X-ray timing and spectral analysis of the propeller
driven pulsar-like white dwarf AE Aquarii

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Abstract. The highly transient multi-wavelength system AE Aqr is an ideal laboratory to
study accretion and related astrophysical fluid dynamics. The system is in a propeller state,
and the turbulent interaction between the fast spinning WD magnetosphere and the accretion
flow is believed to play a crucial role in the characteristic multi-wavelength emission of the
system. We have analysed the system’s X-ray lightcurves and spectra from data observed with
Chandra and Swift-XRT, and the results of this study show that the X-ray characteristics display
a mixed signature of thermal and non-thermal emission. The luminosity of the observed hard
X-rays is three orders of magnitudes less than the spin-down power of the white dwarf, which
tends to correlate with rotation-driven pulsars. In this paper, the results of the analysis will be
discussed, with the aim to propose suitable models for the X-ray emission mechanisms.

1. Introduction
AE Aquarii (AE Aqr) consists of a fast rotating magnetized white dwarf accreting matter from
a late-type K3-5 main sequence companion (e.g. Patterson 1979; Welsh et al 1995; Itoh et al
2006). The binary companions are in orbit with a period of 9.88 h (e.g. Welsh et al 1993).
Although an accretion disc is expected, the observed properties of the system do not conform to
this. Wynn et al (1997) have proposed that the system is in a propeller phase, where the bulk of
the mass flow is expelled from the system by the fast rotating magnetosphere of the white dwarf.
However, plasma instabilities may attach some gaseous material onto the field lines which will
then be accreted on the magnetic polar caps.

AE Aqr has been detected in almost all wavelength bands (e.g. de Jager 1991), from radio,
through optical to TeV γ-rays (e.g. Bookbinder & Lamb 1987; Patterson 1979; Meintjes et al
1994). Patterson (1979) observed a 33 s coherent oscillation in the optical light, which were
later observed in other wavelengths (e.g. Patterson et al 1980; de Jager et al 1994; Eracleous
et al 1994). AE Aqr is a relatively bright X-ray source, and coupled with its close proximity to
the earth, it has been observed regularly (e.g. Patterson et al 1980; Osborne 1989; Reinsch et
al 1995; Itoh et al 2006). This paper will focus on the X-ray characteristics of the system based
on the analysis of data from recent observations with Chandra and Swift.

2. Observations of AE Aquarii
The Chandra X-ray Satellite (e.g. Brissenden 2001) observed AE Aquarii on August 30, 2005
at 06:37 UT for ~ 80 ks (ObsID 5431; e.g. Mauche 2006), using the Advanced CCD Imaging
Spectrometer (ACIS-S) detector and the High Energy Transmission Grating (HETG). Standard
data processing was done at the Chandra X-ray Center (CXC), and data was acquired through
the High Energy Astrophysics Science Archive Research Center (HEASARC) on-line service,
provided by the NASA’s Goddard Space Flight Center (GSFC). Data reduction and analysis
were done using the Chandra Interactive Analysis of Observations (CIAO) software.

The Swift GRB explorer (e.g. Gehrels et al 2004) observed AE Aquarii (target ID = 30295)
between August 30 and September 2, 2005 for a total duration of ~ 10.5 ks, as a pre-planned
target (PPT; e.g. Evans et al 2009). Data were archived in September 2005, and standard
processing was done later at the UK Swift Science Data Centre (UKSSDC). The results presented
in this paper are based on data collected when the XRT was operating in the PC mode, in which
full imaging and spectroscopic resolutions are retained, but timing resolution is limited to 2.5
s (e.g. Burrows et al 2005). The lightcurve and spectral data files were obtained using the on-
demand software (developed by the Swift team) through the HEASARC on-line service, provided
by NASA’s GSFC. The general discussion on the software usage are presented in the original

3. Results
3.1. Lightcurves
Figure 1 shows the background subtracted lightcurve from Chandra data. The source is highly
variable, and exhibit flares. Flares with similar characteristics repeat after ~ 10 hr, which
corresponds to the orbital period of the system. The hardness ratio from the same data is
shown in Figure 2. As can be seen, most of the X-rays are soft. Figure 3 shows the lightcurve
from Swift-XRT data. The lightcurve has gaps because Swift is a low-earth orbit satellite, it can
only take snapshot observations. The corresponding hardness ratio is shown in Figure 4. Similar
characteristics, i.e high variability and predominant soft X-ray emission, are also observed.

![Figure 1. X-ray lightcurve from Chandra.](image1)

![Figure 2. Hardness ratio from Chandra.](image2)

3.2. Chandra spectra
For each diffraction order and grating arm, a background subtracted spectrum was plotted and
models fitted. The energy spectra are plotted in Figures 5 and 6 for HEG, and Figures 7 and 8
for MEG, for the diffraction orders $m = -1$ and $m = +1$ respectively. Each of the HEG spectra
is fitted with a two-temperature vmekal model, whereas the MEG spectra are fitted with a
three-temperature vmekal model. These indicate that a thermal emission process is likely. Each
of the figures is characterised by a number of emission lines superimposed on the continuum
emission, and most of which are in the soft X-ray band, which is the dominant contribution to
Figure 3. X-ray lightcurve from Swift data.

Figure 4. Hardness ratio from Swift data.

Figure 5. HEG spectrum for diffraction order $m = -1$ ($kT_1 \sim 0.65$, $kT_2 \sim 3.37$ keV).

Figure 6. HEG spectrum for diffraction order $m = +1$ ($kT_1 \sim 0.67$, $kT_2 \sim 3.20$ keV).

the X-ray emission. The average flux of X-ray emission is $\sim 8.1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for HEG, and $1.0 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for MEG respectively. For an estimated source distance of 100 pc (e.g. Welsh et al 1993), then it can be shown that the X-ray luminosity for each grating arm is $\sim 9.7 \times 10^{30}$ erg s$^{-1}$ and $1.3 \times 10^{31}$ erg s$^{-1}$ respectively. These values are similar to the X-ray luminosities reported from other observations.

3.3. Swift-XRT spectra

Figure 9 is the spectrum generated in XSPEC, and fitted with a combination of an absorbed power-law and a two-temperature vmekal emission model, suggesting that the X-ray emission has both thermal and non-thermal characteristics. In Figure 10, the unfolded models are plotted with the data, and again one can see emission line features. Hard X-ray data ($kT > 2$ keV) are well fitted by the power-law model. The flux of soft X-rays is $\sim 6.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, and the corresponding hard X-rays is $4.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. These lead to the X-ray luminosities of $7.5 \times 10^{30}$ erg s$^{-1}$ and $5.6 \times 10^{30}$ erg s$^{-1}$ for soft and hard X-rays respectively, for $D \sim 100$ pc. Then, the total X-ray luminosity is $L_X \sim 1.3 \times 10^{31}$ erg s$^{-1}$. 
4. Period analysis

Using the Swift-XRT data, we searched for periodicities in the barycenter corrected lightcurves. Epoch folding method was used, where a lightcurve is folded with large number of periods around an approximate value, and the best period found by chi squared maximization. In this case, the 33.08 s spin period of the WD and the de Jager et al. (1994) \( \bar{P} \sim 5.642 \times 10^{-14} \) s s\(^{-1} \) were used to fold the data. Figures 11 and 12 show the best periods obtained for the soft and hard X-rays. The hard X-ray emission is pulsed at a slightly higher period than the spin period of the WD.

Using the best period of 33.078060116102 s obtained in the epoch folding search for the entire X-ray data (0.3-10 keV), pulse profiles were constructed for each data set using the de Jager et al. (1994) ephemeris. Figures 13 and 14 show the pulse profile for the soft and hard X-rays respectively. The profile for the entire X-ray energy range of the Swift data is shown in Figure 15, and Figure 16 shows the profiles for all the data sets considered. The hard X-ray data shows a shallow modulation, similar to the results reported by Terada et al. (2008) from the analysis of Suzaku data. The average X-ray pulse profile is generally that of soft X-rays since it is the dominant component. The broad pulse profile of the hard X-rays would suggest a different emission region from the soft X-rays. This will be examined in a separate paper.
5. Discussion
The lightcurves of AE Aqr showed that the source is highly variable and it exhibits periodic flares. Since AE Aqr is a non-eclipsing binary system, the variability is most likely the result of the variation in the mass accretion rate. Flares could be the result of sudden increase in the emission due to sporadic mass accretion onto the magnetosphere. Both timing and spectral analysis have revealed that most of the X-ray emission is soft. The spectra show a number of emission line features, and can be fitted with a multi-component thermal emission model. These characteristics suggest the existence of an optically thin emission region.

Using Swift-XRT data, it was shown that the hard X-ray component has a luminosity of $L_{\text{x,hard}} \sim 5.6 \times 10^{30}$ erg s$^{-1}$. For AE Aqr, the spin-down power is $L_{\text{s-d}} \sim 6 \times 10^{33}$ erg s$^{-1}$. Then, it can be seen that $L_{\text{x,hard}} \sim 10^{-3} L_{\text{s-d}}$, a relationship that has observationally been shown to hold for rotation-powered pulsars (e.g. Becker & Trümper 1997). This suggests that only a small proportion of the spin-down power is needed to power the non-thermal X-ray emission.
Figure 15. Folded pulse profiles for the energy range (0.3-10 keV).

Figure 16. Folded pulse profiles for all the data sets considered.

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