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AE Aquarii: A Short Review

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Abstract

The nova-like variable AE Aquarii has been continuously studied since its discovery on photographic plates in 1934. In this short review the peculiar multi-wavelength properties of AE Aquarii will be reviewed and explained in context of its evolution from a high mass transfer phase, during which period it could have been a supersoft X-ray source (SSS).

Keywords: cataclysmic variable: AE Aquarii - radiation mechanisms: non-thermal - line: identification - techniques: spectroscopic.

1 Introduction

Since its discovery on photographic plates in optical wavelengths (Zinner 1938), the rapid variable star AE Aquarii has been a source of continuous observational and theoretical study involving a wide range of frequencies from radio to TeV gamma-rays. Optical photometric studies showed that the system is highly variable, with $\Delta m_{\rm v} \leq 2$ magnitude outbursts occurring nearly continuously (e.g. Henize 1949, Patterson 1979, van Paradijs, Kraakman & van Amerongen 1989). Distance estimates place the source at ~ 100 pc (Welsh, Horne & Oke 1993).

2 Optical and X-ray Pulsations

The first photometric pulse-timing study of AE Aquarii in the optical band (Patterson 1979) revealed steady coherent pulsations in the power spectra at $P_\circ \approx 33$ s and $P_1 \approx 16$ s, which were interpreted as the spin period of an obliquely rotating white dwarf and its associated first harmonic, caused by the second pole reflecting from the inner edge of the accretion disc (Patterson 1979). This led to its initial classification as a DQ Herculis type system (Patterson 1979). Fast optical spectroscopy performed later with the Mount Wilson 2.5 m Coudé spectrograph in the wavelength band 636 - 682 nm, combined with simultaneous photometry in the same wavelength band (Welsh, Horne & Gomer 1993), revealed that the pulsations originate from the white dwarf. However, it has been pointed out (Patterson 1979) that the low pulsed fraction ($\leq 1\%$) of the 33 s oscillation of AE Aquarii is peculiarly low for a disc accreting white dwarf. In order to place AE Aquarii with its rapidly rotating white dwarf in the DQ Herculis sub-class of the cataclysmic variables, accreting in the slow rotator limit from a well developed accretion disc, a magnetic surface field of $B_* \leq 100\,\mathrm{kG}$ is required (e.g. Patterson 1994). This is significantly lower than the inferred surface field of a disc accreting DQ Herculis-type system, which is $B_* \sim 10^6 - 10^7$ Gauss (Patterson 1979). Optical polarimetry (Cropper 1986, Stockman et al. 1992; Beskrovnaya et al. 1995) revealed circular polarization $\sim 0.05 - 0.1\,\%$ in optical light, which confirmed that the dwarf surface magnetic field is at least of the order $B_* \geq 10^6\,\mathrm{G}$ (e.g. Chanmugam & Frank 1987).

X-ray observations made by *EINSTEIN* (0.1 - 4 keV) showed the 33 s oscillation, with no indication of the associated 16 s first harmonic (Patterson et al. 1980). This is confirmed by recent *Chandra* X-ray observations (e.g Oruru & Meintjes 2012), which shows a single coherent pulse at 33 s.

In optical wavelengths the 33 s period often disappears during outbursts (e.g Patterson 1979; Meintjes et al. 1992;1994), while the X-ray pulsed fraction determined with the *EINSTEIN* data seems to show some correlation with increasing count rate according to the relation $\mathrm{PF}(\%) = 45(\%/\mathrm{s}^{-1})\mathrm{CR}(\mathrm{s}^{-1})$ in the observed count rate range 0.15-0.5 s^{-1} (e.g. Meintjes & de Jager 2000). No noticeable changes in the hardness ratio of the X-ray data has been observed during periods of enhanced activity (e.g. Meintjes & de Jager 2000; Oruru & Meintjes 2012). The weak correlation between the optical pulsed fraction of the coherent 33 s period and outbursts, together with the radial velocity measurements of UV lines observed during time-resolved spectroscopic observations made with the Hubble Space Telescope *HST*, suggest a very effective propeller driven mass outflow in AE Aquarii (e.g. Patterson 1994; Eracleous & Horne 1996).

3 The Propeller Phase

Doppler tomography profiles of the AE Aquarii system (e.g. Wynn, King & Horne 1997; Ikhsanov, Neustroev & Beskrovnaya 2004) show tell-tale signatures of a propeller driven mass outflow from the system. The magnetospheric propeller process in AE Aquarii was first explained within the framework of large diamagnetic blobs being propelled by a magnetospheric drag (Wynn & King 1995; Wynn, King & Horne 1997). Roche tomography of the secondary star (Dunford & Smith 2005; Watson et al. 2006; Smith, Dunford & Watson 2012) shows that $\sim 20\%$ of the surface of the secondary star is covered with starspots, which may suggest a magnetically active secondary star. The effect of secondary star magnetic fields on the mass transfer process has been investigated (Meintjes 2004). It has been shown that magnetic prominences can fragment the mass transfer flow into a blob-like stream, which upon interacting with the fast rotating white dwarf field, can be propelled from the system on time-scales that are short compared to the Keplerian periods at the distance of closest approach of the stream (Meintjes & Venter 2005). Recent spectroscopy performed with the 1.9 m telescope at Sutherland revealed broad emission lines, which is most probably an indicator of high velocity gas in the system. The full-width half maximum width of these lines all implies velocities in excess of $v_{\rm esc} \geq 1000\,{\rm km\ s^{-1}}$ (Meintjes, Oruru & Odendaal 2012), which is of the order of the escape velocity from the radius of closest approach of the stream.

It has been shown (Venter & Meintjes 2006) that the interaction between the fast rotating magnetosphere and the stream of material from the secondary star may result in the development of Kelvin-Helmholtz instabilities, resulting in effective turbulence driven mixing of magnetic field with plasma. This results in a very effective transfer of angular momentum to the stream, propelling it from the system (Venter & Meintjes 2006). This has been confirmed by numerical simulations of the interaction between the fast rotating magnetic field of the white dwarf in AE Aquarii and the mass flow from the secondary star (Bisikalo & Zhilkin 2012). The low accretion rate of the white dwarf in AE Aquarii ($\dot{M}_* \sim 10^{14}\,{\rm g\ s^{-1}}$) compared to the mass transfer rate deduced from the UV emission line spectra ($\dot{M}_2 \sim 10^{17}\,{\rm g\ s^{-1}}$) implies that the white dwarf in AE Aquarii is in a super-propeller (ejector) state (Bisikalo & Zhilkin 2012; Ikhsanov & Beskrovnaya 2012). The brightening of the source observed in optical on a regular basis, can therefore not readily be explained in terms of enhanced mass accretion onto the white dwarf. It has been shown (Beardmore & Osborne 1997) that the flaring activity in AE Aquarii can be explained satisfactorily within the framework of colliding blobs propelled form the system by the magnetospheric propeller. These authors showed that collisions between faster and slower blobs will result in heating and resultant radiative cooling which can account for the outbursts in AE Aquarii.

4 Spin-Down and Particle Acceleration

The dissipated MHD power due to the magnetospheric propeller process in AE Aquarii (e.g. Meintjes & de Jager 2000; Meintjes & Venter 2005) is of the order of $P_{\rm mag} \sim 10^{34}\,{\rm erg\ s^{-1}}$, and comes at the expense of the rotational kinetic energy of the rapidly rotating white dwarf. A detailed pulse timing study of the white dwarf spin period, using a 14 year baseline (de Jager et al. 1994) revealed that the white dwarf is spinning down at a rate of $\dot{P}_* \sim 5.64 \times 10^{-14}\,{\rm s\ s^{-1}}$. This translates to a spin-down luminosity of the order of $L_{\rm s-d} = I\Omega\dot{\Omega} \sim 10^{34}\,{\rm erg\ s^{-1}}$. A more recent study (Mauche 2006) revealed that the spin-down rate of the white dwarf has sped-up. This can possibly be explained within the framework of mass transfer variations from the secondary star.

The low accretion in comparison to the mass transfer $\alpha = \dot{\rm M}_*/\dot{M}_2 \sim 0.1\%$ may indicate that the white dwarf in AE Aquarii is currently in a super-propeller (Bisikalo & Zhilkin 2012) or ejector phase (Ikhsanov & Beskrovnaya 2012) and that the white dwarf in AE Aquarii may exhibit the same properties as a spun-up radio pulsar (e.g Ikhsanov & Bierman 2006). This implies that the low mass accretion and rapid rotation of the highly magnetized white dwarf may provide a mechanism for pulsar-like particle acceleration and non-thermal emission. Recent results from Suzaku X-ray satellite (Terada et al. 2008) showed a non-thermal spectrum at energies $\epsilon_{\rm x} \geq 10$ keV. It has been showed recently (e.g. Oruru & Meintjes 2012) that particles can be accelerated in the magnetosphere of the white dwarf to energies in excess of $\epsilon \geq 100\,{\rm GeV}$, which may radiate synchrotron radiation at energies of the order of $\epsilon_{\rm x} \sim 10\,{\rm keV}$ in the weak magnetic field outside the corotation radius.

5 Non-Thermal Emission

Radio observations performed in the late 1980's showed that AE Aquarii is a non-thermal emitter (Bookbinder & Lamb 1987, Bastian, Dulk & Chanmugam 1988), showing continuous radio outbursts with maximum flux $S_{\rm mJy} \leq 15$ at frequencies $\nu \leq 22.5\,{\rm GHz}$. The high brightness temperature measured $T_{\rm b} \geq 10^{10}\,{\rm K}$ definitely implies non-thermal emission, with the spectral slope $S_{\rm mJy} \propto \nu^{\alpha}$, with $\alpha \sim 0.3 - 0.5$ (Bastian, Dulk & Chanmugam 1988). The spectral properties of the radio emission in AE Aquarii can be explained in terms of a superposition of synchrotron emitting plasmoids, which expand and cool radiatively through synchrotron radiation (van der Laan 1963; 1966). Subsequent studies in infrared with *ISO* (Abada-Simon et al. 2005) and *Spitzer* (Dubus et al. 2007) showed that the $S_{\mathrm{mJy}} \propto \nu^{\alpha}$ ($\alpha \sim 0.5$) non-thermal spectrum extends to a frequency $\nu \sim 2000\,\mathrm{GHz}$ (Dubus et al. 2007). The non-thermal radio-IR spectrum has been modeled successfully (Meintjes & Venter 2003; Venter & Meintjes 2006) in terms of synchrotron emission from relativistic electrons in expanding magnetized plasmoids in the propeller outflow. It has been shown that the frequency where the spectrum turns optically thin to radio emission is of the order of $\nu_{\mathrm{t}} \leq 3000\,\mathrm{GHz}$.

Reports of pulsed burst-like VHE and TeV gamma-ray emission in the 1990's (Bowden et al. 1992; Meintjes et al. 1992;1994) sparked interest in AE Aquarii as a non-thermal source of high energy emission. Subsequent studies with various modern Cerenkov detectors could unfortunately not confirm the earlier reports, leaving the VHE-TeV status of AE Aquarii still in doubt (e.g. Lang et al. 1998; Sidro et al. 2008; Mauche et al. 2012).

6 The Evolution

The current properties of AE Aquarii is consistent with a high mass accretion history (Meintjes 2002; Schenker et al. 2002). If one consider initial parameters $P_{\mathrm{orb,i}} \sim 15\mathrm{h}$, $M_{1,\mathrm{i}} \sim 0.6M_{\odot}$, $M_{2,\mathrm{i}} \sim 1.6M_{\odot}$ (i.e. $\mathrm{q_i} \sim 2.7$) and $R_{2,\mathrm{i}} \sim 1.6R_{\odot}$, it can be shown that the initial thermal time-scale ($\tau_{\mathrm{th}} \sim 6.3 \times 10^{6}(M_2/1.6M_{\odot})^{-1}\,\mathrm{yr}$) mass transfer could have been of the order $\dot{M}_{2,\mathrm{i}} \sim 2 \times 10^{19}(M_{2,\mathrm{i}}/1.6\,M_{\odot})(\tau/\tau_{\mathrm{th}})^{-1}\,\mathrm{g\ s^{-1}}$, still below the Eddington value of $\dot{M}_{\mathrm{Edd}} \leq 7 \times 10^{20}(M_{1,\mathrm{i}}/0.6\,M_{\odot})^{-0.8}\,\mathrm{g\ s^{-1}}$. It has been shown that this could have lasted until a critical q-ratio was reached, i.e. $\mathrm{q_{crit}} = 0.73$ (Meintjes 2002) during which time accretion disc torques could have spun-up the white dwarf to periods around ~ 30 s over a time scale $\tau_{\mathrm{su}} \sim 3 \times 10^{6}\,\mathrm{yr}$, which is similar to the thermal mass transfer time scale, i.e. $\tau_{\dot{\mathrm{m}}} \sim \mathrm{few} \times 10^{6}\,\mathrm{yr}$ (Meintjes 2002). The high mass accretion in this initial phase could have resulted in AE Aquarii being a supersoft X-ray source (SSS) (Meintjes 2002; Schenker et al. 2002).

7 Conclusions

The multi-frequency properties of AE Aquarii have been summarized. The current asynchronicity of the spin and orbital period of AE Aquarri can be explained in terms of a high mass accretion history during which period the white dwarf could have been spun-up by accretion disc torques to a short period. In this phase the high accretion rate could have resulted in the system being a SSS. A subsequent decrease in the mass transfer rate from the secondary drove the system into the propeller state, which may be the driving mechanism behind the multi-frequency emission from the system.

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DISCUSSION

DIMITRI BISIKALO: Is there any observational evidence of mass flow surrounding the white dwarf?

PIETER MEINTJES: There is observational evidence of mass being ejected from the system. The propeller is extremely effective, only $\sim 0.1\%$ of the mass transfer flow gets accreted onto the surface. The rest is ejected from the system. Optical and UV spectroscopy indicate high velocity flows. There may be a circumbinary ring of ejected matter present surrounding the system.