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Signs of a dead disk in AE Aquarii

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Abstract. The mass-exchange picture in the close binary AE Aqr is discussed in the frame of the pulsar-like white dwarf model (Ikhsanov 1998, 1999). It is shown that within this approach a dead disk around the white dwarf magnetosphere is expected. The disk forms during (and/or just after) the outburst associated with the white dwarf spin-up $\rightarrow$ spin-down state transition. In the current epoch the inner and the outer radii of the disk are evaluated as 5.5×10^{10} cm and 8×10^{10} cm, respectively, and the average mass-exchange rate in the system is $4.4 \times 10^{16}\,\mathrm{g\,s^{-1}}$. About a half of the accretion energy is released in the boundary layer at the inner edge of the disk in the optical-UV (about 80%) and soft X-ray (about 20%) spectral domains. The mass exchange between the components is governed by the stream-fed mechanism of mass transfer through the L_1 point. The plasma inflowing from the secondary interacts with the outer edge of the dead disk and streams out from the system mainly at phases $0.25 \div 0.75$. The velocity of outflowing plasma in quiescence lies within the interval $380 \div 550\,\mathrm{km\,s^{-1}}$ and its temperature is about 10^4 K. The other parts of the dead disk are relatively cool $\sim (2 \div 3) \times 10^3$ K and contribute to the system radiation in the IR spectral region.

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

1. Introduction

At least three sources of radiation detected from the close binary system AE Aqr (see Table 1) can be distinguished: the secondary (a K3–K5 main sequence red dwarf), the primary (the white dwarf rotating with the 33 s period) and an additional component. While the primary and the secondary of AE Aqr are already relatively well studied the nature and parameters of the additional source remain rather puzzling. This source manifests itself in the blue/UV continuum with a black-body spectrum at $\sim 10^4$ K (Beskrovnaya et al. 1996; de Martino et al. 1995), broad single-peaked emission lines in the optical and UV (e.g. Chincarini & Walker 1981; Reinsch & Beuermann 1994; Jamerson et al. 1980; Eracleous et al. 1994) and X-rays. In the ROSAT energy range the spectrum of this source is reminiscent of those observed from coronally active systems and can be fitted by

Table 1. Parameters of AE Aquarii

System parameters	Value	References*
Distance	(100 ± 30) pc	(1), (2)
Binary period	9.88 hr	(3)
Inclination	$50^\circ < i < 70^\circ$	(1), (4)
Eccentricity	0.02	(3)
Mass ratio	0.77 ± 0.03	(4)
Stellar parameters	Secondary	Primary
Type	K3V–K5V	White Dwarf
Stellar mass ($M_\odot$)	$0.41 \sin^{-3} i$	$0.54 \sin^{-3} i$
Spin period	~ 9.88 hr	33.08 s
Spin derivative ($\mathrm{s\,s^{-1}}$)	–	5.64×10^{-14}

* (1) Welsh et al. (1995); (2) Friedjung (1997); (3) Chincarini & Walker (1981); (4) Reinsch & Beuermann (1994).

a two-temperature optically thin plasma emission model with $kT_1 = 0.2$ and $kT_2 = 1.0$ keV (Clayton & Osborne 1995; Reinsch et al. 1995). The radiation of the additional source is detectable during both the active and quite phases of AE Aqr and is highly variable (for the detailed system description see Eracleous & Horne 1996; Ikhsanov 1997 and references therein).

Some effort has been made to determine the structure of the additional source. Patterson (1979) associated this source with a developed Keplerian accretion disk around the white dwarf magnetosphere. This approach has recently been critically discussed by Wynn et al. (1997) who suggested that the radiation is coming from a stream of diamagnetic blobs which interact with the fast rotating magnetosphere of the white dwarf and then are cruising out from the system.

These models however have not been confirmed by the more precise analysis of the Hα Doppler tomogram of AE Aqr recently reported by Welsh et al. (1998). On one hand, they have found the tomogram to be rather untypical for the binary systems in which accretion is realized via the *developed Keplerian accretion disk*. In particular, the emission is not centered on the white dwarf, it does not show azimuthal symmetry and the strongest emission occurs at low velocities $v \lesssim 500\,\mathrm{km\,s^{-1}}$. On the other hand, the quantitative predictions of the inhomogeneous stream mass transfer approach also have not been identified. Furthermore, the interpretation of some observed properties, namely the “loop” in Doppler tomogram, high velocity widths of emission lines and no evidence for expelled gas in trailed spectrograms faces with problems in the frame of the 'magnetic propeller' model (see for discussion Welsh 1999).

In this paper I consider the mass exchange picture in AE Aqr within the pulsar-like white dwarf model (hereafter the PL-model) suggested in previous papers (Ikhsanov 1998; 1999). In the frame of this model the observed mean spindown rate of the white dwarf ($\dot{P}_{\rm s} = 5.64 \times 10^{-14}\,{\rm s\,s^{-1}}$), which corresponds to the spindown power of $L_{\rm sd} = I\Omega\dot{\Omega} \sim 10^{34}\,{\rm erg\,s^{-1}}$ (de Jager et al. 1994) is interpreted in terms of the canonical spin-powered pulsar mechanism. The magnetic moment of the white dwarf and its surface field strength have been evaluated to be $\mu \gtrsim 1.4 \times 10^{34}$ G cm^3 and $B \sim 50$ MG, respectively. Under this condition the spindown power is spent *predominantly* on the generation of magneto-dipole waves and particle acceleration that explains the situation in which the white dwarf spindown power essentially exceeds the observed bolometrical luminosity of the system.

The origin of the fast rotating, strongly magnetized white dwarf has been explained using the mechanism of the magnetic field amplification in fast rotating compact stars recently presented by Kluźniak & Ruderman (1998) and Spruit (1999). I suggested a scenario in which AE Aqr in a previous epoch was almost an ordinary member of the DQ Her subclass of Cataclysmic Variables (CVs), i.e. a close binary system in which the normal companion transfers material to the moderately magnetized white dwarf (in this particular case $\sim 10^4$ G) via a Keplerian accretion disk. The white 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 stage the rotation of the white dwarf was essentially differential causing the winding-up of the magnetic field inside the white dwarf up to $B_\phi \sim 10^9$ G. The field has been amplified on a time scale of a month and floated up from the white dwarf interior due to buoyancy instability. As a result, the surface magnetic field of the white dwarf increased up to ~ 50 MG, i.e. its present value (Ikhsanov 1999).

In the next section the energetics and the timescale of the white dwarf state transition are investigated. Within this section I also estimate parameters of the mass transfer process after the white dwarf state transition and find the condition for a dead disk formation around the white dwarf magnetosphere to be fulfilled. In Sect. 3 the parameters of the disk are evaluated and the results are summarized and discussed in Sect. 4.

2. White dwarf state transition

According to the PL-scenario, in the previous spin-up epoch of AE Aqr the white dwarf was surrounded by a Keplerian accretion disk. The formation of the accretion disk during that epoch could not be avoided since the circularization radius calculated for the parameters of AE Aqr exceeds the corotational radius of the $33^{\rm s}$ spinning white dwarf at least by a factor of 20. The mass exchange mechanism during this epoch is fed by a stream through the first Lagrange point L_1 with the mean mass transfer rate of $\sim 10^{16}\,{\rm g\,s^{-1}}$.

Since the spin period of the spinning-up compact star decreased below the critical value it became unstable to the gravitational wave mechanism and the amplification of the magnetic field in the star interior occurred. According to Spruit (1999) this should lead to a powerful outburst as the value of B_ϕ reaches the critical value and erupts through the star surface. In the case of a neutron star the energy of the outburst exceeds the binding energy of the initial binary system and no accretion after the state transition can be expected. The question I explore in this section is how the mass-exchange changes in the case of white dwarf spin-up $\rightarrow$ spin-down state transition.

2.1. Energetics of the outburst

For the dipole magnetic field of the white dwarf after the state transition to reach the required value, $B_{\rm p} \simeq 50$ MG, the total amount of energy stored in the differential rotation between the core and the outer shell of the star should be

$$E_{\rm tot} \gtrsim E_0 = \frac{1}{8\pi\varepsilon} \int\limits_{\rm R_{wd}}^{\infty} B_{\rm p}^2(R,\theta) dV \simeq 10^{41}\ \varepsilon^{-1}\ {\rm ergs}\ \times \qquad (1)$$

$$\times \left[\frac{\mu}{1.4 \times 10^{34}\,{\rm G\,cm^3}}\right]^2 \left[\frac{R_{\rm wd}}{6.5 \times 10^8 {\rm cm}}\right]^{-3},$$

where ε is the efficiency of the dipole field component amplification.

The toroidal field erupts through the white dwarf surface when it reaches the critical value $B_{\rm cr} = \sqrt{8\pi f \rho c_{\rm s}^2}$, which in the case of AE Aqr is about 10^9 G[1]. This process is governed by the buoyancy instability which is generally non-axisymmetric, so the field manifests itself at the star surface as arches of force lines forming the white dwarf magnetic corona. A significant fraction of the energy $E_{\rm tot}$ is released during this process mainly in sub-bursts due to the reconnection of the field lines in the corona (Kluźniak & Ruderman 1998). The time scale of a sub-burst is determined by the growth time of the buoyancy instability which for the parameters of AE Aqr can be evaluated in the first approximation as

$$\tau_{\rm b} \sim R_{\rm wd}/v_{\rm a} \sim 200\ \rho_4^{1/2} \left[\frac{B_\phi}{10^9 {\rm G}}\right]^{-1} \left[\frac{R_{\rm wd}}{6.5 \times 10^8 {\rm cm}}\right]\ {\rm s}.$$

Here $v_{\rm a}$ is the Alfvén velocity, and ρ_4 is the plasma density in the region where the toroidal magnetic field is generated expressed in units of $10^4\,{\rm g\,cm^{-3}}$.

The amount of energy released in a sub-burst depends on the scale of the magnetic arches floating up to the corona and the magnetic field strength. Taking into account that the small scale field perturbation $\ll R_{\rm wd}$ are suppressed by the tension of the field lines and the field strength in the arches is limited according to the magnetic flux conservation law I find the energy of a sub-burst:

$$E_{\rm p} \sim 10^{40}\ \ B_8^2\ V_{25}\ \ {\rm erg\,s^{-1}}, \qquad (2)$$

[1] Here 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.

where B_8 is the magnetic field strength of arches floated up to the corona expressed in units of 10^8 G and V_{25} is the volume of the arches expressed in units of $10^{25}\,\mathrm{cm}^3$.

Then, the number of sub-bursts is the number of times the critical toroidal field is built up and the magnetic tube ejected, which is just the ratio

$$N_\mathrm{p} = E_\mathrm{tot}/E_\mathrm{p} \sim 110\,\varepsilon_{0.1}^{-1}, \quad (3)$$

where $\varepsilon_{0.1} = \varepsilon/0.1$ is normalized following Spruit (1999).

The interval between the sub-bursts can be estimated following Kluźniak & Ruderman (1998) as

$$\tau_\mathrm{p} = \frac{1}{(\Omega_\mathrm{s}-\Omega_\mathrm{c})}\frac{B_\mathrm{cr}}{B_\mathrm{p}} \simeq 10^4\,\mathrm{s}\;\Omega_{0.01}^{-1}\,\frac{B_\mathrm{cr}}{10^9\,\mathrm{G}}\,\left[\frac{B_\mathrm{p}}{10^7\,\mathrm{G}}\right]^{-1}, \quad (4)$$

where $\Omega_{0.01} = (\Omega_\mathrm{s}-\Omega_\mathrm{c})/10^{-2}\,\mathrm{rad\,s^{-1}}$ is the effective difference in angular velocity of rotation between the core and the outer shell of the white dwarf.

Hence, the energy stored in the differential rotation is exhausted on a time scale of $t_\mathrm{ch} = N_\mathrm{p}\times(\tau_\mathrm{p}+\tau_\mathrm{b}) \sim 15$ days. During this period the average luminosity of the white dwarf is about $10^{36}\,\mathrm{erg\,s^{-1}}$ with the maximum luminosity of $10^{38\div39}\,\mathrm{erg\,s^{-1}}$ during reconnection events. Under these conditions the major fraction of flaring energy is released in hard X-rays ($E_\gamma \gtrsim 10\,\mathrm{keV}$) and relativistic particles.

Since the amount of energy released in the sub-bursts, E_p, is comparable or even exceeds the binding energy of the accretion disk

$$E_\mathrm{bd} = \frac{1}{2}M_\mathrm{d}v_\mathrm{p}^2(R_\mathrm{in}) \simeq 10^{39}\,\mathrm{ergs}\;R_9^{-1}\left[\frac{M_\mathrm{d}}{10^{22}\,\mathrm{g}}\right]\left[\frac{M_\mathrm{wd}}{0.9\,M_\odot}\right]$$

the initial accretion disk should be completely disrupted. Here, M_d is the mass of the accretion disk, M_wd is the mass of the white dwarf, $v_\mathrm{p}(R_\mathrm{in})$ is the parabolic velocity at the inner radius of the disk and R_9 is the inner disk radius expressed in units of 10^9 cm. On the other hand, the radiation energy density at the distance of the secondary component is much smaller than the binding energy of the system. That is why we do not expect the system parameters to be changed essentially during the outburst. At the same time, one would expect the outburst radiation to heat the surface of the normal component and to enhance the rate of its mass loss.

2.2. *Irradiation-driven mass exchange*

The mass loss rate of the secondary during and just after the outburst can be evaluated using the model of irradiation-driven mass transfer. Hard X-rays ($E_\gamma \sim 10\,\mathrm{keV}$) penetrate down to Thompson optical depth of the order of 10 before losing their energy (Felsteiner & Opher 1976). For late type main sequence stars, the photosphere is located at a Thompson optical depth ~ 2 (Allen 1973). Therefore, the hard radiation released during the suboutbursts penetrates below the photosphere of the secondary and the absorbed X-ray flux is reradiated as a black body. As a result the parameters of isothermal atmosphere in the illuminated part of the secondary are: the temperature $T \sim 10^4$ K and the density at the base of the atmosphere (Hameury et al. 1986)[2]

$$\rho_0 = 2\times10^{-8}\,T_4^{-1/2}\left[\frac{P_\mathrm{orb}}{10\,\mathrm{hr}}\right]^{-1}\,[\mathrm{erf}(\Delta R/H)]^{-1}\;\mathrm{g\,cm^{-3}},$$

where P_orb is the orbital period of the system, ΔR is the distance from the bottom of the isothermal atmosphere to the L_1 point and the scale length, H, calculated using the parameters appropriate for AE Aqr is

$$H \sim 1.57\times10^9\,\left(\frac{T}{10^4\,\mathrm{K}}\right)^{1/2}\;\mathrm{cm}.$$

Taking into account that the normal star in the spin-up epoch was already close to the filling of its Roche lobe[3] I calculate the mass loss rate of the secondary during the outburst as

$$\dot M_\mathrm{p} = Q\rho_{\mathrm{L_1}}c_\mathrm{s} \simeq 10^{18}\,\mathrm{g\,s^{-1}}\;Q_{19.3}\,\rho_{-7}\,c_6, \quad (5)$$

where $Q_{19.3}$ is the effective cross-section of the mass transfer throat at the L_1 point expressed in units of $10^{19.3}\,\mathrm{cm}^2$, ρ_{-7} is the plasma density at L_1 expressed in units of $10^{-7}\,\mathrm{g\,cm^{-3}}$, and $c_6 = c_\mathrm{s}/10^6\,\mathrm{cm\,s^{-1}}$ is the sound speed. It should be noted that the mass loss rate expressed by Eq. (5) is rather the lower limit to the value of $\dot M_\mathrm{p}$ since we did not take into account the influence of accelerated particles on the secondary atmosphere which can be very effective in the considered case (see e.g. Hameury 1996).

On the other hand, the mass transfer rate required for the disk formation in AE Aqr is (Ikhsanov 1998):

$$\dot M_\mathrm{cr} \gtrsim 8\times10^{17}\mathrm{g\,s^{-1}}\;\mu_{34.2}^2\,\alpha_{0.3}^{-2}\,M_{0.9}^{5/3}\left[\frac{P_\mathrm{orb}}{10\,\mathrm{hr}}\right]^{-7/3}, \quad (6)$$

where $\mu_{34.2}$ is the magnetic moment of the white dwarf expressed in units of $10^{34.2}\,\mathrm{G\,cm^{-3}}$, $M_{0.9}$ is the mass of the white dwarf expressed in units of $0.9\,M_\odot$ and $\alpha_{0.3} = \alpha/0.3$ is the ratio of the circularization radius to the Roche lobe radius of the white dwarf. Since $\dot M_\mathrm{p} > \dot M_\mathrm{cr}$ the formation of a disk around the white dwarf magnetosphere during the considered stage of AE Aqr is expected.

The relaxation time of the secondary after the outburst can be evaluated as follows

$$\tau_\mathrm{rx} \gtrsim \tau_0 = \frac{E_\mathrm{tot}}{4\pi a^2\sigma_\mathrm{sb}T^4} \sim 10^7\,\mathrm{s}\;E_{42.3}\,a_{11.2}^{-2}\,T_4^{-4},$$

where $a_{11.2} = a/10^{11.2}$ cm is the binary separation and σ_sb is the Stefan-Boltzmann constant. Hence, the mass transferred from the secondary into the Roche lobe of the white dwarf during the irradiation-driven stage of AE Aqr is $M_\mathrm{p} \simeq \dot M_\mathrm{p}\times\tau_\mathrm{rx} = 10^{25}$ g. Even a small fraction of this mass is sufficient for a disk or a ring to form around the magnetosphere of the white dwarf.

Summarizing this section one can conclude that the powerful outburst associated with the white dwarf state transition

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[2] Here $\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp\{-t^2\}dt$ is the error function

[3] Otherwise the spin-up time of the white dwarf would be incredibly large

leads to the essential enhancement of mass loss rate by the secondary star. During this stage the mass transfer rate between the companions turns out to be above that required for a disk formation around the white dwarf magnetosphere. Hence, within the considered approach the existence of a disk-like quasistationary accretion structure around the white dwarf magnetosphere can be expected. The parameters of this accretion structure are briefly discussed in the following section.

3. Dead disk around the white dwarf magnetosphere

The amplification of the white dwarf dipole magnetic field result in the increase of the magnetosphere (Alfvén) radius:

$$R_{\rm A} = \left(\frac{B}{B_0}\right)^{4/7} \left(\frac{\dot{M}_0}{\dot{M}}\right)^{2/7} R_0, \tag{7}$$

where B_0, $\dot{M}_0$ and R_0 are the white dwarf magnetic field strength, the mass accretion rate and the inner disk radius in the previous spin-up epoch, respectively, and B and $\dot{M}$ are the magnetic field and the mass accretion rate in the current epoch. Substituting the magnetic field strength evaluated from the PL-model: $B = 50\,{\rm MG}$ and the upper limit to the magnetic field strength of the accreting $33^{\rm s}$ spinning white dwarf: $B_0 = 60\,{\rm kG}$ (Lamb & Patterson 1983) to Eq. (7) I find

$$R_{\rm A} \simeq 50\ R_0\ \left(\frac{\dot{M}_0}{\dot{M}}\right)^{2/7} \left[\frac{B}{50\,{\rm MG}}\right]^{4/7} \left[\frac{B_0}{60\,{\rm kG}}\right]^{-4/7}. \tag{8}$$

Taking the inner radius of the initial accretion disk during the previous spin-up epoch to be of the order of the corotational radius,

$$R_{\rm cor} = \left(\frac{GM_{\rm wd}P_s^2}{4\pi^2}\right)^{1/3} \sim 1.5 \times 10^9\ {\rm cm},$$

I find the ratio $R_{\rm cor}/R_{\rm A} \ll 1$ in the current epoch for all reliable values of the mass transfer rate in the system. This indicates that if a disk indeed exists in the system its inner radius essentially exceeds the corotation radius of the white dwarf. The linear velocity of the magnetospheric field at the inner disk radius ($v_{\phi {\rm m}} = \Omega_{\rm s} R_{\rm in}$) is larger than the keplerian velocity at the same radius. That is why, the centrifugal force, $F_{\rm c} = \Omega^2 R_{\rm in}$, dominates at $R_{\rm in}$ and hence, the plasma being penetrated from the inner disk radius into the magnetosphere is pushing back from the magnetosphere rather than flows along the magnetospheric lines to the white dwarf surface. The accretion structure arising in this situation is known in the literature as a 'dead disk' and was described by Sunyaev & Shakura (1977) and Michel & Dessler (1981). The average mass transfer rate along the dead disk is almost zero. The action of viscous forces in the disk is spent to the transferring of the angular momentum extracted from the primary at the magnetospheric radius outward over the disk, which is then taken away by material leaving the system from the outer disk radius. The possible appearances of such a disk in AE Aqr I explore in this section.

3.1. Energetics and geometry

The bolometrical luminosity of the additional accretion component during the quiescent state of AE Aqr can be estimated as

$$L_{\rm q} \simeq \dot{M}\ \frac{GM_{\rm wd}}{R_{\rm in}}, \tag{9}$$

where $\dot{M}$ and $R_{\rm in}$ are the mass transfer rate and the inner radius of the disk in the quiescent state of the system, respectively. Setting the inner radius of the disk (Ghosh & Lamb 1979)

$$R_{\rm in} = \frac{1}{2}\left(\frac{\mu^2}{\dot{M}\sqrt{2GM_{\rm wd}}}\right)^{2/7}, \tag{10}$$

and substituting it to Eq. (9) I get the values of the inner disk radius and the average mass exchange rate in AE Aqr as:

$$R_{\rm in} \simeq 5.5 \times 10^{10}\ {\rm cm}\ \ \mu_{34.2}^{4/7}\, M_{0.9}^{1/9}\ L_{32}^{-2/9}, \tag{11}$$

$$\dot{M} \simeq 4.4 \times 10^{16}\ {\rm g\,s^{-1}}\ \left[\frac{R_{\rm in}}{5.5 \times 10^{10}\ {\rm cm}}\right].$$

Here, L_{32} is the quiescent luminosity of the additional component expressed in units $10^{32}\ {\rm erg\,s^{-1}}$.

The outer radius of the dead disk is limited by the white dwarf Roche lobe radius, which for the stellar separation $a = 2 \times 10^{11}$ cm and the mass ratio $q = 0.8$ (Reinsch & Beuermann 1994) is

$$R_{\rm out} = a\left(0.38 + 0.2\lg q^{-1}\right) \simeq 8 \times 10^{10}\ {\rm cm}. \tag{12}$$

If the disk is optically thick the energy released due to the action of viscous forces heats the disk plasma to the temperature of [4] $T_0 \simeq (2 \div 3) \times 10^3$ K. This indicates, that about a half of energy released in the additional component should be emitted in the IR part of the spectrum.

One would expect however higher temperatures at the inner and the outer radii of the disk due to its interaction with the magnetosphere and the inflowing plasma, respectively.

3.2. Boundary layer

About a half of the accretion energy is released in the boundary layer at the inner radius of the disk. The structure of the layer depends on the mechanism of interaction between the disk and the magnetosphere. In the considered case the relative velocity between the magnetosphere and the disk ($\omega_{\rm c} R_{\rm in} \sim 10^{10}\ {\rm cm\,s^{-1}}$) essentially exceeds the sound speed in the disk plasma and even the free-fall velocity at $R_{\rm in}$. According to Anzer & Börner (1980) under this condition the main MHD instabilities (e.g. Kelvin-Helmholtz, Rayleigh-Taylor) are expected to be suppressed, so the mechanisms previously developed for a 'moderate' propeller, i.e. when $R_{\rm in}$ slightly exceeds the corotational radius (e.g. Wang & Robertson 1985), can not be applied without problems. The situation is rather close to that discussed by Michel & Dessler (1981) with respect to radio pulsars. In this

[4] Here I assume $\alpha \lesssim 1$

case the magnetosphere – disk interaction occurs in a relatively narrow diffusion layer of the thickness

$$\delta_{\rm m} \sim \sqrt{D_{\rm eff}\tau_{\rm ff}}, \tag{13}$$

where $D_{\rm eff}$ is the effective diffusion coefficient and

$$t_{\rm ff}(R_{\rm in}) = \sqrt{R_{\rm in}^3/GM_{\rm wd}}$$

is the free-fall time.

Plasma penetrating into the magnetic field stretches the field lines in the azimuthal direction, so the toroidal component

$$B_\phi = \begin{cases} V_{\rm rel}\sqrt{8\pi\rho(R_{\rm in})}, & \text{for } (v_{\rm rel}(R_{\rm in})/v_{\rm k}(R_{\rm in})) \lesssim 1, \\ B_{\rm p}(R_{\rm in}), & \text{for } (v_{\rm rel}(R_{\rm in})/v_{\rm k}(R_{\rm in})) > 1, \end{cases}$$

in the diffusion layer is generated. Here, $v_{\rm k}(R_{\rm in})$ is the keplerian velocity at the inner radius of the disk. B_ϕ reaches the value of $B_{\rm p}(R_{\rm in})$ on the time scale $\tau_\phi \sim \Omega^{-1}$. The further amplification of B_ϕ leads to the field lines reconnection in the layer on the time scale $\sim \delta_{\rm m}/\sqrt{2}\ v_{\rm k}(R_{\rm in}) \ll \tau_\phi$. The equilibrium configuration of the magnetic field in the layer can be expressed in terms of the *magnetic field with shear* (Ikhsanov & Pustil'nik 1996). Thus, the accretion energy in the diffusion layer is transferred via the magnetic field to the thermal energy of plasma and accelerated particles.

At least half of the energy released in the reconnection regions is spent to plasma heating. If then this energy is radiated by optically thin plasma the temperature in the layer can be estimated setting

$$\tau_{\rm rad} = \frac{3kT}{2n\Lambda(T)} = t_{\rm ff}. \tag{14}$$

Taking into account that the gas pressure at the magnetospheric boundary is balanced by the pressure of magnetic field I get the number density in the layer as

$$n(R_{\rm in}) = \frac{B^2(R_{\rm in})}{8\pi kT} \tag{15}$$

Combining Eqs. (14) and (15) I find

$$T_{\rm dl} \simeq 1.4\times10^7\,{\rm K}\ \mu_{34.2}\ M_{0.9}^{-1/4}\ \Lambda_{-22.7}^{1/2}\ R_{10.74}^{-9/4}, \tag{16}$$

where $\Lambda_{-22.7}$ is the total radiative cooling coefficient expressed in units $2\times10^{-23}\,{\rm erg\,cm^{-3}\,s^{-1}}$ (Rosner et al. 1978).

Hence, the accretion energy in the diffusion layer is released mainly in the form of soft X-rays. The soft X-ray photons ($E_\gamma \sim 1$ keV) propagating through the disk should be absorbed by photoionization at the column density of about $10^{-2}\,{\rm g\,cm^2}$. This corresponds to the radial scale along the accretion disk:

$$l_{\rm r} = 10^{-2}\frac{8\pi kT_{\rm in}}{m_{\rm p}B^2(R_{\rm in})}, \tag{17}$$

where $T_{\rm in}$ is the plasma temperature at the inner disk radius.

The energy absorbed by the disk plasma is then reradiated within the relatively narrow ring ($R_{\rm in}$ and $R_{\rm in}+l_{\rm r}$) with the black body temperature

$$T_{\rm in} = \left(\frac{\dot{E}\mu^2 m_{\rm p}}{0.32\pi^2 kR_{\rm in}^7\sigma_{\rm sb}}\right)^{1/5} \simeq\ 10^4{\rm K}\ \xi_{0.2}^{1/5}\ \mu_{34.2}^{2/5}\ \times \tag{18}$$

$$\times\left[\frac{L_{\rm q}}{10^{32}\,{\rm erg\,s^{-1}}}\right]^{1/5}\ \left[\frac{R_{\rm in}}{5.5\times10^{10}\,{\rm cm}}\right]^{-7/5},$$

where $\dot{E}$ is the rate of energy input from the diffusion layer into the disk plasma and $\xi_{0.2}$ is the ratio $\xi = \dot{E}/L_{\rm q}$ expressed in units of 0.2.

Using Eqs. (17) and (18) I get the scale of the hot ring at the inner disk radius in the radial direction as

$$l_{\rm r}(R_{\rm in}) \simeq 4.3\times10^7{\rm cm}\ \left(\frac{T_{\rm in}}{10^4\,{\rm K}}\right), \tag{19}$$

and the thickness of the ring

$$Z_0(R_{\rm in}) \simeq 1.3\times10^9{\rm cm}\ \times \tag{20}$$

$$\times\ \left(\frac{T_{\rm in}}{10^4{\rm K}}\right)^{1/2}\left[\frac{R_{\rm in}}{5.5\times10^{10}\,{\rm cm}}\right]^{3/2}.$$

The optical thickness of the ring with respect to the soft X-rays is

$$\tau_{\rm x} = 2\times10^{-22}\left(\frac{h\nu}{1\,{\rm keV}}\right)^{-\frac{8}{3}}\int N_{\rm H}dl \simeq 1.6\ \left(\frac{h\nu}{0.9{\rm keV}}\right)^{-\frac{8}{3}}.$$

Thus, the major fraction of energy releases at the magnetosphere – disk boundary is expected to be observed in the optical-UV spectral band. The ratio of the X-ray to the optical luminosity of the additional accretion component is $L_{\rm X}/L_{\rm opt} \sim 0.2$.

3.3. Bright stream

The last point I briefly address in this section is the accretion stream impact region at the outer edge of the dead disk. In contrast to the accretion disk the outer radius of the dead disk cannot be smaller than the Roche lobe radius of the compact star. Otherwise the additional torque extracted from the primary at the inner disk radius cannot be released from the disk and is stored at the outer disk edge leading to an increase of $R_{\rm out}$ to the Roche lobe radius (Sunyaev & Shakura 1977). Correspondingly, the material inflowing from the secondary into the primary's Roche lobe and interacting with the dead disk should be accelerated and flowing out from the system taking away the additional torque from the disk.

Parameters of material inflowing from the secondary through the L_1 point into the primary's Roche lobe can be evaluated using the system parameters of AE Aqr. Namely, I take the cross-section of inflowing stream to be equal to the effective cross-section of the mass transfer throat at L_1 point, which in the case of AE Aqr is

$$Q = \frac{2\pi c_{\rm s}^2 a^3}{kG(M_1+M_2)} \sim 1.85\times10^{19}\left(\frac{T}{10^4\,{\rm K}}\right)\ {\rm cm}^2, \tag{21}$$

the stream velocity through L_1 point $c_{\rm s} \simeq 5\times10^5\,{\rm cm\,s^{-1}}$ and the stream plasma density (using Eq. 11)

$$\rho_{\rm s} = \frac{\dot{M}}{Qc_{\rm s}} \simeq 5\times10^{-9}\,{\rm g\,cm^{-3}}. \tag{22}$$

The stream impacts the dead disk at ϕ_0 within the interval $0 < \phi_0 < 0.25$, where ϕ is the azimuthal angle in the disk plane measured from the apsis in the direction of orbital rotation[5]. Since the relative velocity between the stream and the disk $v_{\rm rel} \sim v_{\rm k}(R_{\rm out}) \gg c_{\rm s}$ the stream plasma will be shocked. Under the conditions of interest the temperature behind the shock is a few $\times 10^6$ K that would lead to heating and expansion of plasma in the impact region (Spruit & Rutten 1998). Since the stream plasma is optically thick with respect to soft X-rays generated in the shock region (the column density is about $5\,{\rm g\,cm^2}$) the energy released in the impact region $L_{\rm stream} \sim (1/2)\dot{M} v_{\rm k}^2(R_{\rm out})$ will be radiated with the blackbody temperature

$$T_{\rm s} \simeq 1.3 \times 10^4\,{\rm K}\, L_{31.5}^{1/4}\, S_{19.3}^{-1/4}, \tag{23}$$

where $L_{31.5}$ is the rate of energy release at the impact region expressed in units of $10^{31.5}\,{\rm erg\,s^{-1}}$ and $S_{19.3}$ is the area of the shocked region expressed in units of $10^{19.3}\,{\rm cm}^2$.

As a result of interaction between the dead disk and the stream, the later extracts the torque from the outer edge of the disk and leaves the system. Investigation of the stream trajectory is beyond the scope of the present paper. I would like only to note, that because of the relatively high temperature and large outer radius of the dead disk the inflowing plasma proves to be beyond the primary's Roche lobe already at $\phi \gtrsim 0.25$. This allows us to suggest that the outflowing matter would leave the system somewhere within $0.25 \lesssim \phi \lesssim 0.75$.

It is interesting that because of the velocity gradient and the high temperature the shock region can be the place of Kelvin-Helmholtz instability. This indicates that after the interaction with the dead disk the outflowing stream may be essentially inhomogeneous.

Finally, I would like to point out that since the cooling time of the plasma at the outer edge of the disk does not exceed the free-fall time at $R_{\rm out}$, the second half of the disk (i.e. $0.75 \lesssim \phi \lesssim 1+\phi_0$) contributes to the system radiation mainly in IR (see above). This indicates that the Hα Doppler tomogram of AE Aqr in the frame of the suggested approach cannot be azimuthaly symmetrical.

4. Discussion

Summarizing, one can conclude that one of the important consequences of the pulsar-like white dwarf model of AE Aqr is the formation of a dead disk around the primary's magnetosphere. The dead disk forms just after the outburst associated with the spin-up $\rightarrow$ spin-down primary state transition. The disk formation occurs due to essential enhancement of mass loss rate from the secondary irradiated by hard X-rays.

In the current epoch the inner and outer radii of the disk are $R_{\rm in} \sim 5.5 \times 10^{10}$ cm, and $R_{\rm out} \sim 8 \times 10^{10}$ cm, respectively. At its inner radius the disk interacts with the fast rotating magnetosphere that leads to the formation of a boundary layer. About 80% of the energy released in the boundary layer radiates in the optical/UV with the black body compatible spectrum at $\sim 10^4$ K and about 20% – in the form of soft X-rays (bremsstrahlung radiation of plasma with the temperature of about 1 keV). At its outer radius the disk interacts with the stream of plasma inflowing from the secondary component through the L_1 point with the average inflowing rate $\sim 4.5 \times 10^{16}\,{\rm g\,s^{-1}}$. The interaction occurs within the interval $0 \lesssim \phi \lesssim 0.25$. As a result of this interaction the inflowing plasma heats up to the temperature ~ 13000 K, accelerates in ϕ-direction and is streaming out from the system within the interval $0.25 \lesssim \phi \lesssim 0.75$ with an average velocity $v_{\rm k}(R_{\rm out}) \div v_{\rm ff}(R_{\rm out})$, which in the considered case is $380 \div 550\,{\rm km\,s^{-1}}$. The rest parts of the disk are relatively cool $\sim (2 \div 3) \times 10^3$ K and contribute to the system radiation in the IR spectral band.

The observational appearance of plasma outflowing from the outer edge of the dead disk in our model is rather similar to that discussed by Wynn et al. (1997). This is even more so, if the stream impact region is the place of Kelvin-Helmholtz instability. In this situation one could expect the outflowing stream to be essentially inhomogeneous. At the same time, the blobs velocities and the average mass outflow rate derived in our model are essentially smaller than required by the model of Wynn et al.

The main feature that makes the suggested model different from those previously discussed is the hot boundary layer at the inner disk radius. Because of this feature the presented model sheds a new light on a number of puzzling properties of the accretion component in AE Aqr. Among them are the optical/UV continuum with the black body compatible spectrum at $(1 \div 1.2) \times 10^4$ K (Beskrovnaya et al. 1996; de Martino et al. 1995) and the non-modulated (with the 33 s) soft X-ray component (Clayton & Osborne 1995; Reinsch et al. 1995). Furthermore, one can expect intensive injection of relativistic particles into the white dwarf magnetosphere from reconnection regions in the diffusion layer and the outflow of hot plasma from the diffusion layer into the disk corona (see e.g. Lovelace et al. 1999). These two additional effects, investigation of which however remains beyond the scope of present paper, can be helpful for the interpretation of the radio plasma blobs formation (Kuijpers et al. 1997) and for the formation of a hot disk corona.

In this paper we discuss only the quiescent state of AE Aqr. If now we ask what may happen with the system during its flaring state we find that the suggested approach gives a new interesting possibility for the interpretation of this phenomenon. Really, the constructed picture contains of a very non-stationary region – the boundary layer. The characteristic timescale for energy release processes in this region is $t_{\rm f} \gtrsim t_{\rm ff} \simeq 850$ s that is close to the typical flaring timescale of AE Aqr. The stronger interaction between the magnetosphere and the disk leads to the increase of energy and flux of X-ray photons generated in the diffusion layer. This should increase the scale of X-ray photons penetration into the disk, i.e. the parameter $l_{\rm r}$, and, correspondingly, the surface area of the hot boundary layer. As a result, optical observations of flaring will not show essential increase of temperature while the X-ray spectrum is expected to be harder because of a higher temperature in the reconnection region. Within this scheme the enhancement of the X-ray and

[5] More precise identification of ϕ_0 is complicated since the outer radius of dead disk is still rather uncertain.

the optical/UV continuum fluxes during the flaring state should show good correlation. Injection of additional energy into the disk under certain conditions leads to the turbulization of disk plasma at the inner radius that may be the reason for the observed flickering during the flaring state of the system (Bruch & Duschl 1993). Finally, the increase of the energy output in the boundary layer leads to an increase of the matter outflow from the inner disk radius in the direction perpendicular to the disk plane (Lovelace et al. 1999).

Though the flaring scheme which I have roughly drawn here needs to be investigated in more details, the presented arguments suggest that the pulsar-like white dwarf approach may be very helpful for the interpretation of not only the quiescent but also the flaring state of AE Aqr.

The last question I would like to address here is a possibility for a similar accretion picture to be realized within the 'magnetic propeller' model of AE Aqr previously suggested by Wynn et al. (1997). In fact, in both approaches the white dwarf acts as propeller with respect to the inflowing material, i.e. in both cases the inflowing material does not accrete onto the white dwarf surface but is flowing out from the system taking away a certain fraction of the primary's torque. Moreover, if the stream inflowing through the L_1 point does not consist of blobs[6] but is homogeneous, the dead disk around the magnetosphere of white dwarf with $\mu \lesssim 10^{32}\,\mathrm{G\,cm}^3$ undergoing accretion with the rate $\sim 10^{17}\,\mathrm{g\,s}^{-1}$ *must* be formed. The accretion picture in this case only slightly differs from that presented in this paper concerning the boundary layer parameters. However the spindown rate of the white dwarf in this situation proves to be smaller by about two orders of magnitude than the spindown rate currently observed and hence, this model cannot be applied to AE Aqr.

On the contrary, within the PL-model the rotational energy of the white dwarf is released due to magneto-dipole losses rather than due to the interaction between the magnetosphere and the inflowing material. In this sense the spindown problem in the frame of the PL-model is solved *by definition* (Ikhsanov 1998). That is why, a relatively small efficiency of the propeller action by the white dwarf ($\sim 10^{-2}$) does not lead to any difficulties in the interpretation of the observed spindown of the white dwarf and is consistent with the ratio $L_\mathrm{q}/L_\mathrm{sd} \sim 10^{-2}$ observed in AE Aqr (de Jager et al. 1994).

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[6] The bloby stream still remains the most controversial assumption of the 'magnetic propeller' model.

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