A PROPELLER-EFFECT INTERPRETATION OF MAXI/GSC LIGHT CURVES OF 4U 1608−52 AND Aql X-1 AND APPLICATION TO XTE J1701−462

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ABSTRACT

We present the luminosity dwell-time distributions during the hard states of two low-mass X-ray binaries containing a neutron star (NS), 4U 1608−52 and Aql X-1, observed with MAXI/GSC. The luminosity distributions show a steep cutoff on the low-luminosity side at \(1.0 \times 10^{36} \text{ erg s}^{-1}\) in both sources. The cutoff implies a rapid luminosity decrease in their outburst decay phases and this decrease can be interpreted as being due to the propeller effect. We estimate the surface magnetic field of 4U 1608−52 to be \((0.5–1.6) \times 10^8 \text{ G}\) and Aql X-1 to be \((0.6–1.9) \times 10^8 \text{ G}\) from the cutoff luminosity and apply the same propeller mechanism to the similar rapid luminosity decrease observed in the transient Z source, XTE J1701−462, with RXTE/ASM. Assuming that the spin period of the NS is on the order of milliseconds, the observed cutoff luminosity implies a surface magnetic field on the order of \(10^9 \text{ G}\).

Key words: stars: neutron – X-rays: binaries – X-rays: individual (Aql X-1, 4U 1608−52, XTE J1701−462)

1. INTRODUCTION

Low-mass X-ray binaries with a neutron star (NS-LMXB) consist of an old weakly magnetized neutron star (NS, \(<10^{10} \text{ G}\)) and an evolved late-type companion star. According to their timing properties and spectral variations represented by color–color and hardness–intensity diagrams, NS-LMXBs are classified into two groups: Z sources and Atoll sources (e.g., Hasinger & van der Klis 1989). However, what causes the difference between the Z sources and the Atoll sources is still under debate.

A theoretical study of the NS magnetic field evolution due to accretion suggested that the magnetic fields of Z sources \((\sim 10^9 \text{ G})\) are greater than those of Atoll sources \((\sim 10^8 \text{ G})\) (Zhang & Kojima 2006). This agrees with the following observational results. The magnetic field of a Z source, Cyg X-2, was estimated to be \(2.2 \times 10^9 \text{ G}\) based on the observed horizontal-branch oscillations and the beat frequency model (Focke 1996). Two Atoll sources, 4U 1608−52 and Aql X-1, were estimated to have magnetic fields of \((1.4–1.8) \times 10^8 \text{ G}\) and \(1 \times 10^8 \text{ G}\), respectively, based on the assumed propeller effect (Chen et al. 2006; Zhang et al. 1998a; Campa et al. 1998). Regarding 4U 1608−52, Weng & Zhang (2011) also derived an estimate of \(\sim 10^8 \text{ G}\) from the interaction between the magnetosphere and the accretion flow. On the other hand, the magnetic field strength of a transient Z source, XTE J1701−462, which exhibited a transition from the Z-type to Atoll-type in the color–color diagram during the outburst decay phase (Homan et al. 2010), was estimated to be \((1–3) \times 10^8 \text{ G}\) from the interaction between the magnetosphere and the radiation-pressure-dominated accretion disk (Ding et al. 2011). However, Titarchuk et al. (2001) suggested that both Z sources and Atoll sources have very low surface magnetic fields of \((\sim 10^6–10^7 \text{ G})\), based on their magneto-acoustic wave model and the observed kHz quasi-periodic oscillations (QPOs).

Further fine state-transition behaviors were investigated in the two Atoll sources, 4U 1608−52 and Aql X-1. Wachter et al. (2002) and Maitra & Bailyn (2008) identified three distinct states, outburst, extended low-intensity state (LIS), and true quiescence (TQ), from the correlation between X-ray and optical or IR data. Matsuoka & Asai (2013), hereafter referred to as MA2013, proposed four states: soft, hard–high, hard–low, and no-accretion (recycled pulsar), according to the mass-flow rate and the NS magnetic field strength. The soft and the hard–high states are characterized by the accretion disk states, which are optically thick (soft) or thin (hard–high). The two hard states, hard–high and hard–low, are classified in terms of the propeller effect. As the mass accretion onto the NS decreases, its magnetosphere expands, and then the accretion flow is finally restricted by the centrifugal barrier in the hard–low state.

Although a number of observational evidences indicating state transitions featured by a simultaneous flux and spectral change have been obtained so far, the interpretations of the underlying physical processes are still rather confused. Chen et al. (2006) and Zhang et al. (1998a) proposed the propeller effect as an interpretation of observed flux decreases accompanied with soft-to-hard state transitions. However, Maccarone & Coppi (2003) pointed out that the propeller effect is not a sole cause for all the observed state transitions. They reported that the luminosity in the hard-to-soft transition in the rising phase is greater than that in the soft-to-hard transition in the decay phase by a factor of \(\sim 5\) or more. If the propeller effect were the sole cause, both the transitions in the rise and the decay would occur at the same luminosity. MA2013 proposed the four-state picture, including both the inner-disk transition (soft to hard–high, Abramowicz et al. 1995) and the propeller effect (hard–high to hard–low), to explain the behaviors of 4U 1608−52 and Aql X-1, as mentioned above.

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6 These values were calculated assuming a distance of 3.6 kpc for 4U 1608−52 and 2.5 kpc for Aql X-1. In this study, we employ distances of 4.1 kpc and 5.0 kpc for 4U 1608−52 and for Aql X-1, respectively. If these values were applied in their studies, the magnetic field values would have been \((1.6–2.0) \times 10^8 \text{ G}\) for 4U 1608−52 and \(2 \times 10^8 \text{ G}\) for Aql X-1.
In this paper, we present luminosity dwell-time distributions of 4U 1608−52, Aql X-1, and XTE J1701−462, and propose the consistent interpretation of these profiles based on the propeller effect with their intrinsic magnetic fields. This may also observationally develop the simplified picture of various NS-LMXB states proposed by MA2013. In Section 2, we describe the MAXI/GSC observations of 4U 1608−52 and Aql X-1 and analyze the data. There, we report that the rapid luminosity decreases in the outburst decay phases and determine the cutoff luminosities from the luminosity dwell-time distributions. In Section 3, we estimate the magnetic field strengths based on the cutoff luminosities. We discuss the validity of the propeller-effect interpretation based on the obtained parameters. Subsequently, we apply the same method to the XTE J1701−462 RXTE/ASM light curve and summarize the results in Section 4.

2. OBSERVATION AND ANALYSIS

The Gas Slit Camera (GSC, Mihara et al. 2011; Sugizaki et al. 2011a) on the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009) payload detected two outbursts from 4U 1608−52 and three outbursts from Aql X-1 from 2009 August to 2012 September (MJD = 55058–56180; Morii 2010 and Sugizaki et al. 2011b for 4U 1608−52 and Yamaoka et al. 2011 for Aql X-1). We used the GSC 2−10 keV light-curve data on the public archive7 provided by the MAXI team. We also utilized the 15−50 keV light-curve data provided by the Swift (Gehrels et al. 2004)/Burst Alert Telescope (BAT; Barthelmy et al. 2005) team.8 The GSC count rates are converted to the luminosities by assuming that the spectrum is Crab-like (Kirsch et al. 2005) and employing the source distances of 4.1 ± 0.4 kpc to 4U 1608−52 and 5.0 ± 0.9 kpc to Aql X-1 (Galloway et al. 2008).

Figure 1 shows GSC light curves, BAT light curves, and the BAT/GSC hardness ratios for 4U 1608−52 and Aql X-1. We identified the spectral state (soft state (SS) or hard state (HS)) from the BAT/GSC hardness ratio using the same method as Asai et al. (2012). The “S” in Figure 1 indicates the SS period that is clearly recognized by the hardness ratio of BAT/GSC. A rapid decrease of GSC luminosity in the 2−10 keV band is seen at the transition time from the SS to HS. This rapid luminosity decrease and spectral hardening occurred as a result of the inner-disk transition proposed by MA2013. The roman numerals in the figures denote the HS periods. These HS periods can be divided into two sub-states: one with a luminosity at around \(10^{36} \text{ erg s}^{-1}\) and another with a luminosity below the detection limit (\(3 \times 10^{35} \text{ erg s}^{-1}\)). The two sub-states correspond to the “hard–high” and the “hard–low” states, respectively, defined in MA2013. They are also considered to coincide with the LIS and the TQ in Wachter et al. (2002), respectively, from the levels of X-ray intensities in the sub-states. These sub-state periods are summarized in Table 1.

While the hard–high states are clearly recognized in the three HSs, 4U 1608−52 (I), 4U 1608−52 (II), and Aql X-1 (II), they are hard to see in the other HSs, that is, 4U 1608−52 (II), Aql X-1 (I), Aql X-1 (III), and Aql X-1 (IV). In the latter cases, the source changed immediately from the SS to the hard–low state; thus we cannot discern the level of the hard–high to hard–low transition at which the propeller effect occurred. To investigate the propeller effect, hereafter we focus on the former three periods: 4U 1608−52 (I), 4U 1608−52 (II), and Aql X-1 (II).

In Figure 2, light curves of the selected three HS periods are magnified. All three curves show a rapid decrease when the luminosity decreased below the threshold of \(10^{36} \text{ erg s}^{-1}\). We call the luminosity threshold starting at the rapid decrease “cutoff luminosity.” In order to evaluate the cutoff luminosity, we create luminosity dwell-time distributions during the three HS periods in Figure 3. In the Appendix, the luminosity distributions for typical light-curve profiles are presented.

In the period 4U 1608−52 (I), the luminosity distribution has a peak at 0.015 \(10^{36} \text{ erg s}^{-1}\) (Figure 3(a)), which corresponds to the flux plateau in the hard–high state (Figure 2(a)). In the luminosity below the peak, the dwell time is very small.

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7 http://maxi.riken.jp/
8 http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/.
This implies that the luminosity decreased rapidly below the hard–high plateau. Therefore, the cutoff luminosity is $1.0 \times 10^{36}$ erg s$^{-1}$ from the luminosity distribution. In the period 4U 1608–52 (III), rapid luminosity decrease occurred several times at several luminosity levels (Figure 2(b)). This variation of cutoff luminosity is also seen in the dwell-time distribution in Figure 3(b), in which the cutoff luminosity ranges between $0.75–1.0 \times 10^{36}$ erg s$^{-1}$. We adopted $1.0 \times 10^{36}$ erg s$^{-1}$ as the common value for the cutoff luminosity of 4U 1608–52. In the period Aql X-1 (II), the rapid luminosity decrease is clearly seen. The cutoff luminosity is estimated from the lower edge of the peak in the histogram to be $1.3 \times 10^{36}$ erg s$^{-1}$ (Figure 3(c)). These cutoff luminosities are also indicated in Figure 2 by dashed lines.

These rapid luminosity decreases occurred in the HS periods (from hard–high to hard–low), and thus differ from the state transition due to the inner-disk transition (from soft to hard–high). Namely, the rapid luminosity decrease occurred at the luminosity lower than the transition luminosity of the soft to hard–high.

### 3. DISCUSSION AND APPLICATION

#### 3.1. Surface Magnetic Fields Derived from Luminosity Dwell-time Distributions

We extracted luminosity dwell-time distributions during the HS period, including both the hard–high and hard–low, and determined the cutoff luminosity below which the luminosity starts to decrease rapidly. This cutoff luminosity corresponds to the transition luminosity from the hard–high to the hard–low when the propeller comes into play (MA2013). If the cutoff luminosity is due to the propeller effect, we can derive the surface magnetic field, $B$, on the NS using the following equation (MA2013):$^9$

$$B = 2.6 \times 10^7 \eta^{-7/4} \left( \frac{P}{1 \text{ ms}} \right)^{7/6} \left( \frac{L}{10^{36} \text{ erg s}^{-1}} \right)^{1/2} \times \left( \frac{M}{1.4 \, M_\odot} \right)^{1/3} \left( \frac{R_{\text{NS}}}{10^6 \text{ cm}} \right)^{-5/2} \mu \text{G},$$

where $P$, $M$, and $R_{\text{NS}}$ denote the spin period, mass, and radius of the NS, respectively. The term $L$ denotes the luminosity at which the propeller effect occurs and the corotation radius equals the Alfvén radius. The model dependence factor $\eta \sim 0.5–1$ is obtained from the definition of the Alfvén radius $R_A = \eta R_\text{A0}$. The ideal Alfvén radius $R_\text{A0}$ is defined in Equation (27) in Ghosh & Lamb (1979).

Consequently, we can derive the surface magnetic field of the NS to be $(0.5–1.6) \times 10^8$ G for 4U 1608–52 and $(0.6–1.9) \times 10^8$ G for Aql X-1. Here, we adopted spin periods of 1.62 ms for 4U 1608–52 (Hartman et al. 2003) and 1.82 ms for Aql X-1 (Zhang et al. 1998b).

#### 3.2. Comparison with Previous Understanding of the Propeller Effect

Soft-to-hard spectral transitions accompanied with a sudden flux decrease during a outburst decay phase observed in Aql X-1 (Campana et al. 1998; Zhang et al. 1998a) as well as 4U 1608–52 (Chen et al. 2006) have been suggested as evidence of the propeller effect. However, such an incident, characterized by a simultaneous flux decrease and spectral change, may occur not only by the propeller effect but also in the inner-disk-state transition from optically thick to optically thin (e.g., Asai et al. 2012). Maccarone & Coppi (2003) concluded that the

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$^9$ Here, an orthogonal dipole magnetic field is assumed and the relations $P_{\text{mag}} = B^2/(4\pi)$, $\mu = BR$ are used, following Ghosh & Lamb (1979).
propeller effect is not the sole cause of the spectral transitions because the transition luminosities at the outburst rise and the decay phases are significantly different. Therefore, to identify the propeller effect correctly, we need to distinguish it from the inner-disk transition. Previous studies on the propeller effect did not take account of the inner-disk transition properly. Thus, their estimates of the magnitude of the propeller level may not be sufficiently accurate.

Using the MAXI/GSC and Swift/BAT data covering the wide energy band with more frequent observations and moderate sensitivity, we were able to separate the two transitions clearly, although we cannot clearly see a change of the BAT/GSC hardness ratio by the propeller effect due to poor statistics in the data. This is remarkably different from previous works. However, our estimates of the magnetic field strengths on both 4U 1608–52 and Aql X-1 were almost consistent with the previous results (although ours were slightly smaller). This is because the two transition luminosities for the inner-disk-state transition and the propeller effect are rather close (within a factor of \(\sim 5\)).

#### 3.3. Knee Features in the Light Curve of the Outburst Decay

Powell et al. (2007), hereafter referred to as PHF2007, reported a knee feature (they labeled it as a “brink”) in the light curve of the outburst decay phase due to a change of the accretion rate coupled with disk irradiation. If the “brink” occurred, the decay tendency would change from exponential to linear decline in the SS of 4U 1608–52 indicated by \(S_{\text{RI}}\), and that of Aql X-1 indicated by \(S_{\text{IV}}\). The luminosity at “brink” is \(\sim 1.6 \times 10^{37} \text{ erg s}^{-1}\) in 4U 1608–52 and \(\sim 3.8 \times 10^{37} \text{ erg s}^{-1}\) in Aql X-1. Campana et al. (2013) reported the “brink” features in both Aql X-1 \(S_{\text{II}}\) and \(S_{\text{III}}\).

The rapid luminosity decrease in the hard–high to the hard–low state transition discussed so far may resemble the “brink” feature. However, the number of data points are too small to make detailed analysis and, consequently, we can fit the decay curve with either of a single linear function or a single exponential function. Note that 4U 1608–52 (I) has six data points in the decay part and Aql X-1 (II) has only two data points. The decay part of 4U 1608–52 (III) is difficult to be defined because rapid luminosity decrease occurred several times. Therefore, it was difficult for us to perform useful fittings. However, the rapid luminosity decrease occurred at the end of the long-lasting (\(\sim 100\) days) hard–high state. It does not occur when the flux is decaying monotonically from the outburst peak in which the “brink” was observed. Thus, the feature of transition from the hard–high to the hard–low state is most probably the propeller effect. Here, note that we derived the cutoff luminosity of the propeller effect using the luminosity dwell-time distribution in Figure 3 since no useful fitting analysis was available.

#### 3.4. Application to XTE J1701–462

The propeller effect occurred during the HS period in 4U 1608–52 and Aql X-1. However, the inner-disk state and propeller effect are independent issues. Depending on magnetic fields and spin period, the propeller effect can occur at a higher or lower luminosity than that of the inner-disk transition. A
rapid luminosity decrease was observed in a transient Z source, XTE J1701−462 (Lin et al. 2009b; Fridriksson et al. 2010). The root cause of that rapid decrease is not yet understood. In this section, we apply our understanding of the propeller effect to the observed XTE J1701−462 data.

3.4.1. Previous Works on XTE J1701−462

The transient X-ray source on the Galactic plane, XTE J1701−462, flared up to super-Eddington luminosity in 2006, continuing the activity for more than 18 months. The RXTE (Bradt et al. 1993)/ASM (Levine et al. 1996) continuously monitored the flux down to near-quiescence. The source transformed from the Z-type to the Atoll-type as the luminosity decreased (Homan et al. 2007a, 2007b, 2010). It also exhibited a rapid luminosity decrease in the outburst decay phase. In Figure 4(a) we plot the ASM light curve obtained from the data archive provided by the RXTE/ASM team at MIT and NASA/GSFC,10 where observed count rates are converted to the luminosities in 2−10 keV band by assuming that the spectrum is Crab-like (Kirsch et al. 2005) and the distance is 8.8 kpc (Lin et al. 2009a). The rapid decrease started on MJD ~ 54303, which agrees with the epoch when the transition in the color–color diagram from the Z-type to the Atoll-type occurred (Lin et al. 2009b). The curves before the onset, MJD ~ 54300, can be fitted with a Gaussian function of a width of ~70 days, as overlaid on the data in Figure 4(a).

Lin et al. (2009b) also reported that the Atoll-state period can be divided into the SS and the HS. The transition from the SS to the HS occurred on MJD ~ 54312 (2007 July 31). This means that the source remained in the SS when the rapid decrease started. We considered that this may be due to the propeller effect and then estimated the surface magnetic field on the NS using the same methods applied to 4U 1608−52 and Aql X-1.

3.4.2. Luminosity Dwell-time Distribution

We derived the luminosity dwell-time distributions in Figure 4(b) for the light curve of Figure 4(b), where the expected distribution for the Gaussian decline model in the light curve is overlaid. The rapid luminosity decrease after MJD = 54300 corresponds to the lower cutoff in the luminosity distributions at the level pointed to by the arrow, which is estimated to be $1.8 \times 10^{37} \text{ erg s}^{-1}$. The cutoff level is also shown on the light curve in Figure 4(a).

3.4.3. Cutoff Luminosity and Magnetic Fields

The cutoff luminosity coincides with the time the transition from Z source to Atoll source occurred (Lin et al. 2009b). This cutoff is not likely to be a “brink” by PHF2007 (described in Section 3.2) since the decrease is exponential (not linear; see Figure 2 in Fridriksson et al. 2010). Thus, it can be interpreted as being due to the propeller effect where the Z–Atoll state transition may occur as a consequence of the mass–accretion decrease. The kHz QPOs were observed from XTE J1701−462 in both the Z state and the Atoll state by Sanna et al. (2010). Based on the obtained QPO variation, they proposed that the accretion flow around the NS changed during the Z–Atoll state transition. This hypothesis is consistent with our propeller effect interpretation.

Since XTE J1701−462 had kHz QPOs, we assume that the spin period of the NS is on the order of milliseconds. The surface magnetic field strength is deduced to be on the order of $10^9 \text{ G}$ (Ding et al. 2011) derived the surface magnetic field strength of XTE J1701−462 as $\sim (1–3) \times 10^9 \text{ G}$ from the interaction between the magnetosphere and the radiation-pressure-dominated accretion disk. Our result is consistent with their result.

Fridriksson et al. (2010) discussed the possibility of the propeller effect being responsible for this rapid decrease and mentioned that there are “several serious problems in general interpretation” of the outburst decay rate in NS transitions. One of the “serious problems” is the fact that not only NS-LMXBs, but also black hole transients have shown similar rapid-decreasing decay features (Chen et al. 1997; Jonker et al. 2004). Indeed, the rapid-decreasing decay features were observed in NS-LMXB transients, black hole transients, and also cataclysmic variables (e.g., Gilfanov et al. 1998 and references therein). The common interpretation of “outer-disk thermal instability” (e.g., Meyer & Meyer-Hofmeister 1981; Mineshige & Wheeler 1989) is proposed (Chen et al. 1997; King & Ritter 1998; Gilfanov et al. 1998). The “brink” in PHF2007 is due to the “outer-disk thermal instability” and we were able to distinguish it from the propeller effect. Therefore, we consider that there is no “serious problem” in the propeller-effect interpretation of the observed rapid luminosity decrease in this NS-LMXB.
Table 2
Spectral States and Propeller Effect in the Three NS-LMXBs: 4U 1608−52, Aql X-1, and XTE J1701−462

| Luminosity | State | Propeller | Disk |
|------------|-------|-----------|------|
| High       | Soft  | No, $R_A < R_c$ | Optically Thick |
| †          | Hard–high | No, $R_A < R_c$ | Thin |
| Low        | Hard–low | Yes, $R_c < R_A$ | Thin |

XTE J1701−462

| Luminosity | State | Propeller | Disk |
|------------|-------|-----------|------|
| High       | Soft (Z-like soft) | No, $R_A < R_c$ | Optically Thick |
| †          | Soft (Atoll-like soft) | Yes, $R_c < R_A$ | Thick |
| Low        | Hard–high (Atoll-like hard) | Yes, $R_c < R_A$ | Thin |

3.4.4. Modification of the Simplified Model of LMXB

We have seen in the previous section that the rapid luminosity decrease of XTE J1701−462 can be understood as the result of the propeller effect. The simplified picture of NS-LMXBs in MA2013 proposed the classification of the spectral states of 4U 1608−52 and Aql X-1 using the combination of the inner-disk state and the propeller state (Table 2). We define the transition luminosity of the disk state and the propeller state as $L_{\text{disk}}$ and $L_{\text{prop}}$, respectively. In the case of $L_{\text{prop}} < L_{\text{disk}}$ including 4U 1608−52 and Aql X-1 (top of Table 2), the observed X-ray spectrum is supposed to undergo the soft, hard–high, hard–low, and no-accretion states in order as the luminosity decreases. In the other case of $L_{\text{disk}} < L_{\text{prop}}$ like XTE J1701−462 (bottom in Table 2), it will change in the order of Z-like soft, Atoll-like soft (Atoll banana), and Atoll-like hard (Atoll island) states, instead.

Depending on the magnetic field strength and the spin period, which are specific parameters for each NS-LMXB, the propeller effect may occur in either the SS or the HS. When a propeller effect occurs, it is expected that the thermal emission from the NS surface would decrease and the non-thermal emission from the surrounding gas would become conspicuous. In addition, Rappaport et al. (2004) noted that even when the propeller effect occurs, the spectrum will change with weak intensity because a part of inflow gases would leak onto the NS. There is a 1 Hz QPO observation in another transient LMXB, SAX J1808.4−3658 (Patruno et al. 2009). The timing information in this case might provide important information about the propeller effect. For further investigation of the propeller effect, various observations and analysis of light curves and spectra for many sources would be needed.

4. SUMMARY

We analyzed the light curves and luminosity dwell-time distributions in the HS periods of 4U 1608−52 and Aql X-1, obtained by MAXI/GSC. The luminosity distributions show a peak with a steep cutoff on the lower luminosity side. This cutoff corresponds to a rapid luminosity decrease in the outburst decay phase. The cutoff luminosity is ~$1.0 \times 10^{36}$ erg s$^{-1}$ in both 4U 1608−52 and Aql X-1.

Any NS-LMXB has two qualitative radii: the Alfvén radius and the corotation radius. When the former exceeds the latter as the luminosity decreases, the propeller effect is expected to occur, and the cutoff can be interpreted as being due to the effect. The obtained cutoff luminosities imply the surface magnetic fields on the NS; (0.5−1.6) $\times 10^8$ G in the case of 4U 1608−52 and (0.6−1.9) $\times 10^8$ G in the case of Aql X-1.

We applied the propeller-effect interpretation to the light curve of a transient Z-source, XTE J1701−462, obtained by RXTE/ASM. This source also showed a rapid luminosity decrease that occurred in the SS. The deduced surface magnetic field is on the order of $10^8$ G and is consistent with previous work. Thus, the rapid luminosity decrease in this source can also be due to the propeller effect regardless of the spectral states.

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APPENDIX

LUMINOSITY DWELL-TIME DISTRIBUTION

In order to study the relation between the light curve and its luminosity dwell-time distribution, we present those for three typical light curves in Figure 5: a random variation in the logarithmic scale, an exponential decrease, and a Gaussian decrease. In case of a random variation in the logarithmic scale, the dwell times are constant and independent of luminosity values if the histogram bins are chosen to have equal widths in...
the logarithmic scale (top panel). When the luminosity varies between $L_{\text{min}}$ and $L_{\text{max}}$, the luminosity dwell-time distributions exhibit equal heights between $L_{\text{min}}$ and $L_{\text{max}}$. In the exponential decrease, the dwell time also becomes constant because the luminosity decrease is represented by a straight line in the logarithmic scale (middle panel). In the case of a Gaussian decrease, luminosity decreases more rapidly, which reduces the dwell time in lower luminosities (bottom panel).

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