1. INTRODUCTION

AE Aquarii (hereafter AE Aqr) is a cataclysmic variable binary system classified as a member of the DQ Herculis or intermediate polar (IP) class (Patterson 1994). It is a non-eclipsing close binary system at a distance of $10^{2+42}$ pc (Friedjung 1997), consisting of a magnetic white dwarf (primary) and a K4–5 V star (secondary) with an orbital period, $P_{\text{orbit}} = 9.88$ hr. The 33.08 s period makes AE Aqr the fastest-spinning magnetized white dwarf (Patterson et al. 1980) and the ultraviolet (Eracleous et al. 1994). In the DQ Herculis class, the white dwarf is generally thought to possess a magnetic field (Terada et al. 2008), suggesting that AE Aqr may accelerate charged particles in a fashion similar to rotation-powered pulsars (e.g., Kaspi 2004). However, the highest temperature found in such models was 4.6 keV (Itoh et al. 2006), which is significantly lower than the average $kT \approx 22$ keV found in the 22 IPs detected by INTEGRAL (Landi et al. 2009). For these reasons, the mechanism and location of the X-ray emission are still uncertain (e.g., Choi et al. 1999; Itoh et al. 2006; Mauche 2009).

Another intriguing feature reported by a Suzaku observation in 2005 is that AE Aqr may emit non-thermal hard X-rays with a very narrow pulse profile at the spin period (Terada et al. 2008), suggesting that AE Aqr may accelerate charged particles in a fashion similar to rotation-powered pulsars (e.g., Kaspi 2004). However, the Suzaku observation in 2006 did not reproduce the earlier result, leaving the detection of non-thermal X-rays from AE Aqr uncertain.

In this paper, we present broad-band X-ray observations of AE Aqr obtained with NuSTAR and Swift. Section 2 details the observations, data reduction, and background modeling. These more sensitive observations in the hard X-ray band can help measure the maximum temperature of the thermal plasma in AE Aqr and test the presence of any beamed non-thermal component. We describe the spectral modeling in Section 3 and the timing analysis in Section 4. The results and a possible interpretation are discussed in Section 5. Throughout this paper, all errors are given at the 90% confidence level unless otherwise stated.
2. OBSERVATIONS AND DATA REDUCTIONS

2.1. NuSTAR

2.1.1. Observation Log and Data Screening

We observed AE Aqr with NuSTAR (Harrison et al. 2013), the first focusing hard X-ray (3–79 keV) telescopes in orbit, from 2012 September 4, 19:20 UT to September 7, 18:50 UT. NuSTAR was operated in its default mode throughout the observation. The acquired data with the observation ID of 30001120 were processed and screened in the standard way using the NuSTAR pipeline software, NuSTARDAS version 1.1.1, with the NuSTAR calibration database (CALDB) version 20130509. The data resulted in a total of 125 ks of dead-time corrected exposure.

All photon arrival times were corrected to the solar system barycenter using the JPL DE200 ephemeris and the Chandra -derived coordinates (20:40:09.185, −00:52:15.08; J2000) which have sub-arcsecond uncertainties. The source photons were extracted from a circular region of radius 1.0 centered on AE Aqr. The source spectra were grouped with a minimum of 50 counts per bin. The background spectra were generated with the background modeling tool, nuskybgd (D. R. Wik et al. in preparation). A detailed description of the background modeling is given in Section 2.1.2. The telescope response files, ARF and RMF were also generated by NuSTARDAS.

2.1.2. Background Spectral Modeling

Since AE Aqr is a faint source in hard X-rays, the NuSTAR background spectrum must be carefully subtracted from the source spectrum. Blank-sky observations show the background rate varies in an energy dependent way with detector position by a factor of ~2 (Harrison et al. 2013). In addition, the internal background rate varies in time due to changes in the cosmic radiation intensity associated with the geomagnetic cutoff rigidly, as well as the elapsed time since SAA passage.

In order to perform accurate background subtraction, the background spectrum was empirically modeled using the NuSTAR background fitting and modeling tool, nuskybgd (revision 52). nuskybgd fits blank-sky spectra in user-selected regions of the same observation, and then generates a background spectrum within any regions with the best-fit parameters (Wik et al. in preparation for a more detailed).

Three blank-sky spectra for each telescope were extracted from annular regions of radius 120′′–270′′, 270′′–370′′, and 370′′–740′′ centered on AE Aqr to model the background spectra of the two NuSTAR telescopes. The blank-sky spectra were well fitted by the model with $\chi^2$/dof $= 1217.6/1124$. The background count spectrum in the source region was modeled with an exposure 20 times longer than the actual one to reduce statistical errors. In order to verify the background model, the background spectrum in a blank-sky region 3.5′ from the source in a northeasterly direction was simulated and compared to the actual spectrum extracted from the same region. The ratio of the actual spectrum to the model in Figure 1 was fitted by a constant factor of 0.98 ± 0.04 with $\chi^2$/dof $= 15.7/27$, showing the background model is consistent with the actual spectrum within statistical errors.

Figure 2 shows the AE Aqr spectra obtained with the two NuSTAR hard X-ray telescopes (FPMA and FPMB) and the background models. The highly ionized iron line can be seen around 6.7 keV. The total count rate in the 3–30 keV energy band after the background subtraction and dead-time correction is $(9.2 \pm 0.1) \times 10^{-2}$ counts s$^{-1}$.

2.2. Swift

Swift (Gehrels et al. 2004) observed AE Aqr simultaneously with NuSTAR from 2012 September 6, 06:07 to 07:53 UT. The Swift X-ray telescope (XRT; Burrows et al. 2005) was operated in the photon counting mode during the observation. The XRT data (observation ID 00030295037) were processed in the standard manner with xrtpipeline (ver. 0.12.6) in HEASoft (ver. 6.13). The total exposure time after the data screening is 1.54 ks. The source photons were extracted from a circular region of radius 1′2 centered on AE Aqr. The source spectrum was rebinned to have at least 20 counts per bin. The background spectrum was extracted from an annular region of radius 1′7–7′0 centered on the source and was scaled by an area ratio of the source region to the background region.
Table 1
Best-fit Parameters of the Three-temperature Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{H}}$</td>
<td>$(10^{20} \text{ cm}^{-2})$</td>
<td>$&lt;82.2$</td>
</tr>
<tr>
<td>$Z$</td>
<td>$(Z_{\odot})$</td>
<td>$0.76_{-0.13}^{+0.17}$</td>
</tr>
<tr>
<td>$kT_1$</td>
<td>(keV)</td>
<td>$0.75_{-0.45}^{+0.18}$</td>
</tr>
<tr>
<td>$F_1$</td>
<td>$(10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2})$</td>
<td>$1.97_{-0.85}^{+0.94}$</td>
</tr>
<tr>
<td>$kT_2$</td>
<td>(keV)</td>
<td>$2.29_{-0.82}^{+0.96}$</td>
</tr>
<tr>
<td>$F_2$</td>
<td>$(10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2})$</td>
<td>$3.53_{-0.64}^{+0.55}$</td>
</tr>
<tr>
<td>$F_3$</td>
<td>$(10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2})$</td>
<td>$9.33_{-2.18}^{+0.07}$</td>
</tr>
<tr>
<td>$C_{\text{FPMB}}/C_{\text{FPMA}}$</td>
<td></td>
<td>$1.00 \pm 0.03$</td>
</tr>
<tr>
<td>$C_{\text{XRT}}/C_{\text{FPMA}}$</td>
<td></td>
<td>$0.94_{-0.42}^{+0.19}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td></td>
<td>$247.1/201$</td>
</tr>
</tbody>
</table>

Notes.

a Solar abundance from Wilms et al. (2000), in which the solar iron abundance relative to hydrogen is $2.69 \times 10^{-5}$. Note that the solar abundance from Anders & Grevesse (1989), in which the solar iron abundance is $4.68 \times 10^{-5}$, is employed in other AE Aqr articles (e.g., Itoh et al. 2006; Terada et al. 2008; Oruru & Meintjes 2012).

b Unabsorbed flux in $0.5–10$ keV.

$C_{\text{FPMB}}/C_{\text{FPMA}}$ Cross-normalization factor between NuSTAR/FPMB and NuSTAR/FPMA.

d Cross-normalization factor between Swift/XRT and NuSTAR/FPMA.

3. SPECTRAL ANALYSIS

3.1. Spectral Fitting with Multi-temperature Models

The X-ray spectra of AE Aqr observed with ASCA (Choi et al. 1999), XMM-Newton (Itoh et al. 2006), and Suzaku (Terada et al. 2008) have been modeled using an optically thin thermal plasma emission model with a few different temperature components in the same way as for other IPs. Therefore in the joint fitting of Swift and NuSTAR spectra, we adopted an emission model from a collisionally ionized diffuse plasma, APEC (Smith et al. 2001). Each APEC model was constrained to have common metal abundances relative to solar from Wilms et al. (2000), but was allowed to have different temperatures and normalizations. We use the tbabs model (Wilms et al. 2000) to account for interstellar and self-absorption. In addition, the cross-normalization factors of XRT/FPMA and FPMB/FPMA were allowed to vary.

In order to determine the number of APEC components with different temperatures, we added new APEC components one by one until the fit was not significantly improved, as determined by the $F$-test. Improvement of the fit is significant with the $F$-test.

![Figure 3](image-url)

Table 1. Best-fit Parameters of the Three-temperature Model

Figure 3. X-ray spectra of (green) Swift/XRT, (black) NuSTAR/FPMA, and (red) NuSTAR/FPMB overlaid with (a) the best-fit three-temperature APEC model and (b) two-temperature model with a power-low emission. The model components are drawn with dotted lines. The bottom panels show fit residuals in terms of $\sigma$ with error bars of size one.

(A color version of this figure is available in the online journal.)

Although other IP spectra commonly contain a strong neutral (or low-ionized) iron line around 6.4 keV with a comparable equivalent width to highly ionized iron emission around 6.7 keV (e.g., Ezuka & Ishida 1999; Yuasa et al. 2010), we do not detect this feature clearly in the AE Aqr spectrum. In fact, XMM-Newton spectra constrained the upper limit to the 6.4 keV equivalent width to be $<61$ eV (Itoh et al. 2006). We tried to add a narrow Gaussian emission model with a center energy fixed at 6.4 keV to the three-temperature APEC model, and simultaneously fit the spectra of Swift and NuSTAR with it. The intensity of the neutral iron line is $1.33_{-1.33}^{+1.26} \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to an equivalent width of $37.9_{-37.9}^{+55}$ eV. On the other hand, the intensity of the highly ionized iron line around 6.7 keV was determined to be $1.11_{-0.99}^{+0.11} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, or an equivalent width of $495_{-53}^{+56}$ eV, with the line central energy of 6.732$_{-0.014}^{+0.063}$ keV. Therefore, the neutral iron line is much weaker than the highly ionized iron line.

3.2. Spectral Fitting with Non-thermal Emission

In order to search for possible non-thermal hard X-rays as suggested by Terada et al. (2008), we simultaneously fitted the spectra of Swift and NuSTAR with a multi-temperature...
plus power-law emission model. In the same way as the determination of the number of APEC components described above, we first fit the spectra using a single APEC with a power-law model, and then added new APEC models one by one until the fit was not significantly improved as determined by the F-test. We find two temperatures with power-law emission is the statistically favored model.

The Swift and NuSTAR spectra with the best-fit model are shown in Figure 3(b), of which are listed in Table 2. Compared with the three-temperature APEC model, the fit with the two-APEC model with the power-law emission is slightly but not significantly preferred. We cannot distinguish whether the hard X-ray component detected with NuSTAR is thermal or non-thermal emission.

4. TIMING ANALYSIS

4.1. Spin Period Determination

We examined the hard X-ray pulse profile for evidence of the narrow pulsation reported by Suzaku (Terada et al. 2008). Previous measurements have shown that soft X-rays below 10 keV are sinusoidally modulated with a single peak in the spin phase of the white dwarf (e.g., Mauche 2006). In this case, the $Z_1^2$-statistic, or Rayleigh test (Buccheri et al. 1983) is more sensitive to determine the spin period than the epoch folding technique with the $\chi^2$ test (Leahy et al. 1983).

Figure 4(a) shows the $Z_1^2$ periodogram using NuSTAR 3–10 keV data with barycenter-corrected time. We found the peak at 33.0769 ± 0.0004 s with $Z_1^2 = 124.1$. Within the uncertainty, the period is consistent with previously measured values in the optical band (Patterson 1979; de Jager et al. 1994), and at X-ray energies (Choi et al. 1999; Choi & Dotani 2006; Mauche 2006; Terada et al. 2008; Oruru & Meintjes 2012).

We also searched for a signal in the 10–20 keV energy band. The hard X-rays above 20 keV were ignored to improve the signal-to-noise ratio since the source rate from AE Aqr falls below that of the background in that energy range (Figure 2). Evidence for a pulsation was found also in this band at the expected pulse period, 33.0765 ± 0.0016 s, with $Z_1^2 = 11.1$, corresponding to a null hypothesis probability of 0.38%, or 2.9\(\sigma\) detection significance (Figure 4(b)).
from the sinusoidal model with a 95% confidence level. We conclude that there is no evidence for an additional sharp pulse component in our data.

5. DISCUSSION

5.1. Comparison of Non-thermal Hard X-Ray Emission with Previous Suzaku Results

The 10–30 keV flux determined with NuSTAR is $5.0_{-1.4}^{+1.3} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, about half of the best-fit Suzaku/HXD-PIN flux in 2005 (Terada et al. 2008). The derived power-law index, $2.5 \pm 0.2$, is also inconsistent with the Suzaku value, $1.1 \pm 0.6$, and is steeper than those found for rotation-powered pulsars, which range from 0.6 to 2.1 (Gottlieb 2003; Kaspi et al. 2006). Here we note that the previously reported Suzaku fitting errors did not include the systematic uncertainty of the Suzaku/HXD-PIN background model because the authors described that the hard X-ray flux was consistent with the narrow pulse flux in the spin profile. However, the systematic uncertainty, 3% (Fukazawa et al. 2009), is comparable to the background-subtracted count rate, and therefore should not be ignored (see Figures 6 and 7 of Terada et al. 2008 for comparison of the rates). It is possible that the discrepancy of the non-thermal emission parameters is due to the neglected systematic error in Terada et al. (2008).

Furthermore, we find no evidence of the narrow pulse profile with a pulse fraction of nearly 100% and a duty cycle of $\sim$0.1 reported by Terada et al. (2008). In contrast with the Suzaku result, we marginally detect the sinusoidal modulation in the 10–20 keV energy band at a significance level of 2.9$\sigma$. In order to determine whether or not NuSTAR is sensitive to the narrow pulse profile suggested by Suzaku, we estimated its count rate considering the NuSTAR telescope response and assuming the Suzaku result. The expected 10–20 keV count rate within a duty cycle of 0.1 is 0.086 $\pm$ 0.003 count s$^{-1}$, 10 times higher than the time-averaged rate measured with NuSTAR, indicating that NuSTAR would have been capable of significantly detecting the narrow pulsation.

A possible explanation of the difference between the Suzaku and NuSTAR results is that AE Aqr may have varied and its hard X-ray flux decreased. However, the soft X-ray flux determined with NuSTAR in 2012 is consistent with previous observations made with Suzaku in 2005 (see Table 1), within the cross-normalization factor of NuSTAR to Suzaku/XIS of $\sim$15% (based on simultaneous observations of calibration targets). It is difficult to explain a mechanism only in hard X-rays that would make the flux vary without correlation of thermal soft X-rays, a part of which also modulates with the spin period.

5.2. Possible Interpretation of the Observed Emission

Two energy sources could, in principle, power the observed X-ray luminosity $L_X \sim 10^{34}$ erg s$^{-1}$: liberation of gravitational energy of accreting matter and the rotational energy of the white dwarf.

The white dwarf was reported to spin down with a rate $\dot{P} = 5.64 \times 10^{-14}$ s$^{-1}$ (de Jager et al. 1994), which corresponds to spindown power $L_{\text{sp}} \sim 10^{33}$ erg s$^{-1} \gg L_X$. This suggests the possibility that the X-ray emission of the white dwarf is fed by rotation (Ikhsanov & Beskrovnaya 2012). The rotation-induced electric field could accelerate particles to high Lorentz factors if the magnetosphere is plasma-starved and the electric field is not screened. Synchrotron emission was suggested as a possible radiative mechanism in such a model (Terada et al. 2008). It is, however, unclear how the observed luminosity, spectrum, and pulse profile observed by NuSTAR would be produced by relativistic particles. The efficiency of synchrotron emission is expected to be small, since the particles are accelerated along the magnetic field lines. Emission from accelerated particles is also expected to be strongly beamed along the field lines, which is inconsistent with the observed broad pulse profile in Figure 5.

Emission powered by accretion is a plausible mechanism. The standard model of accreting IPs involves an accretion column heated by the accretion shock and cooled by thermal
bremstrahlung (Aizu 1973). It explains well the X-ray spectra of many IPs (see Cropper et al. 1999 for Ginga data, Suleimanov et al. 2005 for RXTE, Landi et al. 2009 for Swift/XRT and INTEGRAL/IBIS, Brunschweiger et al. 2009 for Swift/BAT, and Yuasa et al. 2010 for Suzaku). The main parameters of the model are the free-fall velocity \( v_{\text{ff}} = (2GM_{\text{WD}}/R_{\text{WD}})^{1/2} \) and the accretion rate per unit area, \( a = M/4\pi R_{\text{WD}}^2 f \), where \( f \) is the fraction of the white dwarf surface occupied by the accretion column. The standard model assumes that the shock is radiative and pinned to the white dwarf surface, \( h \ll R_{\text{WD}} \).

The shock altitude \( h \lesssim v_{\text{th}}/v_{\text{sh}} \), where \( v_{\text{th}} = v_{\text{th}}/4 \sim 10^6 \text{ cm s}^{-1} \) is the postshock velocity of the accreting gas and \( v_{\text{sh}} \sim 0.3 a s \) is the bremsstrahlung cooling timescale (with \( a \) expressed in units of \( \text{g s}^{-1} \text{ cm}^{-2} \)). The net accretion rate \( M \) is determined from the X-ray luminosity \( L_X = G M_{\text{WD}} M / R_{\text{WD}} \).

This scenario would imply \( M \sim 2 \times 10^{14} \text{ g s}^{-1} \) for AE Aqr, and the condition \( a \gg 10^{-2} \text{ g s}^{-1} \text{ cm}^{-2} \) is satisfied if \( f \ll 10^{-3} \). Such a small \( f \) may be possible if, e.g., the accretion flow in AE Aqr is concentrated in a thin wall of the accretion column (as Basko & Sunyaev 1976 suggested for accreting neutron stars). However, on the assumption of \( M_{\text{WD}} \sim 0.7 M_{\odot} \) determined with the optical measurements (e.g., Watson et al. 2006; Echevarría et al. 2008), our calculations of the spectrum predicted by the standard accretion model do not provide a good fit for the NuSTAR data—the observed spectrum with the highest temperature of \( 9.3^{+50}_{-22} \text{ keV} \) is softer than the predicted postshock temperature of \( 29 \text{ keV} \).

Two modifications might make the accretion model consistent with NuSTAR observations. (1) The shock altitude \( h \) in AE Aqr could be significant, perhaps even comparable to the white dwarf radius. Such tall accretion columns with low accretion rates were recently studied by Hayashi & Ishida (2014). The shallower gravitational potential at the high altitude results in a reduction of the postshock temperature below \( 20 \text{ keV} \) typical of other IPs. The tall accretion column in AE Aqr was previously proposed as the source of the large hot spots on the white dwarf surface inferred from observations by the Hubble telescope (Eracleous et al. 1994) (2) The X-ray spectrum emitted by the accretion column could be affected by additional radiative losses due to cyclotron emission in the infrared band. Cyclotron emission is important when \( B > 10^6 \text{ G} \), and may carry away a significant part of the accretion column energy, especially at large altitudes where the plasma has the highest temperature. This effect could explain the relatively soft extended spectrum of AE Aqr above \( 3 \text{ keV} \). Detailed calculations of such models will be presented elsewhere.

In addition to the low X-ray luminosity and soft spectrum, AE Aqr has another special feature—weak absorption of soft X-rays, which corresponds to \( N_H < 8 \times 10^{21} \text{ cm}^{-2} \), lower than the \( N_H \sim 10^{22} \text{ cm}^{-2} \) observed in many IPs (e.g., Ezuka & Ishida 1999; Yuasa et al. 2010). This feature could be explained by the lower density of the accretion column, and needs to be further investigated with detailed models. Also note that AE Aqr does not show evidence for a neutral (or weakly ionized) iron line. Among other IPs previously studied in the hard X-ray band, EX Hydrae has the lowest luminosity \( L_X < 3 \times 10^{32} \text{ erg s}^{-1} \) and also the lowest column with \( N_H \lesssim 10^{22} \text{ cm}^{-2} \) (Suleimanov et al. 2005). The shape of its 3–30 keV spectrum is not far from that of AE Aqr, although EX Hydrae is a nearly synchronous system with an orbital period of 98.3 min and a long spin period of 67.0 minutes (Belle et al. 2005), unlike AE Aqr.

The much smaller accretion rate of AE Aqr compared to many other IPs is thought to be due to the magnetic propeller effect (Wynn et al. 1997), whereby most of the mass lost by the secondary is being flung out of the binary by the magnetic field of the rapidly rotating white dwarf. Norton et al. (2004, 2008) performed numerical simulations of accretion flows in magnetic cataclysmic variables with wide ranges of magnetic moment, \( \mu = 10^{22–36} \text{ G cm}^3 \), and \( P_{\text{spin}}/P_{\text{orbit}} \sim 10^{-3–1} \). They demonstrated that IPs with a very small ratio of \( P_{\text{spin}}/P_{\text{orbit}} \ll 10^{-2} \) like AE Aqr (\( P_{\text{spin}}/P_{\text{orbit}} = 9.3 \times 10^{-4} \)) show magnetic propeller effects. Therefore, the tall accretion column could be formed in IPs with \( P_{\text{spin}}/P_{\text{orbit}} \lesssim 10^{-2} \), though such systems would also be expected to have low X-ray luminosities, thus making them more challenging to identify. AE Aqr is the only currently known example. It is also possible that nearly synchronous systems similar to EX Hydrae could possess a tall accretion column. The low accretion rate in such systems is consistent with the picture of ring-like accretion discussed by Norton et al. (2008).

6. SUMMARY

We have analyzed X-ray data of the magnetized white dwarf AE Aqr observed with NuSTAR for 125 ks and Swift for 1.5 ks. The 0.5–30 keV spectra are well characterized by either an optically thin thermal plasma model with three temperatures with the highest temperature of \( 9.3^{+50}_{-22} \text{ keV} \), or an optically thin thermal plasma model with two temperatures plus a power-law component with photon index of \( 2.5^{+0.7}_{-0.3} \). The 3–20 keV pulse profile shows a sinusoidal modulation, with a pulsed fraction of \( 16.6\% \pm 2.3\% \). We find no evidence for the previously reported sharp feature in the pulse profile.

The observed soft X-ray spectrum with the broad pulse profile is hard to explain as a result of rotation-powered emission. Instead accretion-powered emission is more likely, although the observed spectrum is softer than predicted by the standard accretion column model. We suggest two modifications of the standard model to explain the AE Aqr spectrum: the shock altitude could be high, comparable to the white dwarf radius, and cyclotron emission with \( B > 10^6 \text{ G} \) could additionally cool down the accretion plasma. Detailed calculations of such models will hopefully reproduce the spectrum and pulse profile of AE Aqr with the white dwarf mass consistent with that determined with the optical measurements.

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Facilities: NuSTAR, Swift

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