ON A SITE OF X-RAY EMISSION IN AE AQUIR II

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Received 2005 June 21; accepted 2006 February 9; published 2006 March 2

ABSTRACT

An analysis of recently reported results of XMM-Newton observations of AE Aqr within a hypothesis that the detected X-ray source is located inside the Roche lobe of the white dwarf is presented. I show this hypothesis to be consistent with the currently adopted model of mass transfer in the system. Possible solutions of this problem are briefly discussed.

Subject headings: accretion, accretion disks — stars: individual (AE Aquarii) — white dwarfs — X-rays: binaries

1 INTRODUCTION

AE Aqr is a close binary system with an orbital period of 9.88 hr, a mass ratio of 0.58–0.89, and an inclination $i = 55^\circ \pm 7^\circ$ (Welsh et al. 1995). The distance to the system is about 100 pc (Friedjung 1997). The degenerate companion is a magnetized white dwarf rotating with a period of $P_i = 33P_a$ s and braking with a rate of $P_\dot{\theta} = 5.64 \times 10^{-14}$ s$^{-1}$, which implies the spin-down power of (de Jager et al. 1994; Welsh 1999)

$$L_{\dot{\theta}} = 6 \times 10^{33} P_3^{-1} I_{50} (P/P_\odot) \text{ ergs s}^{-1},$$

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

The normal companion is a K3–K5 red dwarf that overflows its Roche lobe and loses material through the L1 point toward the white dwarf. This material manifests itself in a form of the optical/UV continuum and emission lines. It is neither accreted onto the surface of the white dwarf nor stored in a disk around its magnetosphere. Instead, it interacts with the magnetic field of the white dwarf via a drag term (King 1993) and is leaving the system without forming a disk (Wynn et al. 1997; Welsh et al. 1998; Ikhsanov et al. 2004).

The system X-ray emission has recently been studied with XMM-Newton (RGS, EPIC) by Itoh et al. (2006). As they have reported, the number density of plasma responsible for the detected X-rays is $n_x \sim 10^{11}$ cm$^{-3}$, and the linear scale of the source is $\ell_x \sim (2–3) \times 10^{10}$ cm. The observed spectrum has been well fitted using the four-temperature (0.14, 0.59, 1.4, and 4.6 keV) VMEKAL model (Mewe et al. 1995). The analysis of the centroids of N and O Ly$\alpha$ lines shows no evidence for any significant orbital Doppler modulation. The widths of these lines are close to 1000 km s$^{-1}$.

Analyzing these results, Itoh et al. (2006) have shown that $n_x$ is a few orders of magnitude smaller than corresponding conventional estimates in the postshock accretion column and $\ell_x$ exceeds the radius of the white dwarf by almost 2 orders of magnitude. On this basis, they have discarded the possibility that the detected X-rays are emitted from the surface of the white dwarf. Instead, they have suggested a hypothesis in which the detected emission is associated with the heating and expansion of the material streaming through the Roche lobe of the white dwarf. According to their scenario, the heating occurs at an adiabatic shock located at a distance of $\sim 10^{10}$ cm from the white dwarf, and the observed emission is powered by the gravitational energy of the streaming material.

In this Letter I show that the above-mentioned hypothesis is inconsistent with the currently adopted model of the mass transfer in the system, and thus a question about the location of the source of X-ray emission in AE Aqr remains open.

2 CAN THE X-RAY SOURCE BE ASSOCIATED WITH AN EXPANDED STREAM?

Within the hypothesis suggested by Itoh et al. (2006), the flow of hot material responsible for the observed X-rays is fed by the stream flowing into the Roche lobe of the white dwarf through the L1 point. The numerical simulations of the H$\alpha$ Doppler tomogram of AE Aqr (Wynn et al. 1997; Welsh et al. 1998; Ikhsanov et al. 2004) have shown that the distance to which the stream could approach the white dwarf, $r_{\text{max}}$, significantly exceeds its corotation radius $r_{\text{cor}} \approx 1.5 \times 10^8 M_{1.4}^{-1/3} P_{3}^{1/3}$ cm. This distance, in the general case, is limited to $r_{\text{max}} \geq \max [r_0, r_i]$, where $r_i$ is the Alfvén radius of the white dwarf and

$$r_0 \approx 10^{10} \left( \frac{q}{0.64} \right)^{-0.464} \frac{a}{1.8 \times 10^{11} \text{ cm}} \text{ cm}$$

is a distance to which the material could approach the white dwarf if its angular momentum along the whole trajectory remains constant (see, e.g., eq. [2.14] in Warner 1995). Here $q$ and $a$ are the mass ratio and orbital separation of the system components, respectively.

The radial distance $r_0$ represents the minimum possible distance to which the material flowing through the L1 point can approach the white dwarf. The value of this parameter does not depend on either the magnetic field strength of the white dwarf or the structure of the inflowing material and is only based on the angular momentum conservation law. For the material to come closer to the white dwarf, its angular momentum must be reduced. However, a question about the mechanism that could be responsible for such a reduction in the case of AE Aqr remains open. Indeed, due to the lack of a disk, the canonical viscosity model of the angular momentum transport is not applicable. On the other hand, the interaction between the stream and the magnetic field at a distance $r_0$ tends to increase the angular momentum of the material since the velocity of field lines, $\Omega r$, significantly exceeds the velocity of
the material, which is limited to the free-fall velocity, \( V_{ff} = (2GM_{\text{wd}}r)^{1/2} \).

A quantitative analysis of the mass transfer process in AE Aqr has been presented first by Wynn et al. (1997). As they have shown, the He I Doppler tomogram of the system can be reproduced by assuming that the stream is inhomogeneous (a sequence of large diamagnetic blobs) and interacts with the magnetic field of the white dwarf via a drag term. The efficiency of this interaction is proportional to \( r^{-n} \), where \( n \geq 2 \). That is why the strongest interaction between the blobs and the magnetic field occurs at their closest approach to the white dwarf. The initial radius of the blobs at \( r_{\text{min}} \) is

\[
l_0 = 10^3 Q_{19}^{1/2} \text{ cm,}
\]

where \( Q_{19} \) is the effective cross section of the mass transfer throat at the L1 point expressed in units of \( 10^{19} \text{ cm}^2 \). The initial sound speed and number density of the material entrained in the blobs are, respectively,

\[
c_s = 10^6 T_{4}^{1/2} \text{ cm s}^{-1}
\]

and

\[
n_b = 10^{14} l_0^{1/2} M_{10}^{1/2} r_0^{1/2} l_b^{-2} \text{ cm}^{-3}.
\]

Here \( l_0 = l_0/10^9 \text{ cm}, r_0 = r_{\text{min}}/10^{10} \text{ cm}, \) and \( T_s \) is the mean temperature of the flowing material expressed in units of \( 10^4 \text{ K} \) (see Beskrovnaya et al. 1996 and Eracleous & Horne 1996).

Let us now consider a scenario in which the hot flow forms at \( r_{\text{min}} \) as a result of strong interaction between the blobs and the magnetic field (independently of the mechanism of this interaction). This implies a heating of the blobs (or their surface layers) and their expansion up to a size of \( \ell_{\text{X}} \). As the gas expands, its density decreases by a factor of \( l_X^3/(l_0^3 \Delta s) \), where \( \Delta s \) is the thickness of the heated layer. This indicates that the initial number density of material in the layer should satisfy the following condition:

\[
n_o \geq n_X \ell_X/(l_0^3 \Delta s),
\]

otherwise the density of the hot flow would be significantly smaller than that evaluated by Itoh et al. (2006). Combining equations (5) and (6), and setting \( n_o = n_o' \), one finds

\[
\Delta s \geq 8 \times 10^{30} n_{10}^{1/7} M_{10}^{1/2} r_{10}^{-1/2} l_{10}^{1/2} l_b^{1/2} \left( \frac{n_X}{10^{11} \text{ cm}^{-3}} \right) \text{ cm}.
\]

Thus, for the considered scenario to be realized, each blob at a distance \( r_{\text{min}} \) should be heated throughout to a temperature of \( 5 \text{ keV} \).

However, as soon as the temperature of a blob reaches \( 5 \text{ keV} \), its X-ray luminosity proves to be

\[
L_X \approx 6 \times 10^{32} T_{7.7}^{1/2} n_{14}^{1/2} l_0^2 \text{ ergs s}^{-1},
\]

i.e., a factor of 60 larger than the X-ray luminosity of the system \((=10^{33} \text{ ergs s}^{-1}; \) see, e.g., Clayton & Osborne 1995 and Choi et al. 1999). Here \( n_{14} = n_0/10^{14} \text{ cm}^{-3} \).

Furthermore, it remains unclear how the temperature of a blob could reach the value of \( 5 \text{ keV} \). Indeed, for the heating of the blobs to occur, the characteristic time of the heating process should be smaller than the cooling time. However, the bremsstrahlung cooling time of the blobs,

\[
t_{\text{cb}} = 15 T_{7.7}^{3/2} n_{14}^{-1} \text{ s},
\]

is significantly smaller than the free-fall time at \( r_{\text{min}} \) \((=70 r_{10}^{1/2} M_{10}^{1/2} \text{ s})\), and, correspondingly, the characteristic time of the drag interaction, which according to Wynn et al. (1997) is limited to \( t_{\text{drag}} > t_{\text{ff}} \). The value of \( t_{\text{cb}} \) is even smaller than the turbulent diffusion time evaluated by Meintjes & Venter (2005).

Thus, the assumption about a significant heating of the blobs at the radius \( r_{\text{min}} \) within any currently considered mechanisms of interaction between the blobs and the magnetic field of the white dwarf is not valid. This means that formation of the hot flow with the number density \( \sim 10^{-11} \text{ cm}^{-3} \), linear scale \( \sim 10^{10} \text{ cm} \), and temperature \( \sim 5 \text{ keV} \) inside the Roche lobe of the white dwarf is impossible within the currently adopted model of the mass transfer. Instead, the source associated with the hot surface layers of the blobs within this model is expected to be dense, \( \sim n_b \), and compact, \( \Delta s \leq 3 \times 10^4 n_{14}^{-2} T_{7.7}^{1/2} \text{ cm} \).

3. DISCUSSION

The problem posed in the previous section suggests that either our current view on the mass transfer picture in AE Aqr is incomplete or a significant part of detected X-rays is generated in a region situated beyond the Roche lobes of the system components, or both. Here I briefly address these two possibilities.

The situation can be partly improved if one invokes the assumption that the mass transfer through the Roche lobe of the white dwarf operates via more than one component. In particular, the formation of the X-ray source with the required parameters inside the Roche lobe of the system could be expected if the blobs were surrounded by a medium of a linear size \( \sim 10^{10} \text{ cm} \) and mean number density \( \sim 10^{11} \text{ cm}^{-3} \). The required rate of mass transfer by this additional flow is \( \sim 5 \times 10^{15} \text{ g s}^{-1} \), i.e., significantly (by more than an order of magnitude) smaller than the rate of mass transferred by the blobs. The heating of the flow, according to equation (9), can be expected even if its interaction with the magnetic field is gentle. In particular, the cooling time of this flow would be larger than the time of heating governed by the drag interaction (see eq. [1] in Wynn et al. 1997). The temperature of the flow, in the first approximation, can be limited by equating the thermal pressure of the material, \( \frac{1}{2} n_{14} m_{14} c^2 \), with the energy density of the external magnetic field, \( B^2/8\pi \).

\[
T \leq 5.8 \times 10^7 B_2 \left( \frac{n_{14}}{10^{11} \text{ cm}^{-3}} \right)^{-1} \text{ K}.
\]

Here \( B_2 \) is the strength of the external magnetic field expressed in units of \( 10^2 \text{ G} \).

It should be noted that both the density and the size of the additional flow component significantly exceed the corresponding parameters of the interblob material considered by Wynn et al. (1997). The hot flow under these conditions screens the blobs from the magnetospheric field, making the drag interaction between them ineffective. However, the suppression of the drag-driven propeller action does not occur at the closest approach of the flow to the white dwarf since the blobs and the hot flow at this distance follow different trajectories. Indeed, being more dense, the blobs would penetrate significantly deeper into the magnetosphere of the white dwarf (for a discussion, see, e.g., Welsh et al. 1998 and Ikhsanov et al. 2004).
This allows ample room for a direct interaction between the blobs and the magnetic field of the white dwarf at the distance \( r_0 \), i.e., just at the point where the efficiency of the drag interaction reaches its maximum value.

At the same time, the origin of this additional component within the currently adopted model of the system remains uncertain. The incorporation of the additional component into the mass transfer scheme implies that either its temperature at the L1 point exceeds \( 2 \times 10^3 \) K (in this case, a formation of the geometrically thick flow at \( r_{\text{min}} \) can be treated in terms of its thermal expansion) or the effective cross section of the mass transfer throat at the L1 point is significantly larger than its canonical value. The reason why these possibilities cannot be simply discarded is that the normal component of AE Aqr is partly (by almost a half of its radius) situated inside the light cylinder of the white dwarf. This situation is unique to all currently known close binaries, and the mass transfer process that could be realized under these conditions is poorly understood so far.

Another problem, which has to be addressed within the above-mentioned scenario, is the lack of any significant orbital Doppler modulation of the N and O Ly\( \alpha \) lines (Itoh et al. 2006). The flow effectively contributes to the X-ray flux of the system only on the timescale of its expansion,

\[
\tau_{\text{exp}} \approx 160 \epsilon_{10} T^{1/2} \text{s,} \tag{11}
\]

and therefore would appear as a local source. Indeed, the temperature and density of an adiabatically expanding fully ionized gas decrease as \( T \propto t^{-2} \) and \( n \propto t^{-3} \), and the luminosity of the flow decreases on a timescale of \( \tau_{\text{exp}} \) by more than an order of magnitude. This argues strongly against the assumption that the hot gas fills the Roche lobe of the white dwarf and spreads around the system (as it has been suggested by Itoh et al. 2006). Under these conditions, however, a modulation of the flow parameters with the system orbital motion would be expected, and the lack of success in searching for this modulation can hardly be interpreted in a simple way.

A modification of the currently adopted mass transfer model is not required if the source of X-ray emission has a multi-component nature. In particular, one can envisage a situation in which a part of the detected X-rays are generated outside the system. The only available energy source in this case is the spin-down power of the white dwarf (the accretion power in this case can obviously be excluded). Can this energy be converted into 5 keV emission in a region situated outside the system?

The answer to this question depends on the ratio of the spin-down power channeled into the mass outflow and particle acceleration, respectively, which is a matter of serious debate at present. It is rather negative if the spin-down power is converted mainly into the kinetic energy of the outflowing material. Indeed, the velocity dispersion of the blobs leaving the system is limited to \( \Delta V \approx 300 \text{ km s}^{-1} \) (Wynn et al. 1997; Welsh et al. 1998; Ikhsanov et al. 2004). This is a factor of 4 smaller than both the thermal velocity of a plasma heated up to a temperature of 5 keV and the velocity evaluated from the analysis of the width of emission lines (see § 1).

The answer might be positive, however, if the spin-down power were released in a form of accelerated particles or MHD waves. As recently shown by Antoniucci & Gómez de Castro (2005), the temperature of X-ray photons emitted by dense \(( n_e \sim 10^{11} \text{ cm}^{-3})\) blobs illuminated by a shower of high-energy electrons \((0.03–1 \text{ MeV})\) ranges within an interval 1–20 keV. The spectrum of this radiation depends on the angle between the line of sight and the velocity vector of electrons. In particular, the spectrum of blobs situated between an observer and the source of accelerated particles differs from the spectrum emitted by blobs situated behind the particle source. Therefore, an accelerator of particles surrounded by the blobs would appear as a multitemperature source of 1–20 keV emission.

Let us check whether such a situation can be realized in AE Aqr. The radius of dense blobs ejected from the system by the propeller action of the white dwarf increases due to their thermal expansion and reaches the value of \( \epsilon_x \) on a timescale

\[
\tau = \frac{\epsilon_x}{c_s} \approx 10^4 \epsilon_{10} \epsilon_{-1}^{-1} \text{s.} \tag{12}
\]

Here the speed of sound, \( c_s = c_p/10^6 \text{ cm s}^{-1} \), is normalized by taking into account that the heating of the dense blobs inside the Roche lobe of the white dwarf is insignificant (see § 2). On this timescale, the blobs moving with an average velocity \( V_{\text{out}} \) reach a distance of

\[
\rho_0 \sim V_{\text{out}} \tau = 3 \times 10^{11} \epsilon_{10} \epsilon_{-1}^{-1} \left( \frac{V_{\text{out}}}{300 \text{ km s}^{-1}} \right) \text{ cm,} \tag{13}
\]

and their number density decreases to

\[
n_0 = n_b \left( \frac{\rho_0}{\epsilon_x} \right) \approx 10^{11} \epsilon_{10} \epsilon_{-1}^{-1} \left( \frac{n_b}{10^{14} \text{ cm}^{-3}} \right) \text{ cm}^{-3}. \tag{14}
\]

The number of blobs ejected by the white dwarf during the time \( \tau \) is

\[
N \approx \frac{3\sqrt{\pi} \tau}{4 \pi n_b m_p l_b^2}. \tag{15}
\]

Combining equations (5), (12), and (15) yields

\[
N \approx 10^4 \epsilon_{10} \epsilon_{-1}^{-1} \epsilon_{-1}^{-1} \epsilon_{-1}^{-1} \rho_{10}^{-1/2}. \tag{16}
\]

Therefore, the stream of the expanded blobs will occupy an area of

\[
A \approx \pi \epsilon_x^2 N \approx 3 \times 10^{29} \left( \frac{\epsilon_x}{10^{10} \text{ cm}} \right)^2 \left( \frac{N}{10^7} \right) \text{ cm}^2, \tag{17}
\]

which constitutes \(0.3\) of the total area of a sphere with a radius of \( r_0 \). This indicates that \(30\%\) of the energy released in the system will be transferred through the stream of the expanded blobs.

If now we assume that the spin-down power releases predominantly in the form of accelerated particles (see, e.g., Ikhsanov 1998 and Meintjes & de Jager 2000), one finds the total flux of the energy released through the area occupied by the stream of the expanded blobs as (see eq. [5] and eqs. [12]–[17])

\[
\rho_1 = \rho_{1d} \frac{A}{4 \pi r_0^2} \approx 10^{33} \epsilon_{10} \epsilon_{-1}^{-1} \epsilon_{-1}^{-1} \epsilon_{-1}^{-1} \rho_{10}^{-1/2} \times \left( \frac{V_{\text{out}}}{300 \text{ km s}^{-1}} \right)^2 \left( \frac{L_{\text{sd}}}{6 \times 10^{33} \text{ ergs s}^{-1}} \right). \tag{18}
\]

Hence, a conversion of only \(2\%\) of this energy into X-rays
would be enough for the luminosity of the corresponding source to be comparable to the X-ray luminosity observed from the system.

The above estimates suggest that the interpretation of the X-ray emission of AE Aqr in terms of expanded blobs illuminated by a flux of accelerated particles might be promising. A further analysis of this scenario, however, requires information about the spectrum and geometry of the wind of particles ejected by the white dwarf, which is currently not available. Furthermore, a question about the region of the wind formation also remains open. If this region (as in the case of spin-powered pulsars; see, e.g., Beskin et al. 1993) is situated at the light cylinder, the surface of the normal companion would also be partly affected by the wind. However, the contribution of this additional source to the X-ray flux is unlikely to be significant since the area occupied by the normal companion at the radius of the light cylinder is a factor of 20 smaller than A (see eq. [17]).

I thank James Pringle, Andrew Fabian, and Christopher Mauche for useful discussions and an anonymous referee for suggesting improvements. I acknowledges the support of the European Commission under the Marie Curie Incoming Fellowship Program. The work was partly supported by the Russian Foundation of Basic Research.

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