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The pulsar-like white dwarf in AE Aquarii

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Abstract. The spindown power of the compact companion in the close binary system AE Aqr essentially exceeds the bolometrical luminosity of the system. The interpretation of this phenomenon under various assumptions about the state and the nature of the primary companion is discussed. It is shown that the rapid braking on the compact companion of AE Aqr can be explained in terms of the pulsar mechanism provided the magnetic moment of the compact star $\mu \gtrsim 1.4 \times 10^{34}\,\mathrm{G\,cm^3}$, that implies a magnetic field strength at the surface of the white dwarf of about 50 MG. Under this condition the spindown power is used predominantly for the generation of magneto-dipole waves and particle acceleration. A stream-fed, diskless mass-exchange picture with the average rate of mass transfer $\dot{M} \sim (0.5 \div 5) \times 10^{17}\,\mathrm{g\,s^{-1}}$ is expected in the frame of the suggested model. Similarity of some properties of the X-ray emission observed from AE Aqr and canonical radio pulsars in the ROSAT energy range (e.g. the power law spectrum of pulsing component with $\alpha \approx -2$ and the ratio $L_{\rm X}/L_{\rm sd} \sim 10^{-3}$) allows to suggest common mechanisms of particle acceleration and the polar cap heating in these systems.

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

1. Introduction

A key question of modelling the mass exchange and energy release processes in the close binary AE Aqr is the state of its primary – a magnetized compact star with the spin period $33^{\rm s}$ (for the system parameters see Table 1 in Ikhsanov 1997). Analysis of the primary parameters performed in the previous paper (Ikhsanov 1995) has shown that the compact companion cannot be an *accreting* white dwarf as it was previously accepted (see Patterson 1994 and references therein). The accretion of the material flowing from the normal companion onto the primary surface can be realized only if the degenerate star in the system is a neutron star. Otherwise, the white dwarf in AE Aqr is in the state of *propeller* or *ejector*.

The central problem, and at the same time a possible clue, for the determination of the primary state in AE Aqr is its mean spindown rate reported by de Jager et al. (1994): $\dot{P} = 5.64 \times 10^{-14}\,\mathrm{s\,s^{-1}}$, which implies a spindown power of

$$L_{\rm sd} = -I\omega_{\rm s}\dot{\omega}_{\rm s} \cong 6 \times 10^{33}\, I_{50}\, \dot{P}\, P^{-3}\,\mathrm{erg\,s^{-1}}\ . \quad (1)$$

Here, I_{50} is the moment of inertia of a *white dwarf* in units of $10^{50}\,\mathrm{g\,cm^2}$, $\omega_{\rm s} = 2\pi/P$ and P is the spin period of the primary. $\dot{P}$ and P are expressed in units of $5.64 \times 10^{-14}\,\mathrm{s\,s^{-1}}$ and 33 s, respectively.

If the primary in AE Aqr is a white dwarf, $L_{\rm sd}$ proves to be larger than the observed UV and X-ray luminosities of the system by a factor of 120 and even its bolometrical luminosity $L_{\rm bol}$ by a factor of more than five (hereafter the distance to AE Aqr is adopted to be 100 pc). This fact opens the question about the form in which the spindown power is released.

In this paper I discuss a possibility to solve this, so called '*spindown problem*' in the frame of various assumptions about the state of the primary: *propeller* (Sect. 2), *accretor* (Sect. 3) and *ejector* (Sect. 3). I conclude that the spindown power of the white dwarf is released predominantly in the form of low frequency magneto-dipole waves and relativistic particles. Within this model the propeller action by the white dwarf determines the picture of mass-exchange between the components but is not the main mechanism of the primary spindown. In this context the white dwarf in AE Aqr can be put in one row with spin-powered (solitary) pulsars and possibly with the pulsar-like white dwarf 1E 2259+586 (Paczyński 1990).

2. Propeller spindown

Some effort has been recently made to explain the observed spindown rate of the primary in AE Aqr in terms of the so called '*propeller*' mechanism. The basic idea of this approach is that the white dwarf is spinning down predominantly due to the interaction between its magnetic field, which is corotating with the star, and the material inflowing from the normal companion. If the magnetospheric (or Alfvén) radius of the primary is larger than its corotational radius ($R_{\rm m} > R_{\rm cor}$), this interaction leads to a deceleration of the star rotation. The spindown power in this case is converted to both the kinetic and the thermal energy of outflowing material (see Lipunov 1992 and references therein).

De Jager (1994) was the first to point out that since the calculated spindown power is significantly larger than the observed *white dwarf* + *accretion disk* luminosity, AE Aqr does not fit the picture of canonical propeller models like the 'dead disk' model of Sunyaev & Shakura (1977) or the 'quasi-stationary turbulent envelope' model developed by Lamb et al. (1977), Davies et al. (1979) and Davies & Pringle (1981). In both models the fraction of the spindown power which is converted to the thermal energy of surrounding material is almost equal to that converted to the kinetic energy of the material streaming out from the system. As a result, the luminosity of such a system is expected to be comparable with the spindown power of the compact star. On the basis of this he suggested that the interaction between the white dwarf magnetosphere and the surrounding accretion disk may lead to the wind of relativistic particles ejected from the white dwarf magnetosphere or from the disk corona (de Jager 1994; Meintjes & de Jager 1995).

An alternative possibility has been discussed by Wynn et al. (1997). Analyzing the Hα Doppler tomogram of AE Aqr they concluded that there is no evidence of a Keplerian accretion disk in the system [1]. They suggested that the matter coming from the normal companion into the primary's Roche lobe does not form a disk but is cruising out of the system being pushed by the magnetic field of the fast rotating white dwarf. They have shown that in the frame of this scenario the observed Hα Doppler tomogram can be reconstructed provided the average velocity of material outflowing from the system is $V_{\rm out} \approx 300\,{\rm km\,s^{-1}}$.

Wynn et al. (1997) have modeled the accretion stream as a superposition of large, diamagnetic blobs. Then considering the blobs as test particles, i.e. neglecting changes in their internal state (see also King 1993), they proposed that almost all spindown power is transferred to the kinetic energy of blobs flowing out from the system. In other words, they considered a situation in which the heating of inflowing material due to its interaction with the magnetosphere of the white dwarf is almost negligible.

The correctness of this limitation in the case of AE Aqr is not obvious. The relative velocity of blobs and the magnetic field of the white dwarf corresponds to Mach numbers $M \gg 1$. Under this condition blobs would be shocked when they encounter the magnetic propeller and their physical state is expected to change dramatically (see Eracleous & Horn 1996).

This, however, is not the only problem of the suggested approach. If the spindown power of the primary is converted predominantly to the kinetic energy of the outflowing stream, the rate of mass exchange between the components in AE Aqr can be estimated *independently on the mechanism of propeller action* using only the energy and mass conservation laws. This however leads to a mass exchange rate much higher than that evaluated in previous models. Really, for a given value of $V_{\rm out}$ the average rate of mass outflowing from the system due to propeller action of the primary is

$$\dot{M}_{\rm out} = \frac{L_{\rm sd}}{V_{\rm out}^2} \simeq 6.5\times10^{18}\,{\rm g\,s^{-1}} \times \left[\frac{L_{\rm sd}}{6\times10^{33}\,{\rm egr\,s^{-1}}}\right] \left[\frac{V_{\rm out}}{3\times10^{7}\,{\rm cm\,s^{-1}}}\right]^{-2}. \quad (2)$$

In the steady state $\dot{M}_{\rm out}$ cannot exceed the rate of mass loss by the normal component $\dot{M}_{\rm loss}$. Hence, the propeller scenario can be satisfied only provided the present rate of the mass loss by the secondary is $\dot{M}_{\rm loss} \gtrsim 7\times10^{18}\,{\rm g\,s^{-1}}$.

Though a high rate of mass exchange is not unusual for Cataclysmic Variables, observations of AE Aqr give no evidence for a realization of such a situation in this system (see Warner 1995).

3. Neutron star spindown

The possibility to avoid the spindown problem assuming that the primary in AE Aqr is an accreting neutron star was discussed in Ikhsanov (1995). Under this assumption the ratio of the spindown power to the UV and X-ray luminosities proves to be $\sim 6\times10^{-3}\,I_{45}\,\dot{P}\,P^3$, where I_{45} is the moment of inertia of a *neutron star* in units of $10^{45}\,{\rm g\,cm^2}$. So, the spindown problem in this case simply does not arise.

If the primary is a neutron star, AE Aqr would be a wind-fed accretor with a very low mass transfer rate. The accretion energy releases at the surface of the neutron star which in the frame of this approach is the main source of primary's radiation (see Ikhsanov 1997).

However the interpretation of some observational data on AE Aqr within this scenario proves to be very complicated. Among them are the UV–optical spectrum of the $33^{\rm s}$ pulsing component, which can be fitted by the spectrum of the white dwarf atmosphere with the temperature $T \sim 26000\,{\rm K}$, the absence of any significant correlation between the amplitudes and profiles of the $33^{\rm s}$ pulses and flaring of the system (Eracleous et al. 1994) and a very soft X-ray spectrum observed from AE Aqr (Reinsch et al. 1995; Osborne et al. 1995), which strongly differs from X-ray spectra of accreting neutron stars. Furthermore, the analysis of the quiescent optical light curve of AE Aqr has shown that the maxima of ellipsoidal wave on phases 0.25 and 0.75 are not equal. This indicates the presence of an additional luminous source situated somewhere away from the compact star (van Paradijs et al. 1989; Beskrovnaya et al. 1998). Taking into account that the luminosity of the additional 'bright spot' is comparable or even exceeds the luminosity of the primary, the origin of such a source within a wind-fed scenario with a relatively low mass transfer rate is rather unclear.

The above discussion forced us to conclude that, in spite of some progress, the origin of the observed spindown of the primary in AE Aqr cannot be regarded as well understood so far. In this situation the investigation of alternative possibilities (if they exist) remains important. One of them – a *pulsar-like white dwarf in a binary system* – is the subject of the following section.

4. Pulsar-like spindown

While the situation in which the spindown power of the compact companion exceeds its bolometrical luminosity is unique

[1] The same conclusion has been previously made by van Paradijs et al. (1989) and Bruch (1991) on the basis of photometric data.

for cataclysmic variables it is not unusual among solitary (radio) pulsars (Manchester & Taylor 1977). In particular, observations of a few spin-powered pulsars (e.g. Crab, Vela, Geminga, PSR B1706–44, PSR B1055–52, PSR B1951+32) in the optical, X-ray and γ-ray ranges revealed the bolometrical luminosities of these pulsars to constitute a relatively small fraction ($\sim 10^{-3} \div 10^{-1}$) of their spindown power (for a review, see Hartmann 1995; Tompson 1996).

Radio pulsars slow down through the loss of their rotational energy in the form of low frequency electromagnetic waves (magneto-dipole radiation) and high energy particles. The spindown power in this case can be evaluated by the magneto-dipole losses of a rotating magnet (Pacini 1968; Goldreich & Julian 1969)

$$L_{\rm sd} \sim L_{\rm md} = \frac{2\mu^2 \sin^2\beta}{3c^3}\ \omega_{\rm s}^4, \quad (3)$$

where β is the angle between the rotational and magnetic axes. The $\omega_{\rm s}$–waves are absorbed by the surrounding plasma and their energy is transferred to the wind of relativistic particles (Rees & Gunn 1974). As a result, the major part of the spindown power proves to be released beyond the detectable parts of the electromagnetic spectrum (for a review, see Michel 1991).

In this section I explore a possibility to solve the spindown problem of AE Aqr within the *ejector* approach. Namely, I assume that the major part of the rotational energy of the white dwarf is spent in the generation of low frequency magneto-dipole waves and particle acceleration.

4.1. Magnetic field of the white dwarf

Within the *ejector* approach the magnetic moment of the white dwarf in AE Aqr can be estimated from Eq. (3):

$$\mu \simeq 1.4\times10^{34}\ \sin^{-1}\beta\, L_{33.8}^{1/2}\, P^2\ {\rm G\ cm^3}, \quad (4)$$

where $L_{33.8}$ is the spindown power expressed in units of $10^{33.8}$ erg s^{-1} and P is expressed in units of 33 s.

Investigating the 33 s pulse profile Eracleous et al. (1994) argued that the angle β in the case of AE Aqr is close to 90°. Taking this into account I calculate the magnetic field strength at the surface of the white dwarf as

$$B(R_{\rm wd}) \gtrsim B_0 = 5\times10^7\ {\rm Gauss}\ \times \quad (5)$$
$$\times\left[\frac{\mu_{\rm wd}}{1.4\times10^{34}\,{\rm G\ cm^3}}\right]\left[\frac{R_{\rm wd}}{6.5\times10^8\,{\rm cm}}\right]^{-3}.$$

4.2. Mass-exchange

If the secondary in AE Aqr is a K3–K5 main sequence red dwarf, (Bruch 1991; Welsh et al. 1995) the ratio of its radius R_2 to the mean radius of its Roche lobe $R_{\rm Roche}$ lies within the range $0.91 \lesssim R_2/R_{\rm Roche} \lesssim 0.93$. Under this condition the rate of mass loss by the secondary through the L_1 point (even taking into account the illumination of the secondary surface by the X-rays emitted from the primary) is of the order of the mass loss rate due to the stellar wind. On the other hand, the assumption that the secondary is a slightly evolved star in the particular case of AE Aqr leads to a serious problem with the determination of the evolutionary status of the system (de Jager 1994). In this situation AE Aqr proves to be a wind-fed accretor with the average rate of mass transfer $\dot{M} \simeq 3\times10^{12}$ g s^{-1} (Ikhsanov 1997).

The situation is qualitatively different if the white dwarf is indeed the source of a strong relativistic wind ($E_{\rm p} > 10$ keV) which carries a significant fraction of its spindown power. In this case the illuminating energy is deposited at a depth $l \gtrsim 1 - 100\,{\rm g\,cm^{-2}}$ which for a K type dwarf corresponds to the region below the photosphere. The efficiency of the irradiation-driven mechanism is then essentially higher than that found assuming irradiation by soft X-rays, and the mass loss rate of the secondary proves to be a few orders of magnitude larger than that estimated by Ikhsanov (1997). Furthermore, according to Hameury (1996) almost adiabatic expansion of the secondary can be expected in this situation. Incorporation of these effects to the case of AE Aqr leads to a *stream-fed* mass-exchange picture with the rate of mass transfer through the L_1 point comparable with the mass transfer rate on the thermal timescale: $\dot{M}_{\rm th} \sim (M_2/t_{\rm th})$ (Masevich & Tutukov 1988).

The stream would penetrate the Roche lobe of the white dwarf if the distance of its closest approach to the compact star, $R_{\rm min}$, is smaller than the mean radius of its Roche lobe $R_{\rm Roche}$. In the considered case $R_{\rm min} \gtrsim R_{\rm mag}$, the radius at which magnetic effects are able to overcome the ram pressure of the stream material. This radius can be normalized as $R_{\rm mag} = \varepsilon R_{\rm A}$, where ε is the numerical coefficient and $R_{\rm A}$ is a canonical Alfvén radius which is defined by equating the ram pressure of inflowing material with the magnetic pressure due to the dipole field of the white dwarf. Then the condition $R_{\rm min} < R_{\rm Roche}$ can be rewritten in the form of the condition for the minimum rate of mass transfer in the system which is given by

$$\dot{M}\ \gtrsim\ \dot{M}_{\rm min}\ =\ \frac{\varepsilon^{7/2}\,\mu^2}{R_{\rm Roche}^{7/2}\,\sqrt{GM}} \quad (6)$$
$$\gtrsim\ 2.5\times10^{15}\ {\rm g\,s^{-1}}\ \varepsilon_{0.37}^{7/2}\ \mu_{34.2}^2\, R_{11}^{-7/2}\ M_{0.8}^{1/2},$$

where $\mu_{34.2}$ is the magnetic moment of the white dwarf expressed in units of $10^{34.2}$ G cm^{-3}, R_{11} is the radius of the primary's Roche lobe expressed in units of 10^{11} cm, $M_{0.8}$ is the mass of the white dwarf expressed in units of $0.8 M_\odot$ and the parameter $\varepsilon_{0.37} = \varepsilon/0.37$ is normalized following Hameury et al. (1986).

On the other hand, the criterion for diskless mass transfer in a binary system presented by Wickramasinghe et al. (1991), in the case of AE Aqr can be written in the following form

$$\dot{M} \lesssim 6.4\times10^{17}{\rm g\,s^{-1}}\ \mu_{34.2}^2\,\alpha_{0.3}^{-2}\,P_{10}^{-7/3}\ M_{0.8}^{5/3}\ , \quad (7)$$

where P_{10} is the orbital period of AE Aqr expressed in units of 10 hours and $\alpha_{0.3} = \alpha/0.3$ is the ratio of the circularization radius to the Roche lobe radius of the white dwarf.

Thus, in the frame of the considered approach AE Aqr can be fitted in the mass-exchange picture reconstructed by Wynn et al. (1997) if the mass transfer rate between the components in the system lies within the interval

$$2 \times 10^{15}\,\mathrm{g\,s^{-1}} \;<\; \dot{M} \;\lesssim\; 5 \times 10^{17}\,\mathrm{g\,s^{-1}}\,.$$

In this case the matter is streaming from the normal component through the L_1 point into the Roche lobe of the white dwarf and then is flowing out from the system due to interaction with the fast rotating magnetosphere of the primary.

The luminosity of a source associated with the "*bright spot*" powered by the interaction between the stream and the magnetosphere in the first approximation can be evaluated as follows

$$L_{\rm st} \sim \dot{M}\frac{GM_{\rm wd}}{R_{\rm mag}} \simeq \tag{8}$$

$$\simeq 7 \times 10^{31}\;\mathrm{erg\,s^{-1}}\;\varepsilon_{0.37}^{-1}\;\dot{M}_{16.5}^{9/7}\;\mu_{34.2}^{-4/7}\;M_{0.8}^{8/7}\,,$$

where $\dot{M}_{16.5}$ is the mass exchange rate between the components expressed in units $10^{16.5}$ g s^{-1}. It is easy to see from Eqs. (8) and (7) that AE Aqr remains in the diskless accretion state even if the luminosity of the 'bright spot' is of the order of the maximum bolometrical luminosity of the system ($L_{\rm bol} \sim 10^{33}\,\mathrm{erg\,s^{-1}}$ van Paradijs et al. 1989; Beskrovnaya et al. 1996; Eracleous & Horne 1996).

Studies (e.g. Illarionov & Sunyaev 1975; Davies & Pringle 1981; Wang & Robertson 1985) have shown that the kinetic luminosity of the material outflowing from the system due to propeller action by a fast rotating, magnetized compact star is of the order of $L_{\rm st}$. Within these models the velocity of matter cruising out from the system is about the parabolic velocity at $R_{\rm mag}$. For the parameters of AE Aqr this gives the average outflowing velocity

$$V_{\rm out} \simeq 5 \times 10^{7}\;\mathrm{cm\,s^{-1}}\varepsilon_{0.37}^{-1/2}\;\dot{M}_{16.5}^{1/7}\;\mu_{34.2}^{-2/7}\;M_{0.8}\,, \tag{9}$$

and the efficiency of the propeller action of the white dwarf: $L_{\rm st}/L_{\rm sd} \sim 10^{-2}$.

4.3. Radiation from the white dwarf

Radiation detected from AE Aqr is coming from at least three separated sources: the normal component, the 'bright sport' and the primary component. The primary's contribution in a superposition of radiation coming from the surface of the white dwarf and the radiation from its magnetosphere.

Radiation from the white dwarf surface was investigated in detail by Eracleous et al. (1994). They argued that the observed optical-UV spectrum and the profile of the 33 s pulsations can be interpreted suggesting that the temperature of the white dwarf surface in the magnetic pole regions is higher than the average surface temperature. The following best fitted model parameters have been derived: the surface temperature at the magnetic poles $T_{\rm max} \simeq 26000$ K, the area of these regions $A_{\rm mp} \simeq 4\times10^{16}\,\mathrm{cm}^2$ and the mean temperature of the rest of the white dwarf surface $T_{\rm int} \sim (10000 \div 16000)$ K.

Analyzing a possible origin of the hot spots in the polar cap regions Eracleous et al. (1994) pointed out that because of a relatively small value of $T_{\rm max}$, the traditional accretion scenarios for heating the magnetic polar caps cannot be applied to AE Aqr without problems. Furthermore, there is some doubt that the X-ray emission detected from AE Aqr is powered by the accretion onto the surface of the white dwarf (Clayton & Osborne 1995). They reported that in contrast to the hard X-ray spectra of all intermediate polars, AE Aqr has a soft spectrum which essentially differs from spectra of almost all accretion powered close binaries. Finally, the mass-exchange picture in AE Aqr presented by Wynn et al. (1997) implies no steady-state accretion onto the surface of the white dwarf. This is the more so with regard to the *ejector* model of AE Aqr in which no accretion onto the surface of the white dwarf is expected.

An alternative scenario for heating the magnetic polar caps may be supposed, in which the source of heating energy is the spindown power of the white dwarf. Virtually almost all models of radio pulsars predict the existence of hot polar caps situated at the magnetic pole regions of compact stars (e.g. Cheng & Ruderman 1980; Arons 1981; Michel 1991; Beskin et al. 1993). Within these scenarios the magnetic polar caps can be heated due to impact of backflowing relativistic electrons or/and non-thermal magnetospheric radiation or/and the dissipation of electric currents in the magnetospheric circuit. Possible applications of these mechanisms to the case of a fast spinning, magnetized white dwarf were discussed by Paczyński (1990) and Usov (1993).

Evidence for a realization of such a scenario in AE Aqr has been discussed by de Jager (1994). He argued that the spectrum and variability of radiation observed from AE Aqr in the radio and γ-rays leave no doubts that the system contains an effective accelerator of particles. The particle energies range from a few MeV (radio emission) up to a few TeV (γ-rays). The detection of coherent oscillations with the spin period of the primary 33 s, and the half period 16.5 s, in TeV γ-rays indicates that high energy particles are accelerated inside the magnetosphere of the white dwarf. The time averaged luminosity of AE Aqr observed in TeV γ-rays: $L_\gamma = (2 \div 3) \times 10^{32}\,\mathrm{erg\,s^{-1}}$ (Meintjes et al. 1992; Bowden et al. 1992) is by the order of magnitude larger than the UV+X-ray luminosity of the system. This indicates that even a relatively small fraction ($0.1\% \div 1\%$) of the spindown power being converted into backflowing relativistic particles or waves is enough to heat the magnetic poles up to a few $\times 10^4$ K.

The maximum value of the potential difference in the magnetosphere of a fast rotating, magnetized compact star following Ruderman & Sutherland (1975) is[2]

$$V \approx \frac{1}{2}\left(\frac{\omega_{\rm s}R}{c}\right)^2\;RB_0 \simeq 10^{14}\;\mu_{34.2}\;\mathrm{V},$$

where B_0 is the magnetic field strength at the star surface.

More precise estimate of the electric potential in the inner gap of the magnetosphere of pulsar was given by Arons &

[2] Note that in gaussian c.g.s. units, V is given in statvolts, where 1 statvolt = 300 V.

Scharlemann (1979)

$$\varphi(r) = \int_{\rm R}^{\rm r} E_{\parallel} ds \simeq 2\sqrt{2} E_{\parallel}^{\rm AS} R \left[\left(\frac{r}{R} \right)^{1/2} - 1 \right] ,$$

where R is the radius of a compact star, s is the distance from the surface of the white dwarf, $r = R + s$ and

$$E_{\parallel}^{\rm AS} \simeq \frac{1}{8\sqrt{3}} \left(\frac{\omega_{\rm s} R}{c} \right)^{5/2} B(R).$$

This approach can be applied to the case of a white dwarf if its surface temperature is less than 10^6 K (see Usov 1988). So, the maximum energy to which the particles can be accelerated in the inner gap of the white dwarf magnetosphere of AE Aqr is

$$E_{\rm p}^{\rm max} \simeq 2 \times 10^{12}\ \mu_{34.2}\ R_{8.8}^{1/2} \left[\left(\frac{r}{R_{\rm wd}} \right)^{1/2} - 1 \right] {\rm eV} \qquad (10)$$

where $R_{8.8}$ is the radius of the white dwarf expressed in units of $10^{8.8}$ cm.

According to de Jager (1994) the polar cap area in the case of AE Aqr lies within the interval

$$\frac{1.6\pi R_{\rm wd}^3}{R_{\rm lc}} \lesssim A_{\rm pc} \lesssim \frac{1.6\pi R_{\rm wd}^3}{R_{\rm mag}} ,$$

where $R_{\rm lc}$ is the radius of the light cylinder. This gives the upper limit

$$A_{\rm pc} \lesssim 2.6 \times 10^{16}\ \varepsilon_{0.37}^{-1}\ \dot{M}_{16.5}^{2/7}\ \mu_{34.2}^{-4/7}\ R_{8.8}^3\ M_{0.8}\ {\rm cm}^2. \qquad (11)$$

From this equation it is easy to see that the value of $A_{\rm pc}$ is comparable with the polar cap area of the white dwarf in AE Aqr determined by Eracleous et al. (1994) provided the mass exchange rate is $\dot{M} \sim (1 \div 2) \times 10^{17}\ {\rm g\ s^{-1}}$.

The detailed investigation of particle acceleration in the magnetosphere of the white dwarf in AE Aqr is beyond the scope of this paper. Here, I would like only to pay attention to an interesting resemblance between some X-ray properties of AE Aqr and the properties of ejecting radio pulsars in the ROSAT energy range. In particular, the X-ray spectrum of pulsing component in AE Aqr fits the power law with the spectral index $\alpha = -2.0 \pm 0.4$ (Reinsch et al. 1995). Moreover, the ratio of the X-ray luminosity to the spindown power of the white dwarf in AE Aqr is

$$\frac{L_{\rm X}}{L_{\rm sd}} \sim 10^{-3}\ d_{100}^2\ M_{0.8}^{0.6}, \qquad (12)$$

where d_{100} is the distance to AE Aqr expressed in units of 100 pc. Both estimates are close to those recently reported by Becker & Trümper (1997) of 26 radio pulsars. This resemblance indicates that the energy release in the magnetospheres of these stars may have a common nature.

5. Discussion

The main consequences of the *ejector* model of AE Aqr is a relatively strong magnetic field of the white dwarf. Because of this feature the presented model differs radically from that discussed previously. Really, the value of the white dwarf's magnetic moment calculated in this paper: $\mu \simeq 1.4 \times 10^{34}\ (\sin\beta)^{-1}\ {\rm G\ cm^3}$, is almost by two orders of magnitude larger than that evaluated in previous models of the system. In this situation a natural question arises: is this estimate consistent with observed properties of AE Aqr ?

In fact, the only more or less model independent estimate of the primary's magnetic field has been made on the basis of polarimetric observations (Cropper 1986; Stockman et al. 1992; Beskrovnaya et al. 1996). Assuming that the observed circularly polarized radiation has a cyclotron origin Bastian et al. (1988) first evaluated the magnetic field of the white dwarf as $B > 10^6$ G. So, if the radius of the white dwarf in AE Aqr is $R_{\rm wd} = 6.5 \times 10^8$ cm (Eracleous et al. 1994), one get the lower limit to its magnetic moment $\mu > 3 \times 10^{32}\ {\rm G\ cm^3}$.

On the other hand, it is not unusual for white dwarfs to have the surface magnetic field of a few tens or even hundreds of MG. In particular, it is well established that the magnetic moment of white dwarfs in polars lies within the interval of $\mu \sim (1 \div 3) \times 10^{34}\ {\rm G\ cm^3}$ (Croper 1990; Chanmugam 1992; Warner 1995).

Thus, the value of the magnetic moment of the white dwarf in AE Aqr derived in the present paper does not contradict either the observed properties of the system or the present views on the values of the magnetic field of white dwarfs. So, there is no ground to consider this estimate as non-realistic.

As it has been shown in Sect. 4.2, the mass-exchange picture of AE Aqr in the frame of the *ejector* model is consistent with the picture reconstructed by Wynn et al. (1997) provided the mass transfer rate $\dot{M} \sim (0.5 \div 5) \times 10^{17}\ {\rm g\ s^{-1}}$. Namely, in this case the system has no developed accretion disk[3]: the material from the normal companion is streaming through the L_1 point into the Roche lobe of the primary and then is pushing out from the system by the fast rotating magnetosphere of the white dwarf. However, in contrast to the model of Wynn et al. (1997) the reason for this picture is the strong magnetic field of the white dwarf rather than particular properties of the accretion stream. In other words, the stream-fed, diskless accretion in AE Aqr within the ejector model is expected independently on whether the accretion stream is homogeneous or it is a superposition of blobs. In principal both possibilities can be realized in the system and incorporated in this model.

Within the suggested scenario the white dwarf is functioning as ejector as well as propeller. However, the contribution of the propeller action to the spindown of the white dwarf is relatively small. That is why, the basic assumption of the 'Speedy Magnetic Propeller' model that almost all spindown power of the white dwarf is converted into the kinetic energy of the outflowing material within the *ejector* model is not necessary. In

[3] In the general case, however, the formation of a ring-type quasi-stationary envelope beyond the radius $R_{\rm mag}$ cannot be excluded.

our case the kinetic energy as well as the luminosity of the material streaming out from the system are the parameters which could be derived from the model. The values of these parameters depend on the mechanism of interaction between the magnetosphere and the stream but never exceed the limits obtained from the energy and mass conservation laws (see Sect. 2). In particular, within the canonical model for the propeller action by a pulsar-like rotator (Illarionov & Sunyaev 1975; Davies & Pringle 1981 and references therein) the luminosity from and the velocity of outflowing material are estimated by Eqs. (8) and Eq. (9), correspondingly. It is easy to see that these estimates are in a rather good agreement with observations (Eracleous & Horne 1996 and references therein).

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