial absorption by neutral matter (pcfabs), a full absorption by ionized matter (zxipcf with the covering fraction fixed at 1), and a partial absorption by ionized matter (zxipcf, in which the covering fraction is a free parameter). The zxipcf model is calculated by using the XSTAR code (Bautista & Kallman 2001). Free parameters in the pcfabs model are the absorption column (N_H^CSM) and the covering fraction (C^CSM), while those of the zxipcf are N_H^CSM, C^CSM, and the ionization parameter (ξ^CSM). There is a systematic deviation in the residual around 0.7–0.8 keV for the full-covering ionized model (figure 6d), while no such deviation is seen in the entire soft-band spectrum for the partial-covering neutral and ionized models (figures 6c and 6e). Indeed, figures 6c and 6e show better χ²_red values of 1.46 (dof = 308) and 1.47 (dof = 307), respectively, than figure 6d of 1.79 (dof = 308). We therefore used partially covering, neutral or ionized matter for the additional absorption in the following steps.

### 4.3.4. Entire fitting

Finally, we combined all of the above-mentioned components to fit the entire spectrum in the 0.35–40 keV band. To the fiducial model, we added a Gaussian line, and convolved with the Compton-reflection model and one of the two additional absorption models; namely, partial absorption by neutral or ionized matter. We conducted the iteration process described in sub-subsection 4.3.2 to reach a geometrical solution that ensures consistency between the fluorescence and Compton scattering. We found that fits of two models for the additional absorption are successfully good, and they are shown in figure 7 and given in tables 2 and 3.

### 4.4. Spectral Analysis (2): Time-Sliced Spectra

We now proceed to the time-sliced spectroscopy. Figure 8 shows the BI spectra in the three phases defined in figure 2. The elevated count rate of phase 2 in the soft band (0.2–2.0 keV) is confirmed in the time-sliced spectra. We applied the model constructed for the time-averaged spectra to the spectra of all slices. The best-fit parameters are given in tables 2 and 3.

The result of the fitting indicates that the time variation in phase 2 is attributable only to a change in the circumstellar absorption; other parameters do not change among the slices. Figure 9 shows contour plots of the best-fit parameters in the circumstellar absorption models. A significant decrease of the covering fraction (C^CSM) is seen in phase 2 of both models.
A hint of change in the hydrogen column density \(N_{\text{H}}^{\text{CSM}}\) is also seen in both models. The ionization parameter \(\xi_{\text{CSM}}\) in the ionized-absorber model remains constant during all the phases. The spectral change in phase 2 is likely to be caused mainly by a change in the covering fraction.

5. Discussion

5.1. Suzaku Confirmation and Expansion of ASCA Results

Z Cam was twice observed with ASCA: in a transition phase and in an outburst phase (Baskill et al. 2001). Our Suzaku observation was the second to be made in the X-ray during the transition phase of the object. Our result both confirms and expands the results presented in the preceding work, which we briefly summarize here. Baskill, Wheatly, and Osborne (2001) clearly showed the presence of circumstellar absorption, which is larger than the interstellar absorption by two orders in both the transition and the outburst phases. The presence of such a large circumstellar absorption was confirmed by our observation (tables 2 and 3). Baskill, Wheatly, and Osborne (2001) argued that the circumstellar absorption was ionized, but our data were explained equally well by partially covering neutral material.

In confirmation of the previous ASCA finding, we further present some new results, obtained by making use of the improved low-energy response and a wider band coverage of Suzaku. First, we found that the circumstellar absorption shows a time variation (figures 8 and 9). The variation is characterized by a decreased spectral hardness the period of which lasted \(\sim 20\) ks in the middle of our observation, which is mostly attributable to a change in the covering fraction. The variation is not associated with the orbital period of the system. We also detected reprocessed emission of the Fe fluorescence and Compton scattering, and constrained the plasma temperature and the reflection geometry.

5.2. Timing of the Suzaku Observation

Our X-ray observation was carried out at the beginning of an optical outburst (figure 1). The rapid rise and slow decay of the optical light curve suggest that this outburst was an
outside-in outburst (e.g., Lasota 2001), in which the heat wave propagates from the outer part of the accretion disk to the inner part. However, X-ray characteristics in the three following points are typical of the quiescent phase.

First, in the Suzaku observation, the observed emission was quite hard with a 2–10 keV luminosity at 163 pc (table 1) of \(8.5^{+0.7}_{-0.6} \times 10^{34} \text{ erg s}^{-1}\). This luminosity is quite similar to that of the EXOSAT measurement made at quiescence (Mukai & Shiokawa 1993), and is larger by 32 times than the ASCA measurement made at an optical and presumably X-ray outburst phase (Baskill et al. 2001). Here, we used the pimms tool\(^5\) for the flux conversion. In the dichotomy between enhanced hard X-ray emission in the quiescent phase and suppressed hard X-ray one in the outburst phase, the observed hardeness and luminosity indicate that the Suzaku observation was carried out during the X-ray quiescent phase.

Second, with the observed X-ray data, we can estimate the accretion rate from the inner part of the disk to the WD surface \(\mathcal{M}_{\text{BL}}\). Assuming that an in-falling particle releases an energy of \(5/2 kT_{\text{max}}\), where \(kT_{\text{max}}\) is the maximum plasma temperature of the boundary layer, the bolometric luminosity of the boundary layer is described as \(L_{\text{BL}} = \left(5 \mathcal{M}_{\text{BL}} kT_{\text{max}}\right) / \left(2 \mu m_H\right)\), where \(\mu\) is the mean molecular weight (typically \(\sim 0.6\)) and \(m_H\) is the mass of hydrogen (Fabian 1994; Pandel et al. 2003). By substituting \(L_{\text{BL}}\) and \(kT_{\text{max}}\) with the observed values, we found that \(\mathcal{M}_{\text{BL}} \approx 3 \times 10^{-11} M_\odot \text{ yr}^{-1}\), which is comparable to a typical value during the quiescence of DNe (Pringle & Savonije 1979; Pandel et al. 2003), but is much smaller than the value required for triggering outbursts \(\sim 10^{-9} M_\odot \text{ yr}^{-1}\); Osaki 1996; Lasota 2001).

Third, we derived a constraint of the reflection geometry from the spectral fitting using the hard X-ray emission above 20 keV and the Fe K fluorescent line (Ishida et al. 2009). Assuming that the WD surface most contributes as the reflector to reprocessing X-rays from the plasma, the solid angle subtended by the reflector \(\Omega/2\pi\) converts to the scale height \(h\) of the X-ray plasma from the WD surface (figure 5). Using the observed value \(\Omega/2\pi = 0.484\) (tables 2 and 3), \(h \approx 0.17 R_{\text{WD}} = 9.7 \times 10^7 \text{ cm} \left[0.167 \times 5.8 \times 10^9 \text{ cm}\right]\), which is in line with the boundary layer being the source of the X-ray emission as in other DNe in the quiescent phase (Mukai et al. 1997; Ishida et al. 2009).

We thus conclude that our observation was carried out between the start of the state change in the outer part of the disk and the arrival of the heat wave to the inner part of the disk, in which the optical outburst and X-ray quiescence co-existed. Such a transition phase is expected to last \(\sim 1 \text{ d}\), which

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\(^5\) For details see [http://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html](http://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html).
is the time for the heating front to traverse the disk (Lin et al. 1985). In fact, some X-ray observations were carried out in such a transition phase of DNe (e.g., Wheatley et al. 2003), including one of the two ASCA observations of Z Cam (Baskill et al. 2001). The entire Suzaku observation was within this transition phase, since we can see no signs of spectral change, except for the change in the circumstellar absorption (subsection 4.3.3 and subsection 4.4); however, the last part of the ASCA observation was in the optical outburst phase, since the X-ray luminosity declined in the last part of the observation with no change in the spectral hardness. This suggests that the phase for an outburst of our Suzaku observation was preceded by that of the ASCA observation.

5.3. Cause for the Circumstellar Absorption

We speculate on the cause of the circumstellar absorption and its time variation. Two possible agents of the absorption are: (i) disk wind and (ii) a geometrically flaring disk. Both models can explain the observed extinction feature modeled by a partially covering neutral or ionized absorption. In the wind model, the ionized partial absorption is expected to intervene in the line of sight with a covering fraction possibly representing the degree of porosity of the wind. In the flaring disk model, a part of the swollen disk is expected to cause a partial covering by either neutral or ionized matter. The two models cannot be distinguished by our spectral results alone. However, we also found a time variation of the circumstellar absorption, which is not associated with the orbital period. We would naturally expect the variation associated with the orbital period in the flaring disk interpretation, and thus we favor the disk-wind interpretation for the cause of the circumstellar absorption. Figure 5 shows a schematic view, in which the disk wind is triggered by the propagation of the heat wave, and causes a partial covering in the line of sight of X-rays from the plasma localized in the boundary layer.

What is perplexing is that the time variation of the circumstellar absorption is not a monotonic increase and eventual saturation of the absorption column, which would be naively expected in the disk-wind interpretation. The variation that we saw might be due to a change in the degree of porosity of the relatively stable wind, rather than a change in the strength of the wind. Longer covering of an outburst phase as well as the covering of other phases far from the outburst and transition phases with the same data quality will help us to test our ideas.

The mechanism to launch disk wind is not yet well understood. If the absorption seen in our observation is caused by wind, we argue that the X-ray radiation pressure does not play an important role, at least in the X-ray quiescent phase. First, the increase of the additional absorption in phase 2 does not accompany any changes in the intrinsic X-ray emission properties. Second, the X-ray radiation energy absorbed by the additional absorber can be derived as a difference between the additional-absorption corrected and uncorrected luminosity in the 0.35–10 keV band. The value $\sim 3 \times 10^{31}$ erg s$^{-1}$ is smaller than the wind mechanical energy of $\sim 8 \times 10^{32}$ erg s$^{-1}$ by more than an order with a mass-loss rate of $\geq 2.4 \times 10^{-9} M_\odot$ yr$^{-1}$ (Robinson 1973) and a mean wind velocity of 1000 km s$^{-1}$ (e.g., Warner 1995).

6. Summary

We conducted a Suzaku X-ray observation of the dwarf nova Z Cam at the onset of an optical outburst by chance. Its X-ray spectral characteristics, however, suggest that the source was in the X-ray quiescent phase. This implies that our observation was carried out at the time when the heat wave had not reached to the inner part of the accretion disk in the development of the outburst, during which optical outburst and X-ray quiescent phases co-exist.

The X-ray spectrum shows clear evidence of extra absorption upon the interstellar absorption, as was presented in the previous work. We found that (i) the extra absorption was modeled successfully by partial covering, either by neutral or by ionized matter, (ii) the absorption shows a time variation on a time scale of $\sim 20$ ks, (iii) the variation is mostly attributable to the change in the covering fraction, and (iv) the variation is not associated with the orbital period of the system. From these findings, we argued that the circumstellar absorption can be by either disk wind or a geometrically flaring disk that intervenes in the line of sight of the X-rays located in the boundary layer between the WD surface and the disk.

The authors acknowledge the referee, Knox S. Long, for improving the paper. The authors appreciate Dai Takei for his help in Suzaku data analysis. KS is financially supported by Japan Society for the Promotion of Science. We acknowledge variable star observations from the AAVSO International Database contributed by observers worldwide. This research made use of data obtained from Data Archives and Transmission System (DARTS), provided by Center for Science-satellite Operation and Data Archives (C-SODA) at ISAS/JAXA.

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