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On a spin-up phase in the evolutionary tracks of AR Scorpii and AE Aquarii

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A question about the origin of a pulsar-like white dwarf in the low-mass binary system AR Scorpii is discussed. In our consideration we follow the accretion-driven spin-up scenario previously developed to explain the origin of a strongly magnetized fast rotating white dwarf in AE Aquarii. We find that the origin of AR Scorpii can be explained within this scenario provided the surface magnetic field of the white dwarf during the spin-up epoch was screened by the accreting matter by a factor of 50-100. This finding suggests that the fast rotating strongly magnetized white dwarfs in both systems were formed by a common mechanism.

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1. Introduction

In a previous paper [1] the problem posed by the existence of pulsar-like white dwarfs in AR Sco and AE Aqr was discussed. These variable stars are associated with close binaries composed of a red dwarf and a strongly magnetized fast rotating white dwarf (hereafter WD). The WDs rotate fast and their rotation decelerates rapidly on a time scale $\tau_{sd} = P_s/2\dot{P} \simeq 10^7$ yr. Here P_s is the spin period of a WD and $\dot{P} = dP_s/dt$ is its spin-down rate. On the other hand, observations suggest that the surface temperature of the WDs is about 10 000 K, which implies their life time (cooling time) to exceed 10^8 yr. Thus, to explain the observed fast rotation of the WDs an assumption about a spin-up torque exerted on the WDs in a previous epoch needs to be invoked. This leads us to an accretion-driven spin-up scenario in which the WDs are assumed to accrete from a disk. Their rotational rate during this spin-up phase increases by the similar mechanism which is responsible for the origin of the recycled neutron star pulsars [see, e.g., 2].

The accretion-driven spin-up scenario has previously been discussed with respect to the origin of a fast rotating strongly magnetized WD in the low-mass binary system AE Aqr [3–6]. The spin-down timescale of the WD in this system is about 10 Myr while the surface temperature (about 12 000 K) indicates that its age exceeds 100 Myr. The spin-up phase in the evolutionary track of this system can be associated with a temporal variation of the mass transfer rate between the system components which occurs as the normal component (red dwarf) overflows its Roche lobe [4, 5]. This scenario is applicable, however, only if the surface magnetic field of the WD does not exceed a few MG. Otherwise, an additional assumption about evolution of the magnetic field of the WD needs to be incorporated into the model [3, 6]. A possibility to use the accretion-driven spin-up scenario for explaining the origin of the pulsar-like WD in AR Sco is discussed in this paper. We show that models built solely around an assumption about a temporal variation of the mass-transfer rate in the system encounters major difficulties explaining the fast rotation of the WD in this system (Sect. 2). These difficulties can be partly avoided by taking into account that the magnetic field of the WD was buried by the accreting material during the spin-up epoch (Sect. 3). Some other possibilities to improve the situation are also briefly discussed in this section. A summary of basic conclusions is given in Sect. 4.

2. Constrains to the spin-up epoch in AR Sco

AR Sco is a close binary with the orbital period of ~ 3.56 h containing a M5 red dwarf and a massive, $\sim 1\,M_\odot$, fast rotating, $P_{sco} \simeq 117$ s, WD with a surface temperature of 10 000 K (indicating its cooling age to be in excess of 100 Myr). The WD appears as a spin-powered pulsar in almost all parts of the spectrum from the radio to X-rays and shows a rapid spin-down on a timescale of about 10 Myr, which implies its dipole magnetic moment to be $\sim 5 \times 10^{34}$ G cm^3 [for a detailed system description see, e.g., 7–10, and references therein].

Since the cooling age of the WD significantly exceeds both the timescale of its currently observed spin-down, τ_{sd}, and the thermal timescale at which the mass-transfer between the system components may reach a high value (about a few × 10 Myr), a hypothesis about the spin-up phase which the system had passed in a previous epoch needs to be invoked. The spin-up of the WD during this phase can be explained within the accretion-driven spin-up scenario, which is based on

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the following steps. First, the spin-up phase starts as the red dwarf overflows its Roche lobe and losses its mass through the L1 point towards the WD at a high rate. The second, the rotational rate of the WD increases as it accretes the transferred matter onto its surface from a keplerian disk. Finally, the spin-up phase ends as the mass ratio of the system components reaches a critical value at which the mass-loss rate by the red dwarf decreases.

For this scenario to be effective the following conditions should be satisfied:

- the accretion disk should be able to form in the system,
- the spin-up torque exerted on the WD by the accreting matter should exceed the spin-down torque,
- the inner radius of the disk, $r_{\rm in}$, should be smaller than the corotation radius, $r_{\rm cor} = \left(GM_{\rm wd}/\omega_{\rm s}^2\right)^{1/3}$, for the currently observed spin period, where $M_{\rm wd}$ is the mass of the WD and $\omega_{\rm s} = 2\pi/P_{\rm s}$ is its angular velocity.

Using parameters of AR Sco one can express these conditions as follows.

2.1 Disk formation

The stream of matter flowing from the red dwarf through the L1 point into the Roche lobe of the WD initially follows the ballistic trajectory and interacts with the magnetic field of the WD. The magnetic field of the WD prevents the stream from approaching the WD to a distance $r \leq r_0$, where [11, 12],

$$r_0 \simeq 1.45 \times 10^{10}\,{\rm cm} \times \mu_{34}^{4/11}\,\sigma_9^{4/11}\,m^{-1/11}\,\dot{\mathfrak{M}}_{16}^{-2/11}, \qquad (1)$$

is defined by equating the ram pressure of the stream with the magnetic pressure due to dipole magnetic field of the WD. Here μ_{34} is the dipole magnetic moment of the WD in units $10^{34}\,{\rm G\,cm^3}$, σ_9 is the radius of cross section of the stream in units 10^9 cm, m is the mass of WD in units $1\,{\rm M_{\odot}}$, and $\dot{\mathfrak{M}}_{16}$ is the mass accretion rate in units $10^{16}\,{\rm g\,s^{-1}}$.

For an accretion disk to form the value of r_0 should be smaller than both the circularization radius [see, e.g., 13],

$$r_{\rm circ} \simeq 1.16 \times 10^{10}\,{\rm cm} \times \left(\frac{P_{\rm orb}^{(0)}}{3.5\,{\rm h}}\right)^{2/3}, \qquad (2)$$

and the corotation radius of the WD, $r_{\rm cor}^{(0)} = \left(GM_{\rm wd}\,P_{\rm s0}^2/4\pi^2\right)^{1/3}$ at the beginning of the spin-up epoch when the spin period of the WD was $P_{\rm s0}$. Solving expression $r_0 \leq r_{\rm circ}$ for $\dot{\mathfrak{M}}$ and $r_0 \leq r_{\rm cor}^{(0)}$ for $P_{\rm s}$ one finds $\dot{\mathfrak{M}} \geq \dot{\mathfrak{M}}_0$, where

$$\dot{\mathfrak{M}}_0 \simeq 10^{18}\,{\rm g\,s^{-1}} \times \sigma_9^2\,m^{-1/2}\left(\frac{\mu}{5.6\times 10^{34}\,{\rm G\,cm^3}}\right)^2\left(\frac{P_{\rm orb}^{(0)}}{3.5\,{\rm h}}\right)^{-11/3}, \qquad (3)$$

and $P_{\rm s} \geq P_{\rm s0}$, where

$$P_{\rm s0} \simeq 765\,{\rm s} \times \sigma_9^{6/11}\,m^{-7/11}\,\dot{\mathfrak{M}}_{18}^{-3/11}\left(\frac{\mu}{5.6\times 10^{34}\,{\rm G\,cm^3}}\right)^{6/11}. \qquad (4)$$

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Here $\dot{\mathfrak{M}}_{18} = \dot{\mathfrak{M}}/10^{18}\,\mathrm{g\,s^{-1}}$ and $P_{\rm orb}^{(0)}$ is the orbital period of the system at the beginning of the spin-up epoch.

Although the required value of mass transfer rate $\sim 10^{18}\,\mathrm{g\,s^{-1}} \simeq 10^{-8}\,\mathrm{M_{\odot}\,yr^{-1}}$ exceeds an average value among cataclysmic variables, it is not unusual and is observed in many presently known low-mass binaries [see e.g., 12].

These findings indicate that the spin period of the WD during the spin-down phase has been decreased at least by a factor of 7.

2.2 Spin-up torque

A necessary condition for the WD in AR Sco to spin-up by accretion of matter from a disk reads $|K_{\rm su}^{(0)}| \geq |K_{\rm sd}^{(0)}|$, where

$$K_{\rm su}^{(0)} \simeq \dot{\mathfrak{M}}\,(r_{\rm in} G M_{\rm wd})^{1/2} \tag{5}$$

is the spin-up torque exerted on the WD from the accreting matter and

$$K_{\rm sd}^{(0)} = I_{\rm wd}\dot{\omega}_{\rm s} \tag{6}$$

is the spin-down torque evaluated from the spin-down rate $\dot{\omega}_{\rm s} = d\omega_{\rm s}/dt$ observed in the current epoch. This condition is satisfied if $\dot{\mathfrak{M}} \geq \dot{\mathfrak{M}}_{\rm su}$, where

$$\dot{\mathfrak{M}}_{\rm su} \simeq 4\times 10^{16}\,\mathrm{g\,s^{-1}}\ \times I_{50}\, m^{-1/2} \left(\frac{P_{\rm s}}{P_{\rm sco}}\right)^{-2} \left(\frac{\dot{P}}{\dot{P}_{\rm sco}}\right) \sqrt{\frac{r_{\rm in}}{r_{\rm cor}(P_{\rm sco})}} \tag{7}$$

Here I_{50} is the moment of inertia of a WD in units $10^{50}\,\mathrm{g\,cm^2}$ and $\dot{P}_{\rm sco} \simeq 4\times 10^{-13}\,\mathrm{s\,s^{-1}}$ is the observed spin-down rate of the WD in AR Sco.

Comparing Eqs. (3) and (7) one finds that under the conditions of interest the value of $\dot{\mathfrak{M}}_0$ exceeds $\dot{\mathfrak{M}}_{\rm su}$. This implies that a formation of a Keplerian disk in the system willlead to the spin-up of the WD up to a moment when either the mass transfer rate decreases below the value of $\dot{\mathfrak{M}}_{\rm su}$, or the corotation radius of the WD decreases to the value of the inner radius of the disk.

2.3 The inner radius of the accretion disk

For the accretion of matter onto the surface of a magnetized rotating WD to occur the inner radius of the disk should be smaller than the corotation radius. Otherwise, the centrifugal barrier at the inner radius of the disk would prevent the accretion flow from reaching the surface of the WD.

The condition $r_{\rm in} \leq r_{\rm cor}(P_{\rm sco})$ for the parameters of AR Sco can be expressed as

$$r_{\rm in} \leq 0.02\, r_{\rm A}\ \times \dot{\mathfrak{M}}_{18}^{2/7} m^{10/21} \left(\frac{P_{\rm s}}{P_{\rm sco}}\right)^{2/3} \left(\frac{\mu}{5.6\times 10^{34}\,\mathrm{G\,cm^3}}\right)^{-4/7}, \tag{8}$$

where

$$r_{\rm A} = \left(\frac{\mu^2}{\dot{\mathfrak{M}}\,(2GM_{\rm wd})^{1/2}}\right)^{2/7} \tag{9}$$

is a so called Alfvén radius, which is defined by equating the ram pressure of the spherically symmetrical accretion flow with the magnetic pressure due to the dipole field of an accreting star.

This finding raises a question about the accretion scenario which could be realized during the spin-up phase in AR Sco. Indeed, a distance at which the Keplerian disk is truncated by the

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magnetic field of an accreting star (i.e., inner radius of the disk) within the conventional scenario is equal or close to the Alfvén radius [see, e.g., 14]. A situation in which the inner radius of the disk is significantly (by almost a factor of 50) smaller than the Alfvén radius is rather unusual. It indicates that either basic parameters in Eq. (8) are normalized incorrectly or/and the accretion scenario realized in AR Sco differs from the conventional one. We discuss some of these possibilities in the following section.

3. Accretion scenario in AR Sco

The result expressed by Eq. (8) indicates that the origin of AR Sco cannot be explained by a scenario in which the spin-up phase is solely associated with variations of the mass transfer rate in the system. The condition $r_{\rm in} = r_{\rm A}$ within such a scenario can be satisfied only if the mass transfer rate in the system during the spin-up phase were in excess of $10^{-2}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$. Such a huge value of the mass transfer rate in a low mass binary system is unlikely to be realized. Furthermore, the luminosity of the system under these conditions would exceed the Eddington luminosity limit by a factor of 1000.

One the other hand, a possibility that the mass transfer rate in AR Sco in a previous epoch was higher than $\dot{\mathfrak{M}}_0$ expressed by Eq. (3) cannot be excluded. As shown in [4] the mass transfer rate in a low mass binary can under certain conditions temporally reach a value of $10^{20}\,{\rm g\,s^{-1}}$. Putting this to Eq. (8) one finds that the Alfvén radius in this case would exceed the inner radius of the disk by a factor of 13. This slightly improves the situation, but still keeps the question about the accretion scenario open.

One can also consider a possibility that the magnetic field of the WD during the spin-up phase was partly screened by the accreting matter [6]. Studies [see, e.g., 2, and references therein] suggest that a maximum possible factor by which the magnetic field of a compact star can be reduced by the accreting matter can reach a value of 125. Incorporating this into Eq. (8) one finds that the condition $r_{\rm in} = r_{\rm A}$ could be satisfied if the rate of mass accretion onto the surface of the WD in AR Sco during the spin-up phase were $\sim 6 \times 10^{19}\,{\rm g\,s^{-1}}$. Hence, the origin of AR Sco can be basically understood within a conventional accretion-driven spin-up scenario provided the system in a previous epoch had passed through a stage when the rate of mass transfer between its components had enhanced over a value of $10^{-6}\,\kappa^{-1}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ and the magnetic field of the WD at the end of the spin-up phase was screened by the accreted matter by a factor of 100. Here $\kappa = \dot{\mathfrak{M}}/\dot{\mathfrak{M}}_{\rm out}$ is the efficiency coefficient which is the ratio of mass transfer rate in the disk to the mass-loss rate by the normal component $\dot{\mathfrak{M}}_{\rm out}$ (the case $\kappa = 1$ corresponds to the conservative mass-transfer in the system).

One cannot, however, exclude another possibility. Namely, that the inner radius of the disk is indeed smaller than the Alfvén radius. In particular, the authors of paper [15] suggested that the inner radius of the Keplerian disk could be a factor of 2 smaller than the Alfvén radius. Furthermore, as pointed out in [16] the value of inner radius of the disk depends on the mode by which the accreting material penetrates from the disk into the magnetic field of the WD at its magnetospheric boundary. The situation in which $r_{\rm in} \sim r_{\rm A}$ is realized only if the magnetospheric boundary is interchange unstable. Otherwise, the rate of plasma penetration into the magnetosphere turns out to be significantly smaller than the mass accretion rate in the disk itself. In this case, the accretion flow in accordance with the continuity equation would be accumulated at the inner radius of the

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disk which in turn would increase the pressure exerted on the magnetic field of the WD by the disk matter. The inner radius of the disk in this case decreases down to a value at which the rate of plasma penetration into the magnetic field of the WD reaches the mass transfer rate in the disk itself. A minimum possible value of the inner radius of the disk in this case is defined by equating the rate of plasma diffusion from the disk into the magnetic field with the mass accretion rate realized in the system. According to [16] the minimum possible value of the inner radius of the disk evaluated within this scenario for the parameters of AR Sco is a factor of 40 smaller than the Alfvén radius [1]. In a combination with previously considered assumptions about the screening of the magnetic field of the WD by the accreting material this finding provides us with a new possible scenario of the origin of AR Sco.

Finally, we would like to note that an incorporation of the effect of screening of the WD magnetic field by the accreting material may also help to answer a question about the transition of the WD from the accretion-powered to spin-powered pulsar. The accretion-driven spin-up phase in this case continues as long as the corotation radius of the WD exceeds the inner radius of the disk. This indicates that the spin-up phase ends as soon as either the spin period of the WD reaches a critical value at which the corotation radius decreases to the inner radius of the disk or the mass transfer rate decreases to a value at which the inner radius of the disk increases to the corotation radius. In both cases the disk can switch into a dead disk state [17] and the WD continues its evolution according to the propeller scenario [18]. If, however, this process is accompanied with a regeneration of the magnetic field of the WD the inner radius of the disk increases dramatically (at least by an order of magnitude). This may lead to a disruption of the disk and a transition of the WD into the spin-powered pulsar state in which it is observed in the present epoch.

4. Conclusions

The presented analysis suggests that the evolutionary track of AR Sco contains a spin-up stage, which the system had passed in a previous epoch. The red dwarf during this stage had overflown its Roche lobe and had been loosing its mass at a rate $\geq 10^{-8}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$. This leads to a formation of a Keplerian accretion disk inside the Roche lobe of the WD and intensive accretion of mass onto its surface. The rotation rate of the WD during this stage was increasing in accordance to the accretion-driven spin-up scenario and its period had decreased at least by a factor of 7.

The above scenario is able to explain the currently observed spin period of the WD only if the effect of screening of the magnetic field by the accreting material is incorporated into the model. The factor by which the magnetic field of a compact star is reduced by this effect in this case lies in the interval 50-100. An exact value of this factor depends on the mass accretion rate onto the surface of the WD and the value of the inner radius of the accretion disk. The latter parameter in turn depends on the mode by which the accretion flow penetrates into the magnetic field of the WD at its magnetospheric boundary and under conditions of interest its value can be up to a factor of 40 smaller than the conventional Alfvén radius.

Comparing our results with the spin-up scenario for the WD in AE Aqr previously developed in [6] one can conclude that the fast rotating strongly magnetized WDs in both systems were formed by a common mechanism.

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References

[1] N. Beskrovnaya and N. Ikhsanov, *Formation of Spin-Powered Pulsing White Dwarfs*, in *Ground-Based Astronomy in Russia. 21st Century*, I.I. Romanyuk, I.A. Yakunin, A.F. Valeev and D.O. Kudryavtsev, eds., pp. 207–213, Dec., 2020, DOI.

[2] G.S. Bisnovatyi-Kogan, *PHYSICS OF OUR DAYS: Binary and recycled pulsars: 30 years after observational discovery*, Physics Uspekhi **49** (2006) 53.

[3] N.R. Ikhsanov, *Rapid spindown of fast-rotating white dwarfs in close binary systems as a result of magnetic field amplification*, A&A **347** (1999) 915.

[4] P.J. Meintjes, *On the evolution of the nova-like variable AE Aquarii*, MNRAS **336** (2002) 265.

[5] K. Schenker, A.R. King, U. Kolb, G.A. Wynn and Z. Zhang, *AE Aquarii: how cataclysmic variables descend from supersoft binaries*, MNRAS **337** (2002) 1105.

[6] N.R. Ikhsanov and N.G. Beskrovnaya, *AE Aquarii represents a new subclass of Cataclysmic Variables*, Astronomy Reports **56** (2012) 595.

[7] T.R. Marsh, B.T. Gänsicke, S. Hümmerich, F.J. Hambsch, K. Bernhard, C. Lloyd et al., *A radio-pulsing white dwarf binary star*, Nature **537** (2016) 374.

[8] D.A.H. Buckley, P.J. Meintjes, S.B. Potter, T.R. Marsh and B.T. Gänsicke, *Polarimetric evidence of a white dwarf pulsar in the binary system AR Scorpii*, Nature Astronomy **1** (2017) 0029 [1612.03185].

[9] N. Beskrovnaya and N. Ikhsanov, *AR Scorpii: a New White Dwarf in the Ejector State*, in *Stars: From Collapse to Collapse*, Y.Y. Balega, D.O. Kudryavtsev, I.I. Romanyuk and I.A. Yakunin, eds., vol. 510 of *Astronomical Society of the Pacific Conference Series*, p. 439, June, 2017.

[10] Y. Gaibor, P.M. Garnavich, C. Littlefield, S.B. Potter and D.A.H. Buckley, *An improved spin-down rate for the proposed white dwarf pulsar AR scorpii*, MNRAS **496** (2020) 4849 [2006.11276].

[11] K. Mukai, *Accretion streams in AM HER type systems.*, MNRAS **232** (1988) 175.

[12] B. Warner, *Cataclysmic variable stars*, vol. 28 of *Cambridge Astrophysics*, Cambridge University Press (1995), 10.1017/CBO9780511586491.007.

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[13] J. Frank, A. King and D.J. Raine, *Accretion Power in Astrophysics: Third Edition*, Cambridge University Press (2002), 10.1017/CBO9781139164245.

[14] J. Arons, *Magnetic Field Topology in Pulsars*, ApJ **408** (1993) 160.

[15] P. Ghosh and F.K. Lamb, *Accretion by rotating magnetic neutron stars. II. Radial and vertical structure of the transition zone in disk accretion.*, ApJ **232** (1979) 259.

[16] N.R. Ikhsanov, Y.S. Likh and N.G. Beskrovnaya, *Spin evolution of long-period X-ray pulsars*, *Astronomy Reports* **58** (2014) 376.

[17] R.A. Siuniaev and N.I. Shakura, *Disc reservoirs in binary systems and their observational appearances.*, *Pisma v Astronomicheskii Zhurnal* **3** (1977) 262.

[18] A.F. Illarionov and R.A. Sunyaev, *Why the Number of Galactic X-ray Stars Is so Small?*, A&A **39** (1975) 185.

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