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High-energy emission of fast rotating white dwarfs

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ABSTRACT

The process of energy release in the magnetosphere of a fast rotating, magnetized white dwarf can be explained in terms of the canonical spin-powered pulsar model. Applying this model to the white dwarf companion of the low mass close binary AE Aquarii leads us to the following conclusions. The system acts as an accelerator of charged particles whose energy is limited to $\mathcal{E}_{\rm p} \lesssim 3$ TeV and which are ejected from the magnetosphere of the primary with the rate $L_{\rm kin} \lesssim 10^{32}$ erg s^{-1}. Due to the curvature radiation of the accelerated primary electrons the system should appear as a source of soft γ-rays (∼100 keV) with the luminosity $<3 \times 10^{27}$ erg s^{-1}. The TeV emission of the system is dominated by the inverse Compton scattering of optical photons on the ultrarelativistic electrons. The optical photons are mainly contributed by the normal companion and the stream of material flowing through the magnetosphere of the white dwarf. The luminosity of the TeV source depends on the state of the system (flaring/quiet) and is limited to $<5 \times 10^{29}$ erg s^{-1}. These results allow us to understand a lack of success in searching for the high-energy emission of AE Aqr with the Compton Gamma-ray Observatory and the Whipple Observatory.

Key words. acceleration of particles – gamma rays: theory – stars: pulsars: general – stars: binaries: close – stars: white dwarfs – stars: individual: AE Aquarii

1. Introduction

As shown by Usov (1988), the process of energy release in the magnetosphere of a fast rotating, magnetized white dwarf can be explained in terms of a canonical spin-powered pulsar model (e.g. Arons & Scharlemann 1979) provided its surface temperature is $T(R_{\rm wd}) \lesssim 10^6$ K. The appearance of such a white dwarf is similar to that of a spin-powered neutron star (i.e. a canonical spin-powered pulsar) in several important aspects. In particular, its energy budget is dominated by the spin-down power

$$L_{\rm sd} \simeq 3 \times 10^{35}\, \mu_{34}^2 \left(\frac{P_{\rm s}}{10\ {\rm s}}\right)^{-4}\ {\rm erg\ s^{-1}}, \quad (1)$$

which is spent mainly for the ejection of a relativistic wind. Here $P_{\rm s}$ is the spin period of the white dwarf and μ_{34} is its dipole magnetic moment expressed in units of 10^{34} G cm^3. The pressure of the wind significantly exceeds the ram pressure of the material surrounding the star at the accretion (Bondi) radius and the particles accelerated in its magnetosphere reach the TeV energies (Usov 1988). According to Lipunov (1992), the state of the white dwarf can be classified as an *ejector*. Following this we will refer such objects as Ejecting White Dwarfs (EWDs).

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The relativistic particles accelerated in the magnetospheres of EWDs manifest themselves in the high-energy part of the spectrum (mainly due to the curvature radiation and the inverse Compton scattering of thermal photons), while the dissipation of the back-flowing current, which closes the current circuit in the magnetosphere, leads to a local heating of the white dwarf surface in the magnetic pole regions. Therefore, EWDs are expected to appear as non-thermal γ-ray pulsars and pulsing X-ray/UV sources with a predominantly thermal spectrum (see Usov 1993).

A detailed analysis of the origin and appearance of EWDs has been performed in the frame of the interpretation of non-identified galactic γ-ray sources by Usov (1988), and of the anomalous X-ray pulsar 1E 2259+586 by Paczyński (1990) and Usov (1993, 1994). As they have shown, the basic appearance of these objects fits well into the EWD-model and the formation of fast rotating, magnetized white dwarfs should be a relatively common phenomenon in our Galaxy. Nevertheless, further development of these approaches was not effective mainly because of a lack of evidence for the white dwarf nature of these sources (see e.g. Mereghetti et al. 2002 and references therein).

A target, to which the application of the EWD-model is currently under consideration, is the degenerate component of the low mass close binary system AE Aqr. This star is unambiguously identified with a fast rotating ($P_s \simeq 33$ s) white dwarf (Eracleous et al. 1994) whose spin-down power exceeds its luminosity by at least a factor of 120 (de Jager et al. 1994; Welsh 1999). The appearance of the system significantly differs from that of magnetic cataclysmic variables whose radiation is powered by the accretion process (Warner 1995). Instead, AE Aqr ejects material in the form of a non-relativistic stream (Welsh et al. 1998; Ikhsanov et al. 2004), and relativistic particles responsible for the radio and, possibly, high-energy emission of the system (de Jager 1994).

In this paper we analyze the appearance of AE Aqr in the high energy parts of the spectrum. The basic information on the system and, in particular, its appearance in TeV γ-rays are briefly outlined in Sect. 2. The process of particle acceleration in the magnetosphere of the white dwarf within the EWD-model is discussed in Sect. 3. In Sects. 4 and 5 we address the appearance of the leptonic and hadronic components of the accelerated particles, respectively. A brief summary and discussion of acceleration mechanisms alternative to the EWD-model are given in Sect. 6.

2. AE Aquarii

AE Aqr is a non-eclipsing binary system with an orbital period of 9.88 h and eccentricity of 0.02, which is situated at the distance of 100 pc. The system inclination angle and the mass ratio are limited to $48^\circ < i < 62^\circ$, and $0.58 \lesssim (q = M_2/M_1) \lesssim 0.89$ (Welsh et al. 1995).

The system emits detectable radiation in almost all parts of the spectrum. It is a powerful non-thermal radio source (Bastian et al. 1988) and, possibly, a γ-ray emitter (see below). Its optical, UV, and X-ray radiation is predominantly thermal and comes from at least three different sites. The visual light is dominated by the normal companion (secondary), which is a K3–K5 red dwarf on or close to the main sequence (Welsh et al. 1995). The primary is a fast rotating, magnetized white dwarf. The remaining light comes from a highly variable extended source, which manifests itself in the blue/UV continuum, the optical/UV broad single-peaked emission lines, and the non-pulsing X-ray component. This source is associated with the stream of material, which flows into the Roche lobe of the white dwarf from the normal companion, interacts with the magnetosphere of the primary and is ejected out from the system without forming a disk (Wynn et al. 1997; Welsh et al. 1998; Ikhsanov et al. 2004). This source is also suspected of being responsible for the peculiar rapid flaring of the star (Eracleous & Horne 1996).

2.1. Parameters of the white dwarf

A justification of the white dwarf nature of the primary has been presented by Eracleous et al. (1994) on the basis of HST observations. As they have shown, the optical/UV pulsing emission comes from two hot spots with the projected area $A_p \sim (0.8\text{–}4.3) \times 10^{16}$ cm^2 and the temperature 20 000 K $\lesssim T_{pol} \lesssim$ 47 000 K. Associating these spots with the magnetic pole regions, they have limited the angle between the rotational and magnetic axes of the primary to $75^\circ \lesssim \beta \lesssim 77^\circ$ and evaluated the temperature of the rest of its surface as 10 000–16 000 K.

The white dwarf is spinning-down with a mean rate $\dot{P}_0 = 5.64 \times 10^{-14}$ s s^{-1}, which implies its spin-down power (de Jager et al. 1994; Welsh 1999)

$$L_{sd} = 6 \times 10^{33}\, I_{50} \left(\frac{P_s}{33\ \text{s}}\right)^{-3} \left(\frac{\dot{P}}{\dot{P}_0}\right) \text{erg s}^{-1}. \quad (2)$$

Here I_{50} is the moment of inertia of the white dwarf expressed in units of 10^{50} g cm^2.

L_{sd} exceeds the luminosity of the system observed in the UV and X-rays by a factor of 120 and its persistent bolometric luminosity by a factor of 5. As mentioned above, such a situation is typical for EWDs. The dipole magnetic moment of the white dwarf within this approach can be evaluated as (Ikhsanov 1998)

$$\mu_0 \simeq 1.4 \times 10^{34} \left(\frac{P_s}{33\ \text{s}}\right)^2 \left(\frac{L_{sd}}{6 \times 10^{33}\ \text{erg s}^{-1}}\right)^{1/2} \text{G cm}^3. \quad (3)$$

This implies that the strength of the surface magnetic field of the white dwarf in the magnetic pole regions is (Alfvén & Fälthammar 1963)

$$B_0 = \frac{2\mu}{R_{wd}^3} \simeq 100\, R_{8.8}^{-3} \left[\frac{\mu}{1.4 \times 10^{34}\ \text{G cm}^3}\right] \text{MG}, \quad (4)$$

and, correspondingly, the surface field strength at its magnetic equator is $B_0/2 = 50$ MG. Here $R_{8.8}$ is the radius of the white dwarf expressed in units of $10^{8.8}$ cm.

As recently shown by Ikhsanov et al. (2004), the above mentioned estimates contradict none of the currently observed properties of the system, and the Doppler Hα tomogram simulated within this approach is in a very good agreement with the tomogram derived from spectroscopic observations of AE Aqr. On this basis estimates (3) and (4) will be used in our analysis.

2.2. High-energy emission

A search for TeV emission of AE Aqr was performed by three independent groups. The Potchefstroom group has reported on about 310 h of observations in 1988–93 (Meintjes et al. 1992, 1994). A few events of pulsing TeV emission with an averaged flux $(0.2\text{–}2) \times 10^{-10}$ cm^{-2} s^{-1} (at a threshold energy 2.4 TeV) were detected during this period. Additionally, they reported a detection of two short (1 and 3 min duration) unpulsed outbursts on 25 June 1993 (the orbital phases 0.04 and 0.05). The flux of the TeV emission during these events was about 8×10^{-9} cm^{-2} s^{-1}, which, under the assumption of isotropic emission, corresponds to the source luminosity of $\sim 10^{34}\, d_{100}^2$ erg s^{-1}. Here d_{100} is the distance to AE Aqr normalized to 100 pc.

A detection of TeV emission from AE Aqr has also been reported by the Durham group (Bowden et al. 1992; Chadwick et al. 1995). They recorded about 170 h of data in 1990–93. A persistent component of pulsing (at 60.46 mHz) TeV emission with a time-averaged flux of about 10^{-10} cm^{-2} s^{-1} (at energy >350 GeV) was detected. Additionally, they reported the detection of a 1 min (13 October 1990, orbital phase 0.40) and a 70 min (11 October 1993, orbital phases 0.62–0.74) outburst. The luminosity of the γ-ray source during these outbursts was $\sim 6 \times 10^{33}\ d_{100}^2$ erg s^{-1} and $3 \times 10^{32}\ d_{100}^2$ erg s^{-1}, respectively. In both cases the signal was modulated with a half of the spin period of the white dwarf (60.46 mHz).

On the other hand, the analysis of data recorded by the Whipple group (68 h of observations in 1991–95) have shown no evidence for any steady, pulsed or episodic TeV emission of AE Aqr (Lang et al. 1998). The upper limits to the flux of a steady emission, $\lesssim 4.0 \times 10^{-12}$ cm^{-2} s^{-1}, and a pulsing emission $\lesssim 1.5 \times 10^{-12}$ cm^{-2} s^{-1}, at an energy threshold of 900 GeV have been derived. This suggests that the persistent luminosity AE Aqr in TeV energy range is unlikely to exceed 5×10^{30} erg s^{-1}. At the same time, the database of the Whipple group is too small for any conclusions on the non-frequent TeV γ-ray events reported by the Potchefstroom and Durham groups (for a discussion see Lang et al. 1998).

Finally, a negative result of a search for 0.1–1 GeV emission from AE Aqr with the Compton Gamma-Ray Observatory (CGRO) has been reported by Schlegel et al. (1995). The derived upper limits suggest that the luminosity of the system in the EGRET energy range is smaller than 10^{31} erg s^{-1}.

A lack of success in searching for γ-ray emission from AE Aqr reported by the EGRET and Whipple groups raises the following questions: do we have any theoretical grounds to suggest that this system can be an emitter of high-energy radiation and particles and if so, how bright this source could be? In order to answer these questions we performed an analysis of particle acceleration based on the EWD-model of the system. We show that the expected intensity of high-energy emission within this model is indeed below the threshold of detectors used by the CGRO and Whipple observatories.

3. Particle acceleration

We consider a process of particle acceleration in the magnetosphere of a white dwarf, whose rotation period $P_{\rm s} = 33\ P_{33}$ s (the angular velocity $\Omega = 2\pi/P_{\rm s} \simeq 0.19$ rad s^{-1}), the mass $M_{\rm wd} = 0.8\ M_{0.8}\ M_{\odot}$, the strength of the magnetic field at the magnetic pole regions $B_0 = 10^8\ B_8$ G and the surface temperature $T < 50\,000$ K. Under these conditions a scale height of its atmosphere,

$$h_{\rm a} \simeq \frac{kTR_{\rm wd}^2}{m_{\rm p}GM_{\rm wd}} \simeq 2.5 \times 10^4\ M_{0.8}^{-1}\ R_{8.8}^2\ \left(\frac{T}{5 \times 10^4\ {\rm K}}\right)\ {\rm cm}, \qquad (5)$$

is significantly smaller than both the radius of the white dwarf ($R_{\rm wd} \simeq 10^{8.8}$ cm) and the lower limit to the radius of its polar caps,

$$\Delta R_{\rm p} \simeq \left(\frac{\Omega R_{\rm wd}}{c}\right)^{1/2} R_{\rm wd} \simeq 4 \times 10^7\ R_{8.8}^{3/2}\ \left(\frac{P_{\rm s}}{33\ {\rm s}}\right)^{-1/2}\ {\rm cm}. \qquad (6)$$

This implies that the vacuum approximation to the medium surrounding the white dwarf is applicable and therefore, the process of particle acceleration can be treated in terms of EWD-model.

According to Arons & Scharlemann (1979), the component of the electric field $E_{\parallel} \equiv (\boldsymbol{E} \cdot \boldsymbol{B})/|\boldsymbol{B}|$ along the magnetic field $\boldsymbol{B}$, which is generated in the polar cap regions of a fast rotating magnetized star surrounded by a vacuum can be evaluated as

$$E_{\parallel} \simeq E_{\rm AS} \times \begin{cases} s/\Delta R_{\rm p} & {\rm at}\ 0 \le s \le \Delta R_{\rm p}, \\ 1 & {\rm at}\ \Delta R_{\rm p} \le s \le R_{\rm wd}, \\ \sqrt{2R_{\rm wd}/r} & {\rm at}\ s > R_{\rm wd}, \end{cases} \qquad (7)$$

where

$$E_{\rm AS} = \frac{1}{8\sqrt{3}} \left(\frac{\Omega R_{\rm wd}}{c}\right)^{5/2} B_0, \qquad (8)$$

and $r = (R_{\rm wd} + s)$ is a distance from the surface of the white dwarf. This means that the electric potential in the magnetosphere of the white dwarf is

$$\varphi_{\rm as}(r) = \int_{\rm R_{wd}}^{\rm r} E_{\parallel}\ {\rm d}s\ \simeq\ 2\sqrt{2}\ E_{\rm AS}\ R_{\rm wd} \left[\left(\frac{r}{R_{\rm wd}}\right)^{1/2} - 1\right]. \qquad (9)$$

The total electric potential in the magnetosphere of a spin-powered neutron star contains two additional terms which represent the effects of general relativity (Muslimov & Tsygan 1992), and the effect of $e^{\pm}$ pairs creation in the outer magnetosphere (Cheng et al. 1986). However, a contribution of these terms to the electric potential in the magnetosphere of a white dwarf (whose radius exceeds that of a neutron star by a factor of 500 and the magnetic field is too weak for a pair creation process to be effective) are small and can be neglected.

An application of the EWD-model to the white dwarf in AE Aqr implies a validity of the following two assumptions. The first is a lack of accretion of material onto the surface of the white dwarf. If this assumption were not valid the star would appear as an accretion-powered X-ray pulsar. The system is indeed an emitter of X-rays. But all of currently established properties of the emission are inconsistent with those predicted by the accretion-powered pulsar model. In particular, the X-ray spectrum of AE Aqr is soft and significantly differs from the typical spectra of accretion-powered white dwarfs (Clayton & Osborne 1995; Choi et al. 1999). Furthermore, the surface temperature of the white dwarf at the magnetic pole regions evaluated by Eracleous et al. (1994) is <50 000 K, i.e. a factor of 2000 smaller than the typical temperature at the base of an accretion column. Finally, observations of AE Aqr with XMM-Newton recently reported by Itoh et al. (2005) suggest that the number density of plasma responsible for the detected X-rays is $n_{\rm e} \sim 10^{11}$ cm^{-3} (i.e. a few orders of magnitude lower than corresponding conventional estimates in the post-shock accretion column) and that the linear scale of the source is $\ell_{\rm p} \gtrsim 2 \times 10^{10}$ cm (i.e. a factor of 40 larger than the radius of the white dwarf). This clearly indicates that the source of the observed X-ray emission is located at a significant distance from the white dwarf and therefore, cannot be powered by an accretion of material onto its surface.

The second assumption is that the material streaming through the magnetosphere of the white dwarf does not significantly effect the electric potential generated at its surface. A hint for a validity of this assumption comes from the model of Michel & Dessler (1981) who have considered a situation in which a spin-powered pulsar is surrounded by a dead disk. According to their results a presence of a disk inside the light cylinder of the pulsar would not suppress the electric potential at the stellar surface. Instead, an interaction between the field lines and the disk material leads to an additional term in the expression of the total electric potential at the stellar surface. This finding has already been used by de Jager (1994) for constructing a dead disk model for AE Aqr. The value of the electric potential in this case is comparable to that of $\varphi_{as}(r_0)$, where r_0 is the radius of the disk (or a distance of closest approach of the stream to the white dwarf). In this light expression (9) represents an upper limit to the electric potential which could be generated in the magnetosphere of the white dwarf within the EWD-model.

The energy of particles accelerated in the $\varphi_{as}(r)$ potential can be limited to $\mathcal{E}_p \lesssim \mathcal{E}_0$, where

$$\mathcal{E}_0 \simeq 2\times10^{11}\,\mu_{34.2}\,R_{8.8}^{1/2}\left(\frac{P_s}{33\ \mathrm{s}}\right)^{-5/2}\left[\left(\frac{l_0}{R_{wd}}\right)^{1/2}-1\right]\ \mathrm{eV}. \quad (10)$$

Here l_0 is the scale of the acceleration region. A precise determination of this parameter is an open problem so far. In general case the value of l_0 can be limited to (e.g. Beskin et al. 1993) $(R_{wd}+\Delta R_p) \leq l_0 \leq R_{lc}$, where $R_{lc} = c/\Omega \simeq 1.6\times10^{11}\ (P/33\ \mathrm{s})$ cm is the radius of the light cylinder of the white dwarf. Following this limitation one can estimate the energy of the accelerated particles as

$$8\ \mathrm{GeV} \lesssim \mathcal{E}_p \lesssim 3\ \mathrm{TeV}. \quad (11)$$

The kinetic luminosity of the particle beam can be evaluated as

$$L_{kin} \simeq e\varphi_{as}(l_0)\dot{N}, \quad (12)$$

where

$$\dot{N} = \pi(\Delta R_p)^2 n_{GJ}(R_{wd})c \quad (13)$$

is the flux of ultrarelativistic particles from the white dwarf and

$$n_{GJ}(R_{wd}) = \frac{(\boldsymbol{\Omega}\cdot\boldsymbol{B})}{2\pi ce} \simeq 5\times10^4\left(\frac{P_s}{33\ \mathrm{s}}\right)^{-1}\left(\frac{B_0}{10^8\ \mathrm{G}}\right)\ \mathrm{cm}^{-3} \quad (14)$$

is the Goldreich-Julian density above the primary surface.

Combining Eqs. (8) and (9) with Eqs. (12)–(14) and setting $l_0 = R_{lc}$ yields

$$L_{kin}^{max} = \frac{1}{4\sqrt{6}}\,\frac{\Omega^4 R_{wd}^6 B_0^2}{c^3}\cos\beta \simeq 0.04 L_{sd}, \quad (15)$$

where it is taken into account that

$$L_{sd} = \frac{2}{3}\frac{\Omega^4 R_{wd}^6 B_0^2}{c^3}. \quad (16)$$

Thus, the maximum kinetic luminosity of the beam of ultrarelativistic particles ejected by the white dwarf in AE Aqr is

$$L_{kin}^{max} \simeq 2\times10^{32}\left(\frac{L_{sd}}{6\times10^{33}\ \mathrm{erg\ s^{-1}}}\right)\ \mathrm{erg\ s^{-1}}. \quad (17)$$

It is comparable to the bolometric luminosity of the system during its optical quiescent state (see Beskrovnaya et al. 1996).

If, however, the scale of the acceleration region is close to its minimum value, i.e. $l_0 \sim (R_{wd}+\Delta R_p)$, the kinetic luminosity of the beam of GeV-electrons does not exceed

$$L_{kin}^{min} \simeq 5\times10^{29}\left(\frac{L_{sd}}{6\times10^{33}\ \mathrm{erg\ s^{-1}}}\right)\ \mathrm{erg\ s^{-1}}. \quad (18)$$

4. Radiative losses of primary electrons

The radiative losses of ultrarelativistic electrons accelerated in the magnetosphere of a magnetized compact star are governed mainly by two mechanisms: i) the curvature radiation, and ii) the inverse Compton scattering of thermal photons (Michel 1991).

4.1. Curvature radiation

The intensity and the mean photon energy of the curvature radiation emitted by ultrarelativistic electrons in the magnetosphere of the white dwarf are (Usov 1988)

$$l_c = \frac{2}{3}\frac{e^2 c}{R_c^2}\gamma^4, \quad (19)$$

$$\bar{E}_{curv} = \frac{3}{2}\,\frac{\hbar c\gamma^3}{R_c}. \quad (20)$$

Here $R_c \simeq (Rc/\Omega)^{1/2}$ is the curvature radius of the magnetospheric field lines and $\gamma = \mathcal{E}_p/mc^2$ is the Lorentz factor of electrons which in the case of AE Aqr can be expressed using Eq. (10) as

$$\gamma_e(r) \simeq 4\times10^5\,\mu_{34.2}\left(\frac{P_s}{33\ \mathrm{s}}\right)^{-5/2}\left[\left(\frac{r}{R_{wd}}\right)^{1/2}-1\right]. \quad (21)$$

Since the Lorentz factor of the electrons and the values of the parameters $l_c(r)$ and $\bar{E}_{curv}(r)$ increase with r, the largest fraction of the curvature radiation is generated near the light cylinder of the white dwarf. Therefore, the upper limit to the mean photon energy and the intensity of the curvature radiation ($L_{curv} \simeq l_c\dot{N}$) expected from AE Aqr can be evaluated from Eqs. (19)–(21) as

$$\gamma_e(R_{lc}) \simeq 6\times10^6$$

$$\bar{E}_{curv}(R_{lc}) \simeq 100\ \mathrm{keV}$$

$$L_{curv}(R_{lc}) \lesssim 3\times10^{27}\mu_{34.2}^5\left(\frac{P_s}{33\ \mathrm{s}}\right)^{-11}\ \mathrm{erg\ s^{-1}}.$$

Hence, the curvature radiation of the primary electrons contributes to the system emission mainly in the soft (∼100 keV) γ-rays with a mean flux of $\sim10^{-15}$ erg cm^{-2} s^{-1}. This value is significantly smaller than the threshold sensitivity of detectors used in the EGRET experiment. This provide us with a reasonable explanation of unsuccessful search for high-energy emission of the system with CGRO.

4.2. Inverse Compton scattering

The mechanism, which can be responsible for the very high-energy emission of the system, is the inverse Compton scattering of the thermal photons on the ultrarelativistic electrons. The energy of the scattered photons is as high as $m_e c^2\gamma(R_{lc}) \sim 3$ TeV, where m_e is the electron mass.

The intensity of the TeV radiation generated due to the inverse Compton scattering is (Ochelkov & Usov 1983, the Klein-Nishina cross-section case)

$$L_{cs} \simeq l_{cs}\dot{N}, \quad (22)$$

where

$$l_{\rm cs} = \frac{3}{8} c\sigma_{\rm T} u_0 \left(\frac{m_{\rm e}c^2}{\epsilon_{\rm th}}\right)^2 \left[\ln \frac{4\epsilon_{\rm th}\gamma}{m_{\rm e}c^2} - \frac{11}{6}\right] \quad (23)$$

is the rate of energy losses of an electron. Here $\epsilon_{\rm th} \simeq 3kT$ is the mean energy of the thermal photons, $\sigma_{\rm T}$ is the Thomson cross section, k is the Boltzmann constant, T is the mean temperature of the thermal emission and

$$u_0 \simeq aT^4 \left(\frac{R_0}{r_{\rm s}}\right)^2 \quad (24)$$

is the radiation energy density. R_0 denotes the effective radius of the source of the thermal emission, $r_{\rm s}$ is the mean distance from this source to the region of scattering and $a = 7.6 \times 10^{-15}$ erg cm^{-3} deg^{-4} is the radiation density constant.

The field of the thermal radiation in the magnetosphere of the white dwarf in the case of AE Aqr is contributed by three separate sources: the normal companion, the white dwarf and the stream of material flowing through its magnetosphere. The relative contribution of these sources depends on the location of the scattering region and the state of the system (quiescent or flaring). As we require the energy of the scattered photons to be ~TeV, the closest distance of the region of their generation to the surface of the white dwarf is $r \gtrsim 2 \times 10^{10}$ cm (see Eq. (21)). The contribution of the white dwarf to the radiation field at this distance is significantly smaller than those of the normal component and of the stream. Furthermore, the ratio $\eta = l_{\rm cs}/eE_{\|}c$ in the vicinity of the white dwarf is

$$\eta \simeq 10^{-4} \left(\frac{T}{10^4\ {\rm K}}\right)^2 \left(\frac{R_{\rm wd}}{r}\right)^{3/2}.$$

This indicates that the thermal emission from the surface of the white dwarf is not essential for the process of particle acceleration. On this basis we neglect the contribution of the white dwarf in further consideration.

As recently shown by Ikhsanov et al. (2004), the closest approach of the stream to the surface of the white dwarf within the EWD-model is limited to

$$r_0 \gtrsim 4 \times 10^{10}\ \eta_{0.37}\ \mu_{34.2}^{4/7}\ M_{0.8}^{-1/7}\ \dot{M}_{17}^{-2/7}\ {\rm cm}, \quad (25)$$

where $\dot{M}_{17}$ is the mass transfer rate expressed in units of 10^{17} g s^{-1} and $\eta_{0.37} = \eta/0.37$ is the parameter accounting for the geometry of the accretion flow, which in the case of a stream is normalized following Hameury et al. (1986). This indicates that the contribution of the stream to the radiation field during the quiescent state ($\dot{M} < 10^{17}$ g s^{-1}) is comparable to that of the normal companion inside the magnetosphere and is almost negligible at the distances close to the light cylinder ($R_{\rm lc} = 1.57 \times 10^{11}$ cm). Therefore, using the parameters of the secondary (i.e. $T_{\rm eff} \simeq 4500$ K, $R_0 \simeq R_\odot$) one can evaluate the intensity of the TeV emission produced by the inverse Compton scattering during the quiescent state of the system as (see Eqs. (22)–(24))

$$L_{\rm cs}^{\rm q} \lesssim 3 \times 10^{27}\ {\rm erg\ s^{-1}}. \quad (26)$$

Here we assumed that the scattering occurs at the light cylinder of the primary.

The most favorable conditions for the generation of TeV emission due to the inverse Compton scattering occur during the flaring state. According to Beskrovnaya et al. (1996), the system emission during the strongest optical flares (which last a few minutes) is dominated by a source with an effective temperature ~20 000 K and an effective area of $\simeq 10^{20}$ cm^2. As this source is situated inside the magnetosphere (at the distances of about r_0) its contribution to the radiation field significantly exceeds that of the normal companion (the optical luminosity of the system during these events reaches $\simeq 10^{33}$ erg s^{-1}). In this case the generation of TeV emission due to the inverse Compton scattering reaches its highest efficiency in a region situated at the distances of about r_0 from the surface of the primary and its intensity (according to Eqs. (22)–(24)) can be limited to

$$L_{\rm cs}^{\rm f} \lesssim 4 \times 10^{29}\ {\rm erg\ s^{-1}} \quad (27)$$

(the mass transfer rate during the strong flares according to the EWD-model is $\sim 5 \times 10^{17}$ g s^{-1}).

Thus, the upper limit to the intensity of TeV radiation of AE Aqr produced due to the inverse Compton scattering of thermal photons on the ultrarelativistic electrons is a factor of a few smaller the threshold sensitivity of detectors used in observations of the system with the Whipple γ-ray telescope.

5. Appearance of a proton beam

One can also envisage a situation in which a significant fraction of $L_{\rm sd}$ is converted to ultrarelativistic protons. The upper limit to the kinetic luminosity of the proton beam in this case is expressed by Eq. (12). The radiative losses of the protons in the magnetosphere of the white dwarf (due to the curvature radiation and the inverse Compton scattering) are significantly smaller than those of electrons and in the first approximation can be neglected. The energy of the beam, however, can be effectively converted into VHE γ-rays if the trajectories of protons intersect a target of a relatively dense (30–80 cm^{-2}) background material. In this case a creation of π-mesons (π^0, $\pi^\pm$) and their subsequent decays into two VHE γ-photons with the energy of about the energy of the primary relativistic protons would be expected.

Two targets with the required column density can be indicated in AE Aqr. Namely, the atmosphere of the normal companion, and the stream of material moving through the magnetosphere of the white dwarf. The interaction of TeV protons with these targets will produce a flux of TeV photons. However, can this emission be detected by an observer at the Earth? A positive answer on this question in the light of currently established geometry of the system is not obvious. Indeed, the photons generated in this process are strongly beamed along the incident particle's velocity vector (see e.g. Vestrand & Eichler 1982). Therefore, an observer can detect only those photons that are produced when protons streaming toward him strike intervening target material. This means that the flux of the TeV photons generated in the atmosphere of the secondary can be detected only at the orbital phases $(2\pi - \Delta\varphi) \lesssim \varphi \lesssim (2\pi + \Delta\varphi)$, where

$$\Delta\varphi = \frac{1}{2\pi}\arctan\left(\frac{R_{L(2)}}{A}\right) = \frac{1}{2\pi}\arctan\left(0.378\, q^{-0.2084}\right), \quad (28)$$

and if the inclination angle of the system is

$$i \gtrsim i_0 \simeq \frac{\pi}{2} - \arctan\left(0.378\, q^{-0.2084}\right). \quad (29)$$

Here $R_{L(2)}$ is the volume radius of the Roche lobe of the secondary and A is the orbital separation. For the parameters of AE Aqr conditions (28) and (29) are $0.94 \lesssim \varphi \lesssim 1.06$ and $i > i_0 \sim 67°–69°$, respectively. Hence the atmosphere of the secondary is definitely not a site of TeV emission detected at orbital phases 0.07–0.93. Furthermore, it is unlikely a site of the TeV emission at the rest of the orbital phases since the assumption $i > 67°$ contradicts optical observations of the system (see Sect. 2).

The TeV emission generated due to the interaction between the relativistic protons and the stream could be observed in a significantly wider range of orbital phases. However, the condition to the inclination angle of the system in this case is

$$i > i_0 \simeq \frac{\pi}{2} - \arctan\left(\frac{r_{str}}{r_0}\right), \quad (30)$$

where r_{str} is the radius of the stream cross section, which in the considered case is limited to (see e.g. Wynn et al. 1997; Ikhsanov et al. 2004):

$$r_{str} \lesssim (Q_{L1}/\pi)^{1/2} \simeq 1.6 \times 10^9 \left(\frac{T_{eff}}{4500\ K}\right)^{1/2} \text{cm}, \quad (31)$$

and r_0 is the distance of closest approach of the stream to the white dwarf, which in the case of EWD-model is expressed by Eq. (25). Here Q_{L1} is the effective cross section of the mass transfer throat at the Lagrange point L1 and T_{eff} is the effective temperature of the photosphere of the secondary. Combining Eqs. (25), (30) and (31) one finds that the TeV photons generated due to interaction between the accelerated protons and the stream could be detected by an observer if the inclination angle of the system were $\gtrsim 86°$. This, however, is inconsistent with the value of i derived from observations (otherwise the system would be an eclipsing binary).

Finally, we would like to point out that in case of any targets a strong collimation of the beam of ultrarelativistic protons is required for the effective production of TeV emission. Indeed, the reported luminosity of the TeV source during outbursts is an order of magnitude larger than the upper limit to the kinetic luminosity of the beam evaluated in Sect. 3. Taking into account that the efficiency of the energy transfer from protons to π^0-mesons does not exceed 20% (Ozernoy et al. 1973), and that only a half of the energy of the π^0-mesons is transferred to γ-rays detected by an observer one can limit the opening angle of the beam to

$$\Delta\Upsilon \lesssim 0.1\varkappa\left(\frac{L_{kin}}{9 \times 10^{32}\ \text{erg s}^{-1}}\right)\left(\frac{L_{obs}}{10^{34}\ \text{erg s}^{-1}}\right)\text{rad}, \quad (32)$$

where

$$\varkappa = \begin{cases} 1 & \text{for} \quad Q_b \lesssim Q_t, \\ Q_t/Q_b & \text{for} \quad Q_b > Q_t. \end{cases} \quad (33)$$

Here Q_b and Q_t are the cross sections of the beam and the target in the direction, perpendicular to the velocity vector of the relativistic protons. This means that the opening angle of the beam for any targets should be less than 7°. This value corresponds to the opening angle of the dipole magnetic field at the distance $r_1 \simeq 2.5\, R_{wd}$ from the surface of the primary. Therefore, to meet this criterium one has to assume that either a target is situated very close to the surface of the white dwarf or the accelerated protons at $r > r_1$ do not follow the magnetic field lines but propagate through the magnetosphere along almost straight trajectories. Both of these assumptions, however, are inconsistent with either the predictions of the EWD-model or the currently reconstructed picture of the mass-transfer in AE Aqr.

6. Summary and discussion

Application of the EWD-model to AE Aqr shows that the high-energy emission of the system is dominated by the radiative losses of TeV electrons accelerated in the magnetosphere of the primary. The energy of these electrons is converted into the TeV photons mainly due to the inverse Compton scattering. The luminosity of the TeV source depends on the optical state of the system and lies within the interval $(3–500)\times10^{27}$ erg s^{-1}. Therefore, the expected maximum flux of TeV radiation from AE Aqr (during the strongest optical flares) within our model is limited to $\lesssim 2\times10^{-13}$ cm^{-2} s^{-1}. This is below the threshold of detectors used in all TeV observations of the system reported so far and therefore, a lack of success in searching for the high-energy emission of AE Aqr by the Whipple group proves to be quite understandable.

On the other hand, the origin of TeV emission detected by the Potchefstroom and Durham groups within our approach appears to be a miracle. If this radiation is indeed emitted by AE Aqr one has to assume that an acceleration mechanism, which is more powerful than that investigated in this paper, operates in the system. What kind of a mechanism could it be?

A lack of a disk in the system forces us to reject a number of previously suggested acceleration scenarios. In particular, the unipolar inductor model of Cheng & Ruderman (1991) and the dead disk model of Michel & Dessler (1981) are not applicable in the light of current view on the mass-transfer process in AE Aqr.

The statistical acceleration mechanisms operating inside the magnetosphere of the primary are not effective due to a relatively small scale of the system. As shown by Kuijpers et al. (1997), the typical Lorentz factor of electrons accelerating by the magnetic pumping in the magnetosphere of the white dwarf is about 100. This indicates that the statistical mechanisms of acceleration can be helpful for the interpretation of the radio emission of the system but their contribution to the very high energy γ-rays is negligible.

One can also envisage a situation in which the system acts as an unipolar inductor due to the interaction between the magnetic field of the primary and the normal companion, which is partly situated inside the light cylinder of the white dwarf. This interaction leads to a perturbation of the magnetospheric field broadening the area of the hot spots at the magnetic pole regions by a factor of $(R_{lc}/R_{L1})^{1/2} \simeq 1.25$ and creating an electric potential in the region of interaction (here R_{L1} is the distance from the white dwarf to the L1 point). The rate of energy release due to this interaction is limited to

$$L_{1-2} \lesssim \frac{Q_2 c B^2(R_{L1})}{8\pi} \simeq 10^{33}\,\mu_{34}^2\,R_{11}^{-6}\left(\frac{R_2}{7\times 10^{10}}\right)^2\ \mathrm{erg\ s^{-1}}, \quad (34)$$

where Q_2 is the effective cross section of the interaction between the normal companion of the radius R_2 and the magnetic field of the primary. As seen from Eq. (34), the total power of this interaction is at least a factor of 6 smaller than the spin-down power of the primary (assuming $\mu \sim 10^{32}$ G cm^3 one finds $L_{1-2} \sim 10^{-5}\,L_{sd}$). This indicates that the contribution of this interaction to the flux of relativistic particles cannot exceed that of the pulsar-like acceleration mechanism presented in this paper. Furthermore, as shown by Rafikov et al. (1999), the energy released in the process of the interaction between the magnetic field and a diamagnetic body moving through the field is converted mainly to the thermal energy of the body and the energy of Alfvén waves generated in this process.

An effective acceleration of charged particles can occur outside the magnetosphere in a region of interaction between the relativistic wind ejected by the white dwarf and the material surrounding the system. This interaction leads to a formation of a shock at a distance (see e.g. de Jager & Harding 1992, and references therein)

$$r_s \simeq 10^{17}\,\rho_{-24}^{-1/2}V_6^{-1}L_{34}^{1/2}\ \mathrm{cm}, \quad (35)$$

where ρ_{-24} and V_6 are the density and the thermal velocity of the material surrounding the system expressed in units of 10^{-24} g cm^{-3} and 10^6 cm s^{-1}, and $L_{34} = L_{sd}/10^{34}$ erg s^{-1}. The energy of particles accelerated in the shock can be as high as

$$E_{sh,max} \sim 10^{13}\,B_{-6}\,(l_0/r_s)\ \mathrm{eV}, \quad (36)$$

where B_{-6} is the magnetic field strength in the shock region expressed in units of 10^{-6} (this normalization is derived by equating the magnetic field energy density, $B^2/8\pi$, to the energy density of the background material, $(1/2)\rho v_s^2$). The radiative losses of these particles under these conditions are dominated by the synchrotron emission and the energy of the corresponding photons lies within the region of ~200 MeV. Furthermore, the radiation time of these electrons is close to 10^6 yr. Therefore, the energy radiated by the electrons on a scale of r_s is small. This indicates that a contribution of the shock into TeV emission of the system is almost negligible.

A situation in which the white dwarf could appear as an ejector of very high energy particles with a rate $\sim 10^{34}$ erg s^{-1} has been discussed by Meintjes & de Jager (2000). A key assumption of their approach is that the efficiency of the drag-driven propeller action by the white dwarf is too low for the most dense blobs to be expelled from the system. These blobs, therefore, are able to reach the circularization radius (which for the parameters of AE Aqr is $r_{circ} \sim 2\times 10^{10}$ cm) and to form a clumpy disk surrounding the magnetosphere of the white dwarf. A mixing of the disk material with the magnetic field, which is assumed to be governed by a turbulent diffusion and the Kelvin-Helmholtz instability, leads to a perturbation and reconnection of the field lines. The energy releases in the corresponding current sheets is assumed to be transferred into the energy of particles accelerated in these regions (for a discussion see also Meintjes & Venter 2005).

The energy of accelerated particles and the rate of their ejection evaluated within the MHD-propeller model are high enough for the flux of TeV emission to be comparable to that reported by Potchefstroom and Durham groups. Furthermore, this model is also helpful for an interpretation of the system radio and mid-infrared emission (Meintjes & Venter 2005). The reasons for a lack of success in searching for the high-energy emission of AE Aqr by the Whipple group in this case might be a relatively low probability to detect infrequent TeV activity of the star (Lang et al. 1998), or/and the energy dependence of the image selection criteria, used by the Whipple group in their data analysis procedure, which may lead to a significant loss of γ-ray events in case of sources with spectra harder that that of Crab Nebular (for a discussion see Bhat et al. 1998).

At the same time, a conclusion that MHD-propeller model provides us with a comprehensive explanation of the energy release process in AE Aqr seems to be rather premature. The model is built around an assumption about a very high rate of plasma penetration into the magnetic field of the white dwarf. In particular, the diffusion coefficient is normalized by Meintjes & Venter (2005) to its absolute maximum value 10^{16} cm^2 s^{-1}, which for the conditions of interest is 10 orders of magnitude larger than the value of the Bohm diffusion coefficient. Such a situation is unique in astrophysical objects. In particular, it has never been observed in solar flares, interplanetary space (see e.g. Priest & Forbes 2000), and accretion-driven compact stars (Frank et al. 1985). Furthermore, the time of blob diffusion into the magnetic field is evaluated to ~30 s. This is a factor of 2 smaller than the free-fall time, $t_{ff} = r^{3/2}/(2GM_{wd})^{1/2}$ at a distance of closest approach of the blobs to the white dwarf ($\sim 10^{10}$ cm). This indicates that the rate of diffusion evaluated within the MHD-propeller model significantly exceeds the rate of plasma penetration into the magnetic field of a neutron star evaluated by Arons & Lea (1976) for the case of spherical accretion and by Ghosh & Lamb (1979) for the case of disk accretion. Finally, the diffusion time of the blobs into the magnetic field within this approach is significantly smaller than the characteristic time of drag interaction between the blobs and the magnetic field, which according to Wynn et al. (1997) is $t_{drag} \gg t_{ff}$. This rises a question about the structure of the Hα Doppler tomogram expected within the MHD-propeller model. A simulation of this tomogram within the MHD-propeller model may help us to answer the question why the contribution of the clumpy disk into the observed tomogram is negligibly small.

The above mentioned items suggest that the theoretical development of the MHD-propeller model remains sofar work in progress. Nevertheless, the basic prediction of this model, namely, a flux of TeV emission from AE Aqr over the level of 10^{-12} cm^{-2} s^{-1} can be observationally tested with the MAGIC (Lorenz 2004), VERITAS (Weekes et al. 2002) and HESS (Hinton 2004) experiments. The corresponding observations will allow us to choose between the MHD-propeller model and EWD-model which suggests that the TeV flux of the system is below the threshold of detectors used in the above mentioned high-energy experiments.

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