A hard-to-soft state transition of Aquila X-1 observed with Suzaku

Ko ONO, Kazuo MAKISHIMA, Soki SAKURAI, Zhongli ZHANG, Kazutaka YAMAOKA, and Kazuhiro NAKAZAWA

Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
MAXI Team, Global Research Cluster, The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Shanghai Astronomical Observatory, Chinese Academy of Sciences, 200030 Shanghai, China
Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

E-mail: ono@juno.phys.s.u-tokyo.ac.jp

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Abstract

The recurrent soft X-ray transient Aquila X-1 was observed with Suzaku for a gross duration of 79.9 ks, on 2011 October 21 when the object was in a rising phase of an outburst. During the observation, the source exhibited a clear spectral transition from the hard state to the soft state, on a time scale of ~30 ks. Across the transition, the 0.8–10 keV X-Ray Imaging Spectrometer count rate increased by a factor ~3, that of Hard X-ray Detector PIN (HXD-PIN) in 15–60 keV decreased by a similar factor, and the unabsorbed 0.1–100 keV luminosity increased from 3.5 \times 10^{37} \text{ erg s}^{-1} to 5.1 \times 10^{37} \text{ erg s}^{-1}.

The broadband spectral shape changed continuously, from a power-law-like one with a high-energy cut-off to a more convex one. Throughout the transition, the 0.8–60 keV spectra were successfully described with a model consisting of a multi-color blackbody and a Comptonized blackbody, which are considered to arise from a standard accretion disk and a closer vicinity of the neutron star, respectively. All the model parameters were confirmed to change continuously, from those typical in the hard state to those typical of the soft state. More specifically, the inner disk radius decreased from 31 km to 18 km, the effects of Comptonization on the blackbody photons weakened, and the electron temperature of Comptonization decreased from 10 keV to 3 keV. The derived parameters imply that the Comptonizing corona shrinks towards the final soft state, and/or the radial infall velocity of the corona decreases. These results reinforce the view that the soft and hard states of Aql X-1 (and of similar objects) are described by the same “disk plus Comptonized blackbody” model, but with considerably different parameters.

Key words: accretion disks — accretion — stars: neutron — X-rays: binaries
1 Introduction

It is well known that black hole binaries make transitions between several distinct spectral states, mainly depending on their luminosity. Among these transitions, the best recognized are those between the soft and the hard states (e.g., Remillard & McClintock 2006). Similarly, neutron star (NS) low-mass X-ray binaries (LMXBs), consisting of mass-donating low-mass stars and mass-accreting, weakly magnetized NSs, exhibit transitions between their hard and soft states, which are realized when their luminosities are lower and higher than ∼4% of their Eddington value, respectively (e.g., Asai et al. 2012).

Although the two states of LMXBs were often studied independently, broad-band Suzaku data have allowed us to explain the LMXB spectra in both these two states using essentially the same three ingredients (Sakurai et al. 2012, 2014; Sakurai 2015; Zhang et al. 2014; Ono et al. 2016): a multi-color disk (MCD) emission from an optically thick accretion disk, a blackbody (BB) component from the NS surface, and a hot electron cloud (a “corona”) which Comptonizes the BB (or sometimes BB+MCD) photons. In terms of this spectral composition, the two states are distinguished primarily by a marked difference in the Comptonization strength (much stronger in the hard state). Furthermore, both the MCD and BB components have generally larger radii and lower temperatures in the hard state.

In order to further strengthen the above unified view of LMXBs, we can utilize their spectral state transitions. That is, the identification of the spectral ingredients and the spectral decompositions can be made less ambiguous by continuously tracing whether each spectral component in one state really transfers into the corresponding one in the other state; thus, we will be able to connect the spectral modeling in the less-understood hard state to those in the better-understood soft state. As a result, such attempts have been carried out by many authors (D’Aì et al. 2010; Egron et al. 2013; Seifina et al. 2015). Although the studies were often hampered by difficulty in catching such transitions, as they are rare and generally difficult to predict with a sufficient accuracy (D’Aì et al. 2010; Egron et al. 2013), some authors successfully detected transitions (e.g., Church et al. 2014; Lin et al. 2007) utilizing, for example, the Rossi X-ray Timing Explorer (RXTE), and found continuous changes of the spectral parameters. In the present study, we attempt to update these results using improved instruments.

For the above purpose, the Suzaku observatory, with its broad energy coverage, is particularly suitable. We hence searched the Suzaku archive for a suitable data set, and found an ideal one. Namely, a Suzaku observation of Aquila X-1, made on 2011 October 21 for a gross duration of 79.9 ks in a rising phase of an outburst, very fortunately caught a hard-to-soft spectral transition of this typical recurrent LMXB. Aquila X-1 (hereafter Aql X-1) repeats outbursts, in which the 2–10 keV flux increases by a factor of >200 (Sakurai et al. 2012), and is associated with an optical counterpart with a magnitude of V = 15–19 (Gottwald et al. 1991). It exhibits type I bursts, by which the distance has been constrained to be 4.4–5.9 kpc assuming that the burst peak luminosity reaches the Eddington luminosity for an assumed NS mass of 1.4 M_⊙ (Jonker & Nelemans 2004). In the present paper, we analyzed this precious data set, employing a distance of D = 5.2 kpc (Sakurai et al. 2012).

2 Observation and data reduction

2.1 Observation

The data set of Aql X-1 to be analyzed here (ObsID 406010020) was acquired on 2011 October 21 12:51:33 UT for a gross duration of 79.9 ks, with the X-ray Imaging Spectrometer (XIS) and the Hard X-ray Detector (HXD) onboard Suzaku. The source was placed at the “XIS nominal” position. To reduce pile-up effects, the XIS was operated in the 1/4 window mode with a read-out time of 2.0 s. Furthermore, the burst mode option was employed, in which the data are accumulated only for 0.5 s per the 2.0 s read-out time.

2.2 XIS data reduction

We utilized the XIS 0 and XIS 3 events of GRADE 0, 2, 3, 4, and 6. On-source events were accumulated in a circle with a radius of 2.5′ around the image centroid. To further reduce the pile-up effects down to <3% (Yamada et al. 2012), events in a circle with a radius of 1′ at the center were discarded. Background events to be subtracted from the on-source data were taken from an annular region with the inner radius of 4′ and the outer radius of 5′.

Figure 1a presents the background-subtracted 0.8–10 keV XIS (XIS 0 plus XIS 3) light curve derived in this way. It shows nine type I bursts, while two more were lost after we adjusted the XIS and HXD exposures. Thus, the source clearly brightened up by a factor of ∼3 in the XIS band, mainly across ∼30 ks from ∼40 ks to 70 ks after the observation started.

As shown in figure 1, we define 10 data segments, to be named P0, P1, . . . to P9, each lasting for ∼2 ks but with the type I bursts excluded. The net XIS exposure summed over P0–P9 is 6.4 ks, which is much shorter than that from the HXD (see subsection 2.3) because of the burst option (subsection 2.1).
Fig. 1. Background-subtracted light curves of Aql X-1 with 128-s binning obtained with (a) XIS (XIS 0 plus XIS 3) in 0.8–10 keV and (b) HXD-PIN in 15–60 keV. Panel (c) is the HXD-PIN vs XIS hardness ratio. Arrows in panel (a) indicate Type I X-ray bursts. Time 0 corresponds to 2011 October 21 12:51:33.

2.3 HXD data reduction

Excluding the type I bursts, HXD cleaned events were accumulated over the same 10 periods, P0–P9, with a summed net exposure of 22.4 ks after dead-time correction. We used non-X-ray background (NXB) events, distributed by the HXD team, to reproduce NXB spectra (Fukazawa et al. 2009) which are subtracted from the on-source data. Cosmic-X-ray background (CXB) included in the on-source data was accounted for by adding a fixed CXB model to the spectral models describing the Aql X-1 emission (see subsection 3.1). Figure 1b shows the dead-time-corrected 15–60 keV light curve thus derived with HXD-PIN. There, the NXB contribution, estimated as $\lesssim 0.7$ counts s$^{-1}$, was already subtracted. Thus, the HXD-PIN count rate decreased clearly, by a factor of 3–4, in anticorrelation with that of the XIS.

Figure 1c shows the ratio of the HXD-PIN to XIS count rates. It clearly shows a continuous and monotonic decrease, which we take as a convincing signature of a hard-to-soft state transition. The associated spectral change is the most significant across P4–P7. Thus, the present observation fortunately witnessed a very rare occasion of the state transition. For reference, the present episode on MJD 55855 is seen in the long-term MAXI (Monitor of All-sky X-ray Image) and Swift light curves of figure 3 of Asai et al. (2015), as a rapid rise in the 2–10 keV MAXI/Gas Slit Camera intensity and a drop in the 15–50 keV Swift/Burst Alert Telescope count rate.

The source was detected significantly with HXD-GSO (gadolinium silicate crystal detector) over P0–P4, but not in P5–P9. In analyzing the P0–P4 spectra, we hence utilize the HXD-GSO data up to an energy where the signal becomes comparable to that of the systematic NXB uncertainty (Fukazawa et al. 2009).

3 Spectral analysis

Figure 2 shows XIS+HXD spectra in several time intervals, all normalized to a common power-law model with a photon index of 2. The P0 and P4 spectra, with a power-law-like shape (somewhat harder than the normalizing power-law) and a cut-off around 30–40 keV, exhibit characteristics which are typical of the hard state. In contrast, the P6, P7, and P9 spectra show those of the soft state. Therefore, we reconfirm our inference made in section 2, that the observation caught a hard-to-soft state transition. The spectra have a pivot at $\sim 8$ keV; the flux density at $\sim 30$ keV decreased nearly by an order of magnitude, while that at 3 keV tripled.

3.1 Continuum modeling

To the 10 spectra, we applied the model consisting of MCD and Comptonized BB emission using XSPEC (version 12.9.0). As the MCD component, an XSPEC model diskbb was utilized. An XSPEC model nthcomp (Zdziarski
et al. 1996; Życki et al. 1999) was utilized as the Comptonized BB emission, because it is suitable for Comptonization with optical depths $\tau > 2$ (Zdziarski et al. 1996), which is the case in the soft state (Sakurai et al. 2012) and presumably at around the transition (Ono et al. 2016). The seed photon source was chosen to be the BB arising from the NS surface. The absorption was taken into account by a multiplicative XSPEC model $\text{wabs}$, with the column density fixed at $3.6 \times 10^{21}$ cm$^{-2}$ which was obtained independently by Sakurai et al. (2014) and Gatuzz et al. (2016). Thus, the model we used is expressed as $\text{wabs} \times (\text{diskbb} + \text{nthcomp})$. The free parameters are the inner disk temperature $T_{\text{in}}$, the MCD normalization corresponding to the inner disk radius $R_{\text{in}}$, the BB temperature $T_{\text{BB}}$, the BB radius (assuming a spherical geometry) $R_{\text{BB}}$, the Comptonizing electron temperature $T_{e}$, and its optical depth $\tau$.

To the continuum model as constructed above, we added an analytical CXB model (Boldt 1987) expressed as

$$\text{CXB}(E) = 9.41 \times 10^{-3} \left(\frac{E}{1 \text{ keV}}\right)^{-1.29} \exp\left(-\frac{E}{40 \text{ keV}}\right),$$

(1)

where the units are photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ FOV$^{-1}$, and $E$ is the energy in keV. The energy range of 1.7–2.2 keV was ignored to avoid calibration uncertainties associated with the silicon K-edge and gold M-edge. The XIS vs. HXD cross-normalization was expressed by multiplying the model for the HXD with the constant factor 1.16 (Kubota et al. 2007).

The fit was good with $\chi_{N-1}^2 \sim 1.1$ for all the 10 spectra. The fit results for P0, 4, 6, 7, and 9 are shown in figure 3, together with residuals of all periods. As expected, the softer and harder parts of the continuum were reproduced by the $\text{diskbb}$ and $\text{nthcomp}$ components, respectively. In addition, the MCD component clearly became more dominant from P0 to P9, while the Comptonization component became weaker with decreasing cut-off energy, indicating a decrease in $kT_e$. The obtained model parameters are summarized in table 1 (after incorporating the iron line; subsection 3.2), and plotted in figure 4 against the time (panels a–d) and the luminosity (e–g). There, the values of $R_{\text{BB}}$, describing the seed photon source, were calculated assuming that the Comptonization process conserves the photon number. The value of $R_{\text{in}}$ was deduced from the MCD normalization $N_{\text{MCD}}$ as

$$R_{\text{in}} = \xi \kappa^2 \left(N_{\text{MCD}}\right)^{1/2} \left(\frac{D}{10 \text{ kpc}}\right) \left(\cos i\right)^{-1/2},$$

(2)

where $D = 5.2$ kpc is the employed distance and $i = 45^\circ$ is an inclination assumed following Sakurai et al. (2012), while $\xi = 0.412$ and $\kappa = 1.7$ describe effects of the inner boundary condition of the disk, and the color-hardening, respectively (Kubota et al. 1998). Panel (d) in figure 4 and table 2 show luminosities of the individual emission components. Here, the seed BB luminosity $L_{\text{BB}}$ was calculated from the BB temperature and the 0.1–50 keV photon flux of $\text{nthcomp}$, assuming spherical emission. The disk luminosity was obtained by the 0.1–10 keV energy flux of $\text{diskbb}$ without correction for the inclination. Finally, the luminosity carried by the Comptonization process, $L_{\text{comp}}$, was derived by subtracting $L_{\text{BB}}$ calculated above from the 0.1–100 keV luminosity of $\text{nthcomp}$.

Figure 4 reveals several important properties of the transition. First, throughout P0–P9, we confirm $R_{\text{BB}} < R_{\text{NS}} \equiv 12 \text{ km} < R_{\text{in}}$ and $T_{\text{in}} < T_{\text{BB}} < T_{e}$, which makes the model physically reasonable. Secondly, the parameters from P0–P3 are consistent with those obtained by Sakurai et al. (2014) from Aql X-1 in its hard state, and those from P8–P9 agree with the soft-state parameters of this object (Sakurai et al. 2012). Thirdly, the parameters changed continuously and monotonically from the hard to the soft state. Fourthly, $L_{\text{BB}}$ keeps a constant fraction ($\sim 30\%$) of the total luminosity $L_e$, as predicted by the virial theorem (the deviation from the rigorous prediction of 50% is considered in subsection 4.3). Finally, the transition is mainly characterized by a monotonic decrease in $L_{\text{comp}}$ and the associated increase in $L_{\text{disk}}$, as reflected most directly in the increase of the XIS count rate and the decrease of the HXD signal (figure 1). This agrees with the theoretical picture of the hard-to-soft transition; the inner accretion flow changes from an optically thin/geometrically thick corona to the optically thick/geometrically thin disk.
Fig. 3. XIS 0 plus XIS 3 (≤10 keV), HXD-PIN (15–60 keV), and HXD-GSO (>50 keV) spectra of P0, P4, P6, P7, and P9, fitted with diskbb+nthcomp. The data and the best-fitting model are presented in νFν forms. The fit residuals are shown for all 10 periods. (Color online)
Table 1. Parameters and the 90% statistical errors obtained by the fit with diskbb+nthcomp+diskline.

|        | diskbb                           | nthcomp                          | diskline† |
|--------|----------------------------------|----------------------------------|-----------|
|        | $T_{in}$ (keV) $R_{in}$ (km)$^1$ | $T_{BB}$ (keV) $R_{BB}$ (km)$^1$ | $T_{e}$ (keV) $\tau^3$ | $E_c$ (keV) $\beta$ EW (eV) $\chi^2$($v$) |
| P0     | 0.499±0.003 31.4±3.8            | 0.90±0.04 11.3±0.3               | 6.6±0.4 1.8 170 1.08 (333) |
| P1     | 0.485±0.003 34.0±3.7            | 0.90±0.04 11.5±0.3               | 6.9±0.2 2.5 130 1.02 (331) |
| P2     | 0.494±0.003 34.2±3.8            | 0.89±0.04 11.8±0.3               | 6.6±0.2 3.0 180 0.98 (332) |
| P3     | 0.529±0.003 32.6±2.4            | 0.98±0.04 9.9±0.3                | 6.4±0.9 6.4 210 1.03 (333) |
| P4     | 0.587±0.002 29.4±1.9            | 1.12±0.05 7.8±0.2                | 6.5±0.2 2.8 130 1.07 (327) |
| P5     | 0.610±0.003 29.7±2.1            | 1.08±0.06 8.5±0.4                | 6.5±0.2 4.8 170 1.04 (328) |
| P6     | 0.762±0.002 22.1±1.0            | 1.37±0.05 6.0±0.1                | 6.6±0.2 2.3 98 1.07 (326)  |
| P7     | 0.839±0.002 20.1±0.9            | 1.34±0.05 6.2±0.3                | 6.6±0.2 3.5 120 1.09 (326) |
| P8     | 0.921±0.004 17.4±0.6            | 1.23±0.04 6.9±0.7                | 6.6±0.2 3.5 120 1.13 (318) |
| P9     | 0.913±0.004 17.9±0.6            | 1.27±0.07 7.2±0.4                | 6.4±0.34 6.4 46 1.18 (298) |

$^1$Lower limit is not shown when is not obtained.

$^2$Inclination is taken into account multiplying the obtained value in subsection 3.1 by 1/cos 45°. Errors are calculated from the model diskbb+nthcomp.

$^3$Calculated by the photon number conservation before and after Comptonization.

$^4$Errors are calculated from the error of either $\Gamma$ or $kT_e$. The larger of the two is shown here.

Let us examine whether the transitions are reproducible from one outburst to another, putting aside the hysteresis between the rising and declining phases. Figure 14 in Lin, Remillard, and Homan (2007) shows that the hard-to-soft state transition of Aql X-1 in 2000 took place within ~1d, which is consistent with our result of ~30 ks (~8 hr) and with those of Asai et al. (2015) (discussed in subsection 4.4 in detail). In the hard-to-soft transition of Lin, Remillard, and Homan (2007), the total luminosity increased from $\sim 3 \times 10^{37}$ erg s$^{-1}$ to $\sim 5 \times 10^{37}$ erg s$^{-1}$, which coincides with the values we obtained in table 2. Furthermore, in figure 8 of Lin, Remillard, and Homan (2007), the ratio of the Comptonized blackbody luminosity (corresponding with $L_{BB} + L_{comp}$) to the thermal component luminosity (corresponding with $L_{disk}$), decreased from 0.8 to 0.5, again in good agreement with table 2. Thus, the rapid but continuous spectral changes seen over P4-P7 of the present data are considered to represent essentially the same phenomenon as the transition caught by Lin, Remillard, and Homan (2007).

3.2 Line emission

In figure 3, residuals in most of the fits reveal a broad positive structure at 6.6–6.9 keV. This is considered to be an iron line, produced on the disk when illuminated by the corona, and broadened due to the relativistic effects near $R_{in}$. Thus, we employed an XSPEC model diskline (Fabian et al. 1989) which incorporates the special and general relativistic effects around a black hole. The spectra were fitted again with a model wabsx(diskbb+nthcomp+diskline), by fixing $R_{in}$ of diskbb and diskline to the value obtained in subsection 3.1 and keeping the inclination angle at 45°. The emissivity parameter $\beta$ was between −10 and 10, and the central object mass as 1.4 M$_{\odot}$. By introducing these 3 degrees of freedom, the fit chi-squared decreased by 11–26 in P0–P8 and by 3 in P9. The energy center was found at ~6.6 keV and did not change significantly during the observation. The equivalent width (EW) against the total continuum was ~100–200 eV in most of the periods.

4 Discussion

During 80 ks of pointing with Suzaku on to Aql X-1 while the source was in the rising phase of an outburst, a complete hard-to-soft state transition was captured. Although the transition involved a drastic spectral hardening, the broad-band (typically 0.8–60 keV) spectrum was reproduced, throughout the event, with the same diskbb+nthcomp+diskline model. The obtained parameters evolved continuously as in figure 4. As indicated by table 2, the total luminosity increased monotonically from $3.5 \times 10^{37}$ erg s$^{-1}$ to 5.1 $\times 10^{37}$ erg s$^{-1}$, which falls on the typical boundary of the hard-to-soft state transition as discussed in the last paragraph of subsection 3.1. To be more specific, those values are even higher, by a factor of 2–3, than those measured in the soft state ($1.5 \times 10^{37}$ erg s$^{-1}$) before a soft-to-hard state transition (Sakurai et al. 2014). This inversion is considered to be a hysteresis effect of spectral transition (Maccarone & Coppi 2003; Asai et al. 2012).
4.1 Evolution of the spectral parameters

As shown in figure 4, this precious observation containing the transition has allowed us to trace the spectral evolution from the hard to the soft state directly. As summarized in figure 4, the model parameters changed continuously from typical hard-state values (e.g., Sakurai et al. 2014) to those typical of the soft state of this and similar sources (e.g., Lin et al. 2010; Sugizaki et al. 2013; Sakurai et al. 2014). This confirms that the model components in the hard state are identical to their counterparts in the soft state, and provides support to our interpretation of the less-understood hard state (Sakurai et al. 2012, 2014; Zhang et al. 2014; Ono et al. 2016) in reference to the better-established picture of the soft state (e.g., Mitsuda et al. 1984; Takahashi et al. 2011).

The transition can be characterized in a straightforward way by the changes of the three luminosities, $L_{BB}$, $L_{\text{comp}}$, and $L_{\text{disk}}$ (figure 4d). As already pointed out in subsection 3.1, these changes can be understood as a process wherein an increased cooling rate causes the outermost part of the coronal flow to progressively change into the innermost region of the optically thick accretion disk. In fact, $R_{\text{in}}$, which is considered to represent the disk-to-corona boundary, decreased from $\sim 30$ km to $\sim 17$ km,
accompanied by a decrease of $T_e$ from 10 keV to 3 keV. These changes are also reflected in the decrease of $R_{BB}$ from $\sim 12$ km to $\sim 6$ km; the accretion in the hard state was occurring rather spherically on to the NS from an inflated corona, whereas in the soft state became limited to the NS equator as the corona gradually shrank.

We further investigate whether or not the post-transition disk actually continues down to the NS surface. In figure 4, $R_{in}$ approached $\sim 17$ km (for $i = 45^\circ$), or $\sim 15$ km (for $i = 0^\circ$). Since these are larger than both $R_{NS}$ and the innermost stable circular orbit (which is also $\sim 12$ km for an NS with 1.4 $M_{\odot}$), the disk is likely to be truncated. Because any magnetosphere effect would appear at much lower luminosities ($\sim 10^{36}$ erg s$^{-1}$; Sakurai et al. 2014), the truncation, if true, is likely to be caused by the spontaneous change in the accretion flow, just like in the hard state. However, we are still left with a possibility that the disk actually reaches $R_{NS}$ (or the innermost stable circular orbit), and yet its innermost region (e.g., from $\sim 12$ km to $\sim 17$ km) is covered by the optically thick corona to become directly invisible. Thus, it is rather difficult to conclude whether the disk reaches the NS surface or not.

Let us examine our premise that the disk can be regarded as a standard accretion disk. If this assumption is correct, and if the gravitational energy all goes to the X-ray radiation, the P0–P9 parameters should satisfy a scaling as $T_e \propto R_{in}^{-3/4} M^{1/4} \propto R_{in}^{-3/4} L_\nu^{1/4}$. To see this, in figure 5 we plot $T_e L^{-1/4}$ against $R_{in}$. Since the expected relation is thus confirmed, we conclude that the disk can be considered standard.

## 4.2 Coronal accretion flows

While the change of the BB and MCD parameters were understood, that of the coronal geometry is yet to be revealed. This can be addressed via the optical depth which represents the amount of the corona along the line of sight. If the coronal geometry were constant across the transition, we would expect $\tau \propto M \propto L$. However, as seen in figures 4c and 4g, $\tau$ remained relatively constant from P0 to P7. This can be explained, at least qualitatively, by the decrease in $R_{in}$, which made the path length shorter and compensated for the $M$ increase. Furthermore, in P8 and P9, $\tau$ increases much more sharply than would be expected by the increase of $M$. This may be attributed to two alternative possibilities. One is the decrease in the radial flow velocity $v_r(R)$, where $R$ is the distance from the NS center. In either case, the coronal electron density $n_e(R)$, averaged over the coronal cross-section, will increase, thus making $\tau$ higher.

After Sakurai et al. (2014), let us quantitatively examine, in several steps, the above two alternatives to explain the final increase in $\tau$. First, in terms of the free-fall velocity $v_{ff} = \sqrt{2GM_{NS}/R}$, we can write as $\nu_i(R) = g v_{ff}(R)$, where $M_{NS} \equiv 1.4 M_{\odot}$ is the NS mass, and $g$ (0 < $g$ < 1) is a numerical factor which is assumed to be a constant over the coronal volume (but can vary through the transition). Next, $\tau$ can be expressed as

$$\tau = \sigma_1 \int n_e dl$$

### Table 2. Luminosities of the model components and its sum.

| P | $L_q$ | $L_{disk}$ | $L_{BB}$ | $L_{comp}$ |
|---|---|---|---|---|
| 0 | 3.54 | 0.76 | 1.10 | 1.64 |
| 1 | 3.57 | 0.80 | 1.12 | 1.65 |
| 2 | 3.62 | 0.87 | 1.14 | 1.61 |
| 3 | 3.64 | 1.05 | 1.17 | 1.42 |
| 4 | 3.70 | 1.29 | 1.24 | 1.17 |
| 5 | 3.78 | 1.55 | 1.28 | 0.95 |
| 6 | 4.15 | 2.09 | 1.40 | 0.66 |
| 7 | 4.65 | 2.54 | 1.61 | 0.50 |
| 8 | 5.04 | 2.78 | 1.55 | 0.54 |
| 9 | 5.08 | 2.83 | 1.71 | 0.54 |

$^a$Values are rounded off to the second decimal place. $L_q$ is not necessarily the same as the sum of the other three components, $L_{disk}$, $L_{BB}$, and $L_{comp}$.

$^b$Luminosity (0.1–10 keV) of the disk. Inclination is not considered.

$^c$Luminosity (0.1–100 keV) of the BB.

$^d$Luminosity (0.1–100 keV) transferred from the corona to the BB photons.

![Fig. 5. Scatter plot between $T_e L^{-0.25}$ and $R_{in}$, covering the complete transition. Dashed line proportional to $R_{in}^{-3/4}$ is shown as a reference.](https://academic.oup.com/pasj/article-abstract/69/2/23/2978930/23-8)
where \( \sigma_T \) is the Thomson scattering cross-section, and the integration is made along our line of sight. Thirdly, \( \nu_i(R) \) and \( n_e \) can be incorporated together into the mass accretion rate \( M \) as

\[
M = S(R) \nu_i(R) \mu m_p n_e(R),
\]

where \( S(R) \) is the coronal cross-section at \( R \), \( \mu \sim 1.2 \) is the average molecular weight and \( m_p \) is the proton mass. In addition, we may assume, for simplicity, that \( S(R) \) is approximated as \( S(R) = 4\pi R^2 \zeta \), where \( \zeta (0 < \zeta < 1) \) is a form factor. Then, as long as \( \zeta \) is rather close to unity, the integration in equation (3) can be approximated by radial integration from \( R = R_{\text{NS}} \) to \( R_{\infty} \). Finally, performing this integration, and eliminating \( M \) through the relation \( L_c = G M_{\text{NS}} M / R_{\text{NS}} \), we obtain

\[
\tau = 0.16 \frac{1}{g \zeta} \left( \frac{1.2}{\mu} \right) \left( \frac{K_0}{R_{\text{NS}}} - 1 \right) L_c (\text{erg s}^{-1}) 10^{37} (\text{erg s}^{-1})
\]

Equating equation (5) with the observed \( \tau \), and substituting the observed values of \( R_{\infty} \) and \( L_c \), we have deduced the behavior of \( g \zeta \) as shown in figure 6. Thus, the factor \( g \zeta \) over P0–P7 has been obtained as \( g = 0.035 \)–0.043, in agreement with the value of \( g = 0.04 \) (assuming \( \zeta = 1 \)) derived by Sakurai et al. (2014) in the hard state. Furthermore, it steeply decreases to \( g \zeta = 0.014 \)–0.018 at P8 and P9.

In this way, the observed increase in \( \tau \) towards the final stage of the transition can be explained by a decrease in either \( \zeta \), or \( g \), or both. The former means the flattening of the corona as already discussed, while the latter means a decrease of the radial flow velocity. In any case, an important consequence is the requirement for \( g \ll 1 \) (assuming \( \zeta \) is not too small), as pointed out by Sakurai et al. (2014); that is, the radial flow velocity of the corona is much lower than the free-fall velocity, and hence the corona is still in a nearly Keplerian motion (particularly at later phases of the transition) with the azimuthal velocity component dominating over \( \nu_i \).

We implicitly assumed so far that the density of the corona, by definition, is low enough not to emit photons by itself. In order to confirm this, the bremsstrahlung emissivity of the corona was estimated from the electron density in equation (4) and utilizing \( g \zeta = 0.013 \)–0.043. The bremsstrahlung emissivity, calculated as \( \dot{n} \sigma_T dV \sim n_e^2 (g \zeta, R_{\infty})(4\pi/3) R_{\text{NS}}^2 \), then becomes \( < 8.6 \times 10^{16} \text{ cm}^{-3} \) over P0–P9. This corresponds to a luminosity of \( 1.3 \times 10^{34} \text{ erg s}^{-1} \) (Chakrabarty et al. 2014), which is negligible compared with \( L_{\text{comp}} > 5 \times 10^{36} \text{ erg s}^{-1} \). Thus, our scenario is self-consistent.

**4.3 Energy budget**

In figure 4d, we find \( L_{\text{BB}} \simeq 0.3L_c \) throughout. Although the consistency of the \( L_{\text{BB}} / L_c \) ratio is consistent with the prediction by the virial theorem applied to the disk and the corona in a Keplerian motion, the absolute value of \( \sim 0.3 \) is lower than the expected value of 0.5. An obvious cause of this discrepancy is in the system inclination; it may be lower than the assumed value of 45°. Another interesting possibility is soft landing of the accreting gas on to the NS surface. The NS in this system is considered to be spinning towards the final stage of the transition can be explained by a decrease in either \( \zeta \), or \( g \), or both. The former means the flattening of the corona as already discussed, while the latter means a
Aql X-1 remained relatively constant at \( \sim 0.3 \) as the luminosity increases during the transition. We hence consider that outflows would not provide a major source of the \( L_{\text{BB}} \) deficit in the present case.

### 4.4 Transition time scales

Based on continuous monitoring of LMXBs with MAXI and Swift, Asai et al. (2015) showed that the state transitions in LMXBs occur in two types; one type of events, involved in “normal outbursts,” take place on a typical time scale of a day or less, while those of the other type, seen in “mini-outbursts” with much smaller flux changes, proceed on longer time scales of a few days. As seen in the MAXI light curve (figure 3 of Asai et al. 2015), the present transition is clearly associated with a normal outburst in their classification, and the transition time scale we observed, about 30 ks, or \( \sim 8 \) hr, is consistent with those seen in that type of transition.

Compared with these episodes in LMXB, the soft vs. hard state transitions in black hole binaries have been observed to take place on considerably longer time scales, from several days to 10 days (e.g., Maejima et al. 1984; Remillard & McClintock 2006; Nakahira et al. 2012). A simple explanation of this difference would be that the radial propagation of changes in the accretion-disk conditions (typically on viscous time scales) takes longer in stellar black holes due to the larger disk size reflecting the mass difference. Alternatively, the difference may be attributed to the stronger Compton cooling of a corona in an LMXB, by the BB photons which are absent from black holes. Further investigation into this issue is beyond the scope of the present paper.

### 5 Conclusion

We analyzed archival data of Aql X-1 taken with Suzaku on 2011 October 21 for a gross duration of 80 ks. The source underwent a transition from the hard state to the soft state, on a time scale of \( \sim 30 \) ks. We have successfully explained the spectral evolution by combining the disk blackbody emission with thermal Comptonization of the blackbody photons from the NS surface. The model parameters changed continuously, which justifies the spectral decomposition, and unifies the interpretations of the soft and the hard state. Utilizing the obtained parameters, particularly \( \tau \), the Comptonizing corona is suggested to shrink radially as the source approaches the soft state. In addition, the transition is likely to involve a vertical flattening of the corona, or a decrease in the radial flow velocity in the corona, or both.

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