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Truncation of the Accretion Disk at One-third of the Eddington Limit in the Neutron Star Low-mass X-Ray Binary Aquila X-1

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Abstract

We perform a reflection study on a new observation of the neutron star (NS) low-mass X-ray binary Aquila X-1 taken with NuSTAR during the 2016 August outburst and compare with the 2014 July outburst. The source was captured at ~32% \( L_{\text{Edd}} \), which is over four times more luminous than the previous observation during the 2014 outburst. Both observations exhibit a broadened Fe line profile. Through reflection modeling, we determine that the inner disk is truncated \( R_{\text{in,2016}} = 11^{+5}_{-3} R_g \) (where \( R_g = GM/c^2 \)) and \( R_{\text{in,2014}} = 14 \pm 2 R_g \) (errors quoted at the 90% confidence level). Fiducial NS parameters \( (M_{\text{NS}} = 1.4 M_{\odot}, \quad R_{\text{NS}} = 10 \text{ km}) \) give a stellar radius of \( R_{\text{NS}} = 4.85 R_g \); our measurements rule out a disk extending to that radius at more than the 6\( \sigma \) level of confidence. We are able to place an upper limit on the magnetic field strength of \( B < 3.0 \times 10^5 \text{ G} \) at the magnetic poles, assuming that the disk is truncated at the magnetospheric radius in each case. This is consistent with previous estimates of the magnetic field strength for Aquila X-1. However, if the magnetosphere is not responsible for truncating the disk prior to the NS surface, we estimate a boundary layer with a maximum extent of \( R_{\text{BL,2016}} \sim 10 R_g \) and \( R_{\text{BL,2014}} \sim 6 R_g \). Additionally, we compare the magnetic field strength inferred from the Fe line profile of Aquila X-1 and other NS low-mass X-ray binaries to known accreting millisecond X-ray pulsars.

Key words: accretion, accretion disks – stars: individual (Aql X-1) – stars: neutron – X-rays: binaries

1. Introduction

Aquila X-1 is a neutron star (NS) residing in a low-mass X-ray binary (LMXB) that has exhibited X-ray pulsations, if intermittently so. A LMXB consists of an accreting compact object with a companion star of approximately solar mass. The companion star in Aquila X-1 is categorized as a K0 V spectral type (Thorstensen et al. 1978; Mata Sánchez et al. 2017). Coherent millisecond X-ray pulsations that were detected for 150 s during persistent emission imply a spin frequency of 550 Hz (Casella et al. 2008). Type-I X-ray bursts blare an upper limit on the distance to Aquila X-1 of 5.9 kpc away, assuming the bursts are Eddington limited (Jonker & Nelemans 2004).

The inclination of the system is constrained to be <31° by infrared photometry measurements performed by Garcia et al. (1999). Intermittent dipping episodes may indicate an inclination as high as 72–79° (Galloway et al. 2016). However, intermittent dipping may not be indicative of a high inclination. Another low inclination system, 4U 1543-47, exhibited intermittent dipping that was suggestive of an accretion instability (Park et al. 2004). Additionally, recent near-infrared spectroscopy rules out a high inclination and implies an inclination 23° < i < 53° when considering conservative constraints (Mata Sánchez et al. 2017). The magnetic field strength is estimated to be (0.4–31) \times 10^8 \text{ G}. This is inferred from pulsations signifying magnetically channelled accretion in Rossi X-ray Timing Explorer (RXTE) observations (Mukherjee et al. 2015). Additionally, the “propeller” phase, where material is thrown off from the disk at low luminosity and can no longer accrete onto the NS, implies a similar magnetic field strength (Campana et al. 1998; Asai et al. 2013).

Broadened and skewed Fe line profiles have been detected from accretion disks in NS LMXBs for the last decade (e.g., Bhattacharyya & Strömher 2007; Cackett et al. 2008, 2010; Papitto et al. 2008; Di Salvo et al. 2009; Egron et al. 2013; Miller et al. 2013). These profiles are shaped from Doppler and relativistic effects (Fabian et al. 1989) and, as a consequence, the red wing can be used to determine the location of the inner edge of the disk.

The accretion disk must extend down to or truncate prior to the surface of the NS. Disk truncation can occur above \( L_{\text{Edd}} \) in one of two ways: either pressure balance between the accreting material and magnetosphere or a boundary layer of material extending from the surface. Below \( L_{\text{Edd}} \), accretion in LMXBs can become inefficient and disk truncation can occur through other mechanisms, such as disk evaporation (Narayan & Yi 1995; Tomsick et al. 2009; Degenaar et al. 2017). By studying sources with truncated accretion disks at sufficiently high \( L_{\text{Edd}} \), we can obtain estimates of magnetic field strengths (Cackett et al. 2009; Ibragimov & Poutanen 2009; Papitto et al. 2009; Miller et al. 2011; Degenaar et al. 2014, 2016; King et al. 2016; Ludlam et al. 2016) and/or extent of potential boundary layers (Popham & Sunyaev 2001; Chiang et al. 2016; King et al. 2016; Ludlam et al. 2016).

It remains unclear whether the magnetic field is dynamically important in Aquila X-1 and other non-pulsating NS LMXBs. Aquila X-1 is frequently active with outbursts occurring about once a year (Campana et al. 2013; Waterhouse et al. 2016) making it a key target. King et al. (2016) obtained observations of Aquila X-1 in the soft state with NuSTAR and Swift during the 2014 July outburst. They found that the disk was truncated at 15 ± 3 \( R_g \) (where \( R_g = GM/c^2 \)) at ~7% of the empirical
Eddington luminosity \( L_{\text{Edd}} = 3.8 \times 10^{38} \text{ erg s}^{-1} \); Kuulkers et al. 2003). This placed a limit on the strength of the equatorial magnetic field of \( B < 7 \times 10^{8} \text{ G} \) that is consistent with previous estimates.

The *Swift*/BAT detected renewed activity on 2016 July 29 (Sanna et al. 2016a), which was confirmed to be a new outburst with a 500 s follow-up *Swift*/XRT observation (Sanna et al. 2016b). Observations were taken with *NuSTAR* (Harrison et al. 2013) on 2016 August 7 when Aquila X-1 was in the soft state at \(-0.32 L_{\text{Edd}}\) during the outburst. We perform a reflection study on the prominent Fe K\(_\alpha\) feature for this observation and compare with the 2014 outburst.

## 2. Observations and Data Reduction

*NuSTAR* observations were taken of Aquila X-1 on 2014 July 17 and 18 (Obsids 80001034002 and 80001034003) and 2016 August 7 (Obsid 90202033002). Figure 1 shows the *Swift*/BAT and *MAXI* daily monitoring light curves with vertical dashed lines to indicate when the *NuSTAR* observations were taken. Using the NUPRODUCTS tool from NUSTARDAS v1.5.1 with CALDB 20170503, we created light curves and spectra for the 2016 observations. We used a circular extraction region with a radius of 100″ centered around the source and another region away from the source for the purpose of background subtraction. No Type-I X-ray bursts occurred during the 2016 observation. Initial modeling of the spectra with a constant fixed to 1 for the FPMA, found the constant component to be within 0.95–1.05. We combine the two source spectra, background spectra, ancillary response matrices and redistribution matrix files via ADDASCASPEC and ADDRMF. Each of these have been weighted by exposure time. The 2014 observations were reduced using the most recent CALDB, 20170503, which has been updated since the reduction and analysis reported in King et al. (2016). The combined spectra were grouped to have a minimum of 25 counts per bin (Cash 1979) using GRPPHA. The net count rate for the combined spectra was 126.8 counts s\(^{-1}\) in 2014 and 424.3 counts s\(^{-1}\) in 2016.

We do not utilize the 2014 *Swift* observations as per King et al. (2016) due to major flux differences between the *NuSTAR* and *Swift* spectra. The *Swift* spectrum required a multiplicative constant of 3.75 to match the *NuSTAR* flux. This flux difference is likely due to the need to exclude the PSF core to avoid pile-up in the *Swift* data. Additionally, excluding the core of the PSF further limits the sensitivity of the *Swift* spectrum and, as a result, the reflection spectrum cannot be detected in the data. Furthermore, *Swift* only performed a short exposure observation (under 200 s) on the same day as the *NuSTAR* observation in 2016, which does not provide constraints. As a consequence, we opted to focus on the comparison of *NuSTAR* observations only in this study.

## 3. Spectral Analysis and Results

We utilize XSPEC version 12.9.1 (Arnaud 1996) in this work with fits performed over the 3.0–30.0 keV energy range (the spectrum is dominated by background above 30 keV). All errors were calculated using a Monte Carlo Markov Chain (MCMC) of length 100,000 and are quoted at the 90\% confidence level. We use TBNEWER\(^7\) to account for the absorption along the line of sight. As *NuSTAR* has a limited lower energy bandpass, it is unable to constrain the equivalent neutral hydrogen column density on its own. We therefore set the equivalent neutral hydrogen column density to the Dickey & Lockman (1990) value of \(4.0 \times 10^{21} \text{ cm}^{-2}\). Moreover, this value is very close to column densities found with low energy spectral fitting to *XMM-Newton* and *Chandra* data (Campana et al. 2014).

King et al. (2016) modeled the 2014 data using a Comptonized thermal continuum with a relativistically blurred emergent reflection emission. We chose to forego this combination of models in an effort to provide a self-consistent approach between components. The reflection model in King et al. (2016) assumes that a blackbody continuum is illuminating the disk, though the continuum is modeled with Comptonization. Further, the assumed blackbody in the reflection model that is providing the emergent reflection spectrum does not peak at the same energy as the Comptonized continuum. This means that the component assumed to illuminate the accretion disk is not consistent with the emergent reflection spectrum. We chose to adopt a continuum model akin to Lin et al. (2007) for NS transients in the soft state. The continuum is described by two thermal components: a single temperature blackbody component (BBODYRAD) and a multi-temperature blackbody (DISKBB). The single temperature blackbody component is used to model the emission from the corona or boundary layer. The multi-temperature blackbody is used to account for the thermal emission from different radii in the accretion disk. The addition of a power-law component may be needed in some cases and is suggestive of weak Comptonization.

Initial fits were performed with two thermal components, which gave a poor fit in each case (\(\chi^2_{2014}/\text{d.o.f.} = 4088.70/591\) and \(\chi^2_{2016}/\text{d.o.f.} = 3946.47/585\), partly due to the presence of strong reflection within the spectrum. We added a power-law component with the photon index bound at a hard limit of 4.0. Steep indices of this nature have been observed in Sobczak et al. (2000) and Park et al. (2004) for black hole X-ray binaries. The additional power-law component improved the overall fit at more than the 9\% level of confidence, as determined via F-test, in each case. However, the reflection is

\(^7\) J. Wilms et al. (2017, in preparation), http://pulsar.sternwarte.uni-erlangen.de/wilms/research/thbvs/index.html.
still unaccounted for by this model. The broadened Fe K emission line can be seen in Figure 2 for each outburst.

We account for the emergent reflection from an ionized disk by convolving REFLIONX\(^8\) (Ross & Fabian 2005) with the relativistic blurring kernel RELCONV (Dauser et al. 2010). The REFLIONX model has been modified to assume the disk is illuminated by a blackbody. We tie the blackbody temperature of the reflection and continuum emission. We use a constant emissivity index, \(q\), fixed at three, as would be expected for an accretion disk illuminated by a point source in an assumed geometry of flat, Euclidean space (Wilkins & Fabian 2012). Different geometries, such as a boundary layer surrounding the inner disk radius, \(R_g\), a radius of 10 km, and a moderately soft equation of state (Wilkins et al. 2000). The inner disk radius, \(R_{in}\), is given in units of innermost stable circular orbit (ISCO). We convert this value to \(R_g\) given that 1 ISCO = 5.2 \(R_g\) for \(a_* = 0.259\) (Bardeen et al. 1972).

The XSPEC model we used for each spectrum was TBNEWER\(^*\) (DISKBB+BBODYRAD+POW+RELCONV+REFLIONX). This provided an improvement in the overall fit at more than the 25\(\sigma\) level of confidence \((\chi^2_{2014}/\text{d.o.f.} = 620.29/583)\) and \(\chi^2_{2016}/\text{d.o.f.} = 603.08/579\) over the prior model that did not account for reflection within the spectra. Figure 3 shows the best-fit spectra and model components. Model parameters and values are listed in Table 1. The exact nature of the power-law component is unknown, as it may or may not be physical, but it is statistically needed at more than the 15\(\sigma\) level of confidence for each case.

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\(^8\) http://www-xray.ast.cam.ac.uk/~mlparker/reflionx_models/reflions_bb.mod

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\(^*\) http://www-xray.ast.cam.ac.uk/~mlparker/reflionx_models/reflions_bb.mod

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For the data taken during the 2014 outburst, the DISKBB component has a temperature of \(kT = 1.64 \pm 0.02\) keV and norm = 12.0\(^\pm\)0.3 \(\text{km}^2/100\ \text{kpc}^2\ \text{cos}(i)\). The BBODYRAD component has a temperature of \(kT = 2.27 \pm 0.02\) keV and normalization of 12.1 \(\pm 0.1\) \(\text{km}^2/100\ \text{kpc}^2\). The power-law has a steep photon index of \(\Gamma = 3.7 \pm 0.1\) with a normalization of 12.0 \(\pm 0.1\) photons \(\text{keV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\) at 1 keV. The inner disk radius is truncated at \(R_{in} = 2.7 \pm 0.4\) ISCO (14 \(\pm\) 2 \(R_g\)). The inclination was found to be 26\(^\circ\)\(^+\)3\(^\circ\)\(^-\).

For the data taken during the 2016 outburst, the DISKBB component has a temperature of \(kT = 2.33\(^\pm\)0.03\) keV and norm = 62 \(\pm\) 2 \(\text{km}^2/100\ \text{kpc}^2\ \text{cos}(i)\). The BBODYRAD component has a temperature of \(kT = 2.33\(^\pm\)0.03\) keV and normalization of 4.1\(^+\)0.4 \(\text{km}^2/100\ \text{kpc}^2\). Again, the photon index is steep at \(\Gamma = 3.96\(^\pm\)0.03\) with a normalization of 4.8\(^+\)0.2 photons \(\text{keV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\) at 1 keV. The inner disk radius is truncated at \(R_{in} = 2.1\(^\pm\)0.3\) ISCO (11\(^\pm\)2 \(R_g\)). The inclination is 26\(^\circ\)\(^\pm\)2\(^\circ\), which also agrees with the previous observation.

The blackbody and disk blackbody normalizations in both fits are implausibly small when used to infer a radial extent of the emitting region. This systematic underestimation was proposed by London et al. (1986) to be the result of spectral hardening as photons travel through an atmosphere above pure blackbody emission and is supported through numerical
Table 1

| Component      | Parameter | 2014       | 2016       |
|----------------|-----------|------------|------------|
| TBNEWER       | $N_\text{H}(10^{22})^2$ | 0.4        | 0.4        |
| DISKBB         | $kT$      | $1.64 \pm 0.02$ | $1.69^{+0.01}_{-0.02}$ |
|                | norm      | $12.0^{+0.3}_{-0.1}$ | 62 ± 2     |
| BODYRAD       | $kT$      | $2.27 \pm 0.02$ | $2.33^{+0.01}_{-0.02}$ |
|                | norm      | $1.2 \pm 0.1$ | $4.1^{+0.4}_{-0.2}$ |
| POWERLAW      | $\Gamma$  | $3.7 \pm 0.1$ | $3.96^{+0.02}_{-0.01}$ |
|                | norm      | $1.2 \pm 0.1$ | $4.8^{+0.2}_{-0.2}$ |
| RELCONV       | $q^\ast$  | 3.0        | 3.0        |
|               | $a^\ast$  | 0.259      | 0.259      |
|               | $\iota^\ast$ | 26.5 ± 0.2 | 26 ± 2     |
|               | $R_{\text{ISCO}}$ | 2.7 ± 0.4 | 2.1 ± 0.2  |
|               | $R_{\text{in}}(R_g)$ | 14 ± 2 | 11 ± 2 |
|               | $R_{\text{out}}(R_g)^\ast$ | 400 | 400 |
| REFLIONX      | $\xi$     | $400^{+50}_{-60}$ | 200 ± 10   |
|               | $\lambda_{\text{flux}}^\ast$ | 0.5 | 0.5 |
|               | $z^\ast$  | 0          | 0          |
|               | norm      | $0.25^{+0.02}_{-0.03}$ | 3.5 ± 0.2 |
|               | $F_{\text{unabs}0.5-50.0\text{keV}}$ | 6 ± 1 | 29 ± 2 |
|               | $L_{0.5-50.0\text{keV}}$ | 2.5 ± 0.4 | 12 ± 2   |
|               | $L_{0.5-50.0\text{keV}/L_{\text{edd}}}$ | 0.07 ± 0.01 | 0.3±0.05 |

$\chi^2$ (d.o.f.) | 1.06 (583) | 1.04 (579) |

Note. Errors are quoted at the 90% confidence level. The $N_\text{H}$ was fixed to the Dickey & Lockman (1990) value for the absorption column density along the line of sight and given in units of cm$^{-2}$. The REFLIONX model used has been modified to fit for an accretion disk-illuminated blackbody. The blackbody temperatures were tied between the continuum and reflection emission. The power-law index was pegged at a hard limit of 4.0. Flux is given in units of $10^{37}$ erg s$^{-1}$, luminosity is calculated at a maximum distance of 5.9 kpc and given in units of $10^{37}$ erg s$^{-1}$. $L_{\text{edd}} = 3.8 \times 10^{38}$ erg s$^{-1}$ (Kuulkers et al. 2003). For reference, 1 ISCO = 5.2 $R_g$ for $a^\ast$ = 0.259.

* Fixed.

Simulations (Shimura & Takahara 1995; Merloni et al. 2000). The consistency in model parameter values with only the normalization changing between the two soft state observations likely indicates similar accretion geometries. We allow the emissivity parameter to be fixed to check if our results are dependent on the emissivity index being fixed at three. The emissivity index tends toward a slightly higher value of $q = 3.1$ for the 2014 observation and $q = 2.5$, which is consistent with the disk extending down to a smaller radius in the most recent observation. All model parameters are consistent within the 3σ level of confidence with those reported in Table 1. Figure 4 shows how the goodness-of-fit changes with inner disk radius for each observation. We use the XSPEC “steppar” command to determine how the goodness-of-fit changes as a function of inner disk radius. At each evenly placed step, $R_{\text{in}}$ was fixed while the other parameters were free to adjust to find the best fit. The ISCO is ruled out at more than the 6σ level of confidence in each case.

4. Discussion

We present a new observation of Aquila X-1 taken with 

Receiver during its 2016 August outburst and compare it to the 2014 July outburst. We perform reflection fits that indicate the disk is truncated prior to the surface of the NS. The location of the inner disk radius during the 2014 observation is $14 \pm 2 R_g$. This is consistent with the previous results found in King et al. (2016), although we modeled the continuum in a different way. The location of the inner disk radius remains truncated ($11^{2}_{-1} R_g$) during the 2016 observation even though the flux is over four times larger. Additionally, both spectra imply an inclination of $26^\circ \pm 2^\circ$ that is consistent with infrared photometric and spectroscopic measurements (Garcia et al. 1999; Mata Sánchez et al. 2017).

By assuming that the ram pressure in the disk is balanced by the outward pressure of the magnetic field, we can place an upper limit on the magnetic field strength using the maximum extent the inner disk of $R_{\text{in}} = 13 R_g$ from the 2016 spectrum. Assuming a mass of $1.4 M_\odot$, taking the maximum distance to be 5.9 kpc, and using the maximum unabsorbed flux from 0.5 to 50.0 keV of $33 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ as the bolometric flux, the magnetic dipole moment, $\mu$, can be estimated from...
Equation (1):
\[
\mu = 3.5 \times 10^{33} k_{A}^{-7/4} \chi^{-4} \left( \frac{M}{1.4 \ M_{\odot}} \right)^{2} \times \left( \frac{f_{\text{mag}}}{\eta} \right) \frac{F_{\text{bol}}}{10^{-9} \ \text{erg cm}^{-2} \ \text{s}^{-1}} \frac{D}{3.5 \ \text{kpc}} \ G \ \text{cm}^{3}
\]
with \(x\) being the number of gravitational radii \(\text{c}\) (Cackett et al. 2009; Ibragimov & Poutanen 2009). If we assume an accretion efficiency of \(\eta = 0.2\) and unity for the angular anisotropy, \(f_{\text{mag}}\), and conversion factor, \(k_{A}\), then \(\mu \approx 6.7 \times 10^{26} \ G \ \text{cm}^{3}\). For an NS of 10 km, this implies a magnetic field strength at the poles of \(B \approx 1.3 \times 10^{9} \ \text{G}\). Alternatively, if we assume a different conversion factor between disk and spherical accretion of \(k_{A} = 0.5\) as proposed in Long et al. (2005), the strength of the magnetic field increases to \(B \approx 4.5 \times 10^{9} \ \text{G}\). For the 2014 outburst, we use the upper limit of \(R_{\text{in}} = 16 \ R_{g}\) and the maximum unabsorbed flux from 0.5 to 50.0 keV of \(7 \times 10^{-9} \ \text{erg cm}^{-2} \ \text{s}^{-1}\) to place a limit on the magnetic field strength to be \(B \approx 0.9 \times 10^{8} \ \text{G}\) for \(k_{A} = 1.0\) and \(B \approx 3.0 \times 10^{9} \ \text{G}\) for \(k_{A} = 0.5\). Note that the magnetic field strength at the equator is half as strong as at the pole. King et al. (2016) found a similar value for the maximum strength of the magnetic field for Aquila X-1 of \(B \approx 1.4 \times 10^{9} \ \text{G}\) at the magnetic poles. We report the upper limit on the magnetic field strength using the conversion factor of \(k_{A} = 0.5\) hereafter, as it encompasses the value for \(k_{A} = 1.0\).

If, however, the magnetosphere was not responsible for truncating the disk, a boundary layer extending from the surface of the NS could plausibly halt the accretion flow. Equation (2), taken from Popham & Sunyaev (2001), provides a way to estimate the maximum radial extent of this region from the mass accretion rate.

\[
\log (R_{\text{max}} - R_{\text{NS}}) \approx 5.02 + 0.245 \left\{ \log \left( \frac{M}{10^{-9.85} \ M_{\odot} \ \text{yr}^{-1}} \right) \right\}^{1/2}
\]

We determine the mass accretion rate using the unabsorbed luminosity from 0.5 to 50.0 keV and an accretion efficiency of \(\eta = 0.2\) to be \(1.1^{+0.3}_{-0.2} \times 10^{-8} \ M_{\odot} \ \text{yr}^{-1}\) during the 2016 observation and \(2.2 \pm 0.4 \times 10^{-9} \ M_{\odot} \ \text{yr}^{-1}\) during the 2014 observation. This gives a maximum radial extent of \(~10 \ R_{g}\) for the boundary layer during 2016 and \(~6 \ R_{g}\) during 2014 (assuming canonical values of \(M_{\text{NS}} = 1.4 \ M_{\odot}\) and \(R_{\text{NS}} = 10 \ \text{km}\)). This is consistent with the location of the inner disk radius during the 2016 outburst, but falls short of the inner disk radius in our 2014 fits. King et al. (2016) found a similar radial extent of the boundary layer of \(~7.8 \ R_{g}\), but this can be increased by rotation of the NS or a change in viscosity to be consistent with the truncation radius.

It is more likely that the magnetic field is responsible for disk truncation in this source. The equatorial magnetic field strength inferred from the Fe line profile \((B \approx 15.0-22.5 \times 10^{8} \ \text{G})\) is consistent with other estimates of the magnetic field strength \((0.4-31 \times 10^{8} \ \text{G})\). Campana et al. 1998; Asai et al. 2013; Mukherjee et al. 2015) and are well within the range to truncate an accretion disk (Mukherjee et al. 2015). Following Equation (1) and rearranging for inner disk radius in terms of flux, the inner disk radius should scale like \(F_{\text{bol}}^{-2/7}\). Thus, for magnetic truncation, the inner disk radius should decrease as the flux increases, which is what we see for the different observations. Conversely, if the boundary layer were responsible for disk truncation in each case, we should see the inner disk radius increase. Additionally, the maximum extent of the boundary layer during the 2014 observation does not agree with the location of the inner disk radius, pointing to the magnetic field being a more probable explanation for disk truncation. Moreover, although the extent of the boundary layer is consistent with the inner disk radius in the 2016 fits, the behavior of decreasing inner disk radius with increasing flux is indicative of magnetic truncation.

4.1. Comparison of Magnetic Field Strengths

\textit{NuSTAR} has observed a number of NS LMXBs with Fe lines that imply truncated disks. This has provided a means of placing an upper limit on the strength of their magnetic fields, assuming the disk is truncated at the Alfvén radius (where the ram pressure of the accreting material is balanced by the magnetic pressure outwards). The implied magnetic field strengths reside between \(10^{8}\) and \(10^{9} \ \text{G}\) and are similar to accreting millisecond X-ray pulsars (AMXPs). Mukherjee et al. (2015) systematically estimated the upper and lower limits to the equatorial magnetic field strengths of 14 known AMXPs using \textit{RXTE}. They used the highest flux that the source exhibited pulsations and the radius of the NS to determine \(B_{\text{min}}\) and the lowest flux that exhibited pulsations and corotation radius with the disk to determine \(B_{\text{max}}\) in each case.

Figure 5 presents a comparison of magnetic field strengths of known AMXPs to NS LMXBs observed with \textit{NuSTAR} versus Eddington fraction, \(F_{\text{Edd}}\). As can be seen, the NS LMXBs populate higher values of Eddington fraction. Each point from Mukherjee et al. (2015) represents a range in magnetic field strength and \(F_{\text{Edd}}\) that the AMXP lies and does not embody an actual measurement. Values can be found in Table 2. The advantage of magnetic field strengths inferred from the Fe line profiles using \textit{NuSTAR} is that they do not suffer from pile-up or instrumental effects until a source reaches \(~10^{5} \ \text{counts s}^{-1}\). We use the maximum Eddington luminosity of \(3.8 \times 10^{38} \ \text{erg s}^{-1}\)
from Kuulkers et al. (2003) when calculating the Eddington fraction for each source. If the Eddington luminosity is smaller, all points would be shifted to higher values of Eddington fraction. Therefore, these are all lower limits.

Another caveat of this comparison is that pulsations have not been detected yet for the sources observed with NuSTAR. For Aquila X-1 in particular, the 2014 observation is within the same $F_{\text{edd}}$ range as the observation taken by RXTE when pulsations were detected. Additionally, our upper limit on the strength of the magnetic field agrees with the estimate when pulsations were detected. It is clear that the strengths implied from Fe line profiles are valuable and consistent with those seen for AMXPs. Therefore, Fe lines can be used to estimate magnetic field strengths to first order.

5. Summary

We present a reflection study of Aquila X-1 observed with NuSTAR during the 2014 July and 2016 August outbursts. We find the disk to be truncated prior to the surface of the NS at $14 \pm 2\ R_\ast$ during 2014 observation when the source was at 7% of Eddington and $11.2\ R_\ast$ during the 2016 observation when the source was at 32% of Eddington. This implies an upper limit on the strength of the magnetic field at the poles of $(3.0\pm4.5) \times 10^8\ G$, if the magnetosphere is responsible for truncating the disk in each case. If a boundary layer is responsible for halting the accretion flow instead, we estimate the maximal radial extent to be $\sim 6\ R_\ast$ for the 2014 observation and $\sim 10\ R_\ast$ during 2016. These values can be increased through viscous and spin effects, but the behavior of decreasing inner disk radius with increasing flux favors magnetic truncation. Finally, when comparing the strength of magnetic fields in NS LMXBs to those of known AMXPs, we find that they are consistent while probing a higher value of Eddington fraction.

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References

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: CA: ASP), 17
Asai, K., Matsuo, M., Mihara, T., et al. 2013, ApJ, 773, 117
Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347
Bhattacharyya, S., & Strohmayer, T. E. 2007, ApJL, 664, L103
Braje, T. M., Romani, R. W., & Rauch, K. P. 2000, ApJ, 531, 447
Cackett, E. M., Altamirano, D., Patruno, A., et al. 2009, ApJL, 694, L21
Cackett, E. M., Miller, J. M., Ballantyne, D. R., et al. 2010, ApJ, 720, 205
Cackett, E. M., Miller, J. M., Bhattacharyya, S., et al. 2008, ApJL, 674, 415
Campana, S., Brivio, F., Degenaar, N., et al. 2014, MNRAS, 441, 1984
Campana, S., Coti Zelati, F., & D’Avanzo, P. 2013, MNRAS, 432, 1695
Campana, S., Stella, L., Mereghetti, S., et al. 1998, ApJ, 499, 65
Casella, P., Altamirano, D., Patruno, A., Wijnands, R., & van der Klis, M. 2008, ApJ, 674, 41
Cash, W. 1979, ApJ, 228, 939
Chiang, C.-Y., Morgan, R. A., Cackett, E. M., et al. 2016, ApJ, 831, 45
Dauser, T., Wilms, J., Reynolds, C. S., & Brenneman, L. W. 2010, MNRAS, 409, 1534
Degenaar, N., Altamirano, D., Parker, M., et al. 2016, MNRAS, 461, 4049
Degenaar, N., Miller, J. M., Harrison, F. A., et al. 2014, ApJL, 796, L9
Degenaar, N., Pinto, C., Miller, J. M., et al. 2017, MNRAS, 464, 398
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Di Salvo, T., et al. 2009, MNRAS, 398, 2022
Egret, E., et al. 2013, A&A, 551, A5
Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729
Galloway, D. K., Ajamian, A. N., Ujoh, J., & Sturte, M. 2016, MNRAS, 461, 3847
García, M. R., Callanan, P. J., McCarthy, J. E., Eriksen, K., & Hjellming, R. M. 1999, ApJ, 518, 422
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Ibragimov, A., & Poutanen, J. 2009, MNRAS, 400, 492
Jonker, P. G., & Nelemans, G. 2004, MNRAS, 354, 355
King, A. L., et al. 2016, ApJL, 819, L29
Kuulkers, E., den Hartog, P. R., in’t Zand, J. J. M., et al. 2003, A&A, 399, 663
Lin, D., Remillard, R. A., & Homan, J. 2007, ApJL, 667, 1073
London, R. A., Taam, R. E., & Howard, W. M. 1986, ApJ, 308, 170L
Long, M., Romanova, M. M., & Lovelace, R. V. E. 2005, ApJ, 634, 1214
Ludlam, R. M., Miller, J. M., Bachetti, M., et al. 2017a, ApJL, 836, 140
Ludlam, R. M., Miller, J. M., Cackett, E. M., et al. 2016, ApJ, 824, 37
Ludlam, R. M., Miller, J. M., Cackett, E. M., Degenaar, N., & Bostrom, A. C. 2017b, ApJL, 838, 79
Mata Sánchez, D., Muñoz-Darias, T., Casares, J., & Jiménez-Ibarra, F. 2017, MNRAS, 464, 41
Merloni, A., Fabian, A. C., & Ross, R. R. 2000, MNRAS, 313, 193
Miller, J. M., Maitra, D., Cackett, E. M., Bhattacharyya, S., & Strohmayer, T. E. 2011, ApJL, 731, L7
Miller, J. M., et al. 2013, ApJL, 779, L2
Miller, M. C., Lamb, F. K., & Poutanen, J. 1998, ApJ, 508, 791
Mukherjee, D., Buit, P., van der Klis, M., & Bhattacharya, D. 2015, MNRAS, 452, 3994
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Papitto, A., Di Salvo, T., et al. 2008, ATel, 1846, 1
Papitto, A., Di Salvo, T., D’Aì, A., et al. 2009, A&A, 493, L39
Park, S. Q., Miller, J. M., McClintock, J. E., et al. 2004, ApJ, 610, 378
Popham, R., & Sunyaev, R. 2001, ApJ, 547, 355
