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Spindown of the primary in AE Aquarii

Nazar R. Ikhsanov[1,2]

[1] Institut für Astronomie und Astrophysik der Universität München, Scheinerstraße 1, 81679 München, Germany
(ikhsanov@usm.uni-muenchen.de)
[2] Central Astronomical Observatory of the Russian Academy of Science at Pulkovo, Pulkovo 65-1, 196140 Saint-Petersburg, Russia

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Abstract. The mass transfer in AE Aqr is discussed. It is shown that if the secondary is a K3–K5 main sequence red dwarf the system is a *wind-fed accretor* with the average rate of mass transfer $\dot{M}_{\rm a} \sim 3 \times 10^{12}\,{\rm g\,s^{-1}}$. Under this condition the rate of accretion of angular momentum is too low for the developed accretion disk to form in the system. Assuming the primary to be an accreting neutron star I have found that the observed rate of its spindown can be easily explained provided the magnetospheric radius of the neutron star $R_{\rm m} \sim R_{\rm cor}$. The 'flip-flop' instability of accretion flow is suggested as a possible mechanism of flaring activity in AE Aqr.

Key words: accretion – stars: cataclysmic variables – stars: neutron – stars: white dwarfs – stars: AE Aqr

1. Introduction

The variable star AE Aqr is a low mass non-eclipsing close binary system (see Table 1). The visual light from the system is dominated by the radiation of the secondary (up to 95%), which is identified with a K3–K5 main sequence red dwarf (Welsh et al. 1995 and references therein). The remaining optical light comes from a source with colors typical for the primary component of the cataclysmic variables (Bruch 1991 and earlier references therein) and exhibits the $33^{\rm s}$ coherent oscillations with a mean amplitude of about 0.02% (Patterson 1979). The visual brightness of the system varies on the timescale from $5^{\rm m}$ up to $1^{\rm h}$ with the amplitude up to $\Delta m \sim 3^{\rm m}$ in the U-passband (see Beskrovnaya et al. 1996 and references therein).

1.1. An 'extreme example' of the DQ Herculis class

On the grounds of the properties observed in the optical, AE Aqr was classified as a novalike cataclysmic variable (Joy 1954; Crawford & Kraft 1956) belonging to the class of Intermediate Polars (IPs) or the DQ Herculis subclass of magnetic cataclysmic variables (Patterson 1979; Warner 1983). This notion played a central role in the early development of theoretical model for AE Aqr. Following the standard view on the mass-exchange and the energy release processes in IPs, Patterson (1979) suggested the model of AE Aqr, which was based on the following assumptions (hereafter I quote this approach as *IP-model*):

- the secondary *overflows* its Roche lobe and loses its mass in the form of a stream through the first Lagrangian point (L_1);
- the primary is a fast rotating, magnetized *white dwarf* undergoing *disk* accretion;
- the primary's radiation is the superposition of radiation from the hot spots at the base of the accretion columns and that of the accretion disk.

However, the following properties of the system do not allow to consider AE Aqr a regular IP. Because of its relatively long orbital period AE Aqr is one of the largest cataclysmic variables (CVs). The $33^{\rm s}$ spin period of the primary is the shortest among those in CVs, and it exceeds the minimum period of a white dwarf rotating close to the breakup speed by a factor of less than three.

Extensive observations have shown AE Aqr to be a peculiar panchromatic emitter, whose behaviour is rather uncharacterisic for the objects of IP class. Among the unusual properties of AE Aqr are the strong, highly variable single-peaked emission lines (Crawford & Kraft 1956; Chincarini & Walker 1981; Robinson et al. 1991; Reinsch & Beuermann 1994; Eracleous et al. 1994), and the $33^{\rm s}$ coherent oscillations in the optical, UV, X-ray and TeV γ-ray spectral bands (see de Jager et al. 1994 and references therein; Eracleous et al. 1994; Meintjes et al. 1994). Whereas the X-ray spectra of all IPs are hard, AE Aqr has a soft X-ray spectrum (Osborne et al. 1995; Reinsch et al. 1995; Clayton and Osborne 1995). Furthermore, in the radio and TeV γ-rays AE Aqr is a powerful nonthermal flaring source, which could be put in one row with Cyg X-3, rather than with any of presently known CVs (Bastian et al. 1988; Abada-Simon et al. 1993; de Jager 1994).

Finally, a particular property which AE Aqr does not share with any of known CVs is the rapid flaring of its brightness in the optical, UV, X-ray and the radio bands. The temporal and

Send offprint requests to: N.R. Ikhsanov

Table 1. Parameters of the AE Aqr system

System parameters

Parameter	Value	References*
Distance	$70 \div 135$ pc	(1), (2), (3), (4), (5)
Binary period	9.88 hr	(6)
Inclination	$i < 70^\circ$	(7)
	$63^\circ < i < 70^\circ$	(6), (8), (9)
	$48^\circ \lesssim i \lesssim 62^\circ$	(5), (10)
Stellar separation	$(1.7 \div 2)\,10^{11}$ cm	
Eccentricity	0.02	(6)
Mass ratio	$0.77 \div 0.79$	(10), (11)
	~ 0.88	(8)
	~ 0.65	(5)
Luminosity**		
radio	$10^{28}\, d_{100}^2$ erg s^{-1}	(12)
optical	$10^{33}\, d_{100}^2$ erg s^{-1}	(3), (13)
UV	$10^{31}\, d_{100}^2$ erg s^{-1}	(14)
X-rays	$10^{31}\, d_{100}^2$ erg s^{-1}	(15), (16)
γrays	$10^{32}\, d_{100}^2$ erg s^{-1}	(17)

Stellar parameters

	Secondary	Primary
Stellar mass ($M_\odot$)	$0.5 \div 0.8$	$0.6 \div 1$
Spin period	~ 9.88 hr	33.08 s
Spin derivative (s s^{-1})	–	5.64×10^{-14}
Type	K3V–K5V	NS or WD***

* (1) Tanzi et al. 1981; (2) Bailey 1981; (3) van Paradijs et al. 1989; (4) Welsh et al. 1993; (5) Welsh et al. 1995; (6) Chincarini & Walker 1981; (7) Chanan et al. 1976; (8) Robinson et al. 1991; (9) Beskrovnaya et al. 1997; (10) Reinsch & Beuermann 1994; (11) Patterson 1979; (12) Abada-Simon et al. 1993; (13) Beskrovnaya et al. 1996; (14) Eracleous et al. 1994; (15) Eracleous et al. 1991; (16) Reinsch et al. 1995; (17) Meintjes et al. 1992.

** d_{100} is the distance to the star in units of 100 pc.

*** NS–neutron star, WD–white dwarf.

energetic characteristics of the active and quiet phases, which irregularly alternate on the timescale up to a few hours without any noticeable transition period, does not allow to assign AE Aqr to any of traditional subclasses of variable stars (Beskrovnaya et al. 1996 and references therein).

On the other hand, analysis of basic assumptions of the *IP-model* also reveals some controversial points. Assuming the secondary to be a K5–K3 red dwarf on the main sequence, Chincarini & Walker (1981) and Bruch (1991) calculated its radius to substitute only 89% and 93% of the mean Roche lobe radius, respectively. This is insufficient to bring the star into contact with the critical surface and thus, the normal Roche lobe overflow mechanism causing mass transfer in CVs cannot be applied to AE Aqr without additional theoretical assumptions.

Analysis of the Hα Doppler tomogram of AE Aqr has shown no evidence of the Keplerian accretion disk in the system (Wynn et al. 1995). The same conclusion has been previously made by van Paradijs et al. (1989) and Bruch (1991) on the basis of photometric data.

Detection of circularly polarized radiation from AE Aqr with the average value of $0.06 \pm 0.01\%$ (Beskrovnaya et al. 1996) implies the magnetic field in excess of 10^6 G, that according to Lamb & Patterson (1983) means impossibility of steady accretion onto the surface of the white dwarf.

Thus, none of the assumptions of *IP-model* can be presently accepted without problems. This makes the classification of AE Aqr as an intermediate polar of DQ Her class rather traditional than effective in understanding the unique properties of this object. At the same time, AE Aqr does not fit well into any of the presently known subclasses of CVs, that makes difficult re-classification of the system. Mainly by this reason AE Aqr acquired a status of an 'extreme example' of the DQ Herculis class.

1.2. The 'spindown problem'

The necessity to reconsider the *IP-model* became obvious only after de Jager et al. (1994) reported the discovery of a brake on the primary of AE Aqr with the mean rate $\dot{P} = 5.64 \times 10^{-14}$ s s^{-1}, implying a spindown power of the white dwarf:

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

Here I_{50} is the moment of inertia of a *white dwarf* in the units of 10^{50} g cm^2, $\omega_{\rm s} = 2\pi/P$, and $\dot{P}$ and P are expressed in the units of 5.64×10^{-14} s s^{-1} and 33.08 s, respectively. This means, that $L_{\rm rot}$ exceeds the UV ($L_{\rm UV}$) and the X-ray ($L_{\rm X}$) luminosities of AE Aqr by a factor of 120 (see Table I). Moreover, $L_{\rm rot}$ exceeds even the bolometrical luminosity of the system more than by a factor of five ($L_{\rm bol} \sim 10^{33} d_{100}^2$ erg s^{-1}, van Paradijs et al. 1989). Thus, the spindown power dominates the energy budget of the system, that is in contradiction with the basic postulate of the *IP-model* about the accretion nature of the primary's radiation (hereafter I quote this contradiction as 'spindown problem').

Some effort has been recently made to explain the observed spindown behaviour of the primary in AE Aqr. De Jager (1994) and de Jager et al. (1994) assumed that the white dwarf in the system is predominantly in the state of *ejector*, i.e. the dissipation of the major portion of its rotational energy occurs in the form of accelerated particles. Another explanation has been suggested by Wynn et al. (1995), under assumption that the spindown of the primary in AE Aqr is caused by the *propeller* action of a magnetized fast rotating white dwarf interacting with the flow of diamagnetic blobs.

In both of these modifications, AE Aqr turns out to be beyond not only the CVs class, but also the class of accretion-driven close binaries in general. As a matter of fact, this is the only way to explain the observed spindown of the white dwarf in the system. However, following this way one encounters a problem, that almost all results of investigations, performed before the discovery of spindown in AE Aqr, need to be reconsidered. Really, suggested explanations for the colors of primary's radiation (Bruch 1991), the (UV + optical) spectrum of the 33$^{\rm s}$

pulsations (Eracleous et al. 1994), the origin of soft X-ray component of radiation (Eracleous et al. 1991), the quasi-periodic oscillations in the optical-UV bands (Patterson 1979) and even for the flaring radio emission (Bastian et al. 1987) are based on the postulate of gas accretion onto the surface of the primary. This is the more so with regards to the "magnetospheric gating" model of flaring activity in AE Aqr (van Paradijs et al. 1989). At the same time, many basic properties of the system, such as its rapid flaring and so fast rotation of the white dwarf remain puzzling even in the modified models (Robinson 1995).

1.3. The NS-approach

While this is not a compelling argument against the primary as predominantly 'ejector' or 'propeller' white dwarf, it suggests that alternative possibilities might be more fruitful. One of them was discussed in my previous papers (Ikhsanov 1995a, hereafter Paper I; Ikhsanov 1995b). Namely, it has been shown that at least some of the difficulties in the interpretation of AE Aqr can be avoided assuming that the primary in this system is a *neutron star* (hereafter I quote this as NS-approach). The most remarkable fact is that under this assumption the 'spindown problem' and, correspondingly, the paradox about the state of the primary in AE Aqr simply does not arise ! In this case, the ratios of the spindown power, Eq. (1), to the UV, X-ray and the bolometrical luminosities of the system are

$$\frac{L_{\rm rot}}{L_{\rm bol}} \ll \frac{L_{\rm rot}}{L_{\rm UV}} \sim \frac{L_{\rm rot}}{L_{\rm X}} \sim 6 \times 10^{-3}\ I_{45}\ \dot{P}\ P^3$$

where I_{45} is the moment of inertia of a *neutron star* in the units of 10^{45} g cm^2. This allows to interpret the majority of observational data on AE Aqr on the basis of an accretion model, i.e. in the frame of the basic postulate about the "oblique rotator" (Patterson 1979) and the accretion nature of the thermal emission from the system at the optical, UV and the X-ray wavelengths.

Analysis of the primary parameters, performed in Paper I, did not reveal any principal contradictions of the basic assumption of the NS-approach with the modern views on the physics of neutron stars (see Lipunov 1992). The commonly adopted lower limit to the primary mass ($M_1 \gtrsim 0.6 M_{\odot}$) does not exclude the presence of a neutron star in the system. The $33^{\rm s}$ spin period and the strong magnetic field are typical for the primary components of X-ray pulsars. In contrast to models that set a white dwarf as the primary of AE Aqr, there are no particular theoretical problems with physics and origin of such a neutron star.

Assuming the accretion nature of primary's radiation, the average rate of gas accretion onto the neutron star surface proves to be of the order of

$$\dot{M}_{\rm ns} = \frac{\tilde{L}_1 R_{\rm ns}}{G M_1} \sim 2 \times 10^{12}\ \tilde{L}\ R_6\ m^{-1}\ d_{100}^2\ \ {\rm g\,s^{-1}} \qquad (2)$$

where $\tilde{L}$ is the average luminosity of the primary component (on the time scale of about one orbital period) in the units of 2×10^{32} erg s^{-1} (de Jager 1995; Beskrovnaya et al. 1997), R_6 is the radius of the neutron star in the units of 10^6 cm, and $m = M_1/M_{\odot}$. From the theoretical point of view, so low rate of mass-exchange in a low mass close binary system can be realized if the normal component does not overflow its Roche lobe (Masevich & Tutukov 1988). If this is the case in AE Aqr, the current evolutionary status of the system can be classified as *a Precursor of Low Mass X-ray Pulsar* (Pre-LMXP), since after the secondary in this system has overfilled its Roche lobe, one will observe a pulsar with parameters typical for the objects of LMXPs class (see Paper I).

This classification, however, does not essentially help to describe the accretion picture in the system in detail. While the numerical computations of evolutionary tracks predict a considerable number of close binaries passing the Pre-LMXPs stage (see Iben et al. 1995), AE Aqr still remains the first and the only candidate to this class. This makes theoretical modeling of accretion process in the objects of this particular class very complicated and, as a consequence, rather poorly developed so far. On the other hand, analysis of several basic properties – the photometric behaviour, the spectrum and the spindown – leaves no doubts that AE Aqr does not fit in the standard accretion picture suggested for the interacting low mass binaries. By these reasons, an independent investigation of the mass-exchange and energy release in AE Aqr, based on the observed properties rather than assumptions about the classification and evolutionary status of the system, appears to be more fruitful.

In this paper I focus on the investigation of the mass-exchange process in AE Aqr. In the next section I consider the average rate of mass transfer in the system. The rate of accretion of angular momentum, $\dot{J}$, the condition for accretion disk formation and the rate of spindown are the subject of Sect. 3. The results obtained are summarized in Sect. 4.

2. The rate of mass transfer

Theoretical modeling of mass-exchange process in a close binary system depends essentially on the ratio of the secondary star radius to the radius of its Roche lobe, $\eta = R_2/R_{\rm Roche}$, the physical conditions in the atmosphere of normal component and the system parameters.

2.1. Estimates of parameter η

Bruch (1991) and Welsh et al. (1995) argued that the secondary in AE Aqr is a K3–K5 red dwarf with no observed deviations from the main sequence. According to Chincarini & Walker (1981) and Bruch (1991) this identification allows to estimate the ratio of the secondary star radius to the mean Roche lobe radius as $\eta \lesssim 0.93$.

An independent estimate of the parameter η is based on the analysis of gradual variations of optical brightness observed at the quiescent light curves of AE Aqr. Van Paradijs et al. (1989) argued that these variations (with the average amplitude in the V-band of ~ 0.2 mag) are likely due to ellipsoidal variations as a result of the tidal distortion of the secondary. According to Bochkarev et al. (1980), the amplitude of these variations depends on the inclination i, the ratio η, the mass ratio q, the gravity-darkening parameter β, and the limb-darkening coefficient u. In the case of AE Aqr the last three parameters can be approximated as q = 0.79, β = 0.55 and u = 0.86 (van Paradijs et al. 1989). Thus, the observed amplitude of ellipsoidal variations can be used to constrain the parameter η, for a given value of inclination.

Taking $i \approx 58^{\circ}$ (Patterson 1979; Reinsch & Beuermann 1994; Welsh et al. 1995), I get $\eta \approx 1$, that corresponds to the result previously derived by van Paradijs et al. (1989) and Welsh et al. (1995). However, repeating this procedure for $i \gtrsim 60^{\circ}$ (Chincarini & Walker 1981; Robinson et al. 1991), I have found that the observed amplitude of ellipsoidal variations in AE Aqr can be explained only assuming $\eta < 1$.

In fact, because of the lack of eclipses the direct determination of inclination of AE Aqr is difficult. The only model-independent estimate of inclination is the upper limit: $i < 70^{\circ}$ (Chanan et al. 1976). Correspondingly, this allows to set only the lower model-independent limit to this parameter: $\eta > 0.91$. Hence, assuming the secondary in AE Aqr to be a main sequence red dwarf, the ratio of its radius to the mean Roche lobe radius can be limited as follows $0.91 \lesssim \eta \lesssim 0.93$. This condition is satisfied if the orbital inclination lies in the range $63^{\circ} \lesssim i \lesssim 70^{\circ}$ (for detailed discussion see Beskrovnaya et al. 1997).

If the secondary in AE Aqr is not a main sequence star, but is slightly evolved, it should be larger than a main sequence star of its spectral type. In this case, the upper limit of η may exceed the value obtained by Bruch (1991) and can be ranged only within the interval: $0.93 \div 1$. This argument has been widely used in the previous modeling of AE Aqr in order to justify one of the basic assumptions of *IP-model* that the radius of the secondary is comparable with its Roche lobe radius, so that the mass transfer via normal Roche lobe overflow takes place in the system.

However, in the particular case of AE Aqr, the assumption $\eta \cong 1$ leads to serious problems with the determination of evolutionary status of the system. Namely, if the primary in AE Aqr is a *white dwarf*, its rapid rotation can be explained only assuming spin-up due to the active accretion process (de Jager 1994). This indicates, that in a previous epoch the mass accretion rate in AE Aqr was significantly higher than at present. In particular, the required minimum value of the mass accretion rate during the active epoch is $\dot{M} \gtrsim 2 \times 10^{18}$ g s^{-1} and its duration was at least $\Delta t \gtrsim 8 \times 10^{6}$ yr (see Paper I). During this epoch the secondary lost at least 25% of its mass on the timescale, which is by three orders less than the characteristic time of evolution of late type main sequence stars (Masevich & Tutukov 1988). Under these conditions the evolutionary track of the secondary cannot be approximated by that calculated for a single red dwarf. On the basis of this de Jager (1994) suggested that the evolutionary status of the secondary should be classified using the notion "hibernation" (Livio 1988a and references therein) rather than the notion "slightly evolved". Otherwise, no reasonable explanation for the origin of so fast rotating white dwarf in the system can be given.

On the other hand, assuming the primary in AE Aqr to be a *neutron star*, the condition $\eta \cong 1$, implies the X-ray luminosity of the system, $L_{\rm X} \sim 10^{37}$ erg s^{-1} (see Paper I), that exceeds the observed value by six orders of magnitude.

Summarizing the results of the above analysis we can conclude, that one of the basic assumptions of *IP-model*, that the normal component in AE Aqr overflows its Roche lobe, has no observational and theoretical grounds. This indicates, that the rate of mass loss by the secondary through the L_1 point might be essentially less than the rate of mass loss by the secondary on the thermal timescale: $\dot{M}_{\rm th} \sim (M_2/t_{\rm th})$ (Masevich & Tutukov 1988), and thus other mechanisms of mass transfer cannot be neglected. In the following subsection I estimate the rate of mass capturing by the primary from the secondary's stellar wind, that gives the lower limit to the rate of mass transfer in the system. In Sect. 2.3 the rate of mass transfer due to the irradiation-driven mechanisms for the case of AE Aqr is discussed.

2.2. The accretion from a stellar wind

The average rate of mass capturing by the compact star from a stellar wind can be evaluated as (Frank et al. 1985):

$$\dot{M}_{\rm wa} \lesssim \dot{M}_{\rm ws} \left(\frac{r_\alpha}{2a}\right)^2 \tag{3}$$

where $\dot{M}_{\rm ws}$ is the rate of mass loss by the normal component in the form of stellar wind, a is the orbital separation and r_α is the accretion radius of the compact star:

$$r_\alpha = \frac{2GM_1}{(\Omega_{\rm orb}a)^2 + V_{\rm ws}^2}, \tag{4}$$

Here, M_1 is the mass of the compact star, $\Omega_{\rm orb}$ is the orbital angular velocity of the system and $V_{\rm ws}$ is the stellar wind velocity in the reference frame of the normal component.

The parameters of the wind from a late-type main sequence star depend on the physical conditions in the corona, star rotation and the flaring activity (Badalyan & Livshits 1992; Katsova 1993; Linsky 1996 and references therein). Because of tidal distortion, the dissipation of rotational energy of late-type components of close binaries is very effective, so that the spin period of normal component usually turns out to be synchronized with the orbital period (see Zahn 1989). According to the results of spectroscopic observations, AE Aqr is not an exception of this rule (see Welsh et al. 1995), so the star rotation is rather unimportant in the case under consideration.

The assumption that the secondary of AE Aqr is a flaring star seems quite reasonable from the theoretical point of view. Extensive investigations (see Byrne 1995; Bastian 1996; Gershberg 1996 and references therein) have shown that it is not unusual for the red dwarfs of K-type to be relatively active flaring stars. Welsh et al. (1995) found that the distribution of absorption-line strength across the normal component of AE Aqr is rather non-uniform, that might be indicative of the star-spot regions and, correspondingly, the flare activity. At the same time, investigations of photometric behaviour of the system at various wavelengths, suggest that if the secondary in AE Aqr is indeed a flaring star, its activity cannot be regarded as extremely vigorous, so its contribution to the exotic rapid flaring observed from AE Aqr is almost negligible (Bastian et al. 1988; Bruch 1991; Beskrovnaya et al. 1996; Eracleous et al. 1996).

Assuming the secondary in AE Aqr to be a moderately active star, the average rate of mass loss due to nonthermal stellar wind can be estimated using the results of Badalyan & Livshits (1992), as $\dot{M}_{\rm ws} \lesssim 10^{-12} {\rm M}_{\odot}\ {\rm yr}^{-1}$. According to radio observations, the plasma temperature in the corona of K-type flaring red dwarf is at least by order higher than that in the corona of the Sun (Linsky 1996). This makes possible to set the average value of the wind velocity as $V_{\rm ws} \sim 400$ km s^{-1}. Substituting the above values of parameters to Eqs. (4) and (3) I find the average rate of mass captured by the primary of AE Aqr from the stellar wind:

$$\dot{M}_{\rm wa} \lesssim 2.45 \times 10^{13} \left(\frac{1}{1 + 2.2 \sin^2 i} \right)^2 \ {\rm g\ s^{-1}} \qquad (5)$$

In particular, for the value of inclination suggested in the previous subsection, $62^{\circ} < i \lesssim 70^{\circ}$, one gets $\dot{M}_{\rm wa} \lesssim 3.3 \times 10^{12}$ g s^{-1} (see Fig. 1).

Some variations of $\dot{M}_{\rm wa}$ around the average value expressed by Eq. (5) can be expected due to deviation of the stellar wind from the spherical symmetry, or due to various events like the coronal mass ejection observed in the Sun (see Chertok 1991). The contribution of such events to the average rate of the solar wind is not essential. Nevertheless, in the case of AE Aqr these effects might be one of the reasons for the small irregular variations of the system brightness.

2.3. Irradiation-driven accretion

In the general case, the condition $\eta < 1$ implies that the rate of mass transfer through the L_1 point is not high. Nevertheless, studies (e.g. Osaki 1985; Hameury et al. 1986; Kovetz et al. 1988; Sarna 1990; Harpaz & Rappaport 1991) have shown that if the secondary in a binary is heated by the primary's radiation, the mass transfer can be enhanced.

Radiation of the primary in AE Aqr manifests itself mainly in the UV and soft X-ray spectral domains with the luminosity of $L_{\rm UV} \sim L_{\rm X} \sim 10^{31} d_{100}^2 {\rm erg\,s^{-1}}$ (Patterson et al. 1980; Eracleous et al. 1991; Eracleous et al. 1994). In the ROSAT energy range the X-ray spectrum of AE Aqr during quiescence can be approximated by a power law plus an emission line feature centered at 0.85 keV. During the active phase the total flux in X-rays increases by a factor of up to three and the spectrum becomes somewhat harder (Reinsch et al. 1995). Combining these results and observational data obtained with the *Einstein* space telescope (Eracleous et al. 1991), it is possible to conclude that the intensity of X-ray flux from AE Aqr has a local maximum centered at $E_{\gamma} = (0.7 \div 0.9)$ keV for the quiescence and the flaring phases, respectively, and it is decreasing rapidly beyond 1 keV. In other words, the illuminating X-ray photons are soft independently on the flaring/quiescent state of the system.

The soft X-ray photons ($E_{\gamma} \sim 1$ keV) are absorbed by photoionization at the column density of about 10^{-2} g cm^2. For a K type main sequence star this corresponds to the region above the photospheric level where the atmospheric density is of the order of $\rho_0 \sim 10^{-10}$ g cm^{-3}. The ionization parameter in the illuminated region is $\xi = L_{\rm X}/nR^2 \lesssim 10^{-4}$, where n is the density of the absorbing material, and R is the distance to the X-ray source. This indicates, that the temperature in the upper atmosphere of the secondary of AE Aqr should be of the order of 10^4 K (Buff & McCray 1975).

The mass overflow rate of the Roche lobe filling secondary star can be expressed as follows (see Meyer & Meyer-Hofmeister 1983):

$$\dot{M}_{\rm ia} = Q \rho_{L_1} c_{\rm s} \qquad (6)$$

where Q is the effective cross section of the mass transfer throat at the L_1 point, ρ_{L_1} is the mass density at L_1, and $c_{\rm s}$ is the sound speed. The effective cross section calculated for the parameters of AE Aqr is

$$Q = \frac{2\pi c_{\rm s}^2 a^3}{kG(M_1 + M_2)} \sim 1.85 \times 10^{19} \left(\frac{T}{10^4\,{\rm K}} \right) {\rm cm}^2, \qquad (7)$$

and the mass density in the vicinity of the L_1 point:

$$\rho_{L_1} = \rho_0 e^{-(\Delta R/H)^2} \qquad (8)$$

Here, k is a dimensionless constant depending on the mass ratio of the components, ρ_0 is the mass density at the base of the isothermal corona, ΔR is the distance from the bottom of the corona to the L_1 point, and the scale length, H, calculated using the parameters appropriated for AE Aqr is

$$H \sim 1.57 \times 10^9 \left(\frac{T}{10^4\,{\rm K}} \right)^{1/2} {\rm cm} \qquad (9)$$

Substituting Eqs. (7) and (9) to Eq. (6) and taking $T \sim 10^4$ K and $\rho_0 \sim 10^{-10}$ g cm^{-3}, I find the rate of mass transfer from the secondary of AE Aqr through the L_1 point in the following form:

$$\dot{M}_{\rm ia}(\Delta R) \approx 1.7 \times 10^{15} \exp \left\{ - \left(\frac{\Delta R}{10^{9.2}\,{\rm cm}} \right)^2 \right\} {\rm g\ s^{-1}} \qquad (10)$$

Since the contribution of photons with energies $E_{\gamma} \gtrsim 1$ keV to the illuminating flux during the flaring phase of AE Aqr remaining comparably small, the irradiation-induced instability of mass transfer is unlikely to be realized in the system (see Hameury et al. 1986). This makes possible to suggest that amplitude of variations of $\dot{M}_{\rm ia}$ due to variations of the illuminating flux remains comparably small.

The function $\dot{M}_{\rm ia} = \dot{M}_{\rm ia}(\eta)$ and the resulting rate of mass transfer in the system: $\dot{M}_{\rm a} = \dot{M}_{\rm wa} + \dot{M}_{\rm ia}$ are shown in Fig. 1. Under the condition $0.96 < \eta < 1$, the mass transfer in AE Aqr is dominated by the mass flux through the L_1 point. Accretion picture in this case is similar to that considered within

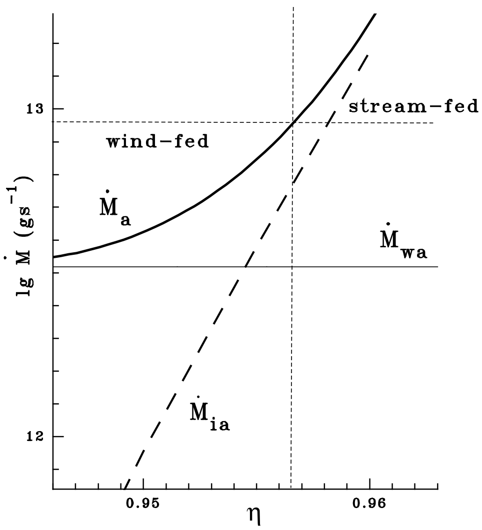

Fig. 1. The average rate of mass captured by the primary in AE Aqr from the stellar wind, $\dot{M}_{\rm wa}$, the rate of mass transfer through the L_1 point, $\dot{M}_{\rm ia}$ and the resulting rate of mass accretion onto the primary, $\dot{M}_{\rm a} = \dot{M}_{\rm wa} + \dot{M}_{\rm ia}$ are plotted in the logarithmic scale versus the ratio of the secondary radius to the mean Roche lobe radius, η.

the *IP-model*. However, the resulting rate of mass transfer, $\dot{M}_{\rm a} \sim 10^{13} \div 10^{15}\,{\rm g\,s^{-1}}$, is significantly lower than that required in the frame of models that place a white dwarf as a primary. On the other hand, the obtained value of $\dot{M}_{\rm a}$ at least by an order exceeds the upper limit to the rate of mass transfer suggested in the NS-approach (see Sect. 1.3). Thus, the case $= 0.96 < \eta < 1$ seems unrealistic in both approaches.

On the contrary, under the condition: $\eta \lesssim 0.96$ (which corresponds to the determination of the secondary as a K3–K5 main sequence red dwarf, see Sect. 2.1), AE Aqr is a *wind-fed accretor* (Nagase 1989 and references therein). In this case the rate of mass transfer is $\dot{M}_{\rm a} \sim$ a few $\times\, 10^{12}\,{\rm g\,s^{-1}}$. This is close to the value of $\dot{M}_{\rm ns}$ estimated within the NS-approach (Eq. 2), rather than that suggested in the frame of *IP-model* and its modifications. Hence, under the condition $\eta \lesssim 0.96$, a white dwarf is unlikely to be the primary of AE Aqr. The accretion picture in this case is discussed in the following section.

3. Accretion of angular momentum

The importance of the rate of angular momentum accretion lies, in particular, in two observable phenomena: (i) the spinup/spindown of the accreting compact star and (ii) the possibility of forming an accretion disk around wind fed accretor.

3.1. The geometry of accretion flow

For a disk to form, the specific angular momentum of the matter captured by the compact star must be sufficient to allow it to enter a Keplerian circular orbit around the magnetosphere (see Lipunov 1992 and references therein):

$$R_{\rm m} < R_{\rm d} = \frac{\dot{J}^2}{\dot{M}_{\rm a}^2 G M_1} \qquad (11)$$

where $R_{\rm m}$ is the equatorial magnetospheric radius of the primary, $R_{\rm d}$ is the inner radius of the accretion disk and $\dot{J}$ is the rate of accretion of angular momentum.

One of the problems associated with accretion from a stellar wind is the fact that the accretion flow cannot be considered homogeneous. Even in the absence of clumpiness in the wind, the mere existence of a velocity (or density) gradient results in a difference in the velocity (or density) of the material entering the accretion cylinder's cross section (see Livio 1988b).

Assuming that all the angular momentum deposited into the symmetric accretion cylinder is accreted by the compact star Illarionov & Sunyaev (1975) and Shapiro & Lightman (1976) have calculated the rate of accretion of angular momentum as

$$\dot{J}_0 = \frac{1}{2}\eta_{\rm k}\Omega_{\rm orb} r_\alpha^2 \dot{M}_{\rm a} \qquad (12)$$

where $\eta_{\rm k}$ is a parameter (of the order of unity) which depends on the density and velocity gradients in the accretion flow beyond the symmetric accretion cylinder (Wang 1981).

However, further analytical investigations (Davies & Pringle 1980; Soker & Livio 1984) as well as the numerical 2D and 3D computations (e.g. Livio et al. 1986a,b; Soker et al. 1986; Anzer et al. 1987; Taam & Fryxell 1988; Sawada et al. 1989; Matsuda et al. 1991) have shown the average rate of angular momentum accretion to be considerably lower (at least by a factor of 5) than that obtained from Eq. (12). Putting $\dot{J} = \xi \dot{J}_0$ to Eq. (11) I find

$$R_{\rm d} \lesssim 3.7 \times 10^8\, \xi_{0.2}^2\, P_{10}^{-2}\, r_{11}^4\, m^{-1}\ {\rm cm} \qquad (13)$$

where $\xi_{0.2} = \xi/0.2$ is the factor by which the average rate of accretion of angular momentum is reduced, P_{10} is the orbital period in units of 10 hr and $r_{11} = (r_\alpha/10^{11}\ {\rm cm})$.

Under the conditions of interest for AE Aqr the relation (11) *cannot be satisfied* by the following reasons. Using the accretion parameters obtained in the previous section the relation (13) implies the magnetic moment of the neutron star $\mu \lesssim 7\times 10^{27}\ {\rm G\,cm^3}$. In this situation the ratio of decelerating to accelerating torques applied to the neutron star is (see Lipunov 1992):

$$\frac{K_{\rm sd}}{K_{\rm su}} \lesssim 4 \times 10^{-2}\, \mu_{28}^2\, \dot{M}_{12}^{-1}\, m^{-1/2} \left(\frac{R}{R_{\rm cor}}\right)^{-3} \left(\frac{R}{R_{\rm d}}\right)^{-1/2}$$

that corresponds to a rapid spin-up of the primary in contrast to the observed spindown behaviour. Here, μ_{28} is the magnetic moment of a neutron star expressed in the units of 10^{28} G cm^3, $\dot{M}_{12} = (\dot{M}/10^{12}\ {\rm g\ s^{-1}})$ and $R_{\rm cor}$ is the corotational radius, which in the case of AE Aqr is

$$R_{\rm cor} = \left(\frac{G M_1 P_s^2}{4\pi^2}\right)^{1/3} \sim 1.5 \times 10^9\ {\rm cm} \qquad (14)$$

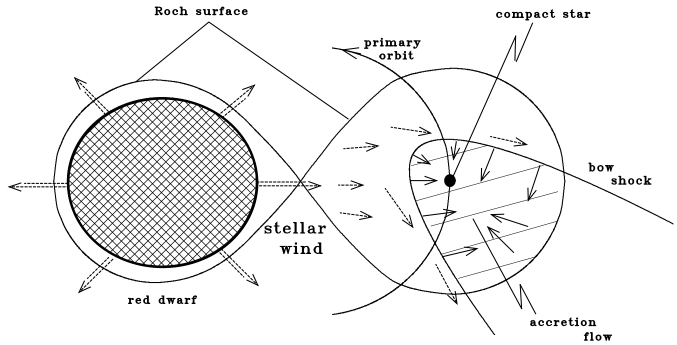

Fig. 2. The schematic two-dimentional picture of mass transfer in AE Aqr under the condition $\eta \lesssim 0.96$

Moreover, assuming the relation (13) to be valid, the linear velocity of plasma in the inner part of accretion disk is $V_{\rm k} = \sqrt{GM_1/R_{\rm d}} \gtrsim 5 \times 10^8$ cm s^{-1}. However, this exceeds by an order the maximum velocities obtained from the width of emission lines observed in the UV spectrum of AE Aqr (Eracleous et al. 1994).

On the basis of this, I am forced to conclude that *the developed α-disk is unlikely to form in* AE Aqr. Hence, the gas captured by the primary is falling onto its magnetosphere *quasi-radially*. The fine geometry of accretion flow in this case is very complicated and is the subject of numerical simulations.

The schematic two-dimensional picture of possible mass transfer in AE Aqr in the frame of suggested approach is shown in Fig. 2. It is interesting, that from this point of view the lack of observational evidence for the developed accretion disk in AE Aqr can be understood without additional assumptions about the specific geometry of the system and/or exceptional physical conditions in the plasma of the accretion flow.

3.2. Fluctuations of the accretion flow

Extensive investigations of the flow parameters in the case of accretion from a stellar wind (e.g. Matsuda et al. 1987; Taam & Fryxell 1988; Sawada et al. 1989; Matsuda et al. 1991) have shown that in some situations the accretion flow does not reach a steady state. Instead, it exhibit a ‘flip-flop’ behaviour (flag-type oscillations of the shock cone from side to side, see Fryxell & Taam 1988) accompanied by large amplitude oscillations in the specific angular momentum of the accreted matter and, as a consequence, by short periods of disk-like envelope formation. Each fluctuation in the flow geometry leads to an accretion episode in which the matter stored in the disk-like envelope is accreted in a flare type event. The corresponding amplitude of fluctuations in the mass accretion rate was found to range in the interval $(\Delta \dot{M}_{\rm a}/\dot{M}_{\rm a}) \sim 2 \div 10$, and the recurrent time of flaring events is of order: a few $\times r_\alpha/\sqrt{(\Omega_{\rm orb} a)^2 + V_{\rm ws}^2}$.

Applying these results to AE Aqr, I find that if the accretion flow is unstable with respect to the flip-flop instability, the flaring activity with the following parameters is *predicted*:

- the flaring luminosity: $L_{\rm f} \sim 2 \times 10^{32} \div 10^{33}$ erg s^{-1};
- the recurrent time: $t_{\rm rec} \sim 20^{\rm m} \div 1^{\rm h}$.

It is easy to see that these values are very close to the observed amplitude and recurrent time of large flaring events in AE Aqr (see Ikhsanov 1995c). This gives a good reason to discuss the flip-flop instability in the accretion flow as a possible mechanism of flaring in this system.

3.3. The spindown rate of the primary

The rate of change in the spin of an accreting neutron star can be calculated using the following expression:

$$\frac{d\omega_{\rm s}}{dt} = \frac{1}{I}(K_{\rm sd} + K_{\rm su}) \qquad (15)$$

where I is the moment of inertia of the neutron star, $K_{\rm sd}$ and $K_{\rm su}$ are the decelerating and accelerating torques, respectively, and $\omega_{\rm s} = 2\pi/P$.

According to the result of previous subsections, the average value of the specific accelerating torque applied to the primary of AE Aqr can be approximated as follows:

$$K_{\rm su} \sim \frac{1}{2}\xi\, \Omega_{\rm orb}\, r_\alpha^2 \dot{M}_{\rm a} \qquad (16)$$

Magnetized compact star undergoing spherical or quasi-radial accretion is losing its rotational energy predominantely due to interaction with the surrounding gas at the magnetospheric boundary (see Lipunov 1992 and references therein).

Under the condition $R_{\rm m} \lesssim R_{\rm cor}$, the maximum value of decelerating torque applied to a spherically accreting compact star can be expressed in the following form (see e.g. Börner et al. 1987, for discussion in a slightly different context):

$$K_{\rm SD} \sim \dot{M}\omega_{\rm s} R_{\rm m}^2$$

If the accretion onto the surface of the star is realized, this value should be reduced to that part of the rotational energy which is converted at the magnetospheric boundary to the kinetic energy of rotational motion of the surrounding gas and is transferred back to the star due to accretion. Hence, the deceleration torque in the considered case can be written as

$$K_{\rm sd} \sim \theta K_{\rm SD} \qquad (17)$$

where parameter θ denotes the fraction of star’s rotational energy converted up through the surrounding gas and lost in a form of outflowing gas and/or accelerated particles.

Putting Eqs. (16) and (17) to Eq. (15), setting $\dot{M}_{\rm a} = \dot{M}_{\rm ns}$ (see Eq. (2)) and substituting the parameters of AE Aqr, I find the mean spindown rate of the neutron star in the system:

$$\dot{P} = \frac{R_{\rm ns} P^2}{2\pi G M_1 I}\, \tilde{L}\, \left(\frac{2\pi}{P}\theta R_{\rm m}^2 - \frac{1}{2}\xi\, \Omega_{\rm orb}\, r_\alpha^2\right) \approx \qquad (18)$$

$$\approx 5.5 \times 10^{-14}\, (\theta R_9^2 - 0.36\, \xi_{0.2}\, r_{10.8}^2)\ {\rm s\,s^{-1}}$$

Here, $R_9 = R_{\rm m}/10^9$ cm, $\xi_{0.2} = \xi/0.2$ and $r_{10.8} = r_\alpha/10^{10.8}$ cm. The function $\dot{P} = \dot{P}(R_{\rm m})$ is shown in Fig. 3.

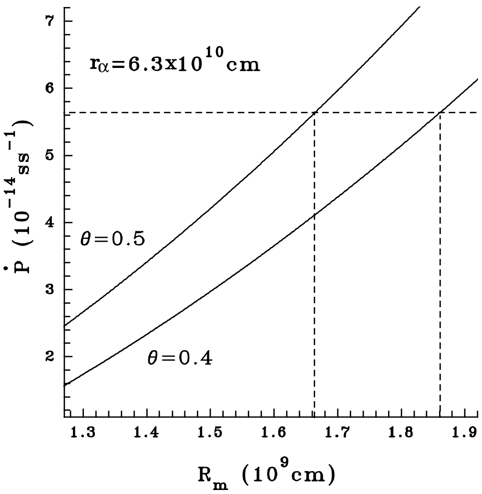

Fig. 3. The average spindown rate of the neutron star in AE Aqr as a function of the magnetospheric radius, $R_{\rm m}$.

The following consequences can be derived from this result. The condition for the primary in AE Aqr to spindown can be written as $R_{\rm m} > R_0$, where

$$R_0 = r_\alpha \left(\frac{\xi P \Omega_{\rm orb}}{4\pi\theta}\right)^{1/2} \sim 7 \times 10^8 \, r_{10.8} \left(\frac{\xi_{0.2}}{\theta}\right)^{1/2} \text{ cm}$$

On the other hand, setting the second term in Eq. (18) equal to zero and substituting $R_{\rm m} = R_{\rm cor}$, I find the upper limit to the spindown rate of the accreting neutron star in the system:

$$\dot{P} \lesssim 1.2 \times 10^{-13} \, \theta \left(\frac{R_{\rm m}}{1.5 \times 10^9 \text{ cm}}\right)^2 \text{ s s}^{-1} \quad (19)$$

Hence, under the condition $\theta^{-1/2} R_0 < R_{\rm m} < \theta^{-1/2} R_{\rm cor}$, the expected spindown rate of the neutron star is very close to the spindown rate of the primary in AE Aqr reported by de Jager et al. (1994).

The parameter θ can be estimated using the fact, that under the condition $R_{\rm m} \gg R_{\rm cor}$ the neutron star is in the state of supersonic propeller and, according to Davies & Pringle (1981), its spindown rate is independent of the spin period. The part of the energy loss rate which in this case is converted up through the surrounding atmosphere, $L_{\rm c}$, can be estimated using Eq. (3.1.6) of the paper by Davies & Pringle. Thus, the absolute maximum for the spindown rate of the neutron star in the system is

$$\dot{P}_{\rm max} \sim \frac{L_{\rm c} P^3}{4\pi^2 I} \sim 6 \times 10^{-14} \, I_{45}^{-1} P \dot{M}_{\rm a} V_\infty^2 \quad (20)$$

where $V_\infty = \sqrt{(\Omega_{\rm orb} a)^2 + V_{\rm ws}^2}$. Setting $\dot{P} \lesssim \dot{P}_{\rm max}$ I find from the Eqs. (19) and (20): $\theta \lesssim 0.5$.

Putting $\dot{P}_0 = 5.64 \times 10^{-14}$ s s^{-1} to Eq. (18) I estimate the mean equatorial radius of the magnetosphere of the neutron star in the frame of suggested scenario as

$$\tilde{R_{\rm m}} \sim 1.66 \times 10^9 \, \theta_{0.5}^{-1/2} \text{cm} \sim 1.1 \, \theta_{0.5}^{-1/2} R_{\rm cor}. \quad (21)$$

where $\theta_{0.5} = \theta/0.5$. Assuming that the magnetospheric shape of the neutron star is the same as described by Arons & Lea (1976), I find the polar magnetospheric radius to be $R_{\rm cusp} \lesssim 0.51 R_{\rm m} = 8.5 \times 10^8$ cm. This indicates, that the state of the neutron star in the system might be classified as *accretor-propeller*.

The stability of $\dot{P}$, as it follows from Eq. (18), is predominantly determined by the stability of the mass accretion rate. Since there is no observational evidence of the long-term variations in the average accretion rate in the system, $\dot{P}$ is expected to be stable of the timescale of decades. At the same time, variations of $\dot{P}$ on short timescales cannot be excluded. However, the mass accretion rate in AE Aqr calculated within presented approach being relatively low, the amplitude of these variations should be essentially lower than that observed in the "classical" X-ray pulsars that makes the detection of these variations difficult.

4. Conclusions

First of all, I would like to emphasize the fact, that *no assumptions about the nature of the compact star as well as about the evolutionary status and the classification of the system have been used in the modeling of mass transfer in* AE Aqr presented in this paper. Moreover, in contrast to previous investigations, I did not use any additional theoretical assumptions about the evolutionary status of the normal component (such as the 'slightly evolved' or the 'hibernation'), but operated only with the observed properties of the secondary, as a K3–K5 red dwarf with no observable deviations from the main sequence.

The limit to the ratio: $\eta = R_2/R_{\rm Roche} \lesssim 0.93$, obtained by Chincarini & Walker (1981) and Bruch (1991), is taken as the basis of the model. It is shown that this estimate implies the inclination to range within $62^\circ \lesssim i \lesssim 70^\circ$.

Under this condition AE Aqr is found to be a *wind-fed* accretor with the average rate of mass captured by the primary: $\dot{M}_{\rm a} \sim 3 \times 10^{12}$ g s^{-1}. The corresponding average rate of accretion of angular momentum was found to be too small for the developed accretion disk to form in the system.

Because of the low rate of mass transfer, a white dwarf is unlikely to be the primary of the system. The obtained value of $\dot{M}_{\rm a}$ is rather close to the mass accretion rate onto the primary calculated within the NS-approach (see Eq. (2)). This indicates, that the alternative assumption – that the primary in AE Aqr is an accreting neutron star – might be more fruitful in the case under consideration.

In order to test this assumption, I calculated the spindown rate of the neutron star for the above values of parameters. I find that under the conditions of interest for AE Aqr the mean spindown rate of the neutron star is limited as $\dot{P} \lesssim 10^{-13}$ s s^{-1}. In particular, the observed mean spindown rate of $\dot{P} = 5.64 \times 10^{-14}$ s s^{-1}, reported by de Jager et al. (1994), can be well described in the frame of the *wind-fed* accretor model of AE Aqr, assuming the magnetospheric radius of the neutron star to be $R_{\rm m} \sim R_{\rm cor}$. This is in good agreement with the estimate of $R_{\rm m}$ derived in Paper I.

Thus, in the frame of the *wind-fed* accretor model of AE Aqr presented in this paper, *there are no particular theoretical problems with interpretation of observed spindown rate of the primary*. This makes the assumption of a neutron star primary in the system to seem more viable.

Among other consequences of the constructed model are the prediction of the 'flip-flop' instability of the accretion flow accompanied by flaring events with

- the flaring luminosity $L_{\rm f} \sim (2 \div 10)\ L^{\rm q}$, and
- the recurrent time $t_{\rm rec} \sim 20^{\rm m} \div 1^{\rm h}$;

the formation of the strong bow shock in front of the neutron star, moving through the accretion flow with the supersonic velocity, and the quasi-periodical formation of the disk-like envelope around the magnetosphere of the neutron star. These factors might be helpful in the interpretation of the quiescent light curve (see Beskrovnaya et al. 1997) as well as of the flaring activity and the optical-UV emission lines.

Finally, the presented scenario of accretion in AE Aqr revealed a very intriguing problem: if the primary in AE Aqr is indeed a neutron star, why its appearance in the optical-UV is very likely to that of an accreting white dwarf. The answer to this question could be given only on the basis of detailed investigation of accretion process at the magnetospheric boundary and inside the magnetosphere of the neutron star. This investigation will be a subject of the forthcoming paper.

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