On the origin of pulsing X-ray emission of AE Aqr

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Abstract. The cataclysmic variable AE Aquarii is a low-mass close binary system containing a red and a white dwarf. The orbital period of the system is about 9.88 hr. The discovery of the 33 s coherent oscillations in the optical and X-ray emission of the system made it possible to determine the spin period of the white dwarf \( P_s \simeq 33.08 \) s. The 16.5 s harmonic in the optical and UV also was detected. According to observations with the Hubble Space Telescope, UV and optical oscillations are identified with two hot spots \( (T_p \sim 26000 \text{K}) \) located in the regions of magnetic poles on the white dwarf surface. However, X-ray oscillations with a period of 16.5 s have not been detected. This peculiarity results in the problem of the origin of pulsing X-ray emission from AE Aqr.

The X-ray emission of cataclysmic variables is usually interpreted as a result of accretion on the white dwarf surface. But this interpretation cannot be applied to AE Aquarii. It is recognized that the white dwarf in this system operates as the rotation-powered pulsar [2]. This star is steadily spinning down at the rate \( \dot{P}_0 = (5.64 \pm 0.02) \times 10^{-14} \text{ss}^{-1} \) which implies that the spin-down power exceeds the bolometric luminosity of the system by a factor of 5. Such feature is typical for rotation-powered pulsars but is very unusual for white dwarfs in cataclysmic variables. The only object with similar properties is currently known is AR Scorpii [3].

It also appears that the white dwarf in AE Aqr operates as a magnetic propeller. MHD simulation suggests that the material streaming into the Roche lobe of the white dwarf through
the L1 point is leaving the system after its interaction with the magnetic field of the white dwarf [4]. It should be noted, however, that the mass injection into the magnetosphere of the white dwarf occurs deep inside its light cylinder and the propeller action contributes into the energy budget of the system by only a few per cent [5].

All available indirect methods of determination of the magnetic field of the white dwarf lead to the estimate of its dipole magnetic moment $\mu \sim 10^{34} \text{ G cm}^3$ [6]. It indicates that the strength of the dipole component of the surface magnetic filed ranges from 50 MG (at the magnetic equator) to 100 MG (in the region of magnetic poles). In this case, the Alfvén radius of the white dwarf, $r_A = \left(\frac{\mu^2}{\dot{M}(2GM_{\text{wd}})^{1/2}}\right)^{2/7} \simeq 4.2 \times 10^{10} \text{ cm}$, significantly exceeds its corotation radius, $r_{\text{cor}} = \left(\frac{GM_{\text{wd}}/\omega^2}{\dot{M}}\right)^{1/3} \simeq 1.4 \times 10^9 \text{ cm}$. The light cylinder radius is $1.6 \times 10^{11} \text{ cm}$. Here $M_{\text{wd}}$ and $\omega$ are the mass and the angular velocity of the white dwarf, $\dot{M}$ is the mass-transfer rate. The centrifugal force at the magnetospheric boundary under these conditions prevents matter from accreting onto the surface of the white dwarf. Observational confirmations of this conclusion are the following. Studies of the Doppler $H_\alpha$ tomogram suggest that in spite of the very intensive mass transfer between the red and white dwarf there is no developed accretion disk in the system (see [5] and references therein). Instead, the matter is expelled from the system due to its interaction with the magnetic field of the rapidly spinning white dwarf. All data collected in X-ray observations also argues against an accretion nature of X-ray emission from AE Aqr (see next section).

All of the above indicate that pulsing X-ray emission cannot be explained by means of accretion process. There is another mechanism based on the interaction of a stream of matter lost by the red dwarf with the white dwarf magnetosphere. We explore a situation in which magnetic poles are heated by backflowing charged particles accelerated in the white dwarf magnetosphere. We suggest that the initial acceleration occurs in the current sheet at the magnetospheric boundary in the region of interaction between the stream and the magnetic field of the white dwarf. The particle injected into the magnetosphere are then accelerated due to electric potential inside the rotating magnetic field of the white dwarf.

2. Properties of X-ray emission of AE Aqr

The X-ray light curve of AE Aqr is characterized by flares that are in good correlation with optical and UV flares [7]. Flaring occurs almost permanently and is separated by relatively short quiescent phases. On the timescale from a few minutes to an hour the luminosity of the object in UV can change by an order of magnitude.

The observed X-ray emission of AE Aqr consists of 33 s pulsing component and non-pulsing component. Contribution of the pulsing component is approximately 16% during quiescence and decreases down to 7% in flares [8]. This indicates that the contribution of the pulsing component into the flare emission is relatively small. According to [9], both pulsing and non-pulsing flux increase as the flare advances, but the net increase of pulsing flux to the quiescence is very small and corresponds to about 3% – 4% of the increase in non-pulsing flux. The total X-ray luminosity of the system in $0.4 - 10 \text{ keV}$ is $\sim 7 \times 10^{30} \text{ erg s}^{-1}$ during quiescence and reaches $\sim 2 \times 10^{31} \text{ erg s}^{-1}$ during flares [7]. It is a factor of a few smaller than the luminosity of the system in the UV. This indicates that the pulsing emission in UV and X-rays can unlikely be explained in terms of the same mechanism. In particular, traditional interpretation of pulsing UV emission as a result of reemission of the X-ray photons in this particular case is not applicable.

The spectrum of X-ray emission of AE Aqr is much softer than typical spectra of accretion-powered white dwarfs. The X-rays are dominated by photons in the range $0.1 - 1 \text{ keV}$ [7]. According to [8], the linear size of the source of non-pulsing X-ray emission is larger than the size the white dwarf by almost two orders of magnitude. Moreover, the plasma density in this source is about $10^{11} \text{ cm}^{-3}$ that is a few orders less than the typical density in the accretion
column of cataclysmic variables. This data argues against an accretion nature of X-ray emission from AE Aqr.

3. Particle acceleration in the white dwarf magnetosphere

We consider a situation in which the hot spot responsible for pulsing X-ray emission of AE Aqr is a result of heating the surface of the white dwarf by backflowing relativistic particles accelerated in its magnetosphere. The X-ray spot is located at the magnetic pole of the white dwarf but its size is smaller than the size of the spots responsible for the optical and UV pulsations. This may indicate that particles responsible for the origin of the X-ray spot are more energetic and accelerated in a local region inside the area of the open field lines. This situation can be expected if the source of these particles is located inside the light cylinder of the white dwarf. In particular, this can be the region of interaction between the magnetic field of the white dwarf and the stream of material which is flowing into the Roche lobe of the white dwarf through the L1 point. According to results of numerical simulations [4], the interaction occurs at a distance of $\sim 50R_{\text{wd}}$ from the surface of the white dwarf. The acceleration scenario in this case can be divided into two steps. The initial (first step) acceleration may occur in the current sheet at the region of interaction between the magnetic field of the white dwarf and the stream of matter. The next (second) step is acceleration of the injected particles into the magnetosphere by the electric field generated according to the conventional scenario of rotation-powered pulsars.

3.1. Acceleration in the current sheet

The linear velocity of matter streaming through the Roche lobe of the white dwarf under the conditions of interest is significantly smaller than the linear velocity at the magnetospheric boundary. It therefore appears that the interaction between the stream and the magnetosphere leads to stretching the field lines in the magnetopause in the azimuthal direction and, hence, to a generation of the toroidal components of the magnetic field at the magnetospheric boundary. As a result of this interaction, a local current sheet (or a number of current sheets) in this region occurs. Rapid flaring of AE Aqr indicates that the field configuration at the magnetospheric boundary is unstable and, hence, an electric field in the region of flaring turbulization of current sheets is generated. The energy of particles accelerated in the electric field can be evaluated as $\varepsilon_0 \approx eE_0a_0$, where $E_0$ and $a_0$ are the electric field and the thickness of the current sheet. We assume that the thickness $a_0$ is a critical thickness that would be required for turbulization of current sheet plasma [11]. It can be estimated as

$$a_0 \approx \frac{B_A c}{4\pi n e u_{cr}}.$$  \hspace{1cm} (1)

Here $B_A$ is the dipole magnetic field strength at the magnetospheric boundary, $n$ is plasma density and $u_{cr}$ is critical velocity at which plasma becomes turbulized. Using results of numerical simulations of plasma flow in AE Aqr [4] one find the following number of the parameters: $B_A \approx 200$ G, $n \approx 10^{11}$ cm$^{-3}$ and $u_{cr} = v_{Te} = \sqrt{kT/m_e} \approx 3.7 \times 10^7$ cm/s for $T \approx 10^4$ K. Also we assume that the electric field generated in the current sheet is of order of the magnetic field at the magnetospheric boundary. As a result, the thickness of the current sheet and the particle energy are $a_0 \approx 300$ cm, $\varepsilon_0 \approx 2.6 \times 10^{-5}$ ergs $\approx 16$ MeV.

3.2. Acceleration inside the magnetosphere

As the second step, we consider acceleration of the injected particles inside the magnetosphere. Efficiency of this acceleration phase can be achieved due to initial pre-acceleration of particles in the current sheet. A detailed description of the acceleration mechanism is beyond the scope of this paper. Here we just explore if the energy budget associated with the voltage in the
magnetosphere of the fast rotating white dwarf is sufficient to power the luminosity of the pulsing X-ray component. To answer this question we use expression for the electric potential in the magnetosphere of the white dwarf from [12]. Particle energy acquired in this electric field is \( \varepsilon_p \approx 50 \text{ergs} \simeq 3 \times 10^7 \text{MeV} \). In this case Lorentz factors of electrons and protons are \( \gamma_e \sim 10^7 \) and \( \gamma_p \sim 10^4 \), respectively. Maximum particle energy is constrained by the radiative losses of relativistic electrons and protons caused by the curvature radiation. The radiative losses of protons are significantly less than of electrons. It therefore appears that relativistic protons might be more effective in heating the pole regions. The required density of heating particles is about \( 10^9 \text{cm}^{-3} \), which represents about 1% of the stream density in the region of its interaction with the magnetosphere of the white dwarf.

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