Modeling X-ray emission and the SED of the binary radio pulsar AE Aquarii

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Abstract. The highly transient novalike variable AE Aqr is perhaps an ideal laboratory to study accretion related astrophysical fluid dynamics. Having one of the fastest spinning white dwarfs, AE Aqr has many unique characteristics that distinguish it from most cataclysmic variables. The system is in a propeller state, and most of its emission properties are associated with this process. Analysis of its X-ray spectra using contemporanous Chandra and Swift X-ray data has revealed that the X-ray emission has both thermal and non-thermal characteristics, which have been modeled to be the result of bremsstrahlung emission and synchrotron radiation respectively. It is suggested that the non-thermal hard X-rays are emitted outside of the light cylinder of the WD, due to the acceleration of the electron population by a large field aligned potential, with magnitude $V > 10^{12}$ V. It is also shown that the characteristic thermal soft X-ray emission, which is the dominant component, is from a location well above the polar caps. The SED is constructed to illustrate the various mechanisms constituting the observed multi-walength radiations.

1. Introduction

The low mass non-eclipsing close binary system AE Aquarii (AE Aqr) has traditionally been classified as a novalike variable (e.g. Joy 1954; Crawford & Craft 1956; de Jager 1991). Based on this classification, Patterson (1979) modeled AE Aqr as a member of the DQ Herculis sub-class of magnetic cataclysmic variables, where a fast rotating magnetized white dwarf is accreting from an accretion disc formed by the mass flow from the secondary companion. However, models and the observed properties suggest that AE Aqr lacks an accretion disc (e.g. Wynn *et al* 1997; Itoh *et al* 2006), and is most probably in a propeller phase where the bulk of the mass flow is being expelled from the binary system.

AE Aqr has a characteristic orbital period of 9.88 h (e.g. Joy 1954; Patterson 1979), which is rather long for a typical CV system, and would imply a larger binary separation. The white dwarf is spinning at $\sim$ 33 s (e.g. de Jager *et al* 1994; Ikhsanov 1997) and has a relatively strong surface magnetic field of $B_{*} \sim 10^{6}$ G, which combine to present the system with unique characteristics similar to those of accreting millisecond pulsars. However, de Jager *et al* (1994) and Mauche (2006) have reported the white dwarf spinning down at a period rate of $\dot{P} \geq 5.642\times10^{-14}$ s s^{-1}, and the resulting spin-down power is thought to be used either to accelerate particles, or driving the propller action (e.g. Wynn *e al* 1997; Meintjes & de Jager 2000).

AE Aqr has been detected in almost the entire electromagnetic spectrum, in which coherent oscillations at the white dwarf spin period have been observed (e.g. Patterson 1979; Patterson *et al* 1980; de Jager *et al* 1994; Eracleous *et al* 1994; Meintjes *et al* 1994). The most unique characteristic of AE Aqr is perhaps its rapid flaring in almost all wavelengths (e.g. Ikhsanov *et al* 2004). In radio and TeV γ-rays, AE Aqr shows up as a powerful non-thermal variable source, and could rather be compared with Cyg X-3 than with any of the presently known CVs (e.g. Ikhsanov 1997). In the remaining parts of the spectrum, the emission is predominantly thermal. However, the recent Suzaku detection (e.g. Terada *et al* 2008) has shown that the X-ray emission has also non-thermal characteristics. Based on this detection, we have analysed X-ray data observed with Chandra and Swift satellites, and showed that there is a non-thermal hard X-ray component of the emission. The results have been presented in a separate paper, and we use them here to propose models to constrain the observed X-ray characteristics. With additional data in other wavelengths, the spectral energy distribution of the system is also constructed.

2. Possible models of X-ray emission

The observed X-ray features of AE Aqr make it quite different from other cataclysmic variables which are mainly accretion driven. The spectra are dominated by a soft component (e.g. Clayton & Osborne 1995; Choi *et al* 1999; Ikhsanov & Biermann 2006). The inferred plasma density of $n_e \sim 10^{11}$ g cm^{-3} (e.g. Itoh *et al* 2005) is a few orders less than the estimate in the postshock accretion column (e.g. Ikhsanov & Biermann 2006), and the inferred linear scale of $l_{\rm p} \geq 2\times 10^{10}$ cm (Itoh *et al* 2006; Ikhsanov & Biermann, 2006) implies that the emission is probably not coming from the surface of the WD. The signature of a non-thermal component seems to indicate some kind of pulsar-like mechanism, driven by the loss of rotational kinetic energy from the fast rotating white dwarf (e.g. Cheng *et al* 1998). In this section, possible emission models are investigated to constrain the observed thermal and non-thermal emission.

2.1. Emission from accretion

Accretion in AE Aqr may be compared to those in X-ray pulsars, where rapidly rotating magnetized neutron stars accrete from their companions (e.g. Bildsten *et al* 1997). This can occur either in the accretor phase or propeller phases, depending on the rotational period and surface magnetic field of the primary star (e.g Lipunov 1992). In the accretor phase, most of the matter is channeled onto the magnetic poles and falls onto the surface creating small heated regions where gravitational energy is radiated away (e.g. Becker & Wolff 2007). The scenario corresponds to the flow of a mixture of gas and radiation inside a magnetic pipe, sealed with respect to the gas but transparent to the radiation (e.g. Bednarek 2009). The accretion luminosity is given by

$$L_{\rm acc} = \frac{GM_*\dot{M}}{R_*} \simeq 1.3\times 10^{34}\left(\frac{M_*}{M_\odot}\right)\dot{M}_{17}R_{*,9}\ {\rm erg\ s^{-1}}, \tag{1}$$

where M_* is the mass of the WD, $R_{*,9}$ its radius in the units of 10^9 cm, and $\dot{M}_{17}$ is the mass accretion rate in the units of 10^{17} g s^{-1} respectively. The estimate of the temperature of a black body radiating this luminosity is

$$T_{\rm eff} = \left(\frac{L_{\rm acc}}{A_{\rm cap}\sigma_{\rm SB}}\right)^{1/4} \simeq 3.27\times 10^5\left(\frac{M_*}{M_\odot}\right)^{1/4}\dot{M}_{17}^{\frac{1}{4}}R_{*,9}^{-1}P_{33}^{\frac{1}{4}}\ {\rm K}, \tag{2}$$

where $A_{\rm cap} = \pi(\Omega R_*/{\rm c})R_*^2$, is the area of the polar cap, $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant, and P_{33} is the WD spin period in units of 33 s. The accretion would occur on a timescale,

$$\tau_{\rm dyn} \equiv \left(\frac{R_*^3}{2GM_*}\right)^{1/2} \sim 2\ {\rm s}\left(\frac{M_*}{M_\odot}\right)^{-1/2}R_{*,9}^{\frac{3}{2}}. \tag{3}$$

The observed X-ray luminosity of AE Aqr ($L_{\rm X} \sim 1.3{\times}10^{31}$ erg s^{-1}) is 3 orders of magnitude less than $L_{\rm acc}$, and also, $T_{\rm X} > 10^6$ K $> T_{\rm eff}$. Therefore, it is unlikely that the X-ray emission is the result of accretion onto the WD.

If the accretion power is liberated at the magnetospheric radius, i.e. the Alfvén radius, the resultant luminosity is

$$L_{\rm acc}^{M} = \frac{GM_*\dot{M}}{R_{\rm M}} \simeq 7\times 10^{32}\left(\frac{M_*}{M_\odot}\right)^{8/7}\dot{M}_{17}^{\frac{9}{7}}\mu_{33}^{-\frac{4}{7}} \text{ erg s}^{-1}, \tag{4}$$

where $R_{\rm M}$ is the Alfvén radius,

$$R_{\rm M} = \left(\frac{\mu^2}{2\dot{M}(2GM_*)^{1/2}}\right)^{2/7} \simeq 2\times 10^{10}\left(\frac{M_*}{M_\odot}\right)^{-1/7}\dot{M}_{17}^{-\frac{2}{7}}\mu_{33}^{\frac{4}{7}} \text{ cm}, \tag{5}$$

and μ_{33} is the magnetic moment of the WD in the units of 10^{33} G cm^3. Results from observations show that $L_{\rm X} \ll L_{\rm acc}^{M}$, unless the actual mass accretion rate is significantly below 10^{17} g s^{-1}. This scenario is in part compartible with the current propeller phase of AE Aqr where very little mass is accreted onto the surface of the WD.

The observed thermal X-rays are most likely the result of bremsstrahlung of heated mass outflow above the polar caps. The characteristic timescale of the emission could be short compared to $\tau_{\rm dyn}$.

2.2. Pulsar model for non-thermal emission

Non-thermal X-ray emission in pulsars have been associated with synchrotron radiation within the magnetospheres (e.g. Cheng *et al 2006*). This has been considered here to propose a model for AE Aqr. Goldreich & Julian (1969) have shown that the magnetospheric plasma within the light cylinder of a star corotates with it. This structure will remain unchanged even if there is a rigid conducting mass flow located at the equatorial plane of the WD, provided its angular velocity is less than that of the pulsar (eg. Leung *et al* 1993).

Possible emission mechanisms, driven by the rotation of WDs, have been discussed by Usov (1988, 1993) and Ikhsanov & Biermann (2006). We adopt here a similar approach, but consider synchrotron emission from primary electrons. Therefore, it is assumed that the WD is rotating in a region of low density. In the surrounding space, an electric field is introduced along the magnetic field. Close to the surface of the star, the electric field force ($e\vec{E}$) will cause charged particles to flow away, forming a magnetosphere whose particle density is given by

$$n_{\rm GJ} = \frac{\Omega B}{2\pi ce} \simeq 2\times 10^3\left(\frac{R_*}{r}\right)^3 B_{*,6}P_{33}^{-1} \text{ cm}^{-3}, \tag{6}$$

where $n_{\rm GJ}$ is the Goldreich-Julian particle density (e.g. Godreich & Julian 1969) and $B_{*,6}$ is the field strength at the surface of the WD in the units of 10^6 G. The electric field component $E_{\|}$ can be evaluated for $s > R_*$, where $r = R_* + s$ (e.g. Arons & Scharlemann 1979).

$$E_{\|} = E_{\rm AS}^{\|}\sqrt{2R_*/r} \simeq 10^3 P_{33}^{-\frac{5}{2}}\mu_{33}r_{l,11}^{-1/2} \text{ V m}^{-1}, \tag{7}$$

where

$$E_{\rm AS}^{\|} = \frac{1}{8\sqrt{3}}\left(\frac{\Omega_* R_*}{c}\right)^{5/2} B_*, \tag{8}$$

and the field is evaluated in the vicinity of the light cylinder radius. A thermal plasma exposed to an electric field in excess of the so-called Dreicer field, $E_{\rm D} \sim 2\times 10^{-10}(n_{\rm e}/T_{\rm eff})$ statvolts cm^{-1}

(e.g. Dreicer 1959; Meintjes & de Jager 2000), will accelerate freely without being hindered by particle-particle collisions. For AE Aquarii,

$$E_{\rm D} \sim 0.1 n_{e,11} T_{eff,7}^{-1} \ {\rm V\ m^{-1}}, \tag{9}$$

where the particle density and temperature are expressed in units of $10^{11}\,{\rm cm^{-3}}$ and $10^{7}\,{\rm K}$ respectively. One can see that $\delta = \frac{E_\parallel}{E_D} \sim 10^4$. Thus, the electric fields along the magnetic fields are large enough to effectively accelerate the electrons.

In the region of the polar cap, the electric potential is

$$V_{\rm pc}(r) = \int_{R_*}^{r} E_\parallel ds \simeq 2\times 10^{11} P_{33}^{-\frac{5}{2}} \mu_{33} R_{*,9}^{1/2} \left[\left(\frac{r}{R_*}\right)^{1/2} - 1\right] \ {\rm V}, \tag{10}$$

and close to the light cylinder radius where $r \sim R_{\rm lc} \simeq c/\Omega_*$,

$$V(R_{\rm lc}) \simeq 3\times 10^{12} P_{33}^{-2} \mu_{33} \ {\rm V}. \tag{11}$$

Figures 1 shows the variation of electric potential with field strength. Close to the surface of the WD, $V = 0$ and particle acceleration is not possible. But far outside, the electric potential is large enough to accelerate electron population. A particle accelerated in $V_{\rm pc}(r)$ has energy,

$$\varepsilon_{\rm p} = eV_{\rm pc}(r) \simeq 2\times 10^{11} P_{33}^{-\frac{5}{2}} \mu_{33} R_{*,9}^{1/2} \left[\left(\frac{r}{R_*}\right)^{1/2} - 1\right] \ {\rm eV}, \tag{12}$$

hence a Lorentz factor of

$$\gamma_{\rm p} = \frac{\varepsilon_{\rm p}}{m_e c^2} \simeq 4\times 10^{5} P_{33}^{-\frac{5}{2}} \mu_{33} R_{*,9}^{1/2} \left[\left(\frac{r}{R_*}\right)^{1/2} - 1\right]. \tag{13}$$

As the electrons are accelerated, they also experience energy losses due to synchrotron radiation and inverse Compton (IC) scattering of radiation from the secondary star and the surface of the WD (e.g. Bednarek & Pabich 2011). Assuming that synchrotron radiation is the dominant process, the energy loss rate of an accelerated electron is

$$L_{\rm syn} = \frac{4}{3} c \sigma_{\rm T} U_B \gamma_{\rm p}^2, \tag{14}$$

where $\sigma_{\rm T} \sim 6.65\ \times 10^{-25}\ {\rm cm^2}$, is the Thomson cross section, and the magnetospheric energy density $U_{\rm B}$ is given by

$$U_B = \frac{B^2}{8\pi} \simeq 10^{12} \left(\frac{B_*}{10^6\ {\rm G}}\right)^2 \left(\frac{R_*}{r}\right)^6 \ {\rm erg\ cm^{-3}}, \tag{15}$$

where $B = B_*(R_*/r)^3$, is the magnetic field at radial distance r from the centre of the WD. The energy radiation rate of the white dwarf is then

$$L_{\rm rad} = n_{\rm GJ} V P_{\rm syn}, \tag{16}$$

where V is the volume of the emission region, which is the spherical shell bounded by the light cylinder radius and the radial distance r:

$$V = 4\pi(r^3 - R_{\rm lc}^3) \simeq 5\times 10^{34} (\eta^3 - 1) \left(\frac{P}{33\ {\rm s}}\right)^3 \ {\rm cm^3}, \tag{17}$$

where $\eta = r/R_{\rm lc}$. The volume V obtained above is an upper limit, a factor of 4 more than the lower limit, if a cylindrical shell is considered. It is easy to show that

$$L_{\rm rad} \approx 1.7 \times 10^{46}(\eta^3 - 1)P_{33}^{-3}B_{*,6}^3\mu_{33}^2 \times R_{*,9}\left(\frac{R_*}{r}\right)^9 \left[\left(\frac{r}{R_*}\right)^{1/2} - 1\right]^2 \text{ erg s}^{-1}. \tag{18}$$

Then, in the vicinity of the light cylinder,

$$L_{\rm syn} \approx 4.5 \times 10^{28}(\eta^3 - 1)P_{33}^{-11}B_{*,6}^3\mu_{33}^2R_{*,9}^9 \text{ erg s}^{-1}. \tag{19}$$

For the model synchrotron power in Eq. 19 to equal the observed value of $L_{\rm x,hard} \sim 5.6\times10^{30}$ erg s^{-1}, the model parameter $\eta \sim 5$ and 8, corresponding to the upper and lower cases of the volume of the emission region. Thus, the emission region is beyond the light cylinder, where the field lines are threaded and the potential is large enough to accelerate particles. It should, however, be noted that the white dwarf in AE Aqr is not isolated, and therefore $n_{\rm e}$ is large. Then, $n_{\rm GJ}$ becomes a lower limit. In other words, $\eta < 5$, i.e. the emission region is much closer to the light cylinder, which is consistent with the observed pulsation period of hard X-rays.

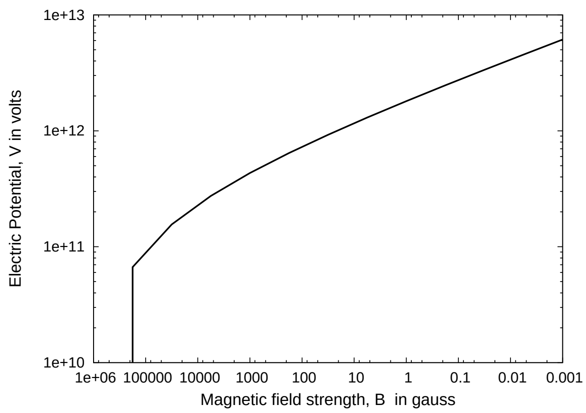

Figure 1. Electric field potential (V) as a function of field strength (B). As B decreases outwards from the WD surface, V increases.

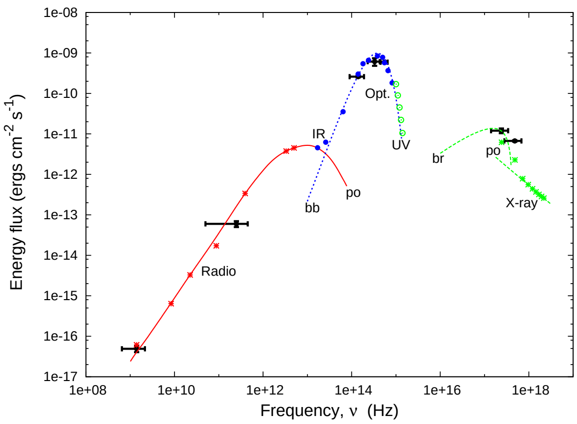

Figure 2. The spectral energy distribution (SED) of AE Aqr with the best fitting models. Catalogue data are the filled black squares.

3. The Spectral Energy Distribution

To study the broad band multi-wavelength emission in AE Aqr, proposed models were used to fit catalogue and analysed data. Extensive use was made of the Vizier on-line service to search for data in all wavelengths. Other published results were used to obtain radio to optical data (e.g. Abada-Simon *et al* 2005; Dubus *et al* 2004). The near-UV and X-ray data were obtained from the analysis of the Swift UVOT and XRT data. Figure 2 shows the spectral energy distribution (SED) of AE Aqr, constructed from catalogue data (the black squares) and analysed data (the rest of the points). A power-law (po) model was used to fit the data in the radio to far IR frequencies, whose emission is modeled to be due to the superposition of expanding magnetized blobs of electrons (e.g. Bastian *et al* 1988) which are optically thin to non-thermal synchrotron radiation. The near-IR, optical, and near-UV data are fitted with a thermal black body (bb) model of temperature, $T_{\rm bb} \simeq 4650$ K, the emission of which should be from the secondary star. Thermal bremsstrahlung (br) model of temperature, $T_{\rm br} \simeq 2\times10^7$ K was used to fit the soft X-ray data, and a power-law model of photon index $p \sim 2$ used to fit the hard X-ray data.

4. Summary

It was shown that the soft and hard companents of the X-ray emission in AE Aquarii come from different locations around the white dwarf, and are the result of different emission mechanisms. The models used to fit the soft and hard X-ray data in the SED reinforce the proposed thermal and non-thermal emission models presented, i.e., the observed X-ray characteristics of AE Aqr are constrained in terms of thermal bremsstrahlung and non-thermal synchrotron radiation.

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