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Rapid spindown of fast-rotating white dwarfs in close binary systems as a result of magnetic field amplification

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Abstract. The rapid braking on the white dwarf in the close binary AE Aqr can be explained in terms of the pulsar mechanism provided the magnetic moment of the star $\mu \gtrsim 1.4 \times 10^{34}\,\mathrm{G\,cm^3}$. Under this condition the magnetic field is strong enough to prevent accretion with the rate $\lesssim 10^{-4.3} M_{\odot}\,\mathrm{yr}^{-1}$ onto the white dwarf surface, so the traditional accretion-driven spin up mechanism cannot be applied to this system without additional assumptions. A scenario in which the initial magnetic moment of the white dwarf was essentially weaker than its present value is explored. A weakly magnetized ($\sim 10^4$ G) white dwarf was slowly spinning up by accretion of matter from its normal companion until its period $P \gtrsim P_{\rm cr} \simeq 20$ s. When the period had decreased beyond $P_{\rm cr}$ the white dwarf lost its angular momentum via the gravitational waves that caused strong differential rotation. The magnetic field inside the star was winding up on a time scale of a month up to $\sim 10^8$–10^9 G. This field manifests itself at the surface due to buoyant instability producing a surface field of 10^7–10^8 G. As a result the white dwarf changed its initial *accretor* state to the presently observed *ejector* state, i.e. it is spinning down predominantly due to the magneto-dipole waves generation and particle acceleration.

Key words: stars: novae, cataclysmic variables – stars: magnetic fields – stars: pulsars: general – stars: individual: AE Aqr

1. Introduction

The close binary system AE Aqr contains one of the most rapidly spinning magnetic white dwarfs: $P_{\rm s} = 33$ s (for the system description see Eracleous & Horne 1996; Ikhsanov 1997 and references therein). It contributes to the system radiation in the form of $33^{\rm s}$ pulsing component which is detectable in the optical, UV and X-rays. Recent investigations have shown no evidence for the white dwarf to be an accretion powered source. The most striking argument has been presented by de Jager et al. (1994) who reported the mean spindown rate $\dot{P} = 5.64 \times 10^{-14}\,\mathrm{s\,s^{-1}}$, which implies a spindown power $L_{\rm sd} \simeq 6 \times 10^{33} I_{50}\,\mathrm{erg\,s^{-1}}$ ($I_{50} = I/10^{50}\,\mathrm{g\,cm^2}$ is the white dwarf moment of inertia). $L_{\rm sd}$ is larger than the observed UV and X-ray luminosities of AE Aqr by a factor of 120 and even than its bolometrical luminosity by a factor of more than five[1]. This indicates that the spindown power dominates the energy budget of the system and only a small fraction (about a few percents) of this energy is transferred to the detectable part of the electromagnetic spectrum.

Study of the optical-UV spectrum and the profile of $33^{\rm s}$ pulsations (Eracleous et al. 1994) has shown the surface temperature in the magnetic pole regions to be $T_{\max} \simeq 26000$ K, which is higher than the average surface temperature of the white dwarf: $T_{\rm int} \sim (10000 \div 16000)$ K. The obtained value of $T_{\max}$ is significantly smaller than the surface temperature in the magnetic pole regions of accreting compact stars that makes the traditional accretion scenarios for heating the magnetic polar caps in this particular case rather unreliable.

The X-ray spectrum of AE Aqr was found to be soft and essentially different from the hard X-ray spectra of all intermediate polars as well as from those of almost all accretion powered close binaries (Clayton & Osborne 1995). Furthermore, due to some properties (e.g. the power law spectrum of pulsing component with $\alpha \approx -2$ and the ratio of the X-ray luminosity to the spindown luminosity $L_{\rm x}/L_{\rm sd} \sim 10^{-3}$) the X-ray emission of AE Aqr is rather similar to the X-rays detected in the ROSAT energy range from canonical radio pulsars (Ikhsanov 1998).

Finally, the detection of circularly polarized radiation from AE Aqr with the average value of 0.06 ± 0.01% (Cropper 1986; Stockman et al. 1992; Beskrovnaya et al. 1996) implies the magnetic field in excess of 10^6 G. Correspondingly, this gives the lower limit to its magnetic moment $\mu > 3 \times 10^{32}\,\mathrm{G\,cm^3}$, that according to Lamb & Patterson (1983) means impossibility of steady accretion onto the surface of the white dwarf.

Some effort has recently been made to determine the *state* of the white dwarf. The central arguments of this determination were the unique spindown, $\dot{P}$, and the mass-exchange picture reconstructed by Wynn et al. (1997) on the basis of the H_α Doppler tomogram of AE Aqr. Analysis of this tomogram has shown no evidence of a Keplerian accretion disk in the system. On the contrary, the matter coming from the normal companion (a K3 – K5 main sequence red dwarf) has been observed to stream out from the system with the average velocity of $V_{\rm out} \approx 300\,\mathrm{km\,s^{-1}}$. On the basis of this Wynn et al. (1997) suggested that the white dwarf is in the state of *propeller*, i.e. it is

[1] The distance to AE Aqr is adopted to be 100 pc.

spinning down *predominantly* due to the interaction between the fast rotating magnetosphere of the white dwarf and the matter inflowing from the normal component (the 'magnetic propeller' model).

This interpretation however contains at least two questionable items. If the spindown power of the white dwarf is converted *predominantly* to the kinetic energy of the outflowing matter, the rate of mass exchange in AE Aqr should be $\dot{M}_{\rm in} \gtrsim \dot{M}_{\rm out} = L_{\rm sd}/V_{\rm out}^2 \simeq 7 \times 10^{18}\,{\rm g\,s^{-1}}$ that is much higher than the mass-exchange rates evaluated from various observations (Warner 1995 and references therein). Then the magnetic propeller model is constructed under the basic assumption that the heating of inflowing material due to its interaction with the magnetosphere of the white dwarf is almost negligible. The correctness of this limitation in the case of AE Aqr is not obvious since the relative velocity of blobs and the magnetic field of the white dwarf at the interaction radius corresponds to Mach numbers $M \gg 1$ that implies an intensive heating at the shock. In this case a significant fraction of the spindown power is expected to be transferred to the detectable parts of the electromagnetic spectrum (see e.g. Davies & Pringle 1981).

A possibility to avoid these problems was discussed in the previous paper (Ikhsanov 1998). It has been shown that the rapid braking on the white dwarf can be explained in terms of the canonical pulsar mechanism provided the magnetic moment of the compact star $\mu \gtrsim 1.4 \times 10^{34}\,{\rm G\,cm^3}$, that implies a magnetic field strength at the surface of the white dwarf of about 50 MG. Under this condition the spindown power is used *predominantly* for the generation of magneto-dipole waves and particle acceleration. The efficiency of interaction between the rotating white dwarf magnetosphere and the inflowing plasma (i.e. the propeller action of the white dwarf) within this model is $\sim 10^{-2}$. Hence, only a small fraction of the spindown energy is converted to the kinetic energy of outflowing non-relativistic matter as well as to the detectable electromagnetic radiation. Nevertheless, the geometry and velocity of the accretion flow are in a good agreement with those reported by Wynn et al. (1997).

If one accepts the strength of the magnetic field at the white dwarf surface $B \gtrsim 50\,{\rm MG}$ the question about the origin of its fast rotation arises. There are no grounds to consider the fast rotation of the white dwarf in AE Aqr as a remnant of the angular momentum of its progenitor (see Ikhsanov 1995). On the other hand, the accretion-driven spin up mechanism also cannot be applied in its canonical form to the particular case of AE Aqr without problems. In Sect. 2 I will show that the magnetic field of the white dwarf is strong enough to prevent the accretion of even very high rate onto its surface. In principal, there are only two possibilities to solve this problem: either one should assume that the rate of mass accretion onto the white dwarf during a previous epoch was comparable with the Eddington mass accretion rate, or the strong magnetic field of the primary has relatively recent origin: it has been generated at the last stage of spin up epoch when the spin period of the white dwarf was already shorter than that presently observed. The second possibility is discussed in Sect. 3. The suggested evolutionary scenario of the white dwarf is summarized and discussed in Sect. 4.

2. The accretion-driven spin up

For the white dwarf in AE Aqr to be spun-up by accretion the following conditions should be satisfied:

i) $R_{\rm m} < R_{\rm cor}$, i.e. the magnetospheric radius of the white dwarf is smaller than its corotational radius, and
ii) $P_{\rm eq} \lesssim P_{\rm s} = 33\,{\rm s}$: the equilibrium period of the white dwarf during a previous accretion epoch is shorter than the presently observed period $P_{\rm s}$.

The first condition in the case of disk accretion means

$$\dot{M}_{\rm pe} > 6 \times 10^{19}\,{\rm g\,s^{-1}}\ \ \mu_{32.5}^2\, P_{33}^{-7/3}\, M_{0.8}^{-5/3}. \qquad (1)$$

Here $\dot{M}_{\rm pe}$ denotes the mass accretion rate during the spin-up epoch, μ is the magnetic moment of the white dwarf expressed in units of $10^{32.5}\,{\rm G\,cm^3}$, i.e. the lower limit of μ derived from polarimetric observations (see above), $P_{33} = P_{\rm s}/33\,{\rm s}$ and $M_{0.8}$ is the mass of the white dwarf in units of $0.8 M_{\odot}$.

The accelerating and decelerating torques applied to an accreting compact star can be evaluated following Ghosh & Lamb (1979) as $K_{\rm su} \cong \dot{M}\sqrt{GM_1 R_{\rm mag}}$ and $K_{\rm sd} \cong -k_{\rm t}\mu^2/R_{\rm c}^3$, respectively. Hence, the equilibrium spin period of the white dwarf is

$$P_{\rm eq} \simeq 2\pi\, k_{\rm t}^{3/7}\, \frac{\mu^{6/7}}{\dot{M}_{\rm pe}^{3/7}(GM_{\rm wd})^{5/7}} \simeq \qquad (2)$$
$$\simeq 220\,{\rm s}\ \ k_{\rm t}^{3/7}\, \mu_{32}^{6/7}\, \dot{M}_{17}^{-3/7}\, M_{0.8}^{-5/7}.$$

Here, $k_{\rm t}$ is a dimensionless parameter of the order of unity ($k_{\rm t} \lesssim 1$, see Lipunov 1992).

The minimum duration of the spin-up epoch can be evaluated assuming $K_{\rm su} \gg K_{\rm sd}$. Then, solving the equation $d\Omega/dt = K_{\rm su}/I$, one gets

$$\Delta t = \frac{2\pi I}{\dot{M}_{\rm pe}\,\sqrt{GMR}}\,\left(\frac{1}{P} - \frac{1}{P_0}\right), \qquad (3)$$

where P_0 is initial period of the white dwarf. The mass accreted onto the surface of the white dwarf during this epoch is

$$M_{\rm a0} = \Delta t \dot{M}_{\rm pe} \gtrsim 6 \times 10^{31}\,{\rm g}\ \ I_{50}\, P_{33}^{-1}\, M_{0.8}^{-1/2}. \qquad (4)$$

Eqs. (1) and (2) clearly show that the white dwarf in AE Aqr could be spun-up by accretion to the presently observed period if either its magnetic moment is $\mu < 10^{31}\,{\rm G\,cm^3}$ or the mass accretion rate in a previous epoch was essentially higher than that in the presently observed spin-down epoch. In particular, for the traditionally accepted value of $\mu \simeq 10^{32}\,{\rm G\,cm^3}$ (e.g. de Jager 1994; Wynn et al. 1997) the value of $\dot{M}_{\rm pe}$ should be al least by two orders larger than the mass exchange rate presently evaluated. However the question on the physical processes and the mechanism which could produce so intensive mass transfer in the particular case of AE Aqr so far has no reliable answer. The Roche lobe overflow mass transfer during a previous epoch could be realized in AE Aqr if the normal component in this system is essentially evolved and is presently in a state of "hibernation". Nevertheless, this hypothesis has not yet been confirmed by observations which have shown no deviations of the normal component from a main sequence red dwarf (for discussion see also Ikhsanov 1997).

This is the more so if the magnetic field at the white dwarf surface is $B(R_{\rm wd}) > 1$ MG (as it was evaluated on the basis of polarimetric observations) and is of the order of 50 MG as it is required in the frame of the pulsar-like model. In this case the required value of $\dot{M}_{\rm pe}$ proves to be in excess of the Eddington mass accretion rate ($\sim 3 \times 10^{21}$ g s^{-1}) with the accretion epoch duration of only 500 yr. Accretion with these characteristics resembles the process of merging of white dwarf with another star rather than the mass exchange between a main sequence red dwarf and a white dwarf in a close binary. If one would like to follow this resemblance it should be assumed that AE Aqr was initially a triple system of the white dwarf, the red dwarf and, possibly, a brown dwarf of mass $\gtrsim 0.03 M_{\odot}$ (see Eq. 4). Investigation of this exotic possibility is however beyond the scope of the present paper. Instead, in the next section I focus on a possibility that the magnetic field of the white dwarf has been essentially amplified during a previous epoch of its evolution.

3. Magnetic field amplification in a fast rotating white dwarf

An alternative scenario for the origin of a fast rotating, magnetized white dwarf is based on the magnetic field amplification in differentially rotating stars. In fact, the assumption about the intensive mass exchange between the components of AE Aqr in a previous active epoch is not the only possible explanation for the fast rotation of white dwarf in AE Aqr. Instead one can assume that the initial magnetic field of the white dwarf was significantly weaker and has been amplified to its present value only at the last stage of the spin-up epoch when the rotation of white dwarf became essentially nonuniform.

If the initial magnetic moment of a white dwarf satisfies the condition:

$$\mu_0 \lesssim 10^{30}\ \dot{M}_{16}^{1/2}\ P_{15}^{7/6}\ M_{0.8}^{5/6}\ {\rm g\ s^{-1}}, \tag{5}$$

it slowly spun up by accretion ($\dot{M}_{\rm pe} \sim 10^{16}$ g s^{-1}) up to the period $P_{15} = P_{\rm s}/15$ s on the time scale of about 10^8 years. However the white dwarf should become secularly unstable to excitation of its oscillation modes by the emission of gravitational waves as the period decreases below the critical value (Shapiro & Teukolsky 1983 and references therein). For the $0.8 M_{\odot}$ white dwarf the critical period is about 20 s (Chanmugam et al. 1987). Under the condition $P_{\rm s} \lesssim P_{\rm cr} \simeq 20$ s its angular momentum is lost by gravitational wave emission which varies through the star, depending on the shape of the unstable eigenfunction. As a result the star rotation cannot remain uniform.

In a differentially rotating compact star, the initial poloidal magnetic field $B_{\rm r0}$ is winding-up into a toroidal configuration B_{ϕ} and amplified as one part of the star rotates about the other:

$$\frac{dB_{\phi}}{dt} = (\Omega_{\rm s} - \Omega_{\rm c}) B_{\rm r}, \tag{6}$$

where $\Omega_{\rm c}$ and $\Omega_{\rm s}$ are the angular velocities of the core and outer shell, respectively[2]. The toroidal magnetic field inside the white dwarf becomes buoyancy unstable when it reaches the critical value $B_{\rm f}$. Following Kluźniak & Ruderman (1998) this value can be evaluated from the equation

$$B_{\rm f}^2/8\pi = f \rho c_{\rm s}^2, \tag{7}$$

where f is the dimensionless parameter accounting for the stratification and ρ and $c_{\rm s}$ are the density and the sound speed in the magnetic field generation region, respectively. The buoyancy instability is generally nonaxisymmetric, forming magnetic arches of field lines which erupt through the surface as it is sketched in Kluźniak & Ruderman (1998). During this process the toroidal field, B_{ϕ}, transforms to the radial component, $B_{\rm r}$, which contributes to the dipole field of the white dwarf with the efficiency ε: $B_{\rm p} = \varepsilon B_{\rm r}$.

The plasma density in the magnetic field generation region for the case of the pulsar-like white dwarf in AE Aqr ($B_{\rm p} \simeq$ 50 MG) can be evaluated from Eqs. (6) and (7) as

$$\rho_0 \sim 500\ f_{-1.5}^{-1}\ \varepsilon_{0.3}^{-2}\ B_{7.7}^2\ T_6^{-1}\ {\rm g\ cm^{-3}}. \tag{8}$$

Here $f_{1.5} = f/10^{-1.5}$, $B_{7.7}$ is the present strength of the poloidal magnetic field of the white dwarf expressed in 50 MG, T_6 is the temperature in the magnetic field generation region in units of 10^6 K and the parameter $\varepsilon_{0.3} = \varepsilon/0.3$ is normalized following Spruit (1999). This indicates, that the magnetic field generation region is situated just over the boundary between the degenerate core and the nondegenerate outer shell. The energy stored in the differential rotation $E = \hat{I}\Omega^2/2 \sim 5 \times 10^{41}\ \hat{I}_{44}\ \Omega_{0.1}^2$ ergs is sufficient to power the generation of the white dwarf magnetic field of $\gtrsim 50$ MG (here, $\hat{I}_{44}$ is the effective moment of inertia of differential rotation expressed in united of 10^{44} g cm^2 and $\Omega_{0.1} = (\Omega_{\rm s} - \Omega_{\rm c})/0.1$ rad s^{-1} is the effective difference in angular velocity of rotation).

4. Conclusion and discussion

Summarizing one can envisage a scenario in which AE Aqr in a previous epoch was almost an ordinary member of DQ Her subclass of Cataclysmic Variables (CVs), i.e. a binary system in which the normal companion transfers material to the moderately magnetized white dwarf via a Keplerian accretion disk. Taking into account that AE Aqr is one of the largest CVs ($P_{\rm orb} \simeq 9.88$ hr) and that it contains a K3–K5 red dwarf with no observational deviations from the main sequence the mass accretion rate during the previous epoch was unlikely higher than that in the thermal timescale, i.e. $\dot{M}_{\rm pe} < \dot{M}_{\rm th} \sim 10^{-9} M_{\odot}$/yr (Ikhsanov 1997)[3]. The magnetic field strength of the white dwarf in a previous epoch was about of 10^4 G (see Eq. 5). The white

[2] Here I assume the core to rotate more slowly than the shell

[3] I would like to point out that no additional assumptions on the evolutionary status as well as the magnetic activity of the normal component are required in the frame of this scheme.

dwarf slowly spun up by accretion and became unstable to the gravitational wave mechanism as its period decreased below the critical value $P_{\rm cr} \sim 20$ s. During this period the rotation of the white dwarf was essentially differential causing the winding-up of the magnetic field up to $B_\phi \sim {\rm a\ few}\ \times 10^8$ G. The field has been amplified on a time scale of a month and floated up from the white dwarf interior due to bouyancy instability. As a result, the surface dipole magnetic field of the white dwarf increased up to ~ 50 MG, i.e its present value. The later spindown of the white dwarf (presently observed) can be explained in terms of the canonical pulsar mechanism, and mass transfer between the components operates according to the propeller mechanism with the efficiency $\sim 10^{-2}$ (Ikhsanov 1998).

In principal, there are no limitations for such a scenario to be realized in other close binaries. The value of the critical period for compact stars depends on their physical parameters (e.g. the mass, the chemical composition, etc.) as well as on the mode of excited oscillations. The critical period of 20 s for the white dwarf in AE Aqr has been evaluated assuming the f-mode to be excited. If the excitation of r-mode (Rossby waves) of compact star oscillations is effective (e.g. Anderson et al. 1999) the critical period could be larger. However recently reported observations of fast rotating, relatively low magnetized white dwarfs in WZ Sge ($P_{\rm s} \simeq 28$ s, Welsh et al. 1997) and UX UMa ($P_{\rm s} \simeq 29$ s, Knigge et al. 1998) suggest that the instability actually sets in at somewhat shorter periods. At the same time these observations give additional strong arguments in favor of the accretion-driven spin up of white dwarfs in close binaries up to very short periods.

Another key point of the suggested scenario is the amplification of the magnetic field in differentially rotating white dwarfs. The nonuniform rotation is not the property of only fast rotating white dwarfs. In particular, Winget et al. (1994) have found strong evidence for differential rotation (outer envelope rotating 1.8 times faster than the core) of the white dwarf GD 358[4]. Using this result Thomas et al. (1995) have shown that the dynamo generation of the magnetic field in the outer layers of the white dwarf allows to explain the observed monthly variations of the strength of its magnetic field. In fact, this can be considered as an indirect confirmation for the magnetic field generation inside the differentially rotating white dwarfs.

Finally, the presented scenario might be also helpful in understanding the origin of very fast rotating, strongly magnetized white dwarf in 1E 2259+586 suggested by Paczyński (1990). Really, putting the calculated parameters of the white dwarf: the mass $\simeq 1.32 M_\odot$, the spin period $P_{\rm s} = 6.98$ s and the magnetic moment $\mu \simeq 3.5 \times 10^{34}\ {\rm G\,cm^3}$ to Eq. (1) one finds the required mass accretion rate onto the white dwarf during the spin-up epoch $\dot{M}_{\rm pe} \gtrsim 0.15 M_\odot\,{\rm yr}^{-1}$. This is however at least by three orders higher than the mass accretion rate realized in the merging of white dwarfs. At the same time this problem proves to be naturally avoided in the frame of suggested scenario for the magnetic field generation in the secularly unstable white dwarf. In this case the winding up of the toroidal magnetic field inside the white dwarf at the last stage of merging process up to the value of 10^9 G would lead to the surface magnetic field of 10^8 G evaluated in the Paczyński's model.

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[4] The rotational period of the envelope is 0.89 day.