Timing and Spectral Study of AX J1745.6–2901 with Suzaku

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Abstract

The eclipsing low-mass X-ray binary AX J1745.6–2901 was observed with Suzaku in its outburst phase. Combining the Chandra observation made 1.5 month earlier than Suzaku, we determined the orbital period to be $30063.76 \pm 0.14$s. We found deep flux dips prior to the eclipse phase of the orbit. The X-ray spectrum of the persistent phase is described by a combination of a direct and a scattered-in components by dust emission. During the eclipse, the X-ray spectrum becomes only the dust scattering (scattered-in) component. The optical depth of the dust scattering layer is $\sim 10.5$ at 1 keV. The direct component is composed of a blackbody likely from the neutron-star surface and a disk-blackbody. No power-law component is found in the hard energy band up to 30 keV. A clear edge at $\sim 7.1$ keV in the deep dip spectrum indicates that the major portion of Fe in the absorber is neutral, or in a low ionization state. We discovered four narrow absorption lines near the K-shell transition energies of Fe XXV, Fe XXVI, Ni XXVII. The absorption line features are well explained by the solar abundance gas in a bulk motion of $\sim 10^3$ km s$^{-1}$. The dips have complicated and cannot be reproduced by simple absorption with neutral materials. A two-component model consisting a compact blackbody and an extended power-law has succeeded to explain the dip and persistent spectra (Parmar et al. 1986; Church & Balucinska-Church 1995; Church et al. 1997). The compact source is heavily absorbed during the dip, while the extended component is gradually absorbed as increasing dip flux. Based on the two-component model, Boirin et al. (2005) and Díaz Trigo et al. (2006) proposed an alternative interpretation that the spectra are simply explained by an ionized absorber using the updated photo-ionization code.

Narrow absorption lines have also been used to diagnose the gas property surrounding a compact object, such as the abundances, ionization states, the photo-ionization parameters, or plasma temperatures of the gas. Accordingly, an X-ray source that exhibits the eclipse, dips, and absorption lines is unique and powerful to study high-inclination LMXB systems. However, only four LMXBs, Her X-1, EXO 0748–676, MXB 1659–298, and GRS 1747–312 (Giacconi et al. 1973; Parmar et al. 1986; in’t Zand et al. 2000, 2003; Sidoli et al. 2001), have been known to show both the eclipse and the dip. Among them, MXB 1659–298 is unique, showing narrow absorption lines from highly ionized atoms. The profiles of the narrow lines in MXB 1659–298 are consistent with resonance scattering by photo-ionized plasma, but show no dependence on the dip and persistent flux. AX J1745.6–2901 was discovered in the ASCA observations of the Galactic center (Maeda et al. 1996; Kennea & Skinner 1996). Showing a type-I X-ray burst and eclipses, it was classified as an eclipsing LMXB at a distance of $\sim 10$ kpc. Except for the X-ray bursts and eclipses, the light curve was nearly constant (Maeda 1998). The X-ray spectrum during the persistent state was featureless, and could be reproduced by a highly absorbed ($N_H \sim 2.5 \times 10^{23}$ cm$^{-2}$) power-law with a photon index of $\sim 2.4$, or thermal bremsstrahlung with a temperature of $\sim 7.4$ keV. The orbital period derived from the periodic eclipse was $8.356 \pm 0.008$ hr (Maeda et al. 1996).

We discovered deep dips and narrow absorption lines from AX J1745.6–2901 with the Suzaku observations. Thus, AX J1745.6–2901 is the second LMXB that exhibits the eclipse, dips, and absorption lines. Furthermore, Suzaku provides us with the best-quality X-ray spectra in the three phases (persistent, dip, and eclipse). This paper reports a unified spectral analysis of the three phases in a combination.

Key words: Galaxy: center — ISM: dust — X-rays: binaries — X-rays: individual (AX J1745.6–2901)

1. Introduction

A number of high-inclination (i.e., close to edge-on) low-mass X-ray binaries (LMXB) show regular and irregular flux decreases that occur at every orbital cycle. The former is the eclipse of a central compact source by a companion low-mass star, and the latter, called a “dip” is thought to be obscuration by a thickened outer region of the accretion disk, where accretion stream from the companion star impacts (White & Holt 1982). Another feature responsible for the gas near a neutron star is narrow absorption lines from highly ionized atoms. The spectral changes during a dip are complicated, and cannot be reproduced by simple absorption with neutral materials. A two-component model consisting a compact blackbody and an extended power-law has succeeded to explain the dip and persistent spectra (Parmar et al. 1986; Church & Balucinska-Church 1995; Church et al. 1997). The compact source is heavily absorbed during the dip, while the extended component is gradually absorbed as increasing dip flux. Based on the two-component model, Boirin et al. (2005) and Díaz Trigo et al. (2006) proposed an alternative interpretation that the spectra are simply explained by an ionized absorber using the updated photo-ionization code.

Narrow absorption lines have also been used to diagnose the gas property surrounding a compact object, such as the abundances, ionization states, the photo-ionization parameters, or plasma temperatures of the gas. Accordingly, an X-ray source that exhibits the eclipse, dips, and absorption lines is unique and powerful to study high-inclination LMXB systems. However, only four LMXBs, Her X-1, EXO 0748–676, MXB 1659–298, and GRS 1747–312 (Giacconi et al. 1973; Parmar et al. 1986; in’t Zand et al. 2000, 2003; Sidoli et al. 2001), have been known to show both the eclipse and the dip. Among them, MXB 1659–298 is unique, showing narrow absorption lines from highly ionized atoms. The profiles of the narrow lines in MXB 1659–298 are consistent with resonance scattering by photo-ionized plasma, but show no dependence on the dip and persistent flux. AX J1745.6–2901 was discovered in the ASCA observations of the Galactic center (Maeda et al. 1996; Kennea & Skinner 1996). Showing a type-I X-ray burst and eclipses, it was classified as an eclipsing LMXB at a distance of $\sim 10$ kpc. Except for the X-ray bursts and eclipses, the light curve was nearly constant (Maeda 1998). The X-ray spectrum during the persistent state was featureless, and could be reproduced by a highly absorbed ($N_H \sim 2.5 \times 10^{23}$ cm$^{-2}$) power-law with a photon index of $\sim 2.4$, or thermal bremsstrahlung with a temperature of $\sim 7.4$ keV. The orbital period derived from the periodic eclipse was $8.356 \pm 0.008$ hr (Maeda et al. 1996).

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of the narrow line analysis, and then presents a new view of the high-inclination LMXB.

2. Observation and Data Reduction

The Suzaku satellite (Mitsuda et al. 2007) has carried out three observations of a field containing the Galactic nucleus Sgr A* in 2005 September, 2006 September, and 2007 September. In the observation conducted on 2007 September 3–5, AX J1745.6–2901 was detected in an outburst. The observation log is given in table 1.

Suzaku has the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007a), consisting of four X-ray CCD cameras, each placed on the focal planes of the X-Ray Telescope (XRT: Serlemitsos et al. 2007). All four XRT modules are co-aligned so as to image the same region of 18′×18′ with a half-power diameter of 1.9–2.3. Three of the cameras (XIS 0, XIS 2, and XIS 3) are front-illuminated (FI) CCDs sensitive in the 0.4–12 keV energy band, and the remaining one (XIS 1) is back-illuminated (BI) CCD sensitive in the 0.2–12 keV energy band. XIS 2 has been dysfunctional due to an anomaly that occurred in 2006 November. Combined with XRT, the total effective area is 400 cm² at 8 keV. To mitigate the energy resolution degradation caused by charged particle radiation, the XIS has been equipped with Spaced-row Charge Injection (SCI). The details of this capability are described in Bautz et al. (2004, 2007), Uchiyama et al. (2007). The SCI technique was used in the observation of 2007 September. We checked the energy scale and resolution using the Mn Kα line from the calibration sources (55Fe) illuminating two corners of each CCD. As a result, we confirmed that the uncertainty of absolute energy scales is less than 5 eV, and that the energy resolutions in the full width at half maximum (FWHM) at 5.9 keV are ~145 eV and ~180 eV for FI and BI CCDs, respectively.

Suzaku also has a non-imaging Hard X-ray Detector (HXD: Kokubun et al. 2007; Takahashi et al. 2007). The HXD is comprised of Si PIN diodes (PIN) sensitive in the 10–60 keV band and a GSO scintillator (GSO) sensitive in the 40–600 keV band, both located inside an active BGO shield. The PIN has a field of view (FOV) of 34′×34′ with the lowest non-X-ray background ever achieved. We use only XIS and PIN data in this paper, because AX J1745.6–2901 is below the detection limit of GSO.

The XIS and PIN data were processed with version 2.1\(^1\) of the pipeline processing software. We removed data taken during the South Atlantic Anomaly passages and at Earth elevation angles below 4°. For PIN data, we further excluded events taken with a cutoff rigidity less than 8 GV. We corrected for the dead time (~5%–7%) of the HXD using hxddtcor. The net exposure time after this filtering is ~58 ks for the XIS and ~42 ks for the PIN.

We also retrieved archived Chandra (Weisskopf et al. 2002) data to study the temporal behavior of AX J1745.6–2901. We found an observation using the Advanced CCD Imaging Spectrometer (ACIS: Garmire et al. 2003) covering a field containing AX J1745.6–2901 in outburst one month and half prior to the Suzaku observation (table 1). For both the Suzaku and Chandra data, barycentric corrections were applied.

3. Analysis and Results

3.1. Light Curve

AX J1745.6–2901 is only ~1.5 away from Sgr A*, and the bright supernova remnant Sgr A East (Maeda et al. 2002) exists in its a close vicinity. Also, both the Galactic center diffuse X-ray emission and point-source population are strongly concentrated adjacent the Galactic center (Koyama et al. 1989; Muno et al. 2003; Koyama et al. 2007b). Thus, it is practically difficult to select the background region near AX J1745.6–2901. We therefore extracted them from the same region observed in 2005 September when the source was not in outburst. We used a source separating method using xissim (Ishisaki et al. 2007), and extracted source photons at various enclosed photon fractions. Consequently, we found that a 48% enclosed photon polygon maximized the signal-to-noise ratio. For the ACIS data, source photons were extracted from a 20′×40′ elliptical region along the elongated point spread function.

Figure 1 shows the ACIS and XIS light curves of AX J1745.6–2901 in the 3.0–10.0 keV energy band. The X-ray flux of AX J1745.6–2901 was highly variable; we found four type-I X-ray bursts, three fast flux drops, and two flux rises, which were already found by Maeda et al. (1996). The presence of type-I bursts confirm that AX J1745.6–2901 is an LMXB. The flux drops and rises are due to the eclipse of a companion star. We refer to the ingress times as T1, T2, and T3 (figure 1). Because the eclipse is expected to occur at every orbit with constant phase and duration, we assume that T2−T1 = nPorb and T3−T2 = Porb, where n is a natural number and Porb is the orbital period. Under this condition,

Table 1. Observation log.

| Start date   | Observatory | Observation ID | Aim point (J2000.0) RA | Dec       | texp (ks) |
|--------------|-------------|----------------|------------------------|-----------|-----------|
| 2005-09-23*  | Suzaku      | 10027010       | 17h46m04s−28°55′36″    | 49        |
| 2005-09-30*  | Suzaku      | 100037040      | 17h46m04s−28°55′36″    | 47        |
| 2007-07-19   | Chandra     | 8567           | 17h47m22s−28°11′36″    | 20        |
| 2007-09-03   | Suzaku      | 102013010      | 17h46m03s−28°55′40″    | 58        |

\(^1\) Observations used to construct the background.

\(^\dagger\) Exposure time after removing periods with a high background level. Those of XIS are shown for Suzaku observations.
Fig. 1. Light curve of AX J1745.6–2901 in the 3.0–10.0 keV energy band with a bin time of 80 s. The red arrows represent the eclipse ingresses. Data jumps are due to type-I X-ray bursts. (a) ACIS light curve, where background is NOT subtracted. (b) XIS light curve of combined data from the three XIS cameras, where background is subtracted.

Fig. 2. (a) XIS 3–10 keV light curve folded with an orbital period of 30063.76 s. Data jumps are due to type I X-ray bursts. (b) Hardness ratio (counts in the 5–10 keV energy band divided by counts in the 3–5 keV energy band) of the folded light curve. In both panels, the background has been subtracted.

we obtained $P_{\text{orb}} = 30063.76 \pm 0.14$ s ($8.35104 \pm 0.00004$ hr). Figure 2a shows the light curve folded with the orbital period, and 2b shows the hardness ratio (counts in the 5–10 keV energy band divided by those in the 3–5 keV energy band). The phase origin point is so defined that the center of the eclipse is 0.5. In addition to the above-mentioned variability, we found relatively slow intensity dips prior to the eclipses for the first time. We here define three states of AX J1745.6–2901: “persistent” with an orbital phase of 0.0–0.193 and 0.524–1, “dip” with an orbital phase of 0.193–0.476, “eclipse” with an orbital phase of 0.476–0.524 (figure 2a). The spectrum in the eclipse phase is softer, while that in the dip phase is harder on average than that in the persistent phase.

3.2. Persistent and Eclipse Spectra

In the spectral analysis, we concentrate on the Suzaku data having a better energy resolution and statistics than those of Chandra. The ancillary response files (ARFs) and response matrix files (RMFs) were produced using xissimarfgen (Ishisaki et al. 2007) and xisrmfgen. Since FI CCDs have almost the same ARFs and RMFs, the XIS 0 and XIS 3 data were summed and simultaneously fitted with the XIS 1 data.

Maeda et al. (1996) reported that the X-ray spectrum during the eclipse is interpreted as dust scattering; a portion of X-rays emitted from the source in small off-set angle from the line of sight are scattered by the interstellar dust into the line of the source sight. We here call this the “scattered-in” component. On the other hand, a vice-versa scattering process should exist; a portion of X-rays in the line of sight are “scattered-out” of the line of the source sight. We therefore fitted the persistent and eclipse spectra simultaneously as below:

$$
\begin{align*}
\text{Persistent} & : \{ \alpha \cdot e^{-\tau(E)} + \beta(E) \cdot [1 - e^{-\tau(E)}] \} \cdot F(E), \\
\text{Eclipse} & : \beta(E) \cdot [1 - e^{-\tau(E)}] \cdot F(E),
\end{align*}
$$

(1)

where $E$ is the photon energy in keV, $\alpha \equiv 0.48$ is the flux ratio coming in the source region (subsection 3.1), and $\beta(E)$ is the fraction of the extended (dust scattering) halo coming into the...
source region. Unlike \( \alpha \), \( \beta(E) \) depends on the X-ray energy \( E \). \( \tau(E) \) is the dust-scattering optical depth, and \( F(E) \) is the source spectrum. For \( \tau(E) \), we assumed that the scattering optical depth is proportional to the inverse square of the photon energy, i.e., \( \tau(E) = \tau_{\text{1keV}} \cdot E^{-2} \), where \( \tau_{\text{1keV}} \) is the scattering optical depth at 1 keV. The first term of the persistent flux (upper equation) indicates that lower energy photons are scattered-out more than higher energy photons. The second term is scattered-in photons.

In order to estimate \( \beta(E) \), we modeled the dust-scattered halo size of AX J1745.6–2901 using another X-ray binary near the Galactic center of GS 1741.2–2859/1741.6–2849 as follows: (1) Mitsuda et al. (1990) measured the energy-dependent size of the dust-scattering halo of GS 1741.2–2859/1741.6–2849 using the lunar occultation. Assuming that the halo size is proportional to the inverse of the photon energy, we made the two-dimensional halo extensions with an energy step of 0.25 keV. (2) We convolved the halo images with the response of the XRT with an energy step of 0.25 keV. (3) Extracting the photons from the source region. Unlike \( \alpha \), \( \beta(E) \) depends on the X-ray energy \( E \). \( \tau(E) \) is the dust-scattering optical depth, and \( F(E) \) is the source spectrum. For \( \tau(E) \), we assumed that the scattering optical depth is proportional to the inverse square of the photon energy, i.e., \( \tau(E) = \tau_{\text{1keV}} \cdot E^{-2} \), where \( \tau_{\text{1keV}} \) is the scattering optical depth at 1 keV. The first term of the persistent flux (upper equation) indicates that lower energy photons are scattered-out more than higher energy photons. The second term is scattered-in photons.

For \( F(E) \), we used the standard model of LMXBs: disk-blackbody (DBB) plus blackbody (Mitsuda et al. 1984; Makishima et al. 1986), both attenuated by a common interstellar extinction (Morrison & McCammon 1983) with solar abundances (Anders & Grevesse 1989). This simple model, however, was rejected with \( \chi^2/\text{d.o.f.} \) (degree of freedom) = 556.0/335 (figure 3). The large \( \chi^2 \) value is mainly attributed to narrow negative residuals around 6.6–8.3 keV. Adding four negative Gaussian lines to the model, we obtained an acceptable fit with \( \chi^2/\text{d.o.f.} = 337.4/327 \). The line widths were consistent with those of the XIS resolution, and the intrinsic 95% upper limit is 40 eV for \( \sigma = 6.7 \) keV line. Allowing the iron abundance \( Z_{\text{Fe}} \) in the interstellar absorber to be free, we obtained a better fit with \( \chi^2/\text{d.o.f.} = 310.4/326 \). The best-fit parameters are given in table 2.

The best-fit line center energies (~6.69 keV, ~6.97 keV, ~7.87 keV, and ~8.19 keV) indicate that these are due to resonance scattering by highly ionized iron and/or nickel, as seen in other LMXBs (Ueda et al. 2001; Sidoli et al. 2001; Parmar et al. 2002; Boirin & Parmar 2003; Boirin et al. 2004, 2005; Church et al. 2005).

We confirmed that any line is significant based on the \( F \)-test. For example, even ~8.19 keV, having the worst statistics among the four lines, is significant at more than the 99.99% confidence level with an \( F \)-value of 9.66. Fe XXV and Fe XXVI absorption edges at 8.828 keV and 9.278 keV should be accompanied by the highly ionized iron absorption lines. Then, adding the \( \text{edge} \) model of XSPEC, we obtained an upper limit of ~0.1 for the optical depths at around 9 keV.

3.3. Dip Spectra

To investigate the spectral shape and its variation during the dip, we divided the dip into two phases: “shallow dip” with XIS count rates more than 0.7 counts s\(^{-1}\), and “deep dip” with those less than 0.7 counts s\(^{-1}\). We first simply assume that the dip spectra are comprised of the scattered and direct components, and the latter is partially absorbed by cold matter. We fitted the spectra with the form

\[
\{ \alpha \cdot PC(E) \cdot e^{-\tau(E)} + \beta(E) \cdot \left[ 1 - e^{-\tau(E)} \right] \} \cdot F(E).
\]

Here, \( PC(E) \) is a partial covering model, given as

\[
PC(E) = f \cdot e^{-N_{\text{HI}} \sigma(E)} + (1 - f),
\]

where \( f \) is the covering fraction \( 0 \leq f \leq 1 \) and \( \sigma(E) \) is the cross section of the absorbing material. All of the parameters included in \( F(E) \) were fixed to those of the best-fit values in the eclipse and persistent phase (see figure 4 and table 3; also see subsection 3.2).
We further examined the upper limit of the ionization state of the partial covering absorber. We used the absor model (Done et al. 1992; Magdziarz & Zdziarski 1995) in XSPEC, and found that the 90% upper limit of ionization parameter, \( \Omega (r_{\text{in}}) \), is 4.7 and 0.03 for the shallow and deep dip states, respectively. Alternatively, we fixed the iron abundance in the absorber to 0 and added an absorption edge. We then obtained the edge energy, \( 7.25^{+0.19}_{-0.12} \) keV and \( 7.16^{+0.08}_{-0.07} \) keV, in the shallow and deep dip states, respectively.

### 3.4. XIS+HXD Analysis

AX J1745.6−2901 is in the high-background area of the Galactic center diffuse X-ray (GCDX) (Koyama et al. 1996, 2007b; Yuasa et al. 2008). Also, transient or time variable sources may be in the PIN FOV. To avoid systematic errors due to the GCDX and transient/time variable sources, we made a “difference-spectrum” of PIN. We first excluded the non-X-ray background (NXB) signals of the PIN from the persistent and eclipse states, respectively, and subtracted the NXB-excluded eclipse spectrum from the NXB-excluded persistent spectrum. (see table 4).

### Table 2. Best-fit parameters of the persistent and eclipse emissions.

| Component                  | Parameter (unit) | Value* |
|----------------------------|------------------|--------|
| Dust scattering            | \( r_{1\text{keV}} \) | 10.5 \( ^{+0.4}_{-0.8} \) |
| Absorption                 | \( N_H \) (10\(^{23}\) cm\(^{-2}\)) | 1.87 \( ^{+0.02}_{-0.01} \) |
|                           | \( Z_{Fe} \) (solar) | 1.26 \( ^{+0.18}_{-0.16} \) |
| DBB                        | \( kT_{in} \) (keV)\(^\dagger\) | 0.72 \( ^{+0.06}_{-0.05} \) |
|                           | \( R_{in}^{-2} \cos i \) (km\(^{2}\))\(^\ddagger\) | 230 \( ^{+5}_{-6} \) |
| Blackbody                  | \( kT \) (keV) | 1.64 \( ^{+0.05}_{-0.06} \) |
|                           | Area (km\(^{2}\))\(^\ddagger\) | 4.02 \( ^{+0.04}_{-0.03} \) |
|                           | \( L \) (10\(^{36}\) erg s\(^{-1}\))\(^\dagger\) | 2.8 |

* The errors are at 90% confidence level.  
\(^\dagger\) Temperature at the innermost radius.  
\(^\ddagger\) A distance of 10kpc is assumed.  
\(^\dagger\) Extinction-corrected luminosity in the 3.0–10.0 keV band.

Since AX J1745.6−2901 resides apart from the optical axis of the HXD by \( \sim 7^\circ \) in the present observation attitude, the effective area of PIN decreases by \( \sim 20\% \). We calculated the corresponding ARF using \texttt{hxdarfgen}, and applied it to the spectral analysis. Making the XIS spectrum in the same way, we performed simultaneous fitting to the XIS and HXD data. We fixed the PIN/XIS cross-normalization factor to 1.15, the mean value of luminous sources (Kokubun et al. 2007; Reeves et al. 2007; Miniutti et al. 2007; Shirai et al. 2008; Markowitz et al. 2008).
The scattered-in component is automatically subtracted in this method, and hence only the direct component is taken into account. Since the photon statistics is limited, the absorption line parameters and $\tau_{1keV}$, responsible for scattering-out, are fixed to those derived in subsection 3.2. The XIS and HXD spectra are well reproduced by almost the same parameters in the direct component in subsection 3.2 (figure 5). As can be seen in figure 5, the hard-band data ($\sim$10–30 keV) is simply described by the blackbody spectrum of $kT = 1.64 \pm 0.07$ keV, which is most likely due to the emission of a neutron star surface. No hard tail (power-law) component, such as Compton-up scattering by possible hot disk corona is absent.

4. Discussion

The X-ray spectra of LMXBs are complex compositions of emission from the accretion disk, corona above the disk (disk corona), and the neutron-star surface. The X-rays are also modified by the gas and dust in and around the accretion flow and inter/circum stellar medium. AX J1745.6–2901 is a rare LMXB of nearly a disk edge-on geometry, with various epochs or phenomena exhibiting intensity dips, total eclipse, X-ray bursts, and absorption lines. Since the X-rays are different combinations of emission from these epochs, the complex X-ray phenomena are decomposed, at least partially, by observations of these various epochs. In the following subsections, we discuss the detailed nature of AX J1745.6–2901 based on these observational results.

4.1. Persistent Spectra

AX J1745.6–2901 is the second low-mass X-ray binary that exhibits dips, eclipse, and X-ray bursts, and absorption lines. Using the best-quality Suzaku spectra of AX J1745.6–2901, we found a clearer picture of this LMXB type. The X-ray spectrum in the persistent phases are described with a combination of direct emission and indirect emission scattered by interstellar dust. The direct component is composed of DBB and a blackbody (likely from the neutron star surface). Although dipping/eclipsing sources are high-inclination (near disk-edge on) systems, we need no power-law component in the high energy band up to 30 keV, and hence Compton-up scattering by possible hot disk corona is absent (see subsection 4.3).

4.2. Eclipse Spectra

The eclipse spectrum is a purely dust-scattering (scattered-in) component with a large optical depth ($\tau_{1keV}$) of 10. Predehl and Schmitt (1995) conducted a systematic study on interstellar absorption and dust scattering using the ROSAT data. They found that $\tau_{1keV}$ and $N_H$ correlates well with $N_H/\tau_{1keV} \sim 2 \times 10^{22}$ cm$^{-2}$ in the $N_H$ range of $0$–$3 \times 10^{22}$ cm$^{-2}$. Our data for AX J1745.6–2901 $N_H/\tau_{1keV} \sim 1.8 \times 10^{22}$ cm$^{-2}$ extends this relation over nearly one order of magnitude of $N_H$, up to $\sim 2 \times 10^{23}$ cm$^{-2}$. Conversely, this good correlation strongly supports our assumption that the eclipse emission is due to dust scattering. Also, the gas-to-dust ratio towards the Galactic center is not largely different from the other regions in the Galaxy.

4.3. Dip Spectra

The spectra are simply explained by a partial covering model in both the deep and shallow dips. No extended emission of the power-law spectrum, such as Compton-up scattering, is required. The flux decrease is mainly due to an increase of the covering factor, together with a slight increase of $N_H$. Unlike the prediction of Díaz Trigo et al. (2006), the absorption gas is not highly ionized. The upper limit of the photo-ionization parameter $\xi = \frac{L}{n r^2}$ is 0.03–4.7, depending on the depth of the dip.

4.4. Absorption Lines

We found four absorption lines with respective line-center energies and equivalent widths of (1) $6690 \pm 15$ eV and $49 \pm 6$ eV, (2) $6969 \pm 11$ eV and $57 \pm 7$ eV, (3) $7866 \pm 57$ eV and $31 \pm 13$ eV, and (4) $8192 \pm 45$ eV and $36 \pm 14$ eV. Since the absorption line features

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**Table 4.** Best-fit parameters for the “difference spectrum”.

| Component | Parameter (unit) | Value$^*$ |
|-----------|-----------------|-----------|
| Absorption | $N_H$ (10$^2$ cm$^{-2}$) | $1.72^{+0.06}_{-0.05}$ |
|           | $Z_{Fe}$ (solar)   | $1.32 \pm 0.18$ |
| DBB       | $kT_{in}$ (keV)    | $0.70 \pm 0.07$ |
|           | $R_{in}^2 \cos i$ (km$^2$) | $190 \pm 20$ |
| Blackbody | $kT$ (keV)        | $1.64 \pm 0.07$ |
|           | Area (km$^2$)      | $4.14 \pm 0.04$ |
| $F_X$     | $(10^{-11}$ erg s$^{-1}$ cm$^{-2}$)$^\dagger$ | $11$ |
| $\chi^2$/d.o.f. |          | 150.8/150 |

$^*$ Persistent minus eclipse spectra of the combined spectra of XIS and HXD. The errors are at 90% confidence level.

$^\dagger$ Absorption-corrected luminosity in the 3–10 keV band. A distance of 10 kpc is assumed.
are found in every orbital phase, these are due to disk corona gas. From the center energies of the absorption lines, we infer that (1) and (2) are Fe XXV Kα and Fe XXVI Kα, respectively. Line (3) would be a complex of Fe XXV Kβ and Ni XXVII Kα, while line (4) is Fe XXVI Kβ plus Ni XXVIII Kα. The EW of the resonance scattering absorption line is a function of both the column density and the velocity dispersion along the line of sight (Δνlos), whereas the absorption edge depth of the corresponding ionic species depends only on the column density. The upper limit of the absorption edge (ν < 0.1) gives an upper limit of ~5 × 10^{18} cm^{-2} for N_{Fe XXV}. Combining the EW of the 6.7 keV line (49 eV), we constrain the lower limit of Δνlos ≥ 4 × 10^{2} km s^{-1} (see figure 3 in Kotani et al. 2006). On the other hand, the upper limit of Δνlos < 2 × 10^{3} km s^{-1} is obtained from the upper limit of the line width of 40 eV.

For simplicity, we assume an intermediate value of Δνlos = 7 × 10^{2} km s^{-1} (kinematic temperature of 10^{2} keV), and discuss the physical condition of iron and nickel by referring to figure 3 of Kotani et al. (2006). Using the EWs of the Fe XXV and Fe XXVI lines of 49 eV and 57 eV, we estimate the column density of Fe XXV (N_{Fe XXV}) and Fe XXVI (N_{Fe XXVI}) to be 1.5 +0.7 _{-0.6} × 10^{18} cm^{-2} and 4.2 +3.6 _{-2.5} × 10^{18} cm^{-2}, respectively. Then, the EWs of Kβ of Fe XXV and Fe XXVI are estimated to be 20 ± 5 eV and 17 ± 0 eV respectively, and hence the EWs of Kα of Ni XXVII and Ni XXVIII are < 24 eV and 19 ± 5 eV. The latter two values constrain N_{Ni XXVII} and N_{Ni XXVIII} to be < 4 × 10^{17} cm^{-2} and 4.2 +4 _{-2.5} × 10^{17} cm^{-2}, respectively. The ion fractions of Fe XXVI and Ni XXVIII are 0.68 ± 0.08 and 0.40 ± 0.05, so the abundance ratio of Ni/Fe is 0.13 +0.13 _{-0.10} which is consistent with the solar value (Anders & Grevesse 1989). Assuming the solar abundance of iron, the NH value for the absorption gas is ~1.3 × 10^{21}, or the optical depth of Thomson scattering (τ_{th}) is ~0.1.

The ratio of N_{Fe XXVI}/N_{Fe XXV} gives a plasma temperature of 13 ± 4 keV in collisional equilibrium (Arnaud & Raymond 1992). On the other hand, if the absorption gas is due to photo-ionized plasma, then the ionization parameter (ξ) is ~10^{-3} and the plasma temperature is ~100 eV. Using the plasma temperatures given above, the random (thermal) velocity of iron/nickel is estimated to be less than 300 km s^{-1}, significantly lower than 700 km s^{-1}. Therefore the velocity of 700 km s^{-1} would be mainly attributable to a bulk motion of the gas.

This velocity is very small as an electron velocity, and therefore in any case, the electron temperature is less than 20 keV, and hence the γ parameter (4τ_{th}kT/511 keV) is less than 0.02. This small value of γ is consistent with no Compton-up scattering flux in the hard energy band (subsection 4.1).

5. Summary

We observed the eclipsing LMXB AX J1745.6−2901 in an outburst phase with Suzaku. The results are summarized as follows:

1. Combining the Chandra data obtained 1.5 month earlier than Suzaku, the orbital period is more accurately constrained than before to be 30063.76 ± 0.14 s.

2. Irregular dipping activity was found for the first time.

3. Narrow absorption lines were detected at ~6.7 keV, ~6.9 keV, ~7.8 keV, and ~8.2 keV.

4. The narrow line profiles are described by absorptions of the K-shell transition of highly ionized iron and nickel in solar abundance.

5. The persistent spectrum is well modeled with direct and scattered-in by dust components.

6. The eclipse spectrum is comprised only of the scattered-in component.

7. The dip spectra are well reproduced by direct emission absorbed by cold matter and the scattered-in component.

8. The HXD signal in the 12–30 keV band was detected by subtracting the eclipse spectrum from the persistent spectrum. The emission was reproduced by a blackbody component with a temperature of ~1.6 keV. No significant hard tail was detected.

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