AE AQUARII: THE FIRST WHITE DWARF IN THE FAMILY OF SPIN-POWERED PULSARS
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Abstract: Simulation of Doppler H α tomogram of the nova-like star AE Aquarii suggests that the dipole magnetic moment of the white dwarf is close to $1.5 \times 10^{34}$ G cm$^3$. This is consistent with the lower limit to the magnetic field strength of the white dwarf derived from observations of circularly polarized optical emission of the system. The rapid braking of the white dwarf and the nature of pulsing hard X-ray emission recently detected with SUZAKU space telescope under these conditions can be explained in terms of spin-powered pulsar mechanism. A question about the origin of strongly magnetized white dwarf in the system remains, however, open. Possible evolutionary tracks of AE Aquarii are briefly discussed.

1 Introduction

Basic parameters of the close binary system AE Aqr are listed in Tab. 1. The red dwarf overflows its Roche lobe and transfers material through the L1 point towards the white dwarf. This material, however, is neither accreted onto the surface of the white dwarf nor stored in a disk around its magnetosphere. Instead, it is streaming out from the system with an average velocity of 300 km s$^{-1}$. The spin-down power of the white dwarf exceeds the bolometric luminosity of the system by a factor of a few (see Tab. 2). Finally, the system shows flaring activity whose properties are absolutely unique among all classes of flaring astrophysical objects (for a review see Beskrovnaya et al., 1996; Ikhsanov et al., 2004, and references therein).

Theoretical studies of the system during the last decade have led to a conclusion that AE Aqr does not fit in any of the accretion-based models developed for Cataclysmic Variables (see, e.g. Wynn et al., 1997). In other words, the white dwarf in the system is not an accretion-powered pulsar. This situation can be explained in terms of the centrifugal inhibition (propeller) model provided that the magnetic field of the white dwarf is strong enough for its magnetospheric radius to exceed the corotational radius (see Tab. 3). However, how strong is the magnetic field? A lack of the white dwarf’s photospheric lines in the system spectra makes impossible a direct measurement of the field strength through Zeeman effect. Among other methods, which can be used to answer this question, are the simulation of Doppler Hα tomogram of the system, the modeling of the rapid braking of the white dwarf, the analysis of the circularly polarized optical emission, and a reconstruction of power source of the pulsing hard X-ray emission recently discovered by SUZAKU space telescope. Following these methods one comes to a conclusion that the dipole magnetic moment of the white dwarf in AE Aqr is close to $1.5 \times 10^{34}$ G cm$^3$ and its rapid braking is governed by the pulsar-like spin-down mechanism.

2 Diskless mass-transfer

As first recognized by Wynn et al. (1997), the observed Doppler Hα tomogram of AE Aqr gives no evidence for a presence of an accretion disk in the system. Simulating the
Table 1: Parameters of AE Aquarii*

| System parameters | Distance | Binary period | Inclination | Eccentricity | Mass ratio |
|--------------------|----------|---------------|-------------|--------------|------------|
| Value              | (100 ± 30) pc | 9.88 hr       | 50° < i < 70° | 0.02         | 0.6 – 0.8  |

Stellar parameters

| Secondary   | K3V–K5V 0.41 sin⁻³ i | ~ 9.88 hr | – | – | – |
| Primary     | White Dwarf 0.54 sin⁻³ i | 33.08 s   | 5.64 × 10⁻¹⁴ | 74° – 76° |

* For references see e.g. Ikhsanov et al. (2004)
** The angle between the rotational and magnetic axes

Table 2: Energy budget of AE Aquarii*

| Component | Balmer Continuum Lines | UV-Emission Lines | Hα | X-rays 0.1–20 keV | Radio 5–240 MHz | Lb † | Lsd † |
|-----------|------------------------|-------------------|----|-----------------|----------------|------|------|
| Quiescence** | 2.0 × 10³¹             | 1.6 × 10³¹        | 4.8 × 10³⁰ | 7.8 × 10³⁰ | 10²⁸           | 10³³   | 6 × 10³³ |
| Flares**   | 8.4 × 10³¹             | 4.1 × 10³¹        | 1.4 × 10³¹ | 1.7 × 10³¹ | 2 × 10²⁹       | 10³³   | 6 × 10³³ |

* For references see e.g. Ikhsanov et al. (2004), Ikhsanov & Biermann (2006)
** in erg s⁻¹
† Lb is the system bolometric luminosity and Lsd is the spin-down power of the white dwarf

mass-transfer in terms of drag interaction between the inhomogeneous stream (a set of large diamagnetic blobs) and the magnetosphere (drag-driven propeller model) they have shown that the material transferred from the normal companion through the L1 point is streaming away from the system without forming a disk.

Ikhsanov et al. (2004) further elaborate on the latter picture concluding that the structure of the simulated tomogram depends on the magnetic field strength of the white dwarf. A best agreement between the observed and simulated tomograms has been found for \( \mu_{wd} \approx 1.5 \times 10^{34} \text{ G cm}^3 \) (see Fig. 1). Under these conditions the stream approaches the white dwarf to a distance

\[
r_0 \gtrsim R_A \approx 3 \times 10^{10} \eta_{0.37}^{4/7} \mu_{34.2}^{4/7} \tilde{M}_{17}^{-2/7} M_{0.9}^{-1/7} \text{ cm},
\]

where \( R_A \) is the Alfvén (magnetospheric) radius of the white dwarf with the dipole magnetic moment, \( \mu_{34.2} \), and mass, \( M_{0.9} \), expressed in units of \( 10^{34.2} \text{ G cm}^3 \) and 0.9 \( M_\odot \). The mass-transfer rate, \( \tilde{M}_{17} \), is expressed in units of \( 10^{17} \text{ g s}^{-1} \), and \( \eta_{0.37} = \eta/0.37 \) is the parameter accounting for the geometry of the accretion flow normalized following Hameury et al. (1986). Under the conditions of interest \( R_A \) exceeds the circularization radius (see Tab.3) and, therefore, prevents a formation of an accretion disk in the system. The stream velocity at \( R_A \) is limited to \( \lesssim 550 \text{ km s}^{-1} \). This is consistent with the upper limit to the velocity of the flow in AE Aqr derived from the observed Doppler Hα tomogram (Welsh et al., 1998). This provides us with a natural solution of the high-velocity loop problem reported by Wynn et al. (1997).

Thus, modeling of mass-transfer in AE Aqr in terms of the drag-driven propeller model suggests that the dipole magnetic moment of the white dwarf is \( \mu \approx 1.5 \times 10^{34} \text{ G cm}^3 \).
the case of Bohm diffusion (i.e. $D = \Delta r$ where $\Delta r$ can be expressed as
\[ \Delta r = \frac{8 \pi}{B^2(r_0)} \sigma_{\text{eff}}(r_0) N_b t_{\text{int}}(r_0) |V_f(r_0) - Vb(r_0)|_\perp, \]

where $B(r_0) = 2\mu_{\text{wd}}/r_0^3$. The number of blobs approaching the white dwarf to a distance $r_0$ in a unit time is limited to
\[ N_b \lesssim 3 \times 10^{11} \rho_{-11}^{-1} l_9^{-3}, \]

where $l_9$ and $\rho_{-11}$ are the radius and density of the blobs expressed in units of $10^9$ cm and $10^{-11}$ g cm$^{-3}$ (see Wynn et al., 1997). Under the conditions of interest (i.e. $r_0 \gg R_{\text{cor}}$) the field velocity, $V_f = \omega_b r_0$, significantly exceeds the velocity of blobs, $V_b \ll V_f = (2GM_{\text{wd}}/r_0)^{1/2}$, and hence, $|V_f(r_0) - Vb(r_0)|_\perp \approx \omega_b r_0$ (the suffix $\perp$ denotes the velocity component perpendicular to the field lines). The time of interaction between the blobs and the magnetosphere at a distance $r_0$ is of the order of free-fall time, $t_{\text{int}} \approx (r_0^3/2GM_{\text{wd}})^{1/2}$. Finally, the effective cross-section of interaction between the blob and magnetic field can be expressed as
\[ \sigma_{\text{eff}} \approx 2\pi l_9^2 \Delta r \sim 2\pi l_9 (D_{\text{eff}} t_{\text{int}})^{1/2}, \]

where $\Delta r$ is a scale of the magnetic field diffusion into the blob on a time scale $t_{\text{int}}$. In the case of Bohm diffusion (i.e. $D_{\text{eff}} = \alpha_B T_i/b$) see, e.g. Ikhsanov & Pustil’nik, 1996) one finds (combining Eqs. 2 - 4)
\[ L_{\text{prop}} \lesssim 10^{32} \text{erg s}^{-1} \alpha_{0.1} N_b \omega_{b0} l_9 \mu_{34}^{3/2} M_{0.8}^{-3/7} T_8^{1/2} \left( \frac{r_0}{3 \times 10^{10} \text{cm}} \right)^{-5/4} \approx 2 \times 10^{-2} L_{\text{sd}}, \]

where $\alpha_{0.1} = \alpha_B/0.1$ is the diffusion efficiency, which is normalized following the results of measurements of solar wind penetrating into the magnetosphere of the Earth (Gosling et al., 1991), $\omega_{b0} = \omega_b/0.2$ and $T_8$ is the temperature of outer layers of the blobs expressed in units of $10^8$ K.

Thus, the efficiency of the propeller action by the white dwarf constitutes only a few per cents of the observed spin-down power. This indicates that the observed braking of the white dwarf is governed by a different mechanism.

### Table 3: Basic scales of AE Aquarii

| Radius* | $R_{\text{wd}}$ | $R_{\text{cor}}$ | $R_{\text{circ}}$ | $R_{L1}$ | $R_{\text{lc}}$ | $a$ |
|---------|----------------|-----------------|-----------------|--------|--------|-----|
| Value (cm) | $(6 - 7) \times 10^8$ | $1.5 \times 10^9$ | $(1.8 - 2) \times 10^{10}$ | $10^{11}$ | $1.6 \times 10^{11}$ | $(1.7 - 1.9) \times 10^{11}$ |

* $R_{\text{wd}}$ is the white dwarf radius; $R_{\text{cor}}$ is the corotational radius; $R_{\text{circ}}$ is the circularization radius; $R_{L1}$ is the distance from the white dwarf to the L1 point; $R_{\text{lc}}$ is the radius of the light cylinder; $a$ is the orbital separation of the system components.

### 3 Spin-down mechanism of the white dwarf

#### 3.1 Propeller spin-down

The spin-down power by the magnetic propeller is limited to the magnetic flux transfer rate through the region of interaction between the magnetic field and the blobs. This condition can be expressed as

\[ L_{\text{prop}} \lesssim \frac{B^2(r_0)}{8\pi} \sigma_{\text{eff}}(r_0) N_b t_{\text{int}}(r_0) |V_f(r_0) - Vb(r_0)|_\perp, \]

where $B(r_0) = 2\mu_{\text{wd}}/r_0^3$. The number of blobs approaching the white dwarf to a distance $r_0$ in a unit time is limited to

\[ N_b \lesssim 3 \times 10^{11} \rho_{-11}^{-1} l_9^{-3}, \]
Figure 1: Doppler Hα tomogram of AE Aquarii. Left-up: observed (Welsh et al., 1998); Left-down: simulated under the assumption $\mu \sim 10^{32} \text{G cm}^3$ (Wynn et al., 1997; Ikhsanov et al., 2004); Right-up: simulated under the assumptions that $\mu \sim 10^{32} \text{G cm}^3$ and the emission comes from outside the system (Welsh et al., 1998); Right-down: simulated under the assumption $\mu \simeq 1.5 \times 10^{34} \text{G cm}^3$ Ikhsanov et al. (2004). For further discussion see Ikhsanov et al. (2004).
3.2 Pulsar-like spin-down

The only astrophysical objects whose spin-down power significantly exceeds their bolometric luminosity are the spin-powered pulsars. The spin-down power of these objects is released mainly in a form of magneto-dipole waves and accelerated particles. As recently shown by Ikhsanov & Biermann (2006), the spin-down mechanism developed for these objects is perfectly applicable to the case of the white dwarf in AE Aqr. In particular, the observed braking of the white dwarf can be explained in terms of the pulsar-like spin-down mechanism provided that its dipole magnetic moment is

$$\mu \approx 1.4 \times 10^{34} \left( \frac{P_s}{33 \text{s}} \right)^2 \left( \frac{L_{sd}}{6 \times 10^{33} \text{erg s}^{-1}} \right)^{1/2} \text{G cm}^3. \quad (6)$$

This implies that the strength of the surface magnetic field of the white dwarf in the magnetic pole regions is

$$B_0 = \frac{2\mu}{R_{wd}^3} \approx 100 \left( \frac{R_{wd}}{7 \times 10^8 \text{cm}} \right)^{-3} \left[ \frac{\mu}{1.4 \times 10^{34} \text{G cm}^3} \right] \text{MG}, \quad (7)$$

and, correspondingly, the surface field strength at its magnetic equator is $B_0/2 = 50 \text{MG}$.

As seen from Eq. (6), the value of $\mu$ required for the interpretation of the rapid braking of the white dwarf in terms of the pulsar-like spin-down mechanism is in excellent agreement with that derived by Ikhsanov et al. (2004) from the simulation of the Doppler Hα tomogram within the drag-driven propeller approach. Thus, analysis of both the mass-transfer and the braking of the white dwarf suggests the same value of the dipole magnetic moment of the white dwarf, namely, $\mu \approx 1.5 \times 10^{34} \text{G cm}^3$.

4 Circularly polarized optical emission

As first shown by Cropper (1986), the optical emission of AE Aqr is circularly polarized at a level of $p = 0.05\% \pm 0.02\%$. An attempt to explain this result in terms of the cyclotron emission from the base of the accretion column has led Bastian et al. (1988) to a serious problem. Namely, they have found that observations reported by Cropper (1986) can be interpreted in terms of the model of Chanmugam & Frank (1987) only if the surface field of the white dwarf exceeds $10^6 \text{G}$. However, the magnetospheric radius of the white dwarf (see Eq. 1) under these conditions is significantly larger than its corotational radius (see Tab. 3) and hence, an accretion of material onto the surface of the white dwarf is impossible (the star turns out to be in the centrifugal inhibition state). But if this is really so, the model of Chanmugam & Frank (1987) is not applicable (because of a lack of the accretion column) and cannot be used for determination of the surface field of the white dwarf.

In order to solve this paradox Beskrovnaya et al. (1996) have performed an independent measurement of the degree of circularly polarized emission of the system. Their result, $p = 0.06\% \pm 0.01\%$, is in excellent agreement with the result of Cropper (1986). Analyzing these observations Ikhsanov et al. (2002) have shown that the hot polar caps at the surface of the white dwarf, which were recognized through observations of the system with the Hubble space telescope (Eracleous et al., 1994), cannot be a source of the observed circularly polarized emission. Otherwise, the intrinsic polarization of the optical emission in these regions turns out to be in excess of 100%. It has also been shown that the polarized emission cannot be interpreted in terms of the linear and quadratic Zeeman
effect. The results of numerical simulations reported by Ikhsanov et al. (2002) show that the degree of polarization in the case of \( B = 1 \) MG is close to zero and for the case of \( B = 50 \) MG is limited to \( \lesssim 0.015\% \), which is a factor of 4 smaller than the observed value.

Thus, a question about the mechanism responsible for the observed circularly polarized optical emission remains so far open. It is, however, absolutely clear that the evaluation of the magnetic field reported by Bastian et al. (1988) has been made under assumptions which are not valid in the case of AE Aqr and, therefore, does not reflect the system properties.

5 Pulsing X-ray emission

As recently reported by Terada et al. (2008), properties of pulsing X-ray emission of the system observed with SUZAKU at 10-30 keV suggest a non-thermal nature of this radiation. The authors of this discovery have associated this emission with radiative losses of electrons accelerated in the magnetosphere of the fast rotating, strongly magnetized white dwarf. The luminosity of the non-thermal pulsing X-ray source has been evaluated as \( \sim (0.5 - 2.3) \times 10^{30} \) erg s\(^{-1}\). It has been noted, however, that the hard X-ray pulsations have a duty ratio of only 0.1, which may reflect the fact that the radiation is anisotropic and highly beamed. This indicates that the source luminosity can be limited to \( L_{\text{x-p}} \gtrsim 5 \times 10^{28} \) erg s\(^{-1}\).

It is widely believed that acceleration of particles by the white dwarf in AE Aqr represents nothing unusual since the electric potential in the magnetosphere of this star \( (\mathcal{V}_e \sim 2\pi R_{\text{wd}}^2 B_{\text{wd}}/P_s) \) has a huge value \( (\sim 10^{14} - 10^{16} \) V\). However, for an acceleration of particles in this potential to be effective the number density of material in the magnetosphere should not exceed the Goldreich-Julian density

\[
n_{\text{GJ}} = \frac{(\vec{\Omega} \cdot \vec{B})}{2\pi ce} \simeq 5 \times 10^4 \left( \frac{P_s}{33 \text{ s}} \right)^{-1} \left( \frac{B}{10^8 \text{ G}} \right) \text{ cm}^{-3}. \tag{8}\n\]

Otherwise, the electric field responsible for particle acceleration would be screened by the magnetospheric plasma. As recently shown by Ikhsanov & Biermann (2006), the kinetic luminosity of the beam of relativistic particles under these conditions is limited to

\[
\frac{d\mathcal{E}_p}{dt} \lesssim e \varphi(l_0) \dot{N} \simeq 5 \times 10^{29} \text{ erg s}^{-1} \left( \frac{B_{\text{wd}}}{10^8 \text{ G}} \right)^2, \tag{9}\n\]

where \( e \) is the electron electric charge and \( l_0 = (R_{\text{wd}} + s) \) is a distance from the surface of the white dwarf to the region of generation of the X-rays.

\[
\varphi_{\text{as}}(l_0) = \int_{R_{\text{wd}}}^{l_0} E_{||} ds \simeq 2\sqrt{2} E_{\text{AS}} R_{\text{wd}} \left[ \left( \frac{l_0}{R_{\text{wd}}} \right)^{1/2} - 1 \right] \tag{10}\n\]

is the electric potential generated in the polar cap regions of a fast rotating magnetized star surrounded by a vacuum (Arons & Scharlemann, 1979). \( E_{||} \equiv (\vec{E} \cdot \vec{B})/|\vec{B}| \) is the component of the electric field along the magnetic field \( \vec{B} \), and

\[
E_{\text{AS}} = \frac{1}{8\sqrt{3}} \left( \frac{\Omega R_{\text{wd}}}{c} \right)^{5/2} B(R_{\text{wd}}). \tag{11}\n\]

\(^1\)This value of \( L_{\text{min}} \) is smaller that that presented by Terada et al. (2008) by a factor of 100. It appears that Terada et al. (2008) have mistakenly evaluated the luminosity of the beamed source by multiplying the luminosity of the isotropic source by \( (4\pi/\gamma_{\text{col}}) \) instead of dividing it by the same value, where \( \gamma_{\text{col}} \) is the opening body angle of the beam.
The flux of relativistic particles from the polar caps of the white dwarf is

\[ \dot{N} = \pi (\Delta R_p)^2 n_{GJ}(R_{wd}) c, \] (12)

where

\[ \Delta R_p \simeq \left( \frac{\omega R_{wd}}{c} \right)^{1/2} R_{wd} \simeq 4 \times 10^7 \left( \frac{R_{wd}}{7 \times 10^8 \text{ cm}} \right)^{3/2} \left( \frac{P_s}{33 \text{ s}} \right)^{-1/2} \text{ cm} \] (13)

is the radius of the polar caps.

As follows from Eq. (9), the observed luminosity of the hard X-ray pulsing component can be explained in terms of the pulsar-like acceleration mechanism only if the surface field of the white dwarf satisfies the condition

\[ B(R_{wd}) \gtrsim 3 \times 10^7 \text{ G} \times \eta^{-1} \left( \frac{L_{\text{min}}}{5 \times 10^{28} \text{ erg s}^{-1}} \right)^{1/2}, \] (14)

where \( \eta < 1 \) is the efficiency of conversion of the energy of accelerated particles into the X-rays. This indicates that the dipole magnetic moment of the white dwarf is \( \mu \gtrsim 10^{34} \text{ G cm}^3 \), i.e. close to the value derived from the simulation of the Doppler H\( \alpha \) tomogram of the system and from the modeling of the braking of the white dwarf in terms of the pulsar-like spin-down.

6 Discussion and conclusions

Simulations of Doppler H\( \alpha \) tomogram, analysis of the rapid braking of the white dwarf, and the modeling of particle acceleration in AE Aqr suggest that the dipole magnetic moment of the white dwarf in this system is \( \mu \simeq 1.5 \times 10^{34} \text{ G cm}^3 \). Under these conditions the spin-down of the white dwarf is governed by the pulsar-like mechanism, i.e. its spin-down power is released predominantly in a form of the magneto-dipole waves and accelerated particles and significantly exceeds the bolometric luminosity of the system. This makes the degenerate companion of AE Aqr the first white dwarf in the family of spin-powered pulsars.

The above evaluation of the magnetic field of the white dwarf does not contradict observations of the circularly polarized optical emission as well as all presently established properties of the system. Moreover, the pulsar-like approach appears to be an effective tool in explanation of the origin of hot polar caps at the white dwarf surface (in terms of the dissipation of the backflowing current in the magnetosphere, see, e.g. Ikhsanov et al., 2004; Ikhsanov & Biermann, 2006) and properties of the system derived from observations in high-energy part of the spectrum.

At the same time, the above conclusion raises a problem about the history of the system. The age of the white dwarf evaluated from its surface temperature \((1 - 1.6) \times 10^4 \text{ K} \) (Eracleous et al., 1994) is limited to \( \gtrsim 10^8 \text{ yr} \) (see, e.g. Schönberner et al., 2000), while the spin-down time scale is only \( P/\dot{P} \sim 10^7 \text{ yr} \). This indicates that the system history contains an accretion-driven spin-up epoch. However, the spin period to which a white dwarf with \( \mu \sim 10^{34} \text{ G s}^{-1} \) could be spun-up by a disk accretion is substantially larger than the currently observed 33 s period (for discussion see Ikhsanov, 1999). It, therefore, appears, that the magnetic field of the white dwarf has been amplified during a previous epoch. As shown by Ikhsanov (1999), this could occur at the end of the accretion-driven spin-up phase due to gravitational waves emission instability of the degenerate core of
the star. In this light, AE Aqr can be considered as a precursor of a polar. The detailed study of the corresponding evolutionary track is now work in progress.

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