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ON THE RAPID SPIN-DOWN AND LOW-LUMINOSITY PULSED EMISSION FROM AE AQUARII

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ABSTRACT

AE Aqr is an unusual close binary system with a very short white dwarf spin period, a high spin-down rate, a relatively low quiescent luminosity, and clear pulse signals. The exact nature of the large spin-down power has not been well explained mainly because the observed luminosities in various energy ranges are much lower than the spin-down power. We consider an unconventional picture of AE Aqr in which an accreting white dwarf, modeled as a magnetic dipole whose axis is misaligned with the spin axis, is rapidly spun down via gravitational radiation emission and therefore the spin-down power is not directly connected to any observable electromagnetic emission. The rapid spin-down is caused by the nonaxisymmetric polar mounds of accreted material slowly spreading away from the magnetic poles over the surface of the star. The effectiveness of the spin-down driven by the gravitational radiation depends on complex diffusion and thermonuclear burning of the accretion mound material. The accretion proceeds at high altitudes toward the magnetic poles of the white dwarf, while a large fraction of the inflowing material is ejected in a propeller-like manner. Based on the observed quiescent X-ray and UV emission, the magnetic field strength is estimated as $\sim 1 \times 10^5 \eta_X^{-1/2}$ G and the mass accretion rate as $\sim 1 \times 10^{15} \eta_X^{-1}$ g s^{-1}, where $\eta_X < 1$ is the X-ray radiative efficiency. A large fraction of the accreted mass is flung out by the propeller action, and $\sim 50\%$ of the accreted material arrives at the magnetic poles. The electromagnetic dipole emission is expected at the level of $\sim 1 \times 10^{29} \eta_X^{-1}$ ergs s^{-1}, which suggests that, for $\eta_X \sim 0.1$, the observed radio luminosity could be well accounted for by dipole radiation.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: flare — stars: individual (AE Aquarii) — ultraviolet: stars

1. INTRODUCTION

AE Aqr, which has a spin period of $P_* = 33.08$ s and an orbital period of 9.88 hr (Patterson 1979; Welsh, Horne, & Gomer 1995), is usually classified as a DQ Her–type magnetic cataclysmic variable (CV) or an intermediate polar. It consists of a magnetic white dwarf and a companion star with a spectral type of K3–K5. This companion fills its Roche lobe and transfers matter to the white dwarf (Casares et al. 1996). However, optical observations (e.g., single-peaked Balmer emission lines) indicate that there is little evidence of a Keplerian accretion disk in the binary system (Welsh, Horne, & Gomer 1998, and references therein).

Pulsations at the spin period are clearly seen from optical to X-ray, but there are no radio pulsations at this period (Bastian, Beasley, & Bookbinder 1996). The optical and UV pulse profiles show a sinusoidal double peak, where the two peaks are separated by 0.5 in phase and their amplitudes are unequal (Eracleous et al. 1994). On the other hand, the X-ray pulse profile has a sinusoidal single peak, which suggests that the X-rays have a different origin (Eracleous, Patterson, & Halpern 1991; Choi, Dotani, & Agrawal 1999). Flares are aperiodic and last for ~ 10 minutes to ~ 1 hr. The flares have been observed for AE Aqr in various wave bands (Patterson 1979; Bastian, Dulk, & Chanmugam 1988; Eracleous & Horne 1996; Choi, Dotani, & Agrawal 1999). During a large flare, the UV and X-ray luminosities increase by a factor of 3 ($\sim 1 \times 10^{32}$ ergs s^{-1} in UV and $\sim 2 \times 10^{31}$ ergs s^{-1} in X-ray) compared with the quiescent luminosities (the quiescent luminosity is $\sim 4 \times 10^{31}$ ergs s^{-1} in the UV and 7×10^{30} ergs s^{-1} in X-rays).

De Jager et al. (1994) found that AE Aqr is steadily spinning down at a rate of $\dot{P}_* = 5.64 \times 10^{-14}$ s s^{-1}. One interesting result from this observation is that the spin-down power $L_{sd} = I\Omega_* \dot{\Omega}_* \approx 5 \times 10^{34} M_{*,1} R_{*,9}^2$ ergs s^{-1}, where $R_{*,9}$ is the white dwarf radius in units of 10^9 cm, $M_{*,1}$ is the stellar mass in units of solar mass, $M_\odot$, and $\Omega_* = 2\pi/P_*$ is much greater than the observed quiescent UV and X-ray luminosities or even the bolometric luminosity. This fact implies that the spin-down power should be mostly converted into different types of energy emission. Eracleous & Horne (1996) and Wynn, King, & Horne (1997) proposed a magnetic propeller model in which most of the accreted matter is expelled from the binary system. In this picture the spin-down power is consumed to expel the accreted matter.

Although the propeller model offers a good explanation for the observational features of AE Aqr, clear evidence of the high-velocity gas stream escaping from the system is yet to be convincingly identified. Eracleous & Horne (1996) inferred that a mean mass transfer rate from the companion star would be $\dot{M} \sim 4 \times 10^{17}$ g s^{-1}. If we assume that the transferred mass is expelled by the propeller action and if we adopt an escape velocity $V_{esc} \sim 10^8$ cm s^{-1} at a distance of $\sim 10^{10}$ cm from the white dwarf, we find the bulk kinetic energy of the expelled gas to be $L_{esc} \sim \dot{M} V_{esc}^2/2 \sim 2 \times 10^{33}$ ergs s^{-1}. This is smaller than the observed spin-down power by roughly 1 order of magnitude. Alternatively, several studies have invoked the pulsar-like spin-down mechanism, where the spin-down power can be used for the generation of electromagnetic dipole radiation and particle acceleration (e.g., de Jager 1994, Ikhsanov 1998). According to the recent study by Ikhsanov (1998), the rapid spin-down rate of AE Aqr can be explained by this mechanism if the white dwarf has a strong surface magnetic field of ~ 50 MG. This field strength exceeds the upper limit of ~ 5 MG derived by Stockman et al. (1992). There have been some

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sporadic attempts to connect the observed spin-down power to the yet-to-be-confirmed TeV γ-ray emission of $\sim 10^{32}$ ergs s^{-1} (Meintjes et al. 1992, 1994; Bowden et al. 1992), which are not convincing. The exact nature of the spin-down power in AE Aqr therefore remains yet to be clarified.

In this paper, we propose that the gravitational radiation emission is the main driver of the spin-down power while accretion, ejection, and electromagnetic radiation from the spinning white dwarf are responsible for the observed luminosities in various energy bands. We construct a self-consistent picture for AE Aqr by removing the large spin-down power from the observable electromagnetic emission. For our numerical estimates, we adopt $R_* = 7 \times 10^8$ cm, $M_* = 0.8\ M_\odot$, and the moment of inertia $I_* = 3 \times 10^{50}$ g cm^2.

2. SPIN-UP AND SPIN-DOWN IN AE AQR

AE Aqr contains a very rapidly spinning white dwarf with spin period $P_* = 33.08$ s. It is an unusual white dwarf, as its spin period is quite close to the theoretically maximum breakup spin period. Such a short spin period could be achieved through accretion only if the accreted mass ΔM over time Δt is at least as high as

$$\Delta M \gtrsim I_* \Omega_*/(GM_* R_*)^{1/2} \sim 0.1\ M_\odot , \qquad (2.1)$$

where this estimate has to be taken as a lower bound since we have assumed that the accreted material has the specific angular momentum $(GM_* R_*)^{1/2}$, which is realized only when the Keplerian accretion disk extends all the way down to the stellar surface. In reality, magnetic truncation could limit the specific angular momentum to a much lower value than the Keplerian value at the stellar surface (e.g., Frank, King, & Raine 1992; see below). For an accretion rate $\dot{M} = 10^{16}\dot{M}_{16}$ g s^{-1}, the accretion of angular momentum has to occur for the duration

$$\Delta t \gtrsim 6 \times 10^7 (\Delta M/0.1\ M_\odot)\dot{M}_{16}^{-1} \text{ yr} . \qquad (2.2)$$

Although such an accretion is possible, it is unclear how the accretion flow–magnetosphere interaction could have affected the spin-up of AE Aqr. Presently, there is no indication of well-defined rotation of accreted material in the form of the accretion disk. If there is no accretion disk in AE Aqr, accretion could occur via diskless accretion such as a ballistic accretion stream. The estimated spin-up timescale is short enough to be realized in binary systems similar to AE Aqr, where the secondary is a K3–K5 main-sequence red dwarf.

There have been discussions on possible spin-down mechanisms without a clear favorite. The main problem for various spin-down mechanisms arises because of the fact that the inferred large spin-down power is not observed in any detectable forms such as high-velocity gas or high luminosities, although detection of cold, high-velocity gas is difficult. The relatively low quiescent luminosities also pose a serious problem for any mechanisms involving accretion. If the white dwarf's dipole-type magnetic field is strong enough, the electromagnetic power due to dipole radiation could account for the rapid spin-down as discussed by Ikhsanov (1998). The electromagnetic power is estimated as

$$L_{\rm em} = 2\mu_*^2 \sin^2\theta \Omega_*^4/3c^3$$
$$\sim 2.5 \times 10^{30} \sin^2\theta B_{*,6}^2 R_{*,9}^6 \Omega_{*,-1}^4 \text{ ergs s}^{-1} , \qquad (2.3)$$

where $\mu_* = B_* R_*^3$ is the magnetic moment of the dipole stellar field, $\Omega_{*,-1} = \Omega_*/0.1$ s^{-1}, $B_{*,6}$ is the stellar polar surface field strength in units of 10^6 G, and θ is the misalignment angle between the rotation axis and the magnetic axis. For AE Aqr with $\Omega_* = 0.19$ s^{-1}, we expect $L_{\rm em} \sim 4 \times 10^{30} B_{*,6}^2$ ergs s^{-1} or, for the observed upper limit $B_{*,6} \sim 5$, $L_{\rm em} \lesssim 1 \times 10^{32}$ ergs s^{-1}, which is at least 2 orders of magnitude lower than the observed spin-down power.

The rapid spin-down has been widely attributed to the propeller action in which the inflowing material is flung out at a radius $R_{\rm X}$. This radius is likely to be beyond the corotation radius and is conventionally understood as the magnetic truncation radius. The spin-down power due to the propeller action could be estimated as

$$L_{\rm prop} \sim \dot{M} R_{\rm X}^2 (GM_*/R_{\rm X}^3) \propto R_{\rm X}^{-1} , \qquad (2.4)$$

where $R_{\rm X}$ is the radius at which the accretion flow is expelled. If the propeller action occurs near the corotation radius,

$$L_{\rm prop} \sim \dot{M}(GM_* \Omega_*)^{2/3} \qquad (2.5)$$

and the observed spin-down power requires

$$\dot{M} \sim L_{\rm prop}/(GM_* \Omega_*)^{2/3} \sim L_{\rm sd}/(GM_* \Omega_*)^{2/3}$$
$$\sim 3 \times 10^{17} \text{ g s}^{-1} . \qquad (2.6)$$

In this case, the expelled material is likely to be flung out at a characteristic speed of $\sim R_c \Omega_* \sim 2.7 \times 10^8$ cm. The expected high-velocity outflow has not been detected in AE Aqr. If the propeller action occurs at the magnetospheric radius $R_{\rm mag} \sim 1.4 \times 10^{10} \dot{M}_{16}^{-2/7} M_{*,1}^{-1/7} B_{*,6}^{4/7}$ (cf. eq. [6.2] below), $L_{\rm sd}$ is accounted for by the propeller action if $L_{\rm sd} \sim GM\dot{M}R_o^{-1}$ or

$$\dot{M} \sim 8 \times 10^{17} B_{*,6}^{4/9} . \qquad (2.7)$$

In short, the mass accretion rate required for the propeller action to account for the spin-down power is likely to be considerably higher than $\sim 10^{17}$ g s^{-1}. The observed luminosities indicate that the mass accretion rate is considerably lower than $\sim 10^{17}$ g s^{-1}. Any magnetized model with the Ghosh-Lamb type (e.g., Frank et al. 1992; Yi 1995, and references therein) would essentially lead to the same conclusion since the torque achieved in variations of the model is essentially limited to the above propeller estimate on the dimensional ground. We therefore conclude that the observed luminosities and spin-down power are incompatible if the spin-down power results in the emission of the observable radiation.

3. SPIN-DOWN DUE TO GRAVITATIONAL RADIATION

We have pointed out that the electromagnetic dipole radiation with $B_* \leq 5 \times 10^6$ G and the propeller action with $\dot{M} \leq 10^{17}$ g s^{-1} are unable to account for the observed spin-down torque. We propose that the spin-down power does not transform into the observed electromagnetic radiation. We consider the gravitational radiation emission as an alternative spin-down mechanism. This mechanism could be an attractive one since the resulting spin-down power does not need to go into the observable electromagnetic radiation, which effectively avoids the long-standing question of nondetection of the observed large spin-down power. The gravitational radiation emission would be a particularly interesting spin-down mechanism if the spin evolution is highly stable and shows no signs of disturbances in accretion flows or the stellar magnetospheres. This appears to be the case in AE Aqr.

Although the white dwarf in AE Aqr spins unusually fast, under normal circumstances, the gravitational radiation emission requires a rather high nonzero quadrupole moment or a large eccentricity. If we define the eccentricity as $\epsilon = 2[1 - (R_2/R_1)]/[1 + (R_2/R_1)]$, where R_2 and R_1 are radial extents of the star in the plane perpendicular to the rotational axis, the gravitational radiation power becomes

$$L_{\rm gr} = \frac{32G}{5c^5} \epsilon^2 I_*^2 \Omega_*^6 . \quad (3.1)$$

The spin-down power of AE Aqr is accounted for by $L_{\rm gr}$ when

$$4\pi^2 I_* \dot{P}_* P_*^{-3} = \frac{32G}{5c^5} I_*^2 \left(\frac{2\pi}{P_*}\right)^6 \epsilon^2 , \quad (3.2)$$

or

$$\epsilon = [5c^5 \dot{P}_* P^3/32(2\pi)^4 G I_*]^{1/2} \sim 1.6 \times 10^{-2} , \quad (3.3)$$

which essentially implies that the nonaxisymmetric distortion of the white dwarf has to be too large to account for the observed spin-down power.

We have argued that a significant mass accretion must have occurred in order to account for the observed unusual spin period (e.g., eqs. [2.1] and [2.2]). One of the plausible possibilities is that the accreted material mostly lands on a small fraction of the total surface area near the magnetic poles. If this is the case, as expected in the significantly magnetized accretion case, the accreted material would provide a source of nonzero quadrupole moment if the magnetic axis is misaligned with the rotation axis. That is, the magnetically channeled material would spread from the magnetic poles while its spread is partially hindered by the strong stellar magnetic field. Conceivably, in a steady state achieved in the high mass accretion rate episode while the rapid spin-up occurred, prior to the present spin-down, the accreted material could form accretion mounds at the magnetic poles (e.g., Inogamov & Sunyaev 1999, and references therein).

If we assume that the accreted material is present at the magnetic poles in the form of the spatially limited blobs or mounds while the rotation axis and the magnetic axis are misaligned by an angle θ, the time-averaged rate of gravitational radiation power could be estimated as

$$L_{\rm gr} = \frac{8G}{5c^5} \delta m^2 R_*^4 \Omega_*^6 \sin^2 \theta (13 \sin^2 \theta + \cos^2 \theta) , \quad (3.4)$$

where δm is the amount of mass accumulated on one magnetic pole. We have assumed for simplicity that the accumulated material exists at the magnetic poles without any significant spatial spread and it remains unperturbed during each stellar rotation.

By comparing $L_{\rm gr}$ calculated above and the observed spin-down power of AE Aqr,

$$4\pi^2 I_* \dot{P}_* P_*^{-3} = \frac{8G}{5c^5} \delta m^2 R_*^4 \left(\frac{2\pi}{P_*}\right)^6 \times \sin^2 \theta (13 \sin^2 \theta + \cos^2 \theta) , \quad (3.5)$$

we get

$$\delta m \sim 1 \times 10^{-2} [\sin^2 \theta (13 \sin^2 \theta + \cos^2 \theta)]^{-1/2} M_\odot , \quad (3.6)$$

which is smaller by roughly 1 order of magnitude than the minimum mass required for the spin-up of AE Aqr during the rapid accretion phase.

This power rapidly becomes negligible as the star slows down because of the sensitive dependence of the gravitational radiation power on the spin frequency. For the AE Aqr parameters, $L_{\rm gr} > L_{\rm em}$ occurs if

$$\delta m > 1.4 \times 10^{-4} (13 \sin^2 \theta + \cos^2 \theta)^{-1/2} B_{*,6} M_\odot \quad (3.7)$$

or, for $\delta m \sim 10^{-2} M_\odot$,

$$P_* < 755 (13 \sin^2 \theta + \cos^2 \theta)^{1/2} B_{*,6}^{-1} \text{ s} . \quad (3.8)$$

AE Aqr could well have been continuously spun-down after reaching a high spin frequency resulting from the high-accretion phase. The above estimate indicates that AE Aqr's current rapid spin-down could continue to periods much longer than the present short spin period.

The effective quadrupole moment of the accreting white dwarf is

$$\epsilon I_* \approx \tfrac{1}{2} \delta_m R_*^2 \sin \theta (13 \sin^2 \theta + \cos^2 \theta)^{1/2} , \quad (3.9)$$

or, for instance, for $\theta = 30°$, $\epsilon I_* \approx \frac{1}{2} \delta m R_*^2$, which implies that the dimensionless signal strength of the gravitational radiation at Earth is

$$h \sim 2G\Omega_*^2 \delta m R_*^2 / Dc^4 \sim 2 \times 10^{-24} \delta m_{-4} , \quad (3.10)$$

where $D = 100$ pc has been adopted for the distance to AE Aqr. This estimated strength is substantially weaker than the projected Large Interferometer for Submillimeter Astronomy (LISA) noise limits of $\sim 3 \times 10^{-22}$ and $\sim 1 \times 10^{-23}$ at $\sim 3 \times 10^{-2}$ Hz for 1 and 5 yr operations, respectively.

The accumulation of mass at the magnetic poles necessary for spin-down driven by the gravitational radiation emission has to be substantial. If the mass accumulation reaches a certain critical level and the pressure built up at the bottom of the accretion mounds becomes comparable to $\sim 5 \times 10^{19}$ dyn cm^{-2}, thermonuclear runaway could set in (Livio 1984; Livio, Shankar, & Truran 1988, and references therein). Since the pressure is $\sim GM_* \delta m / R_*^2 A_{\rm acc}$, the pressure could be as high as $\sim 10^{20} \delta m_{-5} B_{*,6} \dot{M}_{16}^{-2/7}$ where we have assumed that the polar accretion region's area $A_{\rm acc}$ is a fraction $R_* \sin^2 \theta / 2R_{\rm mag}$ of the total white dwarf surface area and $R_{\rm mag}$ is the magnetospheric radius (Yi et al. 1992, and also see below). This implies that AE Aqr's accretion mound could become unstable and show frequent nova-type eruptions. The higher the accretion rate, the lower the probability of a major eruption while small eruptions with higher frequencies result as the ignition point is reached more easily.

It is crucial in the proposed gravitational radiation mechanism that the mass accumulation be allowed before thermonuclear eruptions reduce the mass of the polar mounds. On the other hand, the accretion mounds may not be sustained if rapid diffusion in the direction perpendicular to the field lines occurs. Cross-field diffusion of accreted matter is prevented if the surface magnetic field strength exceeds $\sim 1 \times 10^8 \dot{M}_{16}^{-1/2}$ G assuming that at the bottom of the accretion mound the pressure reaches $\sim 5 \times 10^{19}$ dyn cm^{-2}, which is close to the thermonuclear runaway ignition point (Livio 1984). Therefore, the large accretion mounds could exist when the magnetic field is substantially higher than ~ 50 MG. Therefore, if the gravitational radiation emission mechanism is indeed the dominant spin-down mechanism, the current episode is highly likely to be a transient phenomenon and AE Aqr could show frequent small thermonuclear eruptions or diffusion can quickly drain accreted material out of the polar mounds. Since most of the flares do not appear to be occurring near the polar regions, it is interesting if some of the flares could have a polar origin.

What kinds of magnetized white dwarf systems could show large spin-down powers caused by the gravitational radiation emission as in AE Aqr? Obviously the candidate systems have to be rapidly spinning, which is likely when the systems were spun up by preceding high mass accretion rate flows. With strong magnetic fields, a significant fraction of the accreted mass could reside in the polar regions while the magnetic axes have to be substantially misaligned with the rotation axes. For these systems, if the mass accretion becomes high and the magnetic fields are strong, the propeller-like torque is likely to dominate over the gravitational radiation emission. The accumulated mass near the magnetic poles could spread over the stellar surface, although the details of the spreading process could be highly complicated (e.g., Inogamov & Sunyaev 1999). The gradually cooling accretion mounds could be a source of persistent UV emission, which should show significant pulse signals (see below).

4. ELECTROMAGNETIC EMISSION COMPONENTS AND PHYSICAL PARAMETERS OF AE AQR

Based on the large pulse fraction, as high as $\sim 80\%$ during quiescence (Eracleous et al. 1994), the most likely UV production site is the magnetic poles. The total UV luminosity (pulsed and nonpulsed) in quiescence is $L_{\rm uv} \sim 4 \times 10^{31}$ ergs s^{-1}, which corresponds to the nominal polar accretion rate of $\dot{M} \sim 2 \times 10^{14}$ g s^{-1}. If the UV emission is the result of the low $\dot{M}$ accretion occurring at the magnetic poles, the expected emission temperature in the form of the thermalized radiation is $T_{\rm uv} \sim 2 \times 10^4 a^{-1/4}(\dot{M}/10^{14}\ {\rm g\ s^{-1}})^{1/4}$ K, where $a \leq 1$ is the fraction of the stellar surface area accreting near the magnetic poles.

On the other hand, the X-ray pulse fraction is much lower ($\sim 30\%$) during quiescence (Choi, Dotani, & Agrawal 1999). The straightforward implication from this low pulse fraction is that the X-ray emission site is much more extended than the narrow polar region around the magnetic poles.

If the accretion occurs in the form of the accretion stream directly impacting on the magnetosphere, only a small fraction of the accreted material lands on the magnetic poles. We call such an accretion flow the high-altitude accretion flow, which constitutes a small fraction of the total accretion flow. That is, we consider a picture in which a large fraction of the accretion stream hits low altitudes and a comparable fraction of it hits high altitudes and travels directly to the poles (Fig. 1).

4.1. *Low-Altitude Accretion*

The power resulting from the low-altitude stream–magnetosphere interaction region is simply

$$L_{\rm X} \sim GM_* \dot{M}_{\rm X}/R_{\rm X} , \tag{4.1}$$

where we denote the location and luminosity by subscript X assuming that most of the energy is released in the X-ray range and a certain fraction of the inflowing matter is expelled. X-ray emission is possible if the accretion stream's kinetic energy is virialized after the accreted material gets shocked at the impact region.

The X-ray emission region is characterized by the simple magnetospheric radius (e.g., eq. [6.2])

$$R_{\rm mag} \sim 1.4 \times 10^{10} \dot{M}_{16}^{-2/7} M_{*,1}^{-1/7} B_{*,6}^{4/7}\ {\rm cm} , \tag{4.2}$$

where $\dot{M}_{16} = \dot{M}/10^{16}$ g s^{-1}. At this radius, the low-altitude stream's ram pressure becomes roughly equal to the magnetic pressure of the magnetosphere. We have assumed that the stream is nearly free-falling and the stream's geometric cross section is comparable to the spherical surface area at the interaction region.

If most of the UV emission is due to the low $\dot{M}$ accretion occurring at high altitudes, we expect, as before,

$$L_{\rm uv} \sim GM_* \dot{M}_{\rm uv}/R_* . \tag{4.3}$$

Therefore, we get

$$L_{\rm uv}/L_{\rm X} \sim (\dot{M}_{\rm uv}/\dot{M}_{\rm X})(R_{\rm X}/R_*) , \tag{4.4}$$

or for the magnetospheric radius of the low-altitude accretion $R_{\rm X} \sim R_{\rm mag}$.

Using the observed $L_{\rm uv}/L_{\rm X} \sim 6$ (Eracleous et al. 1994; Choi et al. 1999)

$$\dot{M}_{\rm uv}/\dot{M}_{\rm X} \sim 0.3 \dot{M}_{16}^{2/7} M_{*,1}^{-1/7} B_{*,6}^{-4/7} , \tag{4.5}$$

which is uncertain because of the uncertain B_* and $\dot{M}$ in AE Aqr.

If most of the propeller action occurs near the corotation radius $R_c \sim 1.4 \times 10^9$ cm, which would be close to the magnetospheric radius $R_{\rm mag}$ if $B_* \sim 2 \times 10^4 \dot{M}_{16}^{1/2} M_{*,1}^{-1/7}$, then the accretion rates in the two regions are comparable:

$$\dot{M}_{\rm uv}/\dot{M}_{\rm X} \sim R_*/R_c \sim 0.5 , \tag{4.6}$$

which implies that a large fraction of the accreted matter has to flow to the poles.

If the X-ray emission is from the shocked gas at the propeller action region where the accretion stream hits the magnetosphere and collides with the outflowing material creating localized shocks, the characteristic X-ray emission temperature from the optically thin gas is likely to be

$$T_{\rm X} \sim 3GM_* m_p/16kR_{\rm X} \sim 2 \times 10^7 \dot{M}_{16}^{2/7} B_{*,6}^{-4/7}\ {\rm K} , \tag{4.7}$$

or $kT_{\rm X} \sim 2\dot{M}_{16}^{2/7} B_{*,6}^{-4/7}$ keV, which is very close to the observed X-ray emission temperature $\lesssim 3$ keV. Similarly, for the propeller action occurring near the corotation radius, the expected X-ray emission temperature $kT_{\rm X} \sim 9$ keV, which implies that the propeller action occurring anywhere between the two regions at radii $\sim 10^{10}$ cm and $\sim R_c \sim 1.4 \times 10^9$ cm can account for the bremsstrahlung emission in the X-ray band.

On the other hand, if the propeller action region is responsible for blackbody-like emission, then the characteristic temperature could be as low as $\sim 1 \times 10^4 \dot{M}_{16}^{1/4}$. This temperature corresponds to optical/UV emissions, although the high pulse fraction observed in AE Aqr rules out the possibility that the dominant optical/UV emissions arise from the propeller action region.

In the polar regions, the radially falling material lands on the surface of the white dwarf and the kinetic energy could

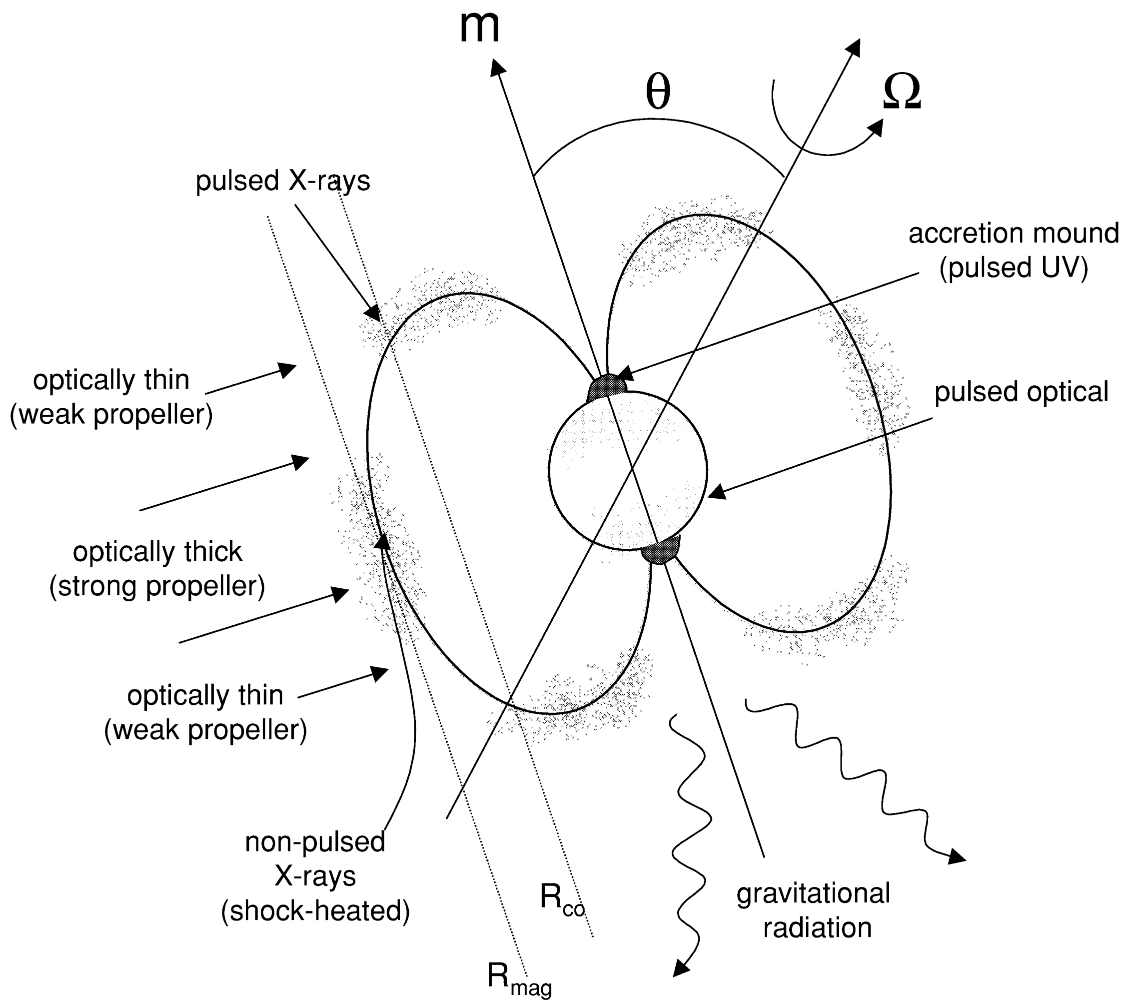

FIG. 1.—Schematic description of the AE Aqr accretion-ejection model as discussed in the text

thermalize and be radiated as blackbody-like emission. If the accreting fraction of the white dwarf is a (≤ 1) of the total stellar surface area, then the expected emission temperature is

$$T_{\rm uv} \sim 2 \times 10^4 a^{-1/4} \dot{M}_{14}^{1/4} \ {\rm K} \ , \qquad (4.8)$$

where $\dot{M}_{14} = \dot{M}/10^{14}$ g s^{-1}, as noted earlier.

Using the observed X-ray luminosity and the X-ray emission temperature, we can estimate the mass accretion rate and the magnetic field strength. First, using the shock temperature in the propeller action region, we require that the shock temperature be close to the observed X-ray emission temperature $\sim$3 keV:

$$\dot{M}_{16} \sim 4.1 B_{*,6}^2 \ . \qquad (4.9)$$

Similarly, the observed X-ray luminosity should be close to the total accretion power (with the radiative efficiency $\eta_{\rm X}$) $\sim 10^{31}$ ergs s^{-1}, or

$$\dot{M}_{16} \sim 0.2 \eta_{\rm X}^{-7/9} B_{*,6}^{4/9} \ . \qquad (4.10)$$

The two constraints are simultaneously satisfied only if $B_* \sim 1.4 \times 10^5 \eta_{\rm X}^{-1/2}$ G and $\dot{M} \sim 8 \times 10^{14} \eta_{\rm X}^{-1}$ g s^{-1}.

Substituting the mass accretion rate and the field strength in the equation for the ratio of $\dot{M}_{\rm uv}/\dot{M}_{\rm X}$ we arrive at

$$\dot{M}_{\rm uv} \sim 4 \times 10^{14} \eta_{\rm X}^{-1} \ {\rm g \ s^{-1}} \ , \qquad (4.11)$$

which is a substantial fraction of the accreted material arriving at the propeller action region. We therefore conclude that a significant fraction of material manages to land on the surface of the white dwarf despite an ongoing propeller action in AE Aqr.

4.2. *High-Altitude Accretion*

In the above calculations, we have considered that a part of the accretion stream hits low magnetic altitudes and most of the X-ray emission is produced from the shock-heated (optically thin) gas near the magnetospheric radius or the corotation radius. On the other hand, the high-altitude accretion flow travels directly to the poles. At low altitudes, the accreting stream remains mostly optically thick until shock heated and expelled by the propeller action. On the other hand, the accretion stream remains optically thin at high altitudes and is continuously heated in a roughly quasi-spherical accretion pattern. The propeller action is relatively weaker at higher altitudes as in the case of the diskless accretion, and hence a substantial fraction of it travels to the poles while emitting X-rays until it reaches the magnetic poles, where the accretion flow gets thermalized and emits optically thick blackbody-like UV emission. In this picture, because the high-altitude gas stream is adiabatically heated to an X-ray emitting temperature near the magnetic poles, we expect pulsed X-ray emission.

For the derived magnetic field strength, the dipole radiation power becomes $L_{em} \sim 8 \times 10^{28} \eta_X^{-1}$ ergs s^{-1}, which suggests that the observed radio emission could be accounted for by the dipole radiation if the X-ray efficiency is $\sim$ 10%. Alternatively, the radio emission could result from accelerated electrons at the shock near R_X, a remote possibility given the fact that there exists no evidence of high-speed material in AE Aqr.

It is unlikely that the TeV emission occurs at the level of $\sim 10^{32}$ ergs s^{-1} based on the above conclusion. Meintjes et al. (1992, 1994) and Bowden et al. (1992) reported detection of TeV γ-rays from AE Aqr that are pulsating at the spin period. However, according to a more recent observation by Lang et al. (1998), there is no evidence for any steady, pulsed, or episodic TeV emission. In the present picture, the TeV emission at the claimed level is not likely since the largest power goes into the gravitational radiation.

Using the mass accretion rate and the magnetic field strength, we estimate that the accretion stream is likely to be stopped at a radius

$$R_X \sim 1 \times 10^{10} \text{ cm} , \quad (4.12)$$

which is compared with the nominal circularization radius for material traveling through the inner Lagrange point in the binary system (e.g., Frank et al. 1992)

$$R_{circ} \sim 3 \times 10^{10} \text{ cm} , \quad (4.13)$$

where we have adopted the secondary to primary mass ratio $\sim$0.6. For the estimated magnetospheric radius, it is possible that the accretion disk does not exist in this system, as has been recently argued based on the nondetection of the double-peaked Hα emission line in AE Aqr. Even if they exist, they could exist in a very narrow radial zone in which the line emission is too weak to detect.

5. FLARES AND LOW-ENERGY EMISSION

Simultaneous observations between optical and UV and between optical and X-ray (Osborne et al. 1995; Eracleous & Horne 1996) show some similarities in their light curves. For example, while UV and optical flares are well correlated, they are less correlated with the X-ray flares. However, radio flares are not correlated with the optical flares (Abada-Simom et al. 1995). The pulse amplitudes in both the UV and X-ray regions do not display any large variations compared with the values of their quiescent states, nor do they follow the variations of the nonpulsed level. The difference between quiescent and flare spectra in the X-ray region is not significant, although a hint of spectral hardening is recognized (Choi, Dotani, & Agrawal 1999). These characteristics strongly suggest that the magnetic poles or accretion columns above the white dwarf surface are hardly connected with the flaring activities. The possibility that a stellar flare might occur in the companion star has been ruled out because it could not account for the kinematic properties of line-emitting gas in the UV data (e.g., Eracleous & Horne 1996). The flares arising from the occasional encounters between propeller-expelled outgoing gas streams (or blobs) and the incoming accretion stream are not realistic because the possible interaction region is too far to account for the high energies observed in the flares.

The exact nature of the flaring activities is beyond the scope of the present study. If the flaring activities indeed occur in a region far beyond the polar area, then a possible region is again the impact region formed by the accretion stream interacting with the magnetosphere. If the gas rotating between R_{circ} and R_X wraps the poloidal component, B_z, of the stellar field and amplifies the toroidal component, B_ϕ, to an equilibrium value $B_\phi \sim (\gamma/\alpha)(\Omega_*/\Omega - 1)B_z$ at a rate $\sim \gamma(\Omega_* - \Omega)B_z$ (e.g., Yi 1995, and reference therein), it would take $t_{amp} \sim (\alpha\Omega)^{-1}$, where $\alpha \sim 0.1$ is the usual α viscosity parameter, $\Omega_* = 2\pi/P_*$, $\Omega = (GM_*/R^3)^{-1/2}$ is the local rotational angular velocity, and γ is the vertical velocity shear parameter of order unity. Here we have assumed that the amplification is balanced by the magnetic diffusion with the magnetic Prandtl number of order unity. Then, a simple-minded characteristic timescale for magnetic amplification is $\sim 10 \times P_* \sim 300$ s provided that the amplification occurs near the corotation radius. On the other hand, based on the AE Aqr parameters $\dot{M} \sim 10^{15}$ g s^{-1} and $B_* \sim 10^5$ G, we estimate that $R_{mag} \sim 8 \times 10^9$ cm and $L_{sd} \sim 1 \times 10^{31}$ ergs s^{-1}. The observed typical flare energy $\sim 10^{35}$ ergs requires the accumulation of the spin-down energy (in the form of the magnetic stress) for a duration of $\sim 10^4$ s, which is longer than the magnetic field amplification timescale by at least a factor of $\sim$30. If the magnetic field amplification is not balanced by magnetic diffusion of the α type (Yi 1995) but by buoyant loss of the Parker type (e.g., Wang 1987), it is conceivable that the flare energy accumulation timescale could be accounted for since the field can grow to a higher value on a longer timescale. The details of this issue are especially hard to describe given the uncertain and complex nature of the accretion flow pattern and density structure near the propeller action region.

6. DISCUSSION AND SUMMARY

Various models have been considered to explain the pulsations and flares in AE Aqr. Among the proposed models, both an oblique rotator model (Patterson 1979, 1994) and a magnetospheric gating model (van Paradijs et al. 1989; Spruit & Taam 1993) have been ruled out by the reason that there is lack of observational evidence for an accretion disk (see Eracleous & Horne 1996 and Welsh et al. 1998 for a detailed discussion). The propeller model is primarily based on this point.

A high-velocity gas that is escaping from the system is predicted from the propeller model. However, Welsh et al. (1998) have argued that they did not detect any signatures for high-velocity gas nor did they obtain any expected pattern from their trailed spectrograms. In addition, the bulk kinetic energy of the expelled gas with $\dot{M} \sim 4 \times 10^{17}$ g s^{-1} is smaller than the observed spin-down power by 1 order of magnitude. We also note that in the propeller scenario mass loss from the companion star is inhomogeneous and intermittent. If this is true, it is questionable why the pulsed emission is sustained almost constantly and stably.

By removing the spin-down power from the observable luminosities, we have constructed a self-consistent model that in essence incorporates all the existing ingredients. Eracleous et al. (1994) analyzed 10 pulse profiles in different wavelengths obtained from the simultaneous *Hubble Space Telescope* (*HST*; UV) and ground (optical) observations. According to their results, there are no discernible phase shifts between pulses at different wavelengths and the amplitude of pulsations decreases with increasing wavelength. This implies that the emission region becomes broader for longer wavelengths (or lower energies). In our model, pulsed X-ray emission is from the adiabatically heated gas in an extended region between the high-altitude magnetosphere and the magnetic poles, which is traveling onto the poles. While the gas travels toward the poles, it cools down because the radiation and UV emission becomes dominant near the polar region. After the gas landed on the polar regions, it would spread over the stellar surface as discussed in § 3. While spreading over the stellar surface, the gas cools down further. Therefore, it is possible that the emission region becomes broader for longer wavelengths. On the other hand, the incoming accreting stream is optically thick at low altitudes and it is mostly expelled. Therefore, optical/UV emission can also arise in this region and partly contribute to the nonpulsed optical/UV emission. Alternatively, if cooling occurs rapidly during the gas infall phase, the kinetic energy of the radially falling material could thermalize at the polar region and be radiated as blackbody-like emission with a temperature of $\sim 2 \times 10^4$ K as estimated in eq. (4.8). The gas then follows similar spreading and cooling processes on the white dwarf surface.

We have considered the possibility that the flares of AE Aqr are due to the release of magnetic stress, which is reminiscent of the solar flares. An alternative possibility, the magnetic pumping model, was proposed by Kuijpers et al. (1997) with an intention to account for radio outbursts or flares. In this model, the radio flares are caused by eruptions of bubbles of fast particles from a magnetosphere surrounding the white dwarf. The model also speculates that at relatively low accretion rates the conversion of spin energy into acceleration (rather than heating) of electrons and protons can be efficient. The accelerated fast particles remain trapped in the magnetosphere, and, when their total energy becomes comparable to the magnetic field energy, an MHD instability sets in. Then synchrotron radiation occurs in the expanding plasmoid at radio and long wavelengths.

The highly stable spin-down implies that the spin-down mechanism remains stable despite propeller action and related possible dynamical instabilities. It has usually been interpreted as a sign of a stable accretion disk. If AE Aqr does not have an accretion disk as often claimed, the spin-down could indeed be due to the gravitational radiation emission, which is obviously quite stable as long as it is the dominating spin-down mechanism.

If there exists a Keplerian accretion disk interacting with the stellar magnetosphere, the accretion flow will exert a torque (Yi 1995)

$$N = \frac{7N_o}{6} \frac{1 - (8/7)(R_{\rm mag}/R_c)^{3/2}}{1 - (R_{\rm mag}/R_c)^{3/2}} , \qquad (6.1)$$

where $N_o = \dot{M}(GM_* R_{\rm mag})^{1/2}$ and $R_{\rm mag}$ is the magnetic truncation or the magnetospheric radius determined by

$$(R_{\rm mag}/R_c)^{7/2} = A \,|\, 1 - (R_{\rm mag}/R_c)^{3/2} \,| , \qquad (6.2)$$

where

$$A = 2(\gamma/\alpha) B_c^2 R_c^3 / \dot{M}(GM_* R_c)^{1/2} , \qquad (6.3)$$

with $B_c = \mu_*/R_c^3$. The observed spin-down will result if $R_{\rm mag}/R_c > 0.9148$ in this particular magnetized accretion model or $A > 5.86$, which for AE Aqr translates into

$$B_* > 1 \times 10^4 (\alpha/\gamma)^{1/2} \dot{M}_{15}^{1/2} , \qquad (6.4)$$

where $\dot{M}_{15} = \dot{M}/10^{15}$ g s^{-1}. Therefore, for the derived AE Aqr parameters, a rotating accretion disk would always exert a spin-down torque although the spin-down is dominated by the gravitational radiation mechanism.

Our proposed model is essentially summarized as follows. (1) The spin-down is driven by gravitational radiation emission. (2) The dipole radiation from the rapidly spinning white dwarf is responsible for radio emission and possible TeV γ-ray emission. (3) UV emission is from the magnetic poles with a low accretion rate or from a cooling accretion mound from a previous high-accretion episode. A large amount of material present at the poles would be compatible with the current rapid white dwarf rotation. (4) Accretion to the poles occurs at high altitudes, while at low altitudes the propeller action drives material outward. However, as long as the accretion rate is lower than $\sim 10^{17}$ g s^{-1}, the spin-down power by propeller action is smaller than the observed spin-down. (5) X-rays are mostly from the accretion stream–magnetosphere boundary, where the propeller action drives material outward while shock heating the accreted material. UV emission could also arise in this region if there exists optically thick gas. (6) Flares are due to the release of magnetic stress much like that seen in solar flares. (7) In sum, $L_{\rm sd} \sim 2 \times 10^{34}$ ergs s^{-1} mostly goes to $L_{\rm gr}$, which is undetectable. $L_{\rm em} \lesssim 10^{32}$ ergs s^{-1} goes to $L_{\rm radio}$ and possibly to L_γ. $L_{\rm uv}$ is either from $\dot{M} \sim 2 \times 10^{14}$ g s^{-1} high-altitude accretion or from the cooling accretion mound at the magnetic poles. The contribution from the disk-magnetosphere interaction region has to be small as required by the high pulse fraction.

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REFERENCES

Abada-Simon, M., Batian, T. S., Horne, K., Robinson, E. L., & Bookbinder, J. A. 1995, in Proc. Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner (San Francisco: ASP), 355
Bastian, T. S., Beasley, A. J., & Bookbinder, J. A. 1996, ApJ, 461, 1016
Bastian, T. S., Dulk, G. A., & Chanmugam, G. 1988, ApJ, 324, 431
Bowden, C. C. G., et al. 1992, Astropart. Phys., 1, 47
Casares, J., Mouchet, M., Martinez-Pais, I. G., & Harlaftis, E. T. 1996, MNRAS, 282, 182
Choi, C. S., Dotani, T., & Agrawal, P. C. 1999, ApJ, 525, 399
de Jager, O. C. 1994, ApJS, 90, 775
de Jager, O. C., Meintjes, P. J., O'Donoghue, D., & Robinson, E. L. 1994, MNRAS, 267, 577
Eracleous, M., & Horne, K. 1996, ApJ, 471, 427
Eracleous, M., Horne, K., Robinson, E. L., Zhang, E.-H., Marsh, T. R., & Wood, J. H. 1994, ApJ, 433, 313
Eracleous, M., Patterson, J., & Halpern, J. 1991, ApJ, 370, 330
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (2d ed.; Cambridge: Cambridge Univ. Press)
Ikhsanov, N. R. 1998, A&A, 338, 521
Inogamov, N., & Sunyaev, R. 1999, Astron. Lett., 25, 269
Kuijpers, J., Fletcher, L., Abada-Simon, M., Horne, K. D., Raadu, M. A., Ramsay, G., & Steeghs, D. 1997, A&A, 322, 242
Lang, M. J., et al. 1998, Astropart. Phys., 9, 203
Livio, M. 1984, A&A, 141, L4
Livio, M., Shankar, A., & Truran, J. W. 1988, ApJ, 330, 264
Meintjes, P. J., de Jager, O. C., Raubenheimer, B. C., Nel, H. I., North, A. R., Buckley, D. A. H., & Koen, C. 1994, ApJ, 434, 292
Meintjes, P. J., Raubenheimer, B. C., de Jager, O. C., Brink, H. I., North, A. R., van Urk, G., & Visser, B. 1992, ApJ, 401, 325
Osborne, J. P., Clayton, K. L., O'Donoghue, D., Eracleous, M., Horne, K., & Kanaan, A. 1995, in Proc. Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner (San Francisco: ASP), 368

Patterson, J. 1979, ApJ, 234, 978
———. 1994, PASP, 106, 209
Spruit, H. C., & Taam, R. E. 1993, ApJ, 402, 593
Stockman, H. S., Schmidt, G. D., Berriman, G., Liebert, J., Moore, R. L., & Wickramasinghe, D. T. 1992, ApJ, 401, 628
van Paradijs, J., Kraakman, H., & van Amerogen, S. 1989, A&AS, 79, 205
Wang, Y.-M. 1987, A&A, 183, 257
Welsh, W. F., Horne, K., & Gomer, R. 1995, MNRAS, 275, 649
———. 1998, MNRAS, 298, 285
Wynn, G. A., King, A. R., & Horne, K. 1997, MNRAS, 286, 436
Yi, I. 1995, ApJ, 442, 768
Yi, I., Kim, S.-W., Vishniac, E. T., & Wheeler, J. C. 1992, ApJ, 391, L25