A STUDY OF THE X-RAY EMISSION OF THE MAGNETIC CATACLYSMIC VARIABLE AE AQUARII

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Received 1998 November 2; accepted 1999 June 15

ABSTRACT

We report results from analysis of the X-ray observations of AE Aqr, made with Ginga in 1988 June and with ASCA in 1995 October. Pulsations are detected clearly with a sinusoidal pulse profile with a period of 33.076 ± 0.001 s (Ginga) and 33.077 ± 0.003 s (ASCA). The pulse amplitude is relatively small, and the modulated flux remains nearly constant despite a factor of 3 change in the average flux during the flare. We reproduce the time-averaged spectrum in the 0.4–10 keV energy band by a thermal emission model with a combination of two different temperatures: $kT_1 = 0.68^{+0.02}_{-0.01}$ keV and $kT_2 = 2.9^{+0.3}_{-0.2}$ keV. There is no significant difference between the quiescent and flare energy spectra, although a hint of spectral hardening is recognized during the flare. We interpret these observational results with a model in which AE Aqr is in a propeller stage. Based on this propeller scenario, we suggest that the X-ray emission originates from magnetospheric radiation.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (AE Aquarii) — X-rays: stars

1. INTRODUCTION

AE Aquarii is a nova-like object classified as a DQ Her-type magnetic cataclysmic variable (CV) or an intermediate polar. It consists of a magnetic white dwarf and a late-type companion star with a spectral type of K3–K5. It is widely believed that the companion star's atmosphere fills its Roche lobe and matter flows out from the companion's Roche lobe to the white dwarf (Casares et al. 1996). Although the strength of magnetic field is not determined, it is believed that the white dwarf has a sufficiently strong field to channel the accretion flow onto its magnetic poles.

AE Aqr has been observed in a wide span of wavelengths from X-ray to radio (Tanzi, Chincarini, & Tarenghi 1981; Eracleous, Halpern, & Patterson 1991a; Richman 1996; Bastian, Beasley, & Bookbinder 1996; Eracleous & Horne 1996, and references therein). Meintjes et al. (1992, 1994) reported that AE Aqr emits TeV γ-rays. Optical photometric and spectroscopic studies indicate that the AE Aqr system is a non-eclipsing binary with an orbital period of 9.88 hr (Welsh, Horne, & Gomer 1995, and references therein). This system is known to switch between flaring and quiescent phases irregularly in its optical light curve (Patterson 1979; Chincarini & Walker 1981; van Paradijs, Kraakman, & van Amerogen 1989). According to the result of simultaneous optical and UV observations by Eracleous et al. (1994), the optical and UV fluxes vary coherently. Similar result was reported by Osborne et al. (1995) for their simultaneous UV and X-ray observations.

One of the distinguishing properties of this system from other magnetic CVs is its flaring activity. The flare lasts for $\sim$10 minutes to 1 hr and appears frequently in the optical light curves (Patterson 1979; van Paradijs et al. 1989; Bruch 1991). Such flares have also been detected in the UV and radio regions (Bastian, Dulk, & Chanmugam 1988; Eracleous & Horne 1996). According to Eracleous & Horne, the UV continuum and emission-line fluxes increase several times over the quiescent state levels during the flares. In the X-ray region, Clayton & Osborne (1995) observed an X-ray flare that reached about 3 times the quiescent flux level. However, the flaring mechanism and the flaring site are poorly understood. Eracleous & Horne analyzed data of a UV flare and obtained some clues about the flare origin, particularly radial velocity curves for several emission lines. They suggested that a magnetic propeller model (Wynn, King, & Horne 1997) is the most promising to explain the velocity curves. In the propeller model, inhomogeneous gas blobs come from the secondary star and interact with the magnetic field of the white dwarf at the closest approach. From this interaction, most of the gas blobs are expelled from the system.

The white dwarf in AE Aqr is known to have the shortest spin period, $P = 33.08$ s, of known CVs. Patterson (1979) discovered stable optical pulsations with $P = 16.5$ and 33.08 s and also reported the detection of quasi-periodic oscillations near these periods during the flare. Subsequently, Patterson et al. (1980) detected the 33.08 s pulsations from the X-ray observation of AE Aqr and suggested that a spinning magnetized white dwarf is responsible for both the optical and the X-ray pulsations. The 33.08 s period is widely believed to be the spin period of the white dwarf, while the period of 16.5 s is its first harmonic. UV pulsations at the spin period were reported by Eracleous et al. (1994), whereas, according to Bastian et al. (1996), there are no radio pulsations at this period.

Based on the X-ray observations of AE Aqr with ROSAT, several authors have reported some new spectral features. Clayton & Osborne (1995) reported that both quiescent and flare spectra in the range of 0.1–2.5 keV can be reproduced by a two-temperature optically thin emission model with temperatures of $kT_1 = 0.2–0.3$ keV and $kT_2 = ...
1.0–1.4 keV. Richman arrived at a similar conclusion, that a single-temperature Bremsstrahlung model is not sufficient to produce the observed quiescent state spectrum. He additionally reported that there is an orbital phase dependence in the softness ratio between the 0.1–0.4 keV and the 0.4–2.4 keV bands.

In this paper, we report the results of the *Ginga* and *ASCA* observations of AE Aqr. Based on these results, together with those obtained at other wavelengths, we first consider the nature of the compact object in AE Aqr. We then discuss the X-ray emission mechanism and the origin of the pulsation and the flare.

### 2. OBSERVATION AND DATA ACQUISITION

The observations of AE Aqr by *Ginga* were made from 1988 June 1 13:17 UT to June 3 20:35 with a net exposure of 63 ks. *Ginga* is the third X-ray astronomy satellite of Japan (Makino 1987), and its main instrument, the Large Area Proportional Counter (LAC; Turner et al. 1989), covers 1–37 keV with an effective area of 4000 cm². Its field of view is restricted to 1° × 2° (FWHM) by the mechanical collimator. During the observations, the LAC was operated in either the MPC1 mode (48 energy channel, 0.5 s/4 s time resolution) in high/medium bit rate or the MPC2 mode (48 energy channel, 2 s time resolution) in low bit rate. The *Ginga* archival data were obtained from the SIRIUS data-base at the Institute of Space and Astronautical Science (ISAS) and were analyzed using the mainframe computer at the institute.

The *ASCA* observations were performed on 1995 October 10 from 23:40 UT to 22:57 UT on the following day. The *ASCA* satellite (Tanaka, Inoue, & Holt 1994) is equipped with four thin-foil X-ray telescopes (Serlemitsos et al. 1995), which focus X-rays onto four focal plane detectors, of which two are Solid-State Imaging Spectrometers (SIS0 and SIS1; Burke et al. 1993) and two are Gas Imaging Spectrometers (GIS2 and GIS3; Ohashi et al. 1996; Makishima et al. 1996). Each SIS consists of four CCD chips with a full width at half-maximum energy resolution of ~60–120 eV in the energy range 0.4–10 keV, while each GIS has an energy resolution of ~200–600 eV (0.8–10 keV). For this observation, SISs were operated in one-CCD faint or bright mode depending on the telemetry bit rate and GISs in the pulse-height (PH) mode. The time resolution of the SISs in one-CCD mode is 4 s, and it is 62.5/500 ms (high/medium telemetry bit rate) for the GISs in PH mode.

We acquired the raw data through the High Energy Astrophysics Science Archive Research Center (HEASARC) on-line service, provided by the NASA/Goddard Space Flight Center. We apply standard data screening procedures to avoid X-ray contamination from the bright Earth and regions of high particle background. During these procedures, data are rejected for the SISs and GISs when the pointing direction of the telescope is less than 30° and 8° from the Earth’s limb, respectively. Regions of cutoff rigidity greater than 10 GeV/c are selected for both of the detectors. Hot and flickering pixels are removed from the SIS data. The net exposure times after the screening are 28 ks for SIS and 32 ks for GIS.

### 3. THE LIGHT CURVE AND ITS MAIN CHARACTERISTICS

We find that AE Aqr is too faint to obtain a light curve or an energy spectrum with the *Ginga* LAC data. The upper limit of the source count rate with the *Ginga* LAC, which is mainly determined by the systematic uncertainty of the background subtraction, is estimated to be about 2 counts s⁻¹. Source confusion is a problem at such a low count rate. Despite the low count rate, however, we could clearly detect the 33.08 s pulsation in the *Ginga* data. Thus, we have a positive detection of AE Aqr, although we could not determine the source flux because of the systematics of the background subtraction. In this section, we concentrate on the *ASCA* data.

Figure 1 shows the light curves obtained with (upper panel) the SIS0 and (lower panel) the GIS3 detectors aboard *ASCA*. The data were binned in 164 s intervals, and the X-ray background, which is negligible in the plot, was not subtracted. The vertical dotted lines in the figure indicate the orbital phases calculated from the ephemeris (MJD 49280.92222) and orbital period (P_orb = 9.8797327 hr) presented by Casares et al. (1996), where phase 0.0 is the superior conjunction of the white dwarf.

It is clear from the SIS0 light curve that there are two flarelke features. A large peak that lasts for ~4 hr is superposed on the light curve at the orbital phase of ~0.8 in Figure 1. In addition, a smaller peak is clearly seen at the orbital phase of ~2.3. Between the larger and smaller peaks, there is a quiescent state that lasts for ~10 hr. Here we consider each of the peaks as an individual flares. For the convenience of later analysis, we choose typical examples of “flare” and “quiescence” states of the data as the phase 0.7–1.2 for the flare and phase 1.2–2.2 for quiescence. We extract an energy spectrum from each phase and analyze it in detail in § 5.

Flares are characterized by the rapid increase of flux and its slow decay. In our data, during the large flare, the X-ray flux increased by a factor of 4 compared to the mean quiescent flux of ~0.3 counts s⁻¹. These features are simultaneously detected in the light curves of the other detectors (SIS1 and GIS2), implying that they are intrinsic to the source. When the X-ray light curve is compared to those
observed in the optical and UV (Bruch 1991; Eracleous & Horne 1996; Welsh, Horne, & Gomer 1998), we find that the X-ray flaring time-scale of the individual flares and the durations of the quiescent state are comparable to those of the optical and UV light curves.

Even in the quiescent state, AE Aqr shows appreciable fluctuations in flux during the observation, from \( \sim 0.2 \) to 0.4 counts s\(^{-1}\) in the SIS0 light curve. To understand the nature of the fluctuations, we fold the light curves using the orbital period and the ephemeris quoted above. However, we find no orbital phase-dependent fluctuations. In addition, no noticeable flux reduction, which might be caused by eclipsing, is detected. Richman (1996) reported that there is an orbital phase dependence in the softness ratio defined as the ratio of counts in the 0.1–0.4 keV band to those in the 0.4–2.4 keV band. In order to identify such a phenomenon, we calculated softness ratios between the energy in the 0.4–1.0 keV band and that in the 1.0–3.0 keV band for the present data (Fig. 2). However, we find that the variation of the ratios is neither significant with the observation time (or the orbital phase), nor in phase with the fluctuations in the light curve.

4. TIMING ANALYSIS

To see whether the optical pulsation periods are consistently present in the X-ray data, we do a pulse-period search by using an epoch folding method. For the period search, we converted the X-ray arrival times to the barycentric time of the solar system. For this process, we do not correct the orbital motion of the binary system, because the difference of the photon arrival time due to the orbital motion (at most \( \pm 3 \) s) is much smaller than the pulse period. AE Aqr has a sinusoidal pulse profile and the smearing of the pulse profile is also negligible for such short time difference.

As explained in the previous section, we could not determine the source flux using the *Ginga* LAC data. However, epoch folding analysis clearly shows the presence of pulsations. In Figure 3, we present the periodogram and folded pulse profile obtained from the *Ginga* LAC data. The pulse period is determined to be 33.076 ± 0.001 s, which is consistent with one of the identified optical periods. The folded pulse has an almost sinusoidal single-peaked profile, with peak-to-peak amplitude of 0.7 counts s\(^{-1}\) (2–9 keV). We tried epoch folding analysis around the optical period of 16.5 s, but no significant peak was found.

The periodograms obtained from the *ASCA* data are presented in Figure 4. In the figure, the upper and lower panels represent the periodograms for the quiescent and the flare data, respectively. From the periodogram of the quiescent data, we find a sharp peak at 33.077 ± 0.003 s with additional peaks at 33.2–33.3 s. In the case of the flare data, there is no such sharp peak, instead several smaller peaks are present in the range of 33.0–33.3 s. These smaller peaks are similar to the quasi periods seen in the optical data of Patterson (1979). We find no significant periodicities near the optical period of 16.5 s in either the quiescent or the flare state X-ray data.

In Figure 5, we plot the phase-averaged pulse profiles obtained at the folding period of 33.077 s, where the pulse phase is arbitrary. The upper and lower pulse profiles of the figure are obtained from the flare and the quiescent data, respectively. As shown in the figure, both the quiescent and the flare state pulse profiles have a single broad peak. This profile agrees well with the earlier results by Patterson et al. (1980) and Eracleous, Patterson, & Halpern (1991b). In contrast, the pulse profiles in the optical and the UV regions have sinusoidal double peaks that are separated by 0.5 in phase, and their amplitudes are unequal (e.g., Eracleous et al. 1994). This profile difference will be discussed later in §6.

We calculate the pulse fractions to be 28% ± 6% (~0.07 counts s\(^{-1}\) peak to peak) for the quiescent state pulse and 8% ± 6% for the flare state pulse, where the pulse fraction is defined as the ratio of the amplitude of pulse minimum to maximum to the nonpulsed flux level. The smaller value of the pulse fraction in the flare state, compared to that in the quiescent state, is mainly due to an increase of the non-pulsed flux. The pulse amplitude of the flare phase is ~0.07 counts s\(^{-1}\), which is almost the same as that of the quiescent

![Fig. 2.—Softness ratio. Upper panel: X-ray light curve obtained with the SIS0 detector. Lower panel: Softness ratio defined as the ratio of counts in the 0.4–1.0 keV band to those in the 1.0–3.0 keV band.](image-url)
phase. This fact strongly suggests that the flare does not originate from the accretion column of the white dwarf.

5. SPECTRAL ANALYSIS

It becomes possible to study the detailed spectral properties of AE Aqr thanks to the high spectral resolution provided by the ASCA SIS. We first extract the energy spectra during the flare and quiescent states to see whether there is a spectral difference between the two spectra. The orbital phase intervals defined in §3 are used to extract the flare and the quiescent energy spectra. To compare the two energy spectra, we calculate pulse-height-to-amplitude (PHA) ratios, ratios of count rates as a function of X-ray energy, and the result is plotted in Figure 6. From the figure, one finds that the ratio spectrum is not perfectly flat. There is a hint of slight increase of the ratio toward lower energies. This may indicate that the flare spectrum is a slightly harder than the quiescent state spectrum. We fit a constant model to the ratio spectrum and find that $\chi^2/\nu = 28.7/37$, where $\nu$ is the degree of freedom. The $\chi^2$ result implies that the difference between quiescent and flare spectra is not statistically significant. Thus, we use the time-averaged spectra for total data not only to investigate overall properties of the X-ray emission of AE Aqr but also to constrain the spectral parameters more accurately.

The time-averaged energy spectra extracted separately from the SIS and GIS data are shown in Figure 7. In the process, we use data obtained from the blank sky region to subtract the background. We add the two energy spectra from SIS0 and SIS1, and similarly from GIS2 and GIS3, to improve statistics. The presence of an iron-line structure is immediately noticed around 6–7 keV by just looking at the raw energy spectrum. In addition to this iron-line feature, a broad feature due to unresolved L lines of iron may be present around 0.8–1 keV. If these features are due to emission lines, the X-ray radiation is likely to have a thermal origin from an optically thin plasma. Although it is not clear whether such line features are seen in neutron star binaries, we try a wider range of model spectra to identify the origin of X-ray emission, since there is a suggestion that AE Aqr could be a neutron star (Ikhsanov 1997). We first try single-component models, such as a power-law, blackbody, or thermal Bremsstrahlung model, modified by the cold matter absorption to reproduce the average energy spectra. However, none of these models provides a good fit to the data. We find that excess emission remains in both the higher and the lower energy bands. Considering the presence of structures, we also attempt fitting an optically thin hot plasma model (“MEKAL” in XSPEC; Mewe, Kaastra, & Liedahl 1995), which also fails to give a good fit to the data. If we optimize the model parameters to reproduce the higher energy part (>3 keV) including the iron structure at 6–7 keV, a large excess emission remains below 2 keV. On the other hand, if the parameters are optimized to reproduce the spectrum at <1 keV range, although the broad feature in 0.8–1 keV is well explained as iron L-line complex, a large hard excess appears above ~2 keV.

Since a single-component model does not fit the data, we try to fit the data by using a two-component model. Because both the 6–7 keV and 0.8–1 keV structures are well reproduced by the “MEKAL” model, it may be natural to use a two-temperature MEKAL model to reproduce the overall spectrum. In fact, we find that the sum of two featureless models, such as power-law, blackbody, or thermal Bremsstrahlung models, cannot reproduce the structures well, but the two-temperature MEKAL model can fit the energy spectra quite well. A similar model is also used to reproduce the ROSAT data (Clayton & Osborne 1995). The
best-fit parameters with the two-temperature MEKAL model are listed in Table 1. In the fit, we assume that the two components have the same elemental abundances and the hydrogen equivalent column density ($N_H$). The best-fit temperatures, 0.7 and 2.9 keV, are rather low for the X-ray emission from magnetic CVs. Upper limits obtained for $N_H$ are consistent with the measurements by ROSAT (a few times $10^{19}$ cm$^{-2}$; Clayton & Osborne 1995).

We also fit the flare and quiescent spectra separately by using the two-temperature MEKAL model, and the best-fit parameters are listed in Table 1. Using those parameters of the energy spectra, we calculate the flare and quiescent luminosity of AE Aqr. The results are $2.1 \times 10^{31}$ and

### Table 1

| Parameter | Average | Quiescence | Flare |
|-----------|---------|------------|-------|
| $N_H$ ($10^{20}$ cm$^{-2}$) | $<2.4$ | $<2.6$ | $<4.8$ |
| $kT_1$ (keV) | $0.68 \pm 0.02$ | $0.69 \pm 0.02$ | $0.66 \pm 0.04$ |
| Normalization* ($10^{-3}$) | $2.0 \pm 0.7$ | $1.9 \pm 0.2$ | $3.1 \pm 0.4$ |
| $kT_2$ (keV) | $2.9 \pm 0.2$ | $2.9 \pm 0.3$ | $3.1 \pm 0.4$ |
| Norm.* ($10^{-3}$) | $4.6 \pm 0.3$ | $3.1 \pm 0.3$ | $9.1 \pm 1.0$ |
| Abundances* | $0.5 \pm 0.1$ | $0.4 \pm 0.1$ | $0.6 \pm 0.1$ |
| $Z_2^+$ | $0.98$ | $0.60$ | $0.69$ |

* Normalization is proportional to the emission measure: Normalization $= (10^{-14}/4\pi D^2) \int n_e n_H \, dV$, where the emission measure $\equiv \int n_e n_H \, dV$ is in units of cm$^{-3}$ and $D$ is the source distance in units of cm.

* The elemental abundances are relative to the solar photospheric values.
7.3 \times 10^{30} \text{ ergs s}^{-1}, \text{ respectively, in the 0.4–10 keV for an assumed distance of 100 pc.}

6. DISCUSSION

We analyzed the timing and the spectral properties of AE Aqr by using Ginga and ASCA archival data. Based on these results, we first consider the nature of the compact object in AE Aqr. Then we discuss about the X-ray emission mechanism including the origin of the pulsation and the flares referring to the propeller model (Eracleous & Horne 1996; Wynn et al. 1997; Welsh et al. 1998).

6.1. The Propeller Model

AE Aqr is usually considered to be a close binary system consisting of a late-type star and a magnetized white dwarf. However, its rapid spin-down might be explained if the accreting object in the AE Aqr is a neutron star (Ikhsanov 1997). Observation of the circular polarization of AE Aqr is difficult to explain in the framework of the accreting white dwarf model (Beskrovnaya et al. 1996). If the compact object in AE Aqr is an accreting neutron star, its energy spectrum is expected to be typical of an accretion-powered pulsar, i.e., a power law with an exponential cutoff (White, Swank, & Holt 1983). The ASCA data of AE Aqr show that its energy spectrum is soft and rich in emission lines and is well explained by the thermal emission from an optically thin hot plasma. This is very different from the nonthermal nature of the X-ray emission from the accretion-powered pulsars. Furthermore, the estimated mass of the compact object in AE Aqr based on the orbital kinematics is $0.79 \pm 0.16 \, M_\odot$ (Casares et al. 1996), which is much smaller than the canonical mass of a neutron star ($1.4 \, M_\odot$). Based on these considerations, we conclude that the compact star in AE Aqr is most likely a white dwarf.

One of the unique characteristics of AE Aqr is a rapid spin-down of the white dwarf. The spin-down rate is so large that the spin-down power exceeds the X-ray luminosity by 3 orders of magnitude and even exceeds the bolometric luminosity (Ikhsanov 1997). Although we cannot confirm the rapid spin-down because of the relatively short observations of Ginga and ASCA, our data are consistent with the spin-down rate derived from the optical measurements ($5.64 \times 10^{-14} \, \text{s}^{-1}$; de Jager et al. 1994). According to the propeller model, the large spin-down power is used to expel the accreting matter from the binary system. However, a small amount of matter is considered to be accreted onto the magnetic poles of the white dwarf because of the presence of UV and X-ray pulsation. The blobs from the companion travel on a near-ballistic trajectory until their closest approach to the white dwarf, where they crash into a magnetic barrier and some of their kinetic energy may be converted to the thermal energy. We consider that the liberated kinetic energy heats up the blobs to emit X-rays (and also UV; Eracleous & Horne 1996). Thus the persistent (nonpulsating) X-ray flux may be explained by magnetospheric emission (e.g., King & Cominsky 1994; Campana et al. 1995). As described below, a simple estimation can show that the observed parameters of the X-ray emission are consistent with such magnetospheric emission.

We assume that the kinetic energy of the blobs liberated through the interaction with the magnetic field equals a fraction $\alpha$ of the potential energy at the closest approach to the white dwarf. Then, the energy liberation rate $\dot{E}_{\text{thermal}}$ and the maximum blob temperature $T_{\text{max}}$, ignoring the
cooling effect, may be estimated as
\[
E_{\text{thermal}} = 1.3 \times 10^{33} \frac{M}{\text{g s}^{-1}} \left( \frac{r_c}{10^{10} \text{ cm}} \right)^{-1} \text{ergs s}^{-1},
\]
\[
T_{\text{max}} = 9.3 \left( \frac{M}{M_\odot} \right) \left( \frac{r_c}{10^{10} \text{ cm}} \right)^{-1} \text{keV},
\]
where \( r_c \) is the radius of the closest approach to the white dwarf. Because \( \alpha \) is considered not to be much smaller than unity, \( E \) easily explains the quiescent X-ray luminosity \( L_X = 7.3 \times 10^{30} \text{ ergs s}^{-1} \) in the 0.4–10 keV band. The maximum blob temperature is estimated to be about 10 keV. If we take into account radiative cooling, the actual temperature of the X-ray–emitting plasma becomes lower than 10 keV. This may explain why the temperature of X-ray–emitting plasma in AE Aqr is lower than that of other intermediate polars (~10 keV). The plasma temperatures obtained with ASCA are 0.7 and 2.9 keV, which are consistent with the above estimation. The magnetospheric emission of AE Aqr may also be related to the relatively smaller emission measure of this source. The ASCA data show that the emission measures of both the high- and the low-temperature plasma are about \( 3 \times 10^{53} \text{ cm}^{-3} \) in the quiescent state for the assumed distance of 100 pc. This is 1–3 orders of magnitude smaller than the emission measure of typical intermediate polars (Ishida 1992). Although the smaller emission measure does not directly support the magnetospheric emission, it indicates that the physical conditions in the X-ray emission region of AE Aqr are quite different from those of typical intermediate polars. This may be considered as indirect support for magnetospheric radiation.

### 6.2. Origin of the Pulsed X-Rays

From the timing analysis of the Ginga and ASCA data, pulsations are clearly detected at 33.08 s. The pulse has a single peak and almost sinusoidal profile. The pulse amplitude is relatively small, 0.7 counts s\(^{-1}\) in Ginga and 0.07 counts s\(^{-1}\) in ASCA (~30% in relative value), but it is clearly detected during the quiescent state. If we convert the pulse amplitude of Ginga to that of ASCA assuming the thermal Bremsstrahlung emission of 2.9 keV, we obtain 0.08 counts s\(^{-1}\). This is consistent with the observed count rate, implying that the pulse amplitude and the pulse profile of AE Aqr have stayed almost constant for the observation interval of 7 yr. Although we could not detect significant pulsation during the flare, it could be because of the large increase of nonpulsed component with no change in the absolute pulse amplitude. These results, i.e., sinusoidal pulse profile, small pulse amplitude, and constant modulated flux during the flare, are consistent with the ROSAT observations (Osborne et al. 1995). However, in the ROSAT observations, the modulated flux was found to increase during the brightest flare, a result which is not confirmed in our data analysis.

As already noticed by many authors, these characteristics of the X-ray pulsations are very different from those of optical and UV pulsations. The optical and UV pulse profiles show sinusoidal double peaks in which the two peaks are separated by 0.5 in phase and their amplitudes are unequal (Eracleous et al. 1994). The pulse amplitude in the UV band is very large, reaching about 40% of the mean quiescent level. The amplitude is lower in the optical band, and no phase shift is observed from the UV oscillations. From these properties, it is almost certain that the emission originates from the two magnetic poles in the UV/optical bands. Simultaneous observations of AE Aqr by ROSAT and the Hubble Space Telescope showed that the X-ray peak coincides with the major peak of the UV profile, whereas the minor peak of the UV profile coincides with the X-ray pulse minimum (Eracleous et al. 1995).

Eracleous et al. (1994) suggested that the UV and optical pulsations originate in the X-ray heated polar caps of the white dwarf. However, one may raise a question about the X-ray heating of the polar caps because the UV luminosity (~3 \( \times \) 10\(^{31}\) ergs s\(^{-1}\)) is brighter than the quiescent X-ray luminosity (7.3 \( \times \) 10\(^{30}\) ergs s\(^{-1}\)). Furthermore, focused illumination of the polar cap regions is difficult if most X-rays come from the magnetospheric boundary. To understand the differences of the pulse properties, we estimate the parameters of the accretion column. Since the amplitude of the UV pulsation is large, it is likely that some of the matter accretes onto the magnetic poles and the UV emission is radiated from the accretion column above the polar cap regions. Although we follow that AE Aqr is in the propeller regime, mass accretion onto the magnetic poles may still be possible if some fraction of the accreted matter is not expelled from the system and attached on the magnetic field lines through plasma instabilities such as Kelvin-Helmholtz instabilities. The mass accretion rate onto the poles may be estimated from the UV luminosity. Note that the optical luminosity is dominated by the secondary (Bruch 1991). If we take appropriate parameters of the white dwarf \( (M = 0.8 M_\odot \text{ and } R = 7 \times 10^8 \text{ cm}) \), the UV luminosity (~3 \( \times \) 10\(^{31}\) ergs s\(^{-1}\)) corresponds to a mass accretion rate of 2 \( \times \) 10\(^{14}\) g s\(^{-1}\). Using this mass accretion rate, we estimate the accretion column height over the magnetic poles (Frank, King, & Raine 1992) by
\[
D_{f f} = 5.4 \times 10^{10} \left( \frac{M}{10^4 \text{ g s}^{-1}} \right)^{-1} \left( \frac{f}{0.01} \right) \left( \frac{M}{0.8 M_\odot} \right)^{3/2} \left( \frac{R}{7 \times 10^8 \text{ cm}} \right)^{1/2},
\]
where \( f \) is the accreting fraction of the white dwarf surface. The estimated accretion column height is \( D_{f f} \approx 3 \times 10^{10} \text{ cm} \). If we use the general upper limit of the magnetic field strength of \(~5\) MG (Stockman et al. 1992) and assume a spherical accretion flow geometry, the upper limit of the magnetospheric radius is \(~2 \times 10^{10} \text{ cm} \). This is comparable to the estimated accretion column height. Therefore, it may be possible that a shock is not formed in the accretion column and that the matter attached on the field lines near the magnetospheric radius drifts gradually toward the polar cap regions. The low X-ray temperature consistent to the magnetospheric emission supports the idea that there is no strong shock in the accretion column. While the matter drifting toward the poles, it cools down because of the radiation and UV emission becomes dominant near the surface of the white dwarf. The drift speed is determined by the cooling rate of the plasma.

Under such circumstances, X-ray emission by the drifting plasma occurs over the magnetic poles of the magnetospheric boundary. Because the height of the X-ray–emitting
plasma is much larger than the white dwarf radius, the plasma will be occulted by the white dwarf only slightly. In this picture, we can observe the X-ray emission from both of the magnetic pole regions. However, if the phase of the two poles are shifted by 180° and the emission has different amplitudes, the pulsations will be partly smeared out, resulting in small amplitude. This may explain the small pulse amplitude and the sinusoidal profile in the X-ray band.

6.3. The Flare Site and Its Mechanism

From the ASCA observation of AE Aqr, we obtain an X-ray light curve characterized by flares. This is consistent with previous observations at various wavelengths. We find that the amplitude of the 33.077 s pulsation in the flare (0.07 counts s⁻¹) is the same as that of the quiescent state, while the nonpulsed component in the flare phase is about 3 times that in the quiescent state. This suggests that the flare is unlikely to originate from the magnetic pole regions on the white dwarf surface. The flare site may therefore be far from the white dwarf.

We find that the energy spectrum during the flare is basically the same as the quiescent spectrum within the statistical uncertainty. This fact may suggest that the flare site is the same as that of the persistent emission, i.e., the vicinity of the magnetospheric boundary. If we assume that the flare arises because of the sudden increase of the magnetospheric radiation triggered by the sporadic mass supply from the companion, we can estimate the flare timescale as the cooling timescale of the plasma through the radiation. During the flare, the emission measure becomes as large as 1 × 10^{54} cm⁻³. If we take the typical size of the plasma responsible for the flare to be the same as the size of the magnetosphere, 2 × 10^{10} cm, number density of the plasma would be 1.7 × 10^{11} cm⁻³. Thus the thermal energy contained in the plasma is estimated to be about 4.3 × 10^{34} ergs. Because the luminosity during the flare is approximately 2 × 10^{31} ergs s⁻¹, the thermal energy can sustain the emission for about 2 × 10³ s. This is roughly comparable to the duration of the X-ray flares. This agreement supports the interpretation that the X-ray flare results from an increase of the magnetospheric radiation due to the sporadic mass accretion from the companion. The almost constant pulse amplitude during the flare in the UV band (Eracleous et al. 1994) indicates that the excess mass is eventually expelled from the system and does not accrete onto the white dwarf.

7. CONCLUSION

From the Ginga and ASCA archival data analysis of AE Aqr, we obtain the following results.

1. Clear pulsations were detected in both the Ginga (33.076 ± 0.001 s) and the ASCA (33.077 ± 0.003 s) data. A single-peaked sinusoidal pulse profile is obtained for the Ginga as well as the ASCA data, indicating stable pulse properties over 7 yr.

2. The pulse amplitude is relatively small, and the modulated flux remains nearly constant, despite of a factor of 3 change in the average flux during the flare. These results are consistent with those of the ROSAT observations.

3. The time-averaged spectrum of AE Aqr is found to be soft. The spectrum (0.4–10 keV) can be reproduced by a two-temperature MEKAL model with kT₁ = 0.68 ± 0.02 keV and kT₂ = 2.9 ± 0.2 keV. There is a suggestion of spectral hardening during the flare, but it is not statistically significant. The emission measure increases by a factor of 3 during the flare.

4. It is found that not only the Ginga and the ASCA results but also the previous results in the other wavelengths can be well interpreted by assuming that AE Aqr stays in the propeller regime. Based on this scenario, it is suggested that the X-ray emission is magnetospheric radiation.

This research has made use of data obtained through the HEASARC on-line service provided by the NASA GSFC.

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