Formation of Spin-Powered Pulsing White Dwarfs

N. Beskrovnaya and N. Ikhsanov

Central (Pulkovo) Astronomical Observatory, Russian Academy of Sciences, Saint Petersburg, Russia
beskrovnaya@yahoo.com

Abstract. A scenario of formation of spin-powered pulsing white dwarfs in close binaries AE Aquarii and AR Scorpii is discussed. We suggest that the white dwarfs were spun-up in a previous epoch by accreting matter from a disk. We find that the inner radius of the disk within this scenario is smaller than the conventional Alfvén radius, and the white dwarf switches its state from the accretion-powered to spin-powered pulsar directly as soon as its corotational radius reaches the inner radius of the disk. This picture fits in the diffusion-driven accretion scenario proposed in a previous paper.

Keywords: novae, cataclysmic variables; pulsars: general; binaries: close, stars: magnetic field

DOI:10.26119/978-5-6045062-0-2_2020_207

1 Introduction

AE Aquarii and AR Scorpii represent a new subclass of Cataclysmic Variables (CVs), with the following properties: i) both of them are panchromatic sources emitting detectable radiation from radio to X-rays, ii) the radio emission of these sources is predominantly non-thermal, iii) there are no signs of the accretion of matter transferred from the normal companion of the system onto the surface of White Dwarf (hereafter WD), and iv) the spin-down power of the WDs significantly exceeds the luminosity of the WD and is even larger than the bolometric luminosity of the systems (see, e.g. Ikhsanov 1998; Ikhsanov & Beskrovnaya 2012; Marsh et al. 2016; Beskrovnaya & Ikhsanov 2017).

The unusual behavior of the sources is associated with strong magnetization of the fast rotating WDs, which currently operate as spin-powered pulsars (Section 2). The spin-down time of the WDs, $\tau_{\rm sd} \sim P_{\rm s}/2\dot{P} \simeq (1-2) \times 10^7\,{\rm yr}$, is smaller than their cooling age, $\tau_{\rm cool} \sim 10^9\,{\rm yr}$, where $P_{\rm s}$ is the spin period of the

WD and $\dot{P} = dP_{\rm s}/dt$. This indicates that the WDs were spun-up in a previous epoch by accreting matter from a disk (Section 3). Evaluating the inner radius of the disk in Section 4 we find that it is smaller than the Alfvén radius, but is comparable to the magnetospheric radius expected within the diffusion-driven accretion scenario onto a magnetized star (Ikhsanov & Mereghetti 2015, and references therein). The transition of the WD from accretion-powered to spin-powered pulsar in this case occurs on a relatively short timescale as soon as its corotation radius reaches the inner radius of the disk (Section 5).

2 Spin-Down Behavior

A situation in which the spin-down power of a magnetized fast rotating compact star exceeds its bolometric luminosity is typical for the classical spin-powered pulsars. Using the same mechanism one finds that the rapid spin-down of WDs in AE Aqr and AR Sco can be explained in term of the pulsar-like spin-down provided the dipole magnetic moment of these stars is (Ikhsanov 1998; Beskrovnaya & Ikhsanov 2017)

$$\mu \sim \begin{cases} 10^{34}\,{\rm G\,cm^3} \times I_{50}^{1/2} P_{33}^{1/2} \left(\dot{P}/\dot{P}_{\rm aqr}\right), & \text{for AE Aqr}, \\ 6 \times 10^{34}\,{\rm G\,cm^3} \times I_{50}^{1/2} P_{117}^{1/2} \left(\dot{P}/\dot{P}_{\rm sco}\right), & \text{for AR Sco}, \end{cases} \tag{1}$$

Here I_{50} is the moment of inertia of a WD in units $10^{50}\,{\rm g\,cm^2}$, $P_{33} = P_{\rm s}/33\,{\rm s}$ and $P_{117} = P_{\rm s}/117\,{\rm s}$ are the spin periods and $\dot{P}_{\rm aqr} = 6 \times 10^{-14}\,{\rm s\,s^{-1}}$ and $\dot{P}_{\rm sco} = 4 \times 10^{-13}\,{\rm s\,s^{-1}}$ are the spin-down rates of WDs in AE Aqr and AR Sco, respectively. This implies that the surface magnetic field of the WDs in AE Aqr and AR Sco are 50 MG and $\geq$ 150 MG, respectively. The efficiency of propeller spin-down (governing by interaction between the magnetic field of the white dwarf and surrounding material or/and the secondary component of the binary system) under the same conditions is about an order of magnitude smaller than the efficiency of pulsar-like spin-down (see Ikhsanov & Beskrovnaya 2012).

3 Spin-Up Epoch

The spin-down timescale $\tau_{\rm sd}$ of the WDs in both systems is about 10^7 yr, while their cooling age (for the observed surface temperature $\sim 10\,000$ K) is close to 10^9 yr. This indicates that fast rotation of the WDs in the current epoch can unlikely be associated with a singularity of their birth (as for solitary neutron star pulsars). It is rather a consequence of binary evolution through a spin-up phase in which the WD was accreting matter from a disk (similarly to the recycled neutron star pulsars).

The necessary (but not sufficient) condition for a WD of the mass $M_{\rm wd}$ to spin-up reads $|K_{\rm su}| \geq |K_{\rm sd}|$, where $K_{\rm su} \simeq \dot{M}\,(r_{\rm in} G M_{\rm wd})^{1/2}$ is the spin-up torque exerted on the WD, which accretes matter at a rate $\dot{M}$ from a Keplerian disk, and $K_{\rm sd} = I\dot{\omega}$ is the spin-down torque evaluated from the spin-down rate $\dot{\omega} = d\omega/dt$ observed in the current epoch. Here $r_{\rm in}$ is the inner radius of the disk, which is usually associated with the magnetospheric radius of the WD, $r_{\rm m}$, and $\omega = 2\pi/P_{\rm s}$ is the angular velocity of the WD. Solving the above inequality for $\dot{M}$ one finds $\dot{M} \geq \dot{M}_0$, where

$$\dot{M}_0 \sim \begin{cases} 8 \times 10^{16}\,{\rm g\,s^{-1}} \times I_{50}\, m^{-1/2} P_{33}^{-2} \left(\dfrac{\dot{P}}{\dot{P}_{\rm aqr}}\right) \sqrt{\dfrac{r_{\rm in}}{r_{\rm cor}}}, & \text{for AE Aqr,} \\ \\ 4 \times 10^{16}\,{\rm g\,s^{-1}} \times I_{50}\, m^{-1/2} P_{117}^{-2} \left(\dfrac{\dot{P}}{\dot{P}_{\rm sco}}\right) \sqrt{\dfrac{r_{\rm in}}{r_{\rm cor}}}, & \text{for AR Sco.} \end{cases} \qquad (2)$$

Here $m = M_{\rm wd}/M_{\odot}$ and $r_{\rm cor} = \left(G M_{\rm wd}/\omega^2\right)^{1/3}$ is the corotation radius of a WD.

The above evaluation of $\dot{M}_0$ assumes that the matter transferred from the normal component through the disk towards the WD has been finally accreted onto its surface. This picture can be realized only if the radius at which the disk is truncated by the magnetic field of the WD is smaller than the corotation radius, $r_{\rm m} \leq r_{\rm cor}$. Otherwise, the centrifugal barrier at the magnetospheric boundary would prevent matter from reaching the surface of the WD. Thus, to validate our assumption we have to evaluate the magnetospheric radius of the WD during the previous spin-up epoch.

4 Magnetospheric Radius

The rate of mass-transfer in AE Aqr through the L1 point is relatively high, $\dot{M}_{\rm obs} \sim 4 \times 10^{17}\,{\rm g\,s^{-1}}$ (Eracleous & Horne 1996). The transferred material, however, does not reach the surface of the WD. Instead, it flows out from the system. Inspection of the observed Hα Doppler tomogram of AE Aqr suggests that the WD with respect to the inflowing material operates as a propeller[1]

[1] Note, that contribution of the propeller action into the observed spin-down rate of the WD in AE Aqr is limited to a few per cents only, while the majority of spin-down power is converted into the energy of accelerated particles, electromagnetic and MHD waves (Ikhsanov & Beskrovnaya 2012).

and its magnetospheric radius in the current epoch significantly exceeds the corotation radius and is close to the Alfvén radius,

$$r_{\rm A} = \left(\frac{\mu^2}{\dot{M}\,(2GM_{\rm wd})^{1/2}} \right)^{2/7} \simeq 5 \times 10^{10}\,{\rm cm} \times \mu_{34}^{4/7} m^{-1/7} \left(\frac{\dot{M}}{\dot{M}_{\rm obs}} \right)^{-2/7}, \qquad (3)$$

which is defined by equating the ram pressure of the inflowing material with the magnetic pressure due to the dipole magnetic field of the WD. Here μ_{34} is the dipole magnetic moment of the WD in units $10^{34}\,{\rm G\,cm^3}$. Hence, to satisfy the condition $r_{\rm m} < r_{\rm cor}$ one has to assume that either the mass-transfer rate in a previous epoch was significantly (by more than two orders of magnitude) higher than that evaluated in the current epoch, or the magnetospheric radius of a star accreting matter onto its surface form a disk is significantly smaller than the Alfvén radius.

The first possibility has been already discussed by Ikhsanov & Beskrovnaya (2012). Although a reason for dramatic variations of the mass-transfer rate in AE Aqr remains rather unclear an assumption about the mass-transfer at the rate of $10^{19} - 10^{20}\,{\rm g\,s^{-1}}$ cannot be rejected. However, even in this case the system evolution cannot be explained without additional assumptions. In particular, for the condition $r_{\rm A} < r_{\rm cor}$ to be satisfed, the magnetic field of the WD during the accretion-driven (at a rate $> 10^{19}\,{\rm g\,s^{-1}}$) spin-up epoch should be almost two orders of magnitude smaller than that evaluated from Eq.(1). This could occur if the magnetic field of the WD were, for example, screened by the material accreted onto its surface. However, application of this scenario to AE Aqr cannot be considered as completely validated.

Considering the second possibility we find that inequality $r_{\rm m} \le r_{\rm cor}$ is satisfied if the ratio of the magnetospheric radius to the Alfvén radius is

$$\frac{r_{\rm m}}{r_{\rm A}} \le \begin{cases} 0.04 \times \mu_{34}^{-4/7} P_{33}^{2/3} \dot{M}_{18}^{2/7} m^{10/21}, & \text{for AE Aqr,} \\ 0.03 \times \mu_{35}^{-4/7} P_{117}^{2/3} \dot{M}_{18}^{2/7} m^{10/21}, & \text{for AR Sco.} \end{cases} \qquad (4)$$

A situation in which the magnetospheric radius of an accreting star is smaller than the Alfvén radius has been discussed by Ikhsanov et al. (2014). This accretion scenario is realized if the interchange instabilities of the magnetospheric boundary are suppressed[2] and the penetration of the accreting material into the magnetic field of the star at the magnetospheric boundary is governed by

[2] For instance, by the magnetic field shear (see, e.g., Ikhsanov & Pustil'nik 1996)

diffusion. The radius of magnetosphere in this case is

$$r_{\rm ma} = \left(\frac{c\, m_{\rm p}^2}{16\sqrt{2}\, e\, k_{\rm B}} \right)^{2/13} \frac{\alpha_{\rm B}^{2/13} \mu^{6/13} (GM_{\rm wd})^{1/13}}{T_0^{2/13} \dot{M}^{4/13}}, \qquad (5)$$

where c is the speed of light, $m_{\rm p}$ is the proton mass, e is the electric charge of an electron, $k_{\rm B}$ is the Boltzmann constant and T_0 is the temperature of the matter at the magnetospheric boundary. The parameter $\alpha_{\rm B} = D_{\rm eff}/D_{\rm B}$ is the ratio of the effective diffusion coefficient, $D_{\rm eff}$, to the Bohm diffusion coefficient, $D_{\rm B} = ck_{\rm B}T_0 r_{\rm ma}^3/(32e\mu)$.

Combining Eqs. (3) and (5) one can evaluate the ratio of the magnetospheric radius which is realized in the diffusion-driven accretion scenario, $r_{\rm ma}$, to the Alfvén radius as

$$\frac{r_{\rm ma}}{r_{\rm A}} \sim 0.025 \times \alpha_{\rm B}^{2/13} \mu_{34}^{-10/91} \dot{M}_{17}^{-2/91} m^{20/91} T_7^{-2/13}, \qquad (6)$$

where T_7 is the temperature of matter at the magnetospheric boundary in units 10^7 K, which is normalized to the typical temperature of X-rays emitted by the accreting white dwarfs.

It is easy to see from Eqs. (4) and (6) that the value of $r_{\rm ma}$ for the parameters of interest is close to the required value of $r_{\rm m}$. This indicates that the spin-up of the WD in AE Aqr can be explained within the diffusion-driven accretion scenario without the assumptions about significant mass-transfer variations and screening of the magnetic field of the WD to be invoked. Namely, a WD with the surface magnetic field of 50 MG which accretes matter from a disk at a rate of a few $\times 10^{17}$ g s^{-1} can reach the spin period of 33 s within the diffusion-driven accretion scenario on a time scale (Ikhsanov 1999)

$$\Delta t = \frac{2\pi I}{\dot{M}\sqrt{GMR}} \left(\frac{1}{P} - \frac{1}{P_0} \right) \simeq 2 \times 10^7\,{\rm yr} \times I_{50} \dot{M}_{17}^{-1} m^{-1/2} P_{33}^{-1} r_9^{-1/2}. \qquad (7)$$

Here P_0 is the initial period of the WD and $r_9 = r_{\rm m}/10^9$ cm.

Applying the same scenario to AR Sco one finds that the origin of the spinning at 117 s period magnetized WD can be explained within the diffusion-driven accretion spin-up scenario provided the mass-transfer rate in this system in a previous spin-up epoch was at the rate of $\sim 10^{18}$ g s^{-1}. This value is rather typical for CVs in which the normal component overflows its Roche lobe.

5 Spin-Up to Spin-Down Transition

The accretion-driven spin-up scenario of AE Aqr within the diffusion-driven accretion approach implies that the mass-transfer rate in the system in a previous (spin-up) epoch was the same as its current value. This raises a question about a mechanism of transition of the WD from the accretion-powered to spin-powered pulsar state. A quantitative study of this mechanism is, however, beyond the scope of this paper. Here we restrict ourselves to a qualitative discussion about possible reasons for this transition.

As seen from Eq. (5), the magnetospheric radius does not strongly depend on the basic parameters and remains almost constant if the magnetic field of the star itself and the mass accretion rate onto its magnetosphere are constant. If the star is a member of a binary system and the transferred matter is accreted onto its surface, the orbital angular momentum is transferred with the accreting material towards the star and is converted to the angular momentum of its axial rotation. The star under these conditions is in the spin-up state. The corotation radius of the star in this state is larger than its magnetospheric radius, but it is decreasing as the star is spinning-up.

The star accreting matter from a Keplerian disk remains in the spin-up state as long as its magnetospheric radius is smaller than the corotation radius. As soon as the corotation radius is approaching the magnetospheric radius the rate at which the angular momentum is transferred towards the star is decreasing and the star switches to the equilibrium rotation state. The spin-up torque exerted on the star in this state is equal to the spin-down torque and the average rate of the angular momentum transfer is close to zero.

It appears, however, that this state of equilibrium rotation should be unstable. Let us consider a situation in which the magnetospheric radius of a compact star in a binary system is equal to its corotation radius. If the mass accretion rate in this situation is decreasing the magnetospheric radius of the star is increasing and exceeds the corotation radius. In this case, however, the transfer of angular momentum changes its direction and the angular momentum starts to be transferred from the star into the disk. The disk in this case switches into a dead state (with zero mass transfer rate) or even to the outflowing state. The pressure from the disk to the magnetosphere in this state decreases and the magnetospheric radius increases. As a result, the star switches into the propeller or even the ejector state in which the mass is flowing out of the system carrying out an excess of the angular momentum transferred from the star.

This indicates that the WD in AE Aqr (and possibly also in AR Sco) could switch its state from the accretion-powered to the spin-powered pulsar without significant variation of the mass-transfer rate in the system. The transition could occur as the corotation radius of the spinning-up WD had reached its magnetospheric radius.

Acknowledgements. The authors are grateful to RFBR for the support of the work (project No. 18-02-00554A).

Bibliography

Beskrovnaya, N. G. & Ikhsanov, N. R. 2017, in Astronomical Society of the Pacific Conference Series, Vol. 510, Stars: From Collapse to Collapse, ed. Y. Y. Balega, D. O. Kudryavtsev, I. I. Romanyuk, & I. A. Yakunin, 439
Eracleous, M. & Horne, K. 1996, ApJ, 471, 427
Ikhsanov, N. R. 1998, A&A, 338, 521
Ikhsanov, N. R. 1999, A&A, 347, 915
Ikhsanov, N. R. & Beskrovnaya, N. G. 2012, Astronomy Reports, 56, 595
Ikhsanov, N. R., Likh, Y. S., & Beskrovnaya, N. G. 2014, Astronomy Reports, 58, 376
Ikhsanov, N. R. & Mereghetti, S. 2015, MNRAS, 454, 3760
Ikhsanov, N. R. & Pustil'nik, L. A. 1996, A&A, 312, 338
Marsh, T. R., Gänsicke, B. T., Hümmerich, S., et al. 2016, Nature, 537, 374