DENSITY DIAGNOSTICS OF THE HOT PLASMA IN AE AQUIRII WITH XMM-NEWTON

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ABSTRACT

We report on XMM-Newton observations of the magnetic CV AE Aqr. High-resolution spectroscopy of the He-like triplet of N and O with the RGS has enabled us to measure the electron number density of the plasma as \( \sim 10^{11} \) cm\(^{-3}\). Incorporating this with the emission measure, we estimate the geometrical scale of the plasma emitting these lines to be \( l_{\rho} \sim (2-3) \times 10^{10} \) cm. Since the density and the scale are both incompatible with the standard postshock accretion column of an mCV, the plasma cannot be a product of mass accretion onto the white dwarf. The widths of the H-like K\( \alpha \) emission lines of N and O (=1250–1600 km s\(^{-1}\)) are of similar magnitude to the thermal velocity dispersion of the hottest part of the plasma, where \( kT_{\text{max}} \) is 4.6 keV. It is known that Balmer series and UV emission lines also show a similar velocity dispersion. In addition, like these lines, the X-ray emission lines are found to show dramatic flaring activity. These facts strongly suggest that all these broad emission lines from X-ray to optical wave bands are produced in the course of adiabatic cooling of the plasma once heated up to \( T_{\text{max}} \) in the deep gravitational potential of the white dwarf. This interpretation can resolve the problem of the absence of the high-velocity component in the H\( \alpha \) emission line spectrum by a scenario where the plasma that is expelled due to the propeller action is still too hot to emit the H\( \alpha \) line within a region of \( r < l_{\rho} \) (roughly equal to the Roche lobe size) from the white dwarf where the high-velocity component is expected to originate.

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

1. INTRODUCTION

AE Aqr is a close binary system composed of a magnetized white dwarf and a late-type secondary star with an orbital period of 9.88 hr (Welsh et al. 1993). The rotation period of the white dwarf is 33.08 s (Patterson 1979). The masses of the primary and the secondary are evaluated to be \( M_1 = 0.79 \pm 0.16 \, M_\odot \) and \( M_2 = 0.50 \pm 0.10 \, M_\odot \), respectively, for an inclination angle of \( 57^\circ \pm 6^\circ \) (Casares et al. 1996). The orbital semimajor axis on the basis of these parameters is evaluated to be \( a = 1.8 \times 10^{11} \) cm. The spectral type of the secondary star has been known to be K3 V–K5 V (Welsh et al. 1995), although a somewhat evolved K3 IV identification has also been suggested (Skidmore et al. 2003).

AE Aqr has been known as one of the most enigmatic magnetic cataclysmic variables (mCVs) in various aspects, including large optical flares and flickering (Patterson 1979), large radio flares (Bastian et al. 1996), TeV \( \gamma \)-ray emissions (Meintjes et al. 1994), and so on. Although the long orbital period leads us to expect an accretion disk, the spectral profile of the H\( \alpha \) emission line is single-peaked, and its centroid velocity is found to be inconsistent with the white dwarf orbit but lags behind the secondary orbit by some \( 70^\circ \sim 80^\circ \) (Welsh et al. 1993). Spectral widths of Balmer emission lines are highly variable, with a full width at zero intensity of \( \sim 1000 \) km s\(^{-1}\) during flares for the H\( \alpha \) line (Welsh et al. 1998). Widths of the same order are also reported for the H\( \beta \) and H\( \gamma \) emission lines (Reinsch & Beuermann 1994). Hard X-ray emission from mCVs originates close to the white dwarf surface from the postshock plasma in an accretion column. Although the temperature of the postshock plasma is a few tens of keV in mCVs in general (Ezuka & Ishida 1999; Ishida & Fujimoto 1995), the maximum temperature of AE Aqr is as low as \( \sim 3 \) keV (Eracleous 1999; Choi et al. 1999). All of these results, along with the discovery of a steady spin-down of the white dwarf at a rate \( \dot{P} = 5.64 \times 10^{-14} \) s s\(^{-1}\) (de Jager et al. 1994), led Wynn et al. (1997) to introduce the magnetic propeller model, which l"obby" accreting matter originally following a ballistic trajectory from the inner Lagrangian point experiences a drag from the magnetic field of the white dwarf and is finally blown out of the binary due to so-called propeller action. This model has stimulated the development of further refined models, such as the shocked-blob model (Eracleous & Horne 1996), the colliding-blob model (Welsh et al. 1998), and the pulsar-like spin-down model (Ichsanov et al. 2004), which are intended to explain the nature of AE Aqr mentioned above.

In this paper, we present new results of X-ray observations of AE Aqr carried out with XMM-Newton. The excellent energy-resolving power of the Reflection Grating Spectrometers (RGS) enables us for the first time to perform density diagnostics of the plasma by means of a well-resolved He-like triplet of nitrogen and oxygen. We discuss the implications of our results on the current understanding of mass transfer in the AE Aqr system in some detail. Throughout the paper, all errors quoted are at the 90% confidence level. For fitting model spectra to the data, we use XSPEC, version 11.2 (Amaud 1996).

2. OBSERVATIONS

AE Aqr was observed with XMM-Newton (Jansen et al. 2001) on 2001 November 7–8. The observation log is given in Table 1. The entire observation consists of two parts. During the first \( \sim 10 \) ks, both the EPIC pn (Strüder et al. 2001) and the MOS (Turner et al. 2001) had been switched off. The RGS (den Herder et al. 2001), on the other hand, was operating normally throughout the observation. As a result, 27 ks of data are available for the RGS and 17 ks for the EPIC pn/MOS.
Figure 1 shows the pn, MOS1, RGS1, and RGS2 light curves. For the data reduction, we use SAS, version 6.0.0. We adopt circular apertures of 57'4 and 50'6 in radius as the source photon integration region for the pn and the MOS, respectively. The background photons are accumulated from concentric annuli outside the source regions whose outer radii are 3 times the radii of the source regions. Source photons are somewhat piled up in the pn data especially during the flare. We thus have excluded the central circular region with a radius of 8' from the analysis of pn data. The light curve of the RGS1 is composed of all the first-order photons in the band 5–35 keV. As shown later, RGS spectra of AE Aqr are dominated by emission lines (Fig. 4). The RGS2 light curve is created from H- and He-like Kα emission line photons of N, O, and Ne. The X-ray emission lines show dramatic flaring activity, as do the optical and UV emission lines (Eracleous & Horne 1996), in correlation with the continuum emission that dominates the EPIC light curves and spectra (Figs. 2 and 3).

We have searched for an X-ray pulsation in the EPIC pn light curve created in the 0.2–10 keV band, after applying the barycentric correction for the event time. By means of the epoch-folding method, we have detected a sinusoidal pulsation at a period of 33.08 ± 0.04 s during both quiescence and flare periods (time intervals of 13,000–18,700 and 21,000–27,000 s in Fig. 1, respectively) with a fractional peak-to-bottom amplitude of 7% ± 1% and 16% ± 1% for the flare and quiescence, respectively. The pulse period is consistent with the optical one (Patterson 1979; de Jager et al. 1994). Results from a detailed pulse-timing analysis will be published elsewhere.

3. DATA ANALYSIS

3.1. EPIC Spectra

The time-averaged energy spectrum extracted from the EPIC MOS2 is shown in Figure 2. A number of H-like and/or He-like Kα emission lines of abundant metals from N through Fe can be recognized. The coexistence of these lines indicates that the X-ray-emitting plasma is optically thin and thermal and has a significant temperature distribution in the range kT ≈ 0.1–10 keV. The spectra of AE Aqr taken with Advanced Satellite for Cosmology and Astrophysics (ASCA) are, in fact, reproduced with an optically thin thermal plasma emission model with a few different temperature components (Eracleous 1999; Choi et al. 1999). In fitting the EPIC spectra, we thus have adopted essentially the same model as these authors (VMEKAL in XSPEC; Mewe et al. 1995).

The abundances of the metals, except for carbon, are allowed to vary freely and independently, but they are constrained to be common among all the VMEKAL components. That of carbon is frozen to the solar value because it cannot be constrained at all. Low-energy attenuation due to photoelectric absorption is represented by a single hydrogen column density model common to all VMEKAL components. In order to determine the number of VMEKAL components with different temperatures, we added new components one by one until the addition of the next did not improve the fit significantly on the basis of the F-test. Spectral fitting was carried out simultaneously with the pn, MOS1, and MOS2 spectra. The resulting best-fit χ² values of the one-temperature five-temperature VMEKAL models are listed in Table 2. Improvement of the fit is significant at more than the 99.99% level until the number of components is increased to four, while no

![Fig. 1. Light curves of EPIC pn and MOS1 in the band 0.2–15 keV, RGS1 in the band 5–35 Å, and RGS2 only with H-like and He-like Kα photons from N, O, and Ne, but excluding the He-like Kα of O for which the corresponding CCD chip is dead. A common bin size of 256 s is adopted. The source integration region is a circle with a radius of 57'4 and 50'6 for pn and MOS1, respectively. The RGS light curves are created with the first-order photons.](image1)

![Fig. 2. Time-averaged spectrum of AE Aqr taken with EPIC MOS2. Energies of hydrogenic and He-like Kα lines from N through Fe are indicated with short vertical lines.](image2)
improvement was found by the addition of another component. We thus have adopted the four-temperature VMEKAL model. The best-fit result is shown graphically in Figure 3, the parameters of which are listed in Table 3. The emission measures of the four components with temperatures of 0.14, 0.59, 1.4, and 4.6 keV are 1.3, 3.6, 2.7, and $5.3 \times 10^{53}$ cm$^{-3}$, respectively, and in total 1.29 $\times 10^{54}$ cm$^{-3}$, for an assumed distance of 100 pc (Welsh et al. 1993; Friedjung 1997). The highest temperature $kT_{\text{max}} = 4.6$ keV is considerably lower than for any other mCVs. We note that Choi et al. (1999) and Eracleous (1999) fitted the spectra of AE Aqr successfully with the two- and three-temperature MEKAL model, respectively. The EPIC data, on the other hand, require four components with different temperatures. This indicates that the X-ray-emitting plasma of AE Aqr has a continuous temperature distribution, and the four-temperature description is an approximation. The fact that the two- or three-temperature model is not acceptable is a result of the greater statistical quality of the XMM-Newton data.

Among all the emission lines, the iron Kα line is most prominent in the EPIC spectra displayed in Figures 2 and 3. Its central energy is 6.7 keV and is of thermal plasma origin. On the other hand, absent is a fluorescent neutral iron Kα emission line at 6.4 keV, which is commonly found in the mCV spectra (Ezuka & Ishida 1999). The upper limit of its equivalent width is <61 eV.

The large effective area of XMM-Newton further allowed us to obtain the abundances of the elements from N to Ni. They are generally subsolar (Anders & Grevesse 1989), except for that of N, which is more than 3 times the solar value.

### Table 2: Resulting $\chi^2$ Values from Multitemperature VMEKAL Fits to the EPIC Spectra

| Number of Components$^a$ | $\chi^2$ | Degrees of Freedom | Significanceb (%) |
|--------------------------|---------|--------------------|------------------|
| 1                        | 5856.3  | 998                | >99.99           |
| 2                        | 1350.0  | 996                | >99.99           |
| 3                        | 1276.6  | 994                | >99.99           |
| 4                        | 1205.5  | 992                | >99.99           |
| 5                        | 1205.4  | 990                | 9.52             |

$^a$ Number of VMEKAL components with different temperatures. $^b$ Significance of adding a new component from the previous step.

### Table 3: Best-Fit Parameters of the Four-Temperature VMEKAL Model Fit to EPIC pn and MOS Spectra

| Parameter                           | Value | Element | Abundance$^a$ |
|-------------------------------------|-------|---------|--------------|
| $N_1 (10^{13} \text{ cm}^{-2})$     | 3.59$^{+1.47}_{-1.20}$ | N       | 3.51$^{+0.92}_{-1.01}$ |
| $kT_1$ (keV)                        | 4.60$^{+0.60}_{-0.47}$ | O       | 0.74$^{+0.27}_{-0.13}$ |
| $kT_2$ (keV)                        | 1.21$^{+0.13}_{-0.08}$ | Ne      | 0.43$^{+0.25}_{-0.19}$ |
| $kT_3$ (keV)                        | 0.59 ± 0.02           | Mg      | 0.70$^{+0.47}_{-0.25}$ |
| $kT_4$ (keV)                        | 0.14$^{+0.05}_{-0.05}$ | Si      | 0.8$^{+0.15}_{-0.12}$  |
| $N_1$ ($10^{14}$)                   | 4.45$^{+0.41}_{-0.44}$ | S       | 0.73$^{+0.28}_{-0.18}$ |
| $N_2$ ($10^{14}$)                   | 2.25$^{+0.52}_{-0.51}$ | Ar      | 0.21$^{+0.08}_{-0.08}$ |
| $N_3$ ($10^{14}$)                   | 3.04$^{+0.47}_{-0.47}$ | Ca      | 0.19$^{+0.11}_{-0.11}$ |
| $N_4$ ($10^{14}$)                   | 1.07$^{+0.74}_{-0.74}$ | Fe      | 0.47$^{+0.07}_{-0.06}$ |

$^a$ Normalization of the VMEKAL component obtained with the pn camera in units of $10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \text{ m}^{-2}$, where D (cm) is the distance to the target star.

$^b$ Ratio of continuum normalizations.

### Figures

**Figure 3:** Averaged spectra of EPIC pn (green), MOS1 (black), and MOS2 (red) overlaid with the best-fit four-temperature VMEKAL model (histograms). The model components are drawn with dotted lines for MOS1 and MOS2. See Table 3 for the best-fit parameters.

**Figure 4:** RGS spectra averaged over the entire 27 ks exposure. The black and red points represent the data from RGS1 and RGS2, respectively. Identifications of the H- and He-like Kα lines of N are shown (dash-dotted line). The other unidentified lines are mainly those associated with Fe I transitions.
critical value inherent in each element, on the other hand, one of the two electrons excited to the upper level of the forbidden line \(3^S_1\) is further pumped to the higher level \(3^P_2\) by another impact of a free electron and is then relaxed by radiating the intercombination line. The relative intensities of the intercombination and forbidden lines can therefore be utilized as a density diagnostic (Gabriel & Jordan 1969; Pradhan & Shull 1981; Porquet et al. 2001).

In order to obtain the electron number density \(n_e\), we begin by evaluating the intensities of the He-like triplets. For this, we utilize the four-temperature VMEKAL model that provides the best fit to the EPIC pn and MOS spectra. We have fixed the hydrogen column density and the four temperatures at the values in Table 3 and the relative normalizations of the four continuum components. The abundances are also fixed at the best-fit values, except for an element to be used as a density diagnostic, for which the abundance is set equal to zero, and instead, four Gaussians are added, representing the He-like triplet and the Ly\(\alpha/C\) line. The line intensities thus obtained for N, O, and Ne are summarized in Table 4, and the best-fit results are displayed in Figures 5a–5c as the histograms. The ionization temperatures \(kT_i\) calculated from the intensity ratio between the Ly\(\alpha\) and r lines are obtained to be 0.18, 0.30, and 0.34 keV for N, O, and Ne, respectively.

The emission measures (EMs) of the plasma components with these temperatures can be calculated from the intensities of the Ly\(\alpha\) and r lines with the aid of the EPIC abundances (see Table 3), which result in \(EM = 1.5, 1.8, \) and \(9.1 \times 10^{53}\) cm\(^{-3}\), respectively.

Given the line intensities of the triplets, we have carried out density diagnostics by means of the intensity ratio \(f/(r+i)\) of each element. In each panel we have also drawn a box indicating the range of the intensity ratio allowed from the data and the resulting density range. The electron number densities are found to be \((0.14^{+0.01}_{-0.02}) \times 10^{11}\), \((0.40\pm0.06) \times 10^{11}\), and \(<9.3 \times 10^{12}\) cm\(^{-3}\) for N, O, and Ne, respectively. As a crude approximation, we obtain \(n_e \approx 10^{11}\) cm\(^{-3}\). This density, together with the emission measure obtained above, results in the linear scale of the plasma components with \(kT_i = 0.2–0.3\) keV of \(l_p = (EM/n_e^2)^{1/3} \approx (2–3) \times 10^{10}\) cm.

### 3.3. Spectra of H-like K\(\alpha\) Lines from the RGS

It is known that the wavelength of the H\textalpha\ line from AE Aqr shows a sinusoidal orbital Doppler modulation with an amplitude of \(~150\) km s\(^{-1}\) (Robinson et al. 1991; Wynn et al. 1997; Welsh et al. 1998). A similar behavior is found from a series of UV emission lines in the band 1300–1900 Å with a velocity amplitude of generally 110–220 km s\(^{-1}\) (Si ii–Si iv and He \textit{n})
with the exceptional case 330 km s\(^{-1}\) for Al \(\Pi\) (Eracleous & Horne 1996). The phases of the H\(\alpha\) and UV line sinusoids lag behind the secondary star orbit by \(\Delta \phi = 0.21\) and 0.27–0.38, respectively. In order to search the X-ray emission lines for a similar orbital modulation, we have made RGS spectra during the first and second flares separately. The spectra are accumulated during time intervals of 3000–8500 and 19000–26000 s in Figure 1 for the two flares. The corresponding orbital phases are \(\phi = 0.81–0.93\) and 0.29–0.46, respectively. We have evaluated profiles of spectrally isolated H-like K\(\alpha\) lines (=Ly\(\alpha\) lines) from N and O by fitting a Gaussian to them. The results are summarized in Table 5. Unfortunately, the line central energies are consistent with those in the laboratory, and any systematic orbital motion of the line-emitting gas is not detected. Limited statistics, however, result in a loose upper limit of \(<300–400\) km s\(^{-1}\), which includes the velocity amplitudes of the H\(\alpha\) and UV lines cited above.

The 1 \(\sigma\) line width \(\Delta E_{\text{Ly} \alpha}\) is \(\approx 1.2\) and \(\approx 2\) eV for the N and O Ly\(\alpha\) lines on average, respectively, which corresponds to a line-of-sight velocity dispersion \(\langle \sigma_1 \rangle = (\Delta E_{\text{Ly} \alpha}/E_{\text{Ly} \alpha})\) of \(\approx 720\) and \(\approx 920\) km s\(^{-1}\), respectively. These values are much larger than the thermal velocity, e.g., \(\sim 0.16\) eV or \(\sim 70\) km s\(^{-1}\) for oxygen, estimated from \(kT_i = 0.3\) keV. Note that these velocities are much larger than the line-of-sight orbital velocity amplitude of the line-emitting plasma, which is of order \(\approx M_1(M_1 + M_2)^{-1}(2\pi/P_{\text{orb}})\alpha \cos i \approx 100\) km s\(^{-1}\). Moreover, we have evaluated the line widths for the first and second flares separately, which span only 0.12 and 0.17 in the orbital phase, respectively. Hence, the orbital motion probably has little effect on the observed line broadening.

### 4. DISCUSSION

#### 4.1. Implications of Low Density Compared to Other mCVs

The electron number density of the plasma measured from the He-like triplets of N and O (\(\approx 10^{11}\) cm\(^{-3}\)) is smaller by several orders of magnitude than the conventional estimate in the postshock accretion column of mCVs, \(n_e \approx 10^{12}\) cm\(^{-3}\) (Frank et al. 2002). Moreover, the resulting scale \([\delta_p \approx (2–3) \times 10^{10}\text{ cm}]\) is larger than the radius of the white dwarf (assumed to be \(\approx 7 \times 10^8\) cm for a 0.79 M\(_d\) white dwarf) by more than 1 order of magnitude and is rather a fraction of the size of the Roche lobe of the primary. We thus conclude that, unlike other mCVs, the X-ray-emitting plasma in AE Aqr is not a product of the mass accretion onto the white dwarf (Ks2001). This conclusion is derived simply on the basis of widely accepted atomic physics and, hence, is free from any specific model.

We would like to remark here, however, that photoexcitation due to UV radiation can also pump a \(3S_1\) electron up to the \(3P_{2,1}\) level, thereby affecting the density diagnostics (Gabriel & Jordan 1969; Praddhan & Shull 1981; Porquet et al. 2001). Since there is no evidence of an accretion disk, a dominant source of UV photons in typical CVs, in AE Aqr (Welsh et al. 1993) and the secondary is a late-type K3–K5 star, devoid of strong UV radiation, the white dwarf is the only possible source of the photoexcitation. In particular, the hot polar cap region, occupying an

### TABLE 4

**Intensities of Ly\(\alpha\) and He-like Triplet of Nitrogen, Oxygen, and Neon with RGS**

| Parameter                  | Nitrogen | Oxygen | Neon  |
|----------------------------|----------|--------|-------|
| E (keV)                    | Energy\(^a\) | Norm\(^b\) | Energy\(^a\) | Norm\(^b\) | Energy\(^a\) | Norm\(^b\) |
| Ly\(\alpha\)               | 0.5003   | 1.85 ± 0.21 | 0.6535 | 3.63 ± 0.34 | 1.0215 | 0.90 ± 0.23 |
| r                          | 0.4307   | 0.97 ± 0.17 | 0.5740 | 1.06 ± 0.22 | 0.9220 | 0.65 ± 0.22 |
| l                          | 0.4262   | 0.57 ± 0.17 | 0.5687 | 0.85 ± 0.22 | 0.9148 | 0.24 ± 0.21 |
| r                          | 0.4199   | 0.26 ± 0.13 | 0.5610 | 0.37 ± 0.17 | 0.9050 | 0.32 ± 0.18 |
| \(kT_i\) (keV)             | 0.18 ± 0.01 | 0.30 ± 0.03 | 0.34 ± 0.09 | 0.34 ± 0.09 |
| EM\(^d\) (10\(^{13}\) cm\(^{-3}\)) | 1.5 ± 1.1 | 1.8 ± 0.5 | 9.1 ± 1.2 | 9.1 ± 1.2 |
| \(n_e\) (10\(^{11}\) cm\(^{-3}\)) | 0.14–1.3 | 0.40–6.8 | 0.23–1.3 | 0.23–1.3 |
| \(\chi^2\) (dof)           | 1.36 (115) | 1.14 (69) | 1.21 (63) | 1.21 (63) |

**Note.**—All errors are at the 90\% confidence level.

\(^a\) Line central energy.

\(^b\) Line normalization in units of 10\(^{-4}\) photons cm\(^{-2}\) s\(^{-1}\).

\(^c\) Ionization temperature evaluated by the intensity ratio between Ly\(\alpha\) and \(\sigma\).

\(^d\) Emission measure evaluated by the intensities of Ly\(\alpha\) and \(r\) and the abundance obtained from the EPIC spectra (see Table 3).

\(^e\) The allowed range of the electron density at the 90\% confidence level.

### TABLE 5

**Orbital-Phase-Resolved Spectra of Ly\(\alpha\) Lines of Nitrogen and Oxygen with RGS**

| Flare | \(\phi\)^\(^a\) | \(E\) (eV) | \(\sigma\) (eV) | \(I\)^\(^b\) | \(E\) (eV) | \(\sigma\) (eV) | \(I\)^\(^b\) |
|-------|----------------|-----------|---------------|-------------|-----------|---------------|-------------|
| 1     | 0.81–0.93      | 500.6 ± 0.5 | 1.0 ± 0.1     | 2.5 ± 0.7   | 653.3 ± 0.4 | 1.7 ± 0.5     | 4.3 ± 0.7  |
| 2     | 0.29–0.46      | 500.1 ± 0.5 | 1.4 ± 0.0     | 2.2 ± 0.6   | 653.4 ± 0.4 | 2.4 ± 0.6     | 6.1 ± 0.7  |

**Note.**—All errors are at the 90\% confidence level.

\(^a\) Orbital phase according to Casares et al. (1996), where \(\phi = 0\) is defined as the inferior conjunction of the secondary star.

\(^b\) Line normalization in units of 10\(^{-4}\) photons cm\(^{-2}\) s\(^{-1}\).
area of η = 0.6% of the white dwarf surface, with the emission spectrum represented by a blackbody with a temperature of $T_r = 47,000$ K (Eracleous & Horne 1996), is the most efficient irradiation source. With this emission, the photoexcitation rate from the initial state $i = 3S_1$ to the final state $j = 3P_2,1$ can be written as

$$\Gamma_{ij}(T_r) = \frac{\pi e^2}{m_e c} f_{ij} W \frac{B(T_r; \nu_j)}{h\nu_j}$$  \hspace{1cm} (1)

(Porquet et al. 2001; Mauche 2002), where $f_{ij}$ is the effective oscillator strength of photoexcitation, which is 0.03574 (Nahar & Pradhan 1999), and $h\nu_j = E_j$ is the excitation energy (6.6 and 7.7 eV for N and O, respectively). The quantity $B(T_r; \nu_j)$ is the intensity of the blackbody radiation from the polar cap region at the frequency $\nu_j$, while $W$ is a geometrical dilution factor to be taken here as $q(R_i/l_p)^2$, where $R_i$ is the radius of the white dwarf. On the other hand, the collisional excitation rate to be compared with $\Gamma_{ij}$ is $\gamma_{ij}$, where

$$\gamma_{ij}(T_e) = \frac{8.63 \times 10^{-6}}{\omega_i T_e^{1/2}} e^{-E_i/kT_e} \gamma_{ij}(T_e) \left[ \text{cm}^3 \text{s}^{-1} \right]$$  \hspace{1cm} (2)

is the rate coefficient of the electron impact excitation (Mewe & Schrijver 1978). In this equation, $\omega_i (= 3)$ is the statistical weight of the lower level, and $\gamma_{ij}$ is the Maxwellian-averaged collision strength, which is tabulated as a function of $T_e$ in Pradhan et al. (1981). Adopting $T_e$ listed in Table 4 as $T_e$, we have obtained $\Gamma_{ij} \approx 2 \times 10^{-3} n_e \gamma_{ij} \ll n_\nu \nu_j$ from equations (1) and (2) for both N and O. Hence, the photoexcitation effect can be neglected. We remark that if the UV radiation is unexpectedly stronger than the estimate here, the density obtained in $\S$ 3.2 should be regarded as an upper limit. Even in that case, the conclusion above does not change because the resulting density shifts to a lower value, and hence, the geometrical scale of the plasma ($l_p$) becomes even larger.

4.2. Site of the Plasma Heating and Propeller Conditions

From the XMM-Newton observations, we have obtained a maximum temperature of the plasma $kT_{\text{max}}$ of 4.6 keV (Table 3). This implies that the matter transferred from the secondary star is accelerated at least to the corresponding thermal velocity $v_{\text{th}} = (3kT_{\text{max}}/\mu m_p)^{1/2} \approx 1500$ km s$^{-1}$. Such a high velocity can naturally be achieved by utilizing the gravitational potential of the white dwarf. Theoretical model calculations of the Doppler tomograms by Wynn et al. (1997) and Welsh et al. (1998) also predict that the high velocity can be realized only within the Roche lobe of the white dwarf. We thus assume, as in Choi et al. (1999), that the observed maximum temperature is attributed to the release of the gravitational energy. We can then make an order-of-magnitude estimate of the radius $r_{\text{th}}$ where such thermalization takes place from

$$\frac{3}{2} kT_{\text{max}} \sim \frac{GM}{r_{\text{th}}} \mu m_p,$$  \hspace{1cm} (3)

which results in $r_{\text{th}} \sim 1 \times 10^{10}$ cm. This number is roughly of the same order as the theoretical minimum distance estimates of blobs $r_{\text{min}} > 10^{10}$ cm by Wynn et al. (1997) or $r_{\text{min}} > 4 \times 10^{10}$ cm by Ikhsanov et al. (2004). At $r_{\text{th}}$, the corotation velocity $v_{\text{co}} = 1.9 \times 10^5$ cm s$^{-1}$ is much larger than the local Kepler velocity $v_K = 1.0 \times 10^8$ cm s$^{-1}$. Hence, the plasma heated at $r \sim r_{\text{th}}$ can be expelled due to the magnetic propeller action by the white dwarf.

4.3. Implications of the Broad H-like Kα Line from N and O

As presented in $\S$ 3.3, the observed spectral widths of the Lyα lines result in a line-of-sight velocity dispersion ($v_1$) of $\approx 720$ km s$^{-1}$ for N and O, respectively. These values are much larger than that expected from the natural width and the thermal broadening, and they are affected little by the orbital motion ($\S$ 3.3). It is interesting to note that the three-dimensional velocity dispersion ($v_2$) of 1250–1600 km s$^{-1}$ ($\sqrt{3} v_1$) is comparable to the thermal velocity of the plasma $v_{\text{th}} = (3kT_{\text{max}}/\mu m_p)^{1/2} = 1500$ km s$^{-1}$, where $kT_{\text{max}} = 4.6$ keV ($\S$ 3.1). The plasma of the N and O emission ($kT_\nu = 0.2–0.3$ keV) can thus be regarded as having been cooled through adiabatic expansion of the seed blob, which is once heated up to $T_{\text{max}}$ in the deep gravitational potential of the white dwarf. This scenario is supported by the fact that the expansion timescale

$$t_{\exp} = \frac{l_p}{v_{\text{th}}} = 100 \left( \frac{l_p}{10^{10} \text{cm}} \right) \left( \frac{v_{\text{th}}}{10^8 \text{cm s}^{-1}} \right)^{-1} \left[ \text{s} \right]$$  \hspace{1cm} (4)

is much shorter than the radiative cooling timescale of the plasma

$$t_{\text{cool}} = \frac{3 n_e kT_e V}{L_X} = \frac{3 kT_e \text{EM}}{n_e L_X} = 4.8 \times 10^4 \left( \frac{kT_e}{1 \text{keV}} \right) \left( \frac{\text{EM}}{10^{54} \text{cm}^{-3}} \right) \times \left( \frac{n_e}{10^{11} \text{cm}^{-3}} \right)^{-1} \left( \frac{L_X}{10^{35} \text{ergs s}^{-1}} \right)^{-1} \left[ \text{s} \right].$$  \hspace{1cm} (5)

Theoretically, Wynn et al. (1997) estimated the density and the size of the original blob to be $10^{13}–10^{14}$ cm$^{-3}$ and $10^9$ cm, respectively. By comparing these numbers with our estimates $n_e \sim 10^{11}$ cm$^{-3}$ and $l_p = (2–3) \times 10^{10}$ cm ($\S$ 3.2), we conclude that the plasma of the N and O emission can be interpreted as a result of the adiabatic expansion of the blob.

The observed N and O Lyα line width of $\langle v_1 \rangle = 720–920$ km s$^{-1}$ is reminiscent of that of the Balmer series and UV emission lines. During optical flares, the spectral width of Hβ and Hγ lines increases up to a full width at half-maximum (FWHM) of $\approx 25$ Å (Reinsch & Beuermann 1994). Dividing the FWHM by a factor of 2.355, we obtain $\langle v_1 \rangle = 650–730$ km s$^{-1}$ for the Hβ and Hγ. Welsh et al. (1998) have obtained a full width at zero intensity of the Hα emission line during optical flares of $\approx 4000$ km s$^{-1}$. Assuming the corresponding FWHM roughly to be $\approx 2000$ km s$^{-1}$, we obtain $\langle v_1 \rangle \approx 850$ km s$^{-1}$. Eracleous & Horne (1996) have estimated the FWHM of the He n line ($\lambda 1640$) to be 1700 km s$^{-1}$, equivalent to $\langle v_1 \rangle \approx 720$ km s$^{-1}$. The common observed spectral width of all these X-ray to optical emission lines strongly suggests that the plasmas responsible for these lines are all descendants of the blob that has been heated to $T_{\text{max}}$ and then cooled through adiabatic expansion. The observed X-ray to optical broad lines can be considered as being emitted in the course of this cooling process. Like the optical and UV emission lines, the X-ray emission lines also show dramatic flaring activity, as shown in Figure 1. This also supports the picture that all the emission lines from optical to X-ray have a common origin.
One might suspect that the $\langle v_t \rangle$ of the Balmer series and UV emission lines should be significantly smaller than that of the Ly$\alpha$ lines of N and O because, in the present picture, the current lines should be emitted after the expelled flow ascends the gravitational potential from the N and O emission region ($r \sim \lp$). However, the potential energy at $r = \lp$ is smaller than the thermal energy there. If we convert the potential energy into equivalent kinetic energy through $\frac{1}{2} \lp^2 = GM \ln \lp$, then $v_p \approx 900 \text{ km s}^{-1}$, whereas $\langle v_t \rangle = 1500 \text{ km s}^{-1}$. Hence, even if, at infinity, the gravitational energy is compensated entirely by the thermal energy, the velocity dispersion still amounts to $\langle v_t^2 - v_p^2 \rangle^{1/2} = 1200 \text{ km s}^{-1}$. This velocity drop cannot be resolved with the currently available data, and hence the velocity dispersion will be observed as approximately constant while the expelled flow ascends the gravitational potential from $r = \lp$ to infinity throughout.

The picture presented here can provide a solution to one of the problems (Welsh 1999) in the original propeller model, the absence of the theoretically predicted high-velocity loop component (Wynn et al. 1997) in the observed H$\alpha$ tomogram, which leads Welsh et al. (1998) to introduce the colliding-blob model. This model intends to exclude the H$\alpha$ emission location from the Roche lobe of the primary by introducing distributions for the density and the size of the blobs. Our results, on the other hand, suppress the high-velocity component of the H$\alpha$ emission line without any additional assumption because the propelled plasma is still too hot ($kT_p = 0.2–0.3$ keV) to emit H$\alpha$ lines within a radius of $\lp$ (roughly equal to the Roche lobe size) from the white dwarf, where the high-velocity component is expected to originate.

5. CONCLUSION

We have presented the results from XMM-Newton observations of AE Aqr carried out on 2001 November 7–8. Owing to the high energy-resolving power of the RGS, the intensity ratio of the intercombination to forbidden lines of the He-like triplet from nitrogen and oxygen is found to be larger than that expected for the plasma in the low-density limit, which has enabled us to measure the electron number density of the plasma as $\sim 10^{13}$ cm$^{-3}$. This, together with the emission measure ($\sim 10^{53}$–$10^{54}$ cm$^{-3}$), results in a geometrical scale $\lp$ of the plasma of the N and O line emissions, with the ionization temperature $kT_p$ of 0.2–0.3 keV, of $\sim (2–3) \times 10^{10}$ cm. The density is smaller than that of a standard postshock plasma of mCVs by several orders of magnitude, and $\lp$ is much larger than the radius of a 0.79 $M_\odot$ white dwarf. We thus conclude that the X-ray–emitting plasma in AE Aqr cannot be a product of mass accretion onto the white dwarf.

Average spectra of the EPIC cameras can be reproduced by a four-temperature optically thin thermal plasma emission model with a maximum temperature $kT_{\text{max}}$ of 4.6 keV. Assuming that this temperature is achieved by converting gravitational potential energy into heat, we have made an order-of-magnitude estimate of the radius where the heating occurs: $r_{\text{th}} \approx 1 \times 10^{10}$ cm. As the corotation velocity with the white dwarf at $r_{\text{th}}$ is much larger than the Keplerian velocity, the resulting hot plasma can be expelled due to the magnetic propeller action by the white dwarf.

RGS spectroscopy of H-like K$\alpha$ emission (=Ly$\alpha$) lines of N and O has revealed that they show a significant broadening with a $\sigma$ of $\sim 1.2$ and $\sim 2$ eV, respectively, corresponding to a line-of-sight velocity dispersion $\langle v_t \rangle$ of 720–920 km s$^{-1}$. Since the velocity dispersion $\langle v_t \rangle = 1250–1600 \text{ km s}^{-1}$ ($=\sqrt{3} \langle v_t \rangle$) is comparable to the thermal velocity of the plasma with $kT_{\text{max}} = 4.6$ keV ($v_{\text{th}} = (3kT_{\text{max}}/\mu m_p)^{1/2} = 1500 \text{ km s}^{-1}$), the plasma producing the N and O emission lines ($kT_p = 0.2–0.3$ keV) can be interpreted as having expanded adiabatically after it is heated to $T_{\text{max}}$ in the deep gravitational potential of the white dwarf. It is interesting to note that the Balmer series and UV emission lines also show a spectral width with a similar $\langle v_t \rangle$ of 650–850 km s$^{-1}$. This strongly suggests that all these broad emission lines from X-ray to optical wave bands emanate from the plasma, which is once heated to $T_{\text{max}}$ at $r_{\text{th}}$, in the course of its adiabatic cooling. The dramatic flaring activity of the X-ray emission lines, along with the optical and UV lines, requires a common origin for all these lines. The picture presented here can explain the high-velocity component of the H$\alpha$ emission line by a scenario in which the plasma that is expelled due to the propeller action is still too hot ($kT_p = 0.2–0.3$ keV) to emit the H$\alpha$ line within a region of $r < \lp$ (roughly equal to the Roche lobe size) from the white dwarf where the high-velocity component is expected to originate.

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