On the origin of the peculiar cataclysmic variable AE Aquarii

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Abstract

The nova-like variable AE Aquarii is a close binary system containing a red dwarf and a magnetized white dwarf rotating with the period of 33 seconds. A short spin period of the white dwarf is caused by an intensive mass exchange between the system components during a previous epoch. We show that a high rate of disk accretion onto the white dwarf surface resulted in temporary screening of its magnetic field and spin-up of the white dwarf to its present spin period. Transition of the white dwarf to the ejector state occurred at a final stage of the spin-up epoch after its magnetic field had emerged from the accreted plasma due to diffusion. In the frame of this scenario AE Aqr represents a missing link in the chain of Polars evolution and the white dwarf resembles a recycled pulsar.

Keywords: white dwarf; magnetic field; accretion; close binaries

1. Introduction

AE Aquarii is a peculiar nova-like star which exhibits rapid flaring in almost all parts of the spectrum from radio to X-rays. It is a non-eclipsing
close binary system at a distance of $\sim 100 \pm 30$ pc with the orbital period $P_{\text{orb}} \approx 9.88$ h and almost zero eccentricity. The system components are a K3–K5 red dwarf and a white dwarf in a very unusual state. First, it rotates with the period of $P_s \approx 33$ s. Second, it brakes so rapidly that the spin-down power exceeds the bolometric luminosity of the system. Finally, its magnetic field prevents the inflowing material from approaching the star to a distance smaller than $(3-5) \times 10^{10}$ cm, which is a factor of 20 larger than the corotation radius of the white dwarf and 40 times larger than the radius of the white dwarf itself (for detailed system description and corresponding references see e.g. Ikhsanov & Beskrovnaya, 2012).

These peculiar properties can be explained in terms of the pulsar-like white dwarf scenario provided the surface magnetic field of the white dwarf is in excess of 50 MG (Ikhsanov, 1998; Ikhsanov et al., 2004). But how such a white dwarf was formed? We suggest that the white dwarf in AE Aqr was spun-up by intensive accretion in a previous epoch. The high rate of disk accretion onto the surface of the white dwarf resulted in temporary screening of its magnetic field. This has allowed the white dwarf to reach its present spin period. Transition of the white dwarf to the ejector state occurred at a final stage of the spin-up epoch after its magnetic field had emerged from the accreted plasma due to diffusion. In the frame of this scenario AE Aqr represents a missing link in the chain of Polars evolution and the white dwarf resembles a recycled pulsar.

2. Accretion-driven spin-up epoch

A hint to answer the question about the origin of the fast rotating strongly magnetized white dwarf in AE Aqr is provided by a discrepancy between the age of the white dwarf determined by its cooling time and the spin-down time scale $t_{\text{sd}} \approx P_s/2\dot{P_s} \approx 10^7$ years (de Jager et al., 1994). Indeed, the age of a $M_{\text{wd}} \sim 0.8 M_{\odot}$ white dwarf with the surface temperature $T_{\text{wd}} \leq 16000$ K is limited to $\geq 10^8$ yr (Schönberner et al., 2000). This exceeds the spin-down timescale of the white dwarf in AE Aqr by more than an order of magnitude. Hence, the fast rotation of the white dwarf cannot be connected with peculiarities of its origin but is a product of the binary evolution which contained an epoch of rapid spin-up of the degenerate component caused by intensive accretion onto its surface.

The accretion-driven spin-up of a white dwarf can be effective only if the mass-transfer rate between the system components satisfies the condition
\( \dot{M}_{\text{pe}} > \dot{M}_{\text{crit}} \). Here \( \dot{M}_{\text{crit}} \simeq 10^{-7} \, \text{M}_{\odot} \, \text{yr}^{-1} \) is a critical value of the accretion rate at which the hydrogen burning in the matter deposited onto the white dwarf surface is stable. Otherwise, the spin behavior of the star will be similar to dwarf novae in which spin-up of the degenerate component is prevented by thermonuclear runaways followed by the expanded envelope mass-loss spin-down of the white dwarf (Livio & Pringle, 1998).

As shown by Meintjes (2002), the mass transfer rate in AE Aqr during a previous epoch could be as high as \( \dot{M}_{\text{pe}} \sim 10^{19} - 10^{20} \, \text{g s}^{-1} \) (\( \sim 10^{-7} - 10^{-6} \, \text{M}_{\odot} \, \text{yr}^{-1} \)). If the magnetic field strength of the white dwarf, and, correspondingly, its magnetospheric radius, remains unchanged during this epoch, its spin period decrease down to 33 s on the time scale (Ikhsanov, 1999)

\[
\Delta t_{\text{max}} \geq \frac{2\pi I}{\dot{M}_{\text{pe}} \sqrt{G M_{\text{wd}} R_{\text{m}}}} \left( \frac{1}{P_{\text{s}}} - \frac{1}{P_{\text{f}}} \right) \simeq 2 \times 10^{5} \, I_{50} \, \dot{M}_{19}^{-1} \, M_{0.8}^{-1/2} \, R_{9}^{-1/2} \, P_{33}^{-1} \, \text{yr.}
\]

Here \( I_{50} \) is the moment of inertia of the white dwarf in units \( 10^{50} \, \text{g cm}^{2} \) and \( \dot{M}_{19} = \dot{M} / 10^{19} \, \text{g s}^{-1} \). \( M_{0.8}, R_{9} \) and \( P_{33} \) are the mass, radius and spin period of the white dwarf in units \( 0.8 \, \text{M}_{\odot}, 10^{9} \, \text{cm} \) and 33 s, correspondingly. Finally, \( P_{\text{i}} \) is an initial spin period of the white dwarf, which is assumed to satisfy inequality \( P_{\text{i}} \gg 33 \, \text{s} \).

The ultimate period which the white dwarf can reach in the process of disk accretion is given by \( P_{\text{min}} = \max\{P_{\text{m}}, P_{\text{eq}}\} \). Here \( P_{\text{m}} \) is a solution to equation \( R_{\text{m}} = R_{\text{cor}} \), and \( P_{\text{eq}} \) is an equilibrium period defined by equality of the spin-up torque, \( K_{\text{su}} = \dot{M}_{\text{pe}} (G M_{\text{wd}} R_{\text{m}})^{1/2} \), and spin-down torque, \( K_{\text{sd}} = (1/4)k_{t}B_{s}^{2}R_{\text{wd}}^{6}/R_{\text{cor}}^{3} \), applied to the white dwarf from the accretion flow. Here \( R_{\text{m}} \) and \( B_{s} \) are the magnetospheric radius and the magnetic field strength on the surface of the white dwarf at the final stage of the accretion-driven spin-up, and \( k_{t} \) is a numerical coefficient. In the case of stationary accretion and under the conditions of interest \( P_{\text{eq}} \leq P_{\text{m}} \). Taking \( P_{\text{eq}} = 33 \, \text{s} \) in equation \( K_{\text{su}} = K_{\text{sd}} \) and solving it for \( B_{s} \), we find that the observed spin period of the white dwarf in AE Aqr can be reached within the scenario of accretion-induced spin-up provided \( B_{s} \leq B_{0} \), where

\[
B_{0} \simeq 1.5 \, \text{MG} \, k_{0.3}^{-7/12} \, M_{0.8}^{5/6} \, R_{8.8}^{-3} \, P_{33}^{7/6} \, \dot{M}_{19}^{1/2}.
\]

and \( k_{0.3} = k_{t}/0.3 \). This indicates that reconstructing the evolutionary track of the system it is necessary to take into account not only the spin evolution of the white dwarf (as it has been done by Meintjes, 2002), but also the evolution of its magnetic field.
3. Magnetic field screening during the spin-up epoch

The magnetic field of the white dwarf may decrease during the spin-up epoch due to screening by the accreting material (Bisnovatyi-Kogan & Komberg, 1974). The hypothesis about a possibility to bury the magnetic field of accretors has been actively investigated for neutron stars (Konar & Choudhuri, 2004; Lovelace et al., 2005) and white dwarfs (Cumming, 2002). The efficiency of screening has been shown to depend on the mass accretion rate and a duration of the intensive mass exchange between the system components. Under favorable conditions the surface magnetic field of a star can be reduced by a factor of 100. Afterwards the field is expected to reemerge in the process of diffusion through the layer of accreted plasma.

Following this hypothesis we can assume that prior to the epoch of active mass exchange the magnetic field strength on the surface of the white dwarf in AE Aqr was close to its current value. At that time the system was likely to behave as a Polar (since the magnetospheric radius of the compact component under the condition $\dot{M} \ll \dot{M}_{\text{pe}}$ essentially exceeds its circularization radius). The start of spin-up epoch was caused by increase of the mass exchange rate up to $\dot{M}_{\text{pe}} \geq 10^{19}$ g s$^{-1}$ due to red dwarf overfilling its Roche lobe. This resulted in decrease of the magnetospheric radius of the white dwarf down to $R_{\text{m}}^{(i)} \leq 10^{10}$ cm and subsequent formation of the accretion disk in the system. The accretion of matter onto the surface of the white dwarf in this case could occur under condition $R_{\text{m}}^{(i)} < R_{\text{cor}}$ which was satisfied provided the initial spin period of the white dwarf was $P_i \geq 11$ min.

The field of the compact object was found to be strongly screened by plasma accumulating in its polar caps for accretion rates greater than the critical value $\geq 3 \times 10^{16}$ g s$^{-1}$ (Cumming, 2002). Because of surface field decay the magnetospheric radius of the white dwarf is decreasing and, correspondingly, the area of the hot spots on its surface is increasing. The maximum possible factor of field reduction during the epoch of intensive accretion is limited to $\sim (1/\sin \theta_i)^{7/2} \sim 125$, where $\theta_i = \arcsin \left( R_{\text{wd}}/R_{\text{m}}^{(i)} \right)^{1/2}$ is the opening angle of the accretion column at the beginning of spin-up epoch. This implies that at the final stages of spin-up epoch the magnetic field of the white dwarf did not exceed 1 MG and, hence, could not prevent decrease of the spin period down to its current value.

The spin-up time of the white dwarf with account for screening of its magnetic field in the process of accretion can be evaluated by solving the equation $I \dot{\omega}_s = \dot{M}_{\text{pe}} (GM_{\text{wd}}R_{\text{cor}})^{1/2}$ (de Jager et al., 1994) based on the assumption...
that the magnetospheric radius of the white dwarf is decreasing at the same rate that its corotation radius. The solution to this equation

$$\Delta t_{\text{min}} = \frac{3}{4} \frac{(2\pi)^{4/3} I}{\dot{M}_{\text{pe}} (GM_{\text{wd}})^{2/3} P_{s}^{4/3}},$$

(3)
determines the minimum duration of the spin-up epoch. The amount of matter accumulated on the white dwarf surface during this period can be estimated as

$$\Delta M_a = \dot{M}_{\text{pe}} \Delta t_{\text{min}} = \frac{3}{4} \frac{(2\pi)^{4/3} I}{(GM_{\text{wd}})^{2/3} P_{s}^{4/3}}.$$

(4)

After the accretion epoch is over the surface magnetic field of the white dwarf is gradually increasing due to diffusion of the buried field through the layer of screening plasma. The diffusion timescale of the field can be estimated as

$$t_{\text{diff}} \sim 4\pi \sigma h^2 / c^2,$$

where $\sigma$ is the electron conductivity and $h = p/\rho g$ is the pressure scale height. Here $p \sim 6.8 \times 10^{20} \rho_{5}^{5/3} \rho_{5}^{-5/3}$ erg cm$^{-3}$ is the pressure of non-relativistic degenerate gas, $\rho$ in the plasma density at the base of the screening layer ($\rho_{5} = \rho / 10^{5} \rho_{5} g$ cm$^{-3}$) and $g = GM_{\text{wd}}/R_{\text{wd}}^{2}$. Cumming (2002) has shown that reemergence of the field of the white dwarf having undergone the stage of active accretion occurs on the timescale

$$\tau_{\text{diff}} \simeq 3 \times 10^{8} \left( \Delta M_a / 0.1 M_{\odot} \right)^{7/5} \text{ yr.}$$

(5)

4. The pulsar-like white dwarf formation

An appearance of a rapidly rotating highly magnetic white dwarf can be expected only under the condition $\tau_{\text{diff}} \leq t_{\text{sd}}$. Otherwise the spin period of the compact component will essentially increase on the timescale of field reemergence. Solving this inequality for the parameters of AE Aqr we find

$$\Delta M_a \leq 0.009 P_{33}^{5/7} \left( \frac{\dot{P}_{s}}{5.64 \times 10^{-14} \text{ s s}^{-1}} \right)^{-5/7} M_{\odot}.$$

(6)

Putting this value to Eq. (4) leads to a conclusion that the origin of an ejecting white dwarf in AE Aqr can be explained in terms of accretion-induced spin-up provided its moment of inertia is

$$I \leq 6 \times 10^{49} P_{33}^{4/3} \left( \frac{M_{\text{wd}}}{M_{\odot}} \right)^{2/3} \left( \frac{\Delta M_a}{0.009 M_{\odot}} \right) \text{ g cm}^2.$$

(7)
According to Andronov & Yavorskij (1990), this condition is satisfied for white dwarfs with the mass in the range $1.1 - 1.2 \, M_\odot$.

The result obtained allows to make some conclusions about the system parameters in general. First of all, relatively large mass of the white dwarf indicates that the angle of orbital inclination is close to 50$^\circ$. This value is within the range of permitted values for this parameter (Welsh et al., 1995). It implies the mass of the red dwarf companion in excess of 0.7 $M_\odot$ and, accounting for its tidal distortion (van Paradijs et al., 1989), lead to the estimate of its tidal radius (along the system major axis) comparable to the radius of its Roche lobe. Finally, a correction of the inclination angle (its shift towards lower values) leads us to conclusion that the velocity of the gaseous stream in the Roche lobe of the white dwarf is somewhat greater than initially adopted and, hence, the distance of the stream closest approach to the white dwarf is somewhat less than previously estimated. This fact has to be taken into account in the modeling of the mass transfer in the system in the present epoch.

5. Conclusions

Our analysis shows that the origin of the peculiar white dwarf in AE Aqr can be connected with intensive mass exchange between the system components in a previous epoch. In the process of accretion which took place in that epoch, the material deposited from the accretion disk onto the white dwarf surface temporarily screened the internal magnetic field of the white dwarf thus making possible accretion-induced spin-up up to its current level. The transition of the white dwarf into the ejector state was caused by reemerging of the magnetic field by diffusion through the layer of accreted matter.

Relatively large age of the white dwarf ($\sim 10^9$ yr) derived from its average surface temperature, limitation on its intrinsic spin period ($P_i > 11$ min) and our estimate of its dipole magnetic moment ($\mu \sim 10^{34}$ G cm$^3$) make us to suggest that before the spin-up epoch AE Aqr could manifest itself as a Polar. During the spin-up epoch its X-ray luminosity exceeded $10^{36}$ erg s$^{-1}$ and the system could be seen as extremely bright Intermediate Polar. One cannot exclude that during the final phase of spin-up, the accretion of matter onto the white dwarf surface occurred directly from the accretion disk (as in non-magnetic CVs) and a component pulsing at the spin period of the white dwarf was not present in the X-ray emission from the system. The duration of the present epoch is likely to be determined by the spin-down time-scale of
the white dwarf which is close 10 million years. At the end of this epoch one can expect dissipation of electric currents in the white dwarf magnetosphere and its transition to the propeller state. Further the system will appear as a Polar.

In the frame of this scenario AE Aqr can be considered as a missing evolutionary link in the evolution of Polars, with its origin resembling in some aspects evolutionary scenario for recycled pulsars. At the same time, the analogy with evolution of recycled pulsars is incomplete since before the spin-up epoch the white dwarf was in the accretor state with relatively slow rotation. Thus, in the case of AE Aqr we deal with essentially new evolutionary stage of low-mass binaries requiring introduction of a new subclass of cataclysmic variables. The degenerate objects in the systems from this subclass are in the ejector state. Intensive matter outflow from a system and a presence of high-luminous non-thermal component in its emission can be considered as indirect attribute of these systems, while the contribution of accretion luminosity to their energy budget is insignificant.

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