SPITZER SPACE TELESCOPE OBSERVATIONS OF THE MAGNETIC CATACLYSMIC VARIABLE AE AQUARII

GUILLAUME DUBUS
Laboratoire d’Astrophysique de Grenoble, UMR 5571, CNRS and Université Joseph Fourier, F-38041 Grenoble, France; gudubs@obs.ujf-grenoble.fr

RONALD E. TAAM
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208; Institute of Astronomy and Astrophysics, Academia Sinica; and Theoretical Institute for Advanced Research in Astrophysics, Academia Sinica and National Tsing Hua University, Hsinchu 30013, Taiwan; r-taam@northwestern.edu

CHAT HULL AND DAN M. WATSON
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627; chat.hull@gmail.com, dmw@pas.rochester.edu

AND

JON C. MAUERHAN
Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095; mauerhan@astro.ucla.edu

ABSTRACT

The magnetic cataclysmic variable AE Aquarii hosts a rapidly rotating white dwarf that is thought to expel most of the material streaming onto it. Observations of AE Aqr have been obtained in the wavelength range 5–70 μm with the IRS, IRAC, and MIPS instruments on board the Spitzer Space Telescope. The spectral energy distribution reveals a significant excess above the K4 V spectrum of the donor star, with the flux increasing with wavelength above 12.5 μm. Superposed on the energy distribution are several hydrogen emission lines, identified as Pfα, Hα, Hβ, and Hγ. The infrared spectrum above 12.5 μm can be interpreted as synchrotron emission from electrons accelerated to a power-law distribution $dN \propto E^{-2.4} dE$ in expanding clouds, with an initial evolutionary timescale of seconds. However, too many components must then be superposed to explain satisfactorily both the mid-infrared continuum and the observed radio variability. Thermal emission from cold circumbinary material could contribute, but it requires a disk temperature profile intermediate between that produced by local viscous dissipation in the disk and that characteristic of a passively irradiated disk. Future high time resolution observations spanning the optical-to-radio regime could shed light on the acceleration process and the subsequent particle evolution.

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

Online material: color figures

1. INTRODUCTION

Multiwavelength observational investigations of cataclysmic variable binaries (CVs) are of continuing interest, since they provide important diagnostic information concerning the characteristics of the white dwarf, main-sequence–like donor, and accretion disk in these systems. Within the last decade, observational studies of CVs at near- to mid-infrared wavelengths have been carried out in order to determine the spectral types of the mass-losing stars. Further interest in long-wavelength studies of CVs stems from the possibility of detecting cool gas surrounding such systems, as its presence could have some effect on the secular evolution of these systems (Spruit & Taam 2001). Circumstantial evidence for the presence of such material has been provided by the existence of faint features characterized by narrow line widths in the optical and far-ultraviolet spectra of several objects (see, e.g., references in Dubus et al. 2004), although such features are not present in all systems (Belle et al. 2004). Recently, Spitzer Space Telescope observations have revealed the presence of excess infrared emission in magnetic CVs (Howell et al. 2006; Brinkworth et al. 2007) and black hole low-mass X-ray binaries (Muno & Mauerhan 2006).

In view of the accumulating observational evidence for the presence of cool gas surrounding CVs and its possible importance for CV evolution, AE Aquarii was observed with the Spitzer Space Telescope. AE Aqr is a particularly unusual CV, as the white dwarf in the system rotates (with period 33.08 s) asynchronously with the orbital motion ($P_{\text{orb}} = 9.88$ hr). It is highly variable, exhibiting flaring behavior in the optical (van Paradijs et al. 1989), radio (Bastian et al. 1988), and ultraviolet (Eracleous & Horne 1996) wavelength regions. More recent observations of AE Aqr in the mid-infrared and far-infrared wavelengths using the Infrared Space Observatory (ISO) (Abada-Simon et al. 2005) have led to the measurement of a crude spectral energy distribution (SED) from 3.6 to 170 μm. Observations in the mid-infrared wavelength region were also carried out at Keck Observatory (Dubus et al. 2004), leading to the detection of excess emission in AE Aqr at 12 μm above that extrapolated from shorter wavelengths and variable on timescales less than an hour.

To significantly improve on the measurement of the SED in the wavelength range from 5 to 70 μm, to identify any possible thermal contribution, and to further test the synchrotron emission interpretation for the mid-infrared, based on the model of multiple injections of expanding clouds (Bastian et al. 1988) that has been successfully used in the radio regime, we report on observations of AE Aqr based on measurements obtained with the IRAC, IRS, and MIPS instruments on the Spitzer Space Telescope. Recently, Harrison et al. (2007) independently reported on the
2. OBSERVATIONS

2.1. IRAC and MIPS

Observations of AE Aqr were performed with the Infrared Array Camera (IRAC; Fazio et al. 2004) in all four channels (3.6, 4.5, 5.8, and 8.0 μm) beginning at JD 2,453,501.1. Images were obtained in subarray mode, producing two composites of 64 × 0.1 s exposures in a four-point dither pattern for each channel. The final mosaic images were produced for photometric extraction using the Basic Calibrated Data (BCD) products (pipeline ver. S12.0.2). Aperture photometry was performed with the IRAF APHOT package using the standard IRAC 10 pixel aperture radius with a sky annulus extending from 10 to 18 pixels (IRAC Data Handbook, ver. 3.0). Since a high signal-to-noise ratio (>23–167) was achieved in all four IRAC channels, the photometric errors in these bands are dominated by an absolute calibration uncertainty of 10%, resulting from the not yet fully characterized IRAC filter bandpass responses in subarray mode (Quijada et al. 2004; Reach et al. 2005; Hines et al. 2006).

The results are listed in Table 1.

AE Aqr was also imaged with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) at 24 and 70 μm, beginning JD 2,453,503.8. A single 3 s exposure was obtained at 24 μm, and a 10 × 10 s composite was obtained at 70 μm. Photometry was extracted from the Post-BCD products (pipeline ver. S12.4.0) using the IRAF APHOT package. A 13′′ aperture radius with a sky annulus extending from 20′′ to 32′′ and aperture correction of 1.167 was used for the MIPS 24 μm image, whereas a 35′′ aperture radius with sky annulus extending from 39′′ to 65′′ and aperture correction of 1.21 was used for the 70 μm image. The signal-to-noise ratio (S/N) at 24 and 70 μm was sufficiently high (>100 and 10, respectively) that the photometric uncertainty is dominated by absolute calibration errors of 10% and 20% for MIPS 24 μm and 70 μm, respectively (MIPS Data Handbook, ver. 3.2). The total uncertainty for the 70 μm measurement was obtained by summing in quadrature the 20% absolute calibration error with the inverse of the S/N, resulting in a final error of 22%. These results are also listed in Table 1.

2.2. IRS

Observations of AE Aqr were carried out with the Infrared Spectrograph (IRS) on 2004 November 13 (Spitzer AOR 12699904), as part of the “IRS.DISKS” Guaranteed Time Observer program. In somewhat different form, these data were analyzed and discussed by Harrison et al. (2007). We used the IRS long-slit, low spectral resolution modules (λ/Δλ = 60–100) to record the 5.3–36 μm spectrum of AE Aqr. Four 14 s exposures were taken at 5.3–14 μm, and six 30 s exposures were taken at 14–36 μm, divided equally in each case between two sets of observations with the object nodded along the slit by one-third of a slit length. We reduced the resulting spectra using the SMART software package (Higdon et al. 2004). Starting with non–flat-fielded (“droop”) two-dimensional spectral data products from the Spitzer Science Center IRS pipeline (ver. S14), we removed sky emission by subtraction of differently nodded observations and extracted signal for each within a narrow window matched to the instrumental point-spread function. The resulting one-dimensional spectra were multiplied by the ratio of a template spectrum of the A0 V star α Lac (Cohen et al. 2003) to identically prepared IRS observations of this star, to produce calibrated spectra for each exposure. Averaging all of the exposures, we obtain the final spectrum shown in Figure 1.

Like most grating spectrographs, the modules of the IRS respond better to light polarized parallel to the grating rulings than to the orthogonal linear polarization. The ratio of the response in the two linear polarizations is however poorly characterized at present. Our observations of AE Aqr were performed with the 5.3–14 μm slit at position angle –22.5° and the 14–36 μm slit nearly perpendicular, at –106.1°. These slit orientations are fixed with respect to each other and cannot be adjusted significantly on the sky for objects as close to the ecliptic plane as AE Aqr. It appears from the continuity of the IRS spectrum at 14 μm (difference less than 4% of the signal) that AE Aqr does not have significantly on the sky for objects as close to the ecliptic plane as AE Aqr. It appears from the continuity of the IRS spectrum at 14 μm (difference less than 4% of the signal) that AE Aqr does not have a large linear polarization in either slit direction at these wavelengths. It is possible that the object is more highly polarized at the longest IRS wavelengths than it is at 14 μm, and because we cannot check the orthogonal polarization at long wavelengths, this possibility adds an unknown additional uncertainty to the flux calibration there; at shorter wavelengths, we estimate the photometric uncertainty to be 5% (1σ).

3. RESULTS

The SED based on the fluxes obtained from the IRS instrument is illustrated in Figure 1. It can be seen that the flux in the spectrum exhibits a significant excess at longer wavelengths compared

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TABLE 1

| Wavelength (μm) | Flux (mJy) |
|-----------------|------------|
| 3.6             | 138.9 ± 13.9 |
| 4.5             | 73.2 ± 7.3   |
| 5.8             | 56.1 ± 5.6   |
| 8.0             | 38.2 ± 3.8   |
| 24              | 39.2 ± 3.9   |
| 70              | 52.5 ± 11.6  |

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**Figure 1.** IRS Short-Low–Long-Low spectrum of AE Aqr, with line detections indicated. The uncertainties in the fluxes, as derived from the standard deviation from the mean of individual exposures, are also shown.

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1. The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.
with the expected Rayleigh-Jeans contribution of the K4 V companion star. The flux actually increases at wavelengths longer than 12.5 μm, as noted by Harrison et al. (2007). In addition to the hydrogen emission lines at 7.5 μm (Pfα and Hα) and 12.4 μm (Hγ) identified by Harrison et al., we also find evidence for the \( \text{H} \gamma \) transition at 5.9 μm.

The sensitivity of the observations was sufficient to investigate the variability of AE Aqr on the scale of the times of individual exposures. Figure 2 is a plot of the flux in the Pfα-Hα line blend (\( \lambda = 7.5 \) μm) and of the continuum flux within bands at 20–28 and 28–32 μm as functions of time. The uncertainties in Figure 2 were propagated from the IRS noise-based uncertainties in each wavelength channel of the individual exposures and (in the case of Pfα) the uncertainty in the fit of a Gaussian profile to the line. Although there is a hint of substantial variability in Pfα/Hα on timescales of minutes, the statistical significance is not high (about 2 \( \sigma \)), and this remains to be confirmed with a longer observation. The long-wavelength continuum bands show no significant variation on minute-long timescales. Given the uncertainties in each measurement, detecting variability at the 3 \( \sigma \) level would have required a deviation of 50%–100% from the mean flux in one bin. By comparison, Dubus et al. (2004) found 30%–50% variability between flux measurements taken about an hour apart at 4.6, 11.3, and 17.6 μm (with integration times of several minutes).

The overall SED including the fluxes obtained by the IRAC and MIPS instruments is shown in Figure 3. The fluxes obtained...
from measurements with ISO and the Infrared Astronomical Satellite (IRAS) (Abada-Simon et al. 2005), average radio and millimeter fluxes from Abada-Simon et al. (1993), and Keck measurements in the optical and near-infrared are also plotted (Dubus et al. 2004), to provide a spectrum extending over 6 orders of magnitude in frequency. For comparison, the spectrum of a K4 V star was fitted to the optical and near-infrared data (see Dubus et al. 2004 for details) and is plotted overlaying the SED to illustrate the presence of excess infrared emission for wavelengths longer than 5.8 μm. The flux measurements for the two long wave bands of the IRAC instrument are consistent not only with those obtained from the IRS instrument, but also with the Keck mid-infrared fluxes obtained in 2002. Overall, the average infrared spectrum from 10 to 100 μm is well approximated by a ν^{-0.7} power law.

4. DISCUSSION

4.1. Nonthermal Synchrotron Radiation

Nonthermal synchrotron radiation provides a common framework in which to interpret the SED from radio to mid-infrared frequencies. Although Harrison et al. (2007) considered cyclotron emission from the white dwarf, they concluded that the synchrotron radiation interpretation was more likely, confirming the earlier work of Dubus et al. (2004). The inverted radio spectrum is typical of superposed emission from multiple synchrotron self-absorbed components, as seen in jets from X-ray binaries and active galactic nuclei. Indeed, Bastian et al. (1988) modeled the radio emission as multiple clouds of particles undergoing adiabatic expansion. The average spectrum then steepens around 2 × 10^{12} Hz to F_ν ∝ ν^{-0.7}, as expected for optically thin synchrotron emission from electrons in freshly injected clouds. The required index p = 2.4, assuming a power-law distribution dN ∝ E^{-p} dE, is the canonical index derived from shock acceleration theory.

As described by Bastian et al. (1988), the clouds are characterized by their initial radius R_0, particle density n_0, and magnetic field B_0. These values probably change from cloud to cloud but are assumed identical here (representing a time-averaged value). The expansion scales as ρ ∝ R/R_0 = (1 + t/t_0)^(p+1), with t_0 = R_0/v_0 and t_0 the initial expansion velocity. Reproducing the average radio slope ν^{0.5} with p = 2.4 requires β ≈ 0.53 (see eq. [1] of Dubus et al. 2004), faster than expansion in a uniform medium (β = 1/2) but slower than steady expansion (β = 1). Adiabatic cooling arguably dominates, since the infrared spectrum up to a few tens of terahertz appears unaffected by synchrotron or inverse Compton losses, which would steepen the power law at high frequencies. Requiring that the timescale for adiabatic losses (t_0) be shorter than the synchrotron timescale of electrons emitting at 10^{13} Hz sets an upper limit to t_0 of 2.4 × 10^3 Φ_{20}^{-3/2} ν_1^{-0.5} s.

Although the average SED can be reproduced by multiple clouds (see below), reconciling this interpretation with the variability leads to two puzzles. The first is that the variability is not as strong as expected if a single cloud dominated the infrared SED. In this case, the initial optically thin emission would decrease rapidly with time (F_ν ∝ ρ^{−2β}). Either most of the variability occurs on longer timescales than those sampled in individual observations (t_0 ≳ 1000 s), or it occurs very quickly (t_0 ≲ 30 s; Fig. 2) and is smoothed out by the continuous ejection of new clouds, combined with a coarse time resolution. A long t_0 is unlikely, as radio observations would then show little variability: the peak frequency for a single cloud moves from far-infrared to radio frequencies on a timescale t ∝ 100t_0(v_1/v_0)^0.77, so the variation in radio would be extremely slow. Conversely, observations of radio variability on kilosecond timescales directly set t_0 ≈ 10 s. The infrared emission is then the average flux from clouds evolving on a subminute timescale with an average elapsed time between cloud ejections t_{flare} ≲ t_0. This flaring timescale cannot be too long compared with t_0 (or the peak flux would need to be very high to average out to ≈ 100 mJy at 2 × 10^{12} Hz), nor can it be too short (since then the average SED would require superposing many clouds with small peak flux, implying little variability at any wavelength). The most plausible case appears to be t_{flare} ∝ t_0 ∼ 10 s. In this case, each 30 s bin in Figure 2 would be an average of three consecutive flares, explaining why the light curve shows little variation over 6 minutes.

Figure 3 shows the average SED expected using t_{flare} = t_0 = 10 s, n_0 = 4.7 × 10^{10} cm^{-3}, R_0 = 1.3 × 10^6 cm, and B_0 = 1830 G. To obtain these numbers, which are comparable to those found from the analysis of the radio data by Bastian et al. (1988), an equipartition magnetic field was assumed and the values of the initial peak emission (210 mJy at 3 × 10^{12} Hz) were adjusted so as to have the average spectrum peak at about 100 mJy at 2 × 10^{12} Hz. The average flux corresponds to the emission from a single cloud integrated over time and multiplied by the flaring rate f_{flare}. However, if the peak is on average at 40 μm with a flux of ≈ 50 mJy, then the multiple-clouds interpretation will fail to reproduce the average radio flux.

With the peak position fixed, B_0, R_0, and n_0 are set uniquely by the observations inasmuch as equipartition is assumed and t_{flare} = t_0 (regardless of the actual value). A weaker (subequipartition) magnetic field would actually be preferable, as the synchrotron timescale at 10^{13} Hz for the equipartition field (3 s) is smaller than the adiabatic timescale (10 s). The cloud size compares well with the size of the magnetized blobs through which mass transfer has been proposed to occur in AE Aqr. These blobs approach the white dwarf down to ≈ 10^{10} cm, at which point the spinning magnetic field of the white dwarf presumably propels them out of the system. Note that P_{spin} ∝ t_0 and that the escape velocity at closest approach is comparable to the expansion velocity v_0 = R_0/t_0 ≈ 1300 km s^{-1}.

Figure 3 also shows the instantaneous emission from a cloud at t = 0 and t = t_0 (before a new ejection occurs). Strong variability is expected on a timescale of a few seconds (less than that sampled here by Spitzer), and this can be tested by a high time resolution mid- or far-infrared light curve. Emission to near-infrared frequencies requires electrons of a few hundred MeV. The maximum electron energy is arbitrarily set at 500 MeV in Figure 3. The high-energy electrons contribute a little to the optical V-band flux, but this is not sufficient to explain the 0.5 mag flaring that is observed on timescales of minutes (van Paradijs et al. 1989). Although the flaring at optical (and X-ray) frequencies has also been attributed to propelled gas (Eracleous & Horne 1996), the connection to the nonthermal flaring at low frequencies remains obscure.

The rapid cloud evolution illustrated in Figure 3 raises the second puzzle. The peak flux from a single cloud varies as S_{peak} ∝ ν^{-13}, so that a cloud initially emitting 100 mJy in the infrared can emit at most a few tenths of a millijansky in radio. The radio emission therefore consists of a superposition of hundreds of faint clouds, at odds with the observations of variation of 1–10 mJy in amplitude. A possible solution is that the clouds are reenergized during their expansion (Meintjes & Venter 2003). The variability properties would change, enabling longer variations in infrared to be compatible with the radio flares. Again, a comparison between light curves at infrared and radio frequencies, notably to characterize lags, would shed light on the conditions during expansion.
4.2. A Thermal Component?

The circumstantial evidence points toward nonthermal emission. However, in the absence of variability directly linking the infrared emission to the radio, we cannot exclude a contribution from circumbinary material. A multicolor disk blackbody fit to the infrared requires a temperature distribution $T \propto R^{-0.54}$, between the $-\frac{1}{2}$ slope of a thin disk passively heated by irradiation and the $-\frac{3}{2}$ slope of a thin disk heated by viscous dissipation. We note that a profile of a similar form, $T \propto R^{-1/2}$, has been found from detailed vertical-structure models of irradiated accretion disks (D’Alessio et al. 1998) to provide satisfactory fits to the emission properties of young stellar objects (D’Alessio et al. 1999).

The Spitzer data are fitted adequately (Fig. 3) by such a disk extending out to 1.2 AU at a temperature of 55 K, taking a distance of 102 pc (Friedjung 1997) and an inclination of 55°. Here the disk peaks around 40 μm. This is a better fit than a single-temperature (140 K) blackbody (Harrison et al. 2007). Optically thin emission from material at larger distances, not taken into account here, may contribute to longer wavelengths. The dominant contribution below $\sim 10^{12}$ Hz would still be nonthermal flaring. The constraints on the flare peak frequency and flux are therefore relaxed compared with § 4.1, but not enough to account for the amplitude of the radio flares without, for example, reenergizing the clouds.

The expected infrared variability from circumbinary material is slow, since the thermal timescale is roughly Keplerian and hence $\geq P_{\text{orb}}$. Variability on timescales of years might explain the discrepancy between the Spitzer and ISO far-infrared measurements. However, the disk would have to be colder and larger to account for the ISO flux at 90 μm. The variability seen on a sub-hour timescale in Dubus et al. (2004) argues against thermal infrared emission but has yet to be confirmed by a more extensive set of observations. A disk could be resolved by interferometric observations at millimeter wavelengths, or possibly in the mid-infrared, where the emission is already a few milliarcseconds wide. Polarimetric observations may also distinguish between scattered light and synchrotron emission.

4.3. Infrared Line Emission

The detection of P$\alpha$, H$\alpha$, H$\beta$, and H$\gamma$ in the IRS spectrum is consistent with observations of intense Brackett and Pfund lines in the near-infrared from AE Aqr by Dhillon & Marsh (1995). These lines were attributed to the accretion disk because of their lines in the near-infrared from AE Aqr by Dhillon & Marsh (1995).

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5. CONCLUSION

The presence of infrared emission in excess of expectations from the stellar companion in AE Aqr, already present in Keck data up to 17 μm (Dubus et al. 2004) and in ISO data (Abad-Simon et al. 2005), is confirmed by Spitzer. Synchrotron emission from multiple expanding clouds provides a coherent framework in which to interpret the SED from radio to infrared wavelengths. Alternatively, interpreting the infrared SED as thermal emission from circumbinary material provides an intriguing parallel with disks surrounding T Tauri stars. This interpretation would still require nonthermal flaring to explain the radio emission, and it would be ruled out if fast, large-amplitude variability is confirmed at infrared wavelengths. On the other hand, synchrotron emission from electrons injected with a canonical $E^{-2.4}$ power law reproduces well the whole spectrum down to radio frequencies.

However, the multiple-cloud picture raises several riddles. Rapid (seconds) variability is expected in the infrared but remains undetected, probably for lack of an adequately sampled light curve. In addition, the number of clouds required in order to reproduce the average radio spectrum is too large to also explain the amplitude of the variations seen at these frequencies (Meintjes & Venter 2003). This requires modification of the basic assumptions adopted by Bastian et al. (1988). A continuous outflow from the propeller, rather than discrete ejections, may provide a better description of the process operating in AE Aqr. Other questions remain open, such as the nature of the particle acceleration process and the link to the flaring behavior at optical–to–X-ray frequencies. Better multiwavelength sampling for short-timescale (<30 s) spectral evolution studies is needed to obtain further insights into the physics of this unique system.

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