PROPERTIES OF THE EMISSION REGIONS IN AM HER STARS

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ABSTRACT. The emission regions on the white-dwarf primaries of AM Her type systems are suggested to be extended and offset from the magnetic pole similar to the oval arc of emission formed by the Earth's auroral zone. In ST LMi and EF Eri, the emitting areas of the bremsstrahlung, the soft X-ray, and the cyclotron sources are shown to display a hierarchy with a small bremsstrahlung core being surrounded by a larger cyclotron halo. Core and halo are characterized by large differences in specific accretion rate with that in the bremsstrahlung core corresponding to a sizable fraction ($\gtrsim 10\%$) of the Eddington rate.

1. "X-RAY AURORAL OVALS"

In AM Her stars, the accretion stream is thought to penetrate to a stagnation radius r_s where it breaks up into individual blobs due to Kelvin-Helmholtz instabilities (Lamb, 1985; Liebert and Stockman, 1985; Hameury et al., 1986). These weakly magnetized blobs are penetrated by the magnetospheric field and subsequently guided to the white dwarf surface. It is conceivable that, before attaching to magnetospheric field lines, some blobs or neutral gas manage to continue their path in the orbital plane, approximately following the single-particle trajectory. Accretion may, therefore, occur over some range in azimuth. The plasma arrives at the surface of the white dwarf at an angular separation θ which depends on r_s. The emission region on the white dwarf is expected to show some extent in azimuth, streching along a circular arc with angular radius θ and forming what may effectively be termed part of an "X-ray auroral oval". In analogy to particle entry into the Earth's magnetospere, we may also expect that emission from the accretion region fluctuates both in the spatial coordinates and in time.

Lamb (1985) derived r_s from the equality of the magnetic-field pressure and the ram pressure of the stream (see, however, Hameury et al., 1986). I suggest that the appropriate particle density in the equation for r_s is that in the line-emitting region which is roughly given by $n_e \simeq 10^{13} - 2\ 10^{14}$ cm^{-3} (Liebert and Stockman, 1985). Then,

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using the equatorial magnetic field strength,

$$r_s/R = 7.2\ B_7{}^{2/5}\ n_{14}{}^{-1/5}\ R_{8.7}{}^{2/5} \qquad (1)$$

$$\sin\theta = (r_s/R)^{-1/2} = 0.37\ B_7{}^{-1/5}\ n_{14}{}^{1/10}\ R_{8.7}{}^{-1/5} \qquad (2)$$

where B_7, n_{14}, and $R_{8.7}$ are the polar field strength, the electron density near the stagnation point, and the radius R of the white dwarf in units of 10^7 Gauss, 10^{14} cm^{-3}, and 5 10^8 cm, respectively, and a simplified mass radius relation of white dwarfs was assumed, $(M/M_\odot)\ R_{8.7} = 1$. For $B_7 = 1-3$, $n_{14} = 0.1-2$, and $R_{8.7} = 0.8-1.6$, the field line along which accretion takes place is offset from the pole by $\theta = 12°-25°$. If m is the co-latitude of the magnetic axis, the angle between the direction of this field line and the rotational axis is $b \simeq m + (3/2)\theta$ (provided field line and magnetic axis are located on the same meridian). Note that linear-polarization measurements permit the determination of b rather than m, along with the inclination i.

2. THE EMITTING AREAS ON THE WHITE DWARF

The emitting area A_{bb} of the soft X-ray source may be derived from the luminosity L_{bb} assuming black-body emission while the area A_{cyc} of the cyclotron source follows from the Rayleigh-Jeans limited cyclotron flux F_K in the K-band, provided the temperatures can be estimated in both cases.

The emitting area A_{brems} of the hard bremsstrahlung source may be estimated from the observed emission measure EM and the relevant pre-shock particle density. The latter is obtained from the particle density at r_s and variation along the field line as $r^{-2.5}$ (dipole field). I make the assumption that n_{14} also describes the density of the plasma which attaches to the near-polar field lines at r_s.

An approximate analytic expression for EM may be obtained from the hydrodynamic equations (e.g., Kylafis and Lamb, 1982) with the simplifying assumptions of a plane-parallel cooling flow without gravity (valid near the surface of the white dwarf) and a pure-hydrogen plasma with a constant cooling rate Λ (erg cm^{3}s^{-1}). With these assumptions, the plasma parameters of the post-shock flow in terms of the compression $x = \rho/\rho_1$ are found to vary as

$$(r-R)/h = (10/7)\ x^{-3} - (3/7)\ x^{-4} \qquad (3)$$

$$T/T_1 = (4/3)\ x^{-1} - (1/3)\ x^{-2} \qquad (4)$$

where $\rho_1 = 4\rho_o$ is the post-shock density and T_1 the shock temperature. The stand-off distance of the shock and the emission measure are given by

$$h = (7/768)\ m_H{}^2\ v_o{}^3/(\Lambda\rho_o) \qquad (5)$$

$$EM = (1/2)\ A_{brems}\ \rho_o\ v_o{}^3/\Lambda \qquad (6)$$

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where $v_o = 7\ 10^8\ R_{8.7}^{-1}$ cm s^{-1} is the free-fall velocity and m_H the unit mass. With $\Lambda \simeq 3\ 10^{-23}$ erg $cm^3\ s^{-1}$ and the observed emission measure EM_{55} in units of $10^{55}\ cm^{-3}$

$$A_{brems} = 7.5\ 10^{13}\ EM_{55}\ R_{8.7}^2\ B_7^{-1}\ n_{14}^{-1/2}\ cm^2. \qquad (7)$$

3. APPLICATION TO ST LMI AND EF ERI

In ST LMi = CW1103+254, the accreting pole is on the opposite hemisphere as the observer. According to Schmidt et al. (1983) and Cropper (1986), $i \simeq 56°-69°$, $b \simeq 34°-46°$, $B_{8.7} \simeq 3$, and $R_{8.7} \simeq 1.7$. With $n_{14} \simeq 0.5$, $r_s/R \simeq 16$, and $\theta \simeq 14°$. The magnetic co-latitude is then $m = 13°-25°$, i.e. the inclination of the magnetic axis is small. The emission region is always close to the horizon and is best seen at a glancing angle β of only about 5°. (Even if $\theta = 0°$, β would not exceed 12°). The soft X-ray light curves display a steep fall at the end of the bright phase which appears to be a stable feature of the system. The base width is 0.4 in phase, but the rise is more (less) rapid when the system is bright (faint) (Beuermann and Stella, 1985). This suggests that the main accretion stream is stable in phase and that its disappearance behind the white dwarf produces the steep fall of the light curve. As the accretion rate increases some material penetrates further around in the orbital plane before attaching to magnetospheric field lines, causing the bright part of the emission region to extend further in azimuth. We also note that the K-band light curve (Bailey et al., 1985) is wider than the X-ray light curves observed so far which suggests that the cyclotron emission region is more extended than the X-ray emitting region.

For a distance of 135 pc (Bailey et al., 1985; Szkody et al., 1985; Cropper, 1986), the relevant quantities for calculating the emitting areas are $L_{brems} \simeq 5\ 10^{31}$ erg/s, $EM \simeq 4\ 10^{54}\ cm^{-3}$, and $kT_{brems} \simeq 20$ keV, $L_{bb} = (2-8)\ 10^{31}/\sin\beta$ erg/s, and $kT_{bb} = 18-40$ eV (Beuermann et al., 1985), and finally $F_K = 1.6\ 10^{-26}$ erg $cm^{-2}\ s^{-1}$ (peak K-band flux, Bailey et al., 1985) and $kT_{cyc} = 15-30$ keV (Wickramasinghe and Meggitt, 1985). The cyclotron emission can not originate from far above the surface of the white dwarf because the ends of the bright phases at X-ray and optical wavelengths approximately agree. Nevertheless, the effective angle β may be larger for the cyclotron-emitting volume than for the soft X-ray (blackbody) source. With $\beta = 5°-10°$ (blackbody) and $\beta = 5°-20°$ (cyclotron) I obtain the emitting areas listed in Table I. It may be appropriate to add the caveat that A_{brems} will be underestimated by the above method if the bremsstrahlung-emitting region is not dominated by bremsstrahlung losses.

In EF Eri = 2A0311-227, the accreting pole is located on the same hemisphere as the observer. According to Cropper (1985), $65° < i < 75°$ and $0° < b < 15°$, while Piirola et al. (1986) suggest $i = 55±5°$ and $b = 38±5°$. For a low magnetic moment (B_7 and $R_{8.7}$ low), θ may approach or even exceed 20°. The co-latitude of the magnetic axis is then $m \lesssim 20°$ in agreement with Cropper's (1985) suggestion. With i as large as

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suggested by Cropper (1985), an "X-ray auroral oval" on the white dwarf in EF Eri will suffer a partial self-eclipse as the system revolves (Beuermann et al., 1986). This self-eclipse would naturally explain the smooth orbital variation of the X-ray and K-band light curves (Watson et al., 1985; Beuermann et al., 1986) and also provide an explanation of the double-humped optical light curve by the combined effect of beaming of the higher cyclotron harmonics and the partial self-eclipse.

At X-ray and K-band maximum, our line of sight makes a sizable angle with the emitting surface, $\beta \gtrsim 45°$. Hence, the uncertainties in the emitting areas are somewhat less than in ST LMi. The relevant quantities for the lower limit to the distance, d = 100 pc, are EM = $1.0\ 10^{55}$ cm^{-3}, $kT_{brems} \simeq 22$ keV, $L_{bb} = (0.2-4.3)\ 10^{32}$ erg/s, kT_{bb} = 16-33 eV, $F_K = 6.0\ 10^{-26}$ erg/cm^{2}s Hz (Beuermann et al., 1986), and an estimated $kT_{cyc} \simeq kT_{brems}$ which yield the areas listed in Table I.

TABLE I Emitting areas A and corresponding fractions f of the white-dwarf surface

	ST LMi[a]	EF Eri[b]
A_{brems}	$\sim 0.04\ 10^{15}$	$(0.02-0.6)\ 10^{15}$
A_{bb}	$(0.04-8)\ 10^{15}$	$(0.02-6.0)\ 10^{15}$
A_{cyc}	$(4-32)\ 10^{15}$	$(3.2-12)\ 10^{15}$
f_{brems}	$\sim 5\ 10^{-6}$	$6\ 10^{-6} - 2\ 10^{-4}$
f_{bb}	$5\ 10^{-6} - 9\ 10^{-4}$	$6\ 10^{-6} - 2\ 10^{-3}$
f_{cyc}	$4\ 10^{-4} - 4\ 10^{-3}$	$1\ 10^{-3} - 4\ 10^{-3}$

[a] Areas in cm^2 for d = 135 pc, f calculated with $R_{8.7} = 1.7$.

[b] Areas in cm^2 for lower limit to distance, d = 100 pc; f calculated with $R_{8.7} = 1$.

4. CONCLUSION

The shape of the light curves of AM Her stars contain information on the geometry of the emission regions. The variable shape of the light curves in ST LMi and the smooth orbital variation in EF Eri are suggestive of an extended emission region on the white dwarf (King and Shaviv, 1984). Accrection occurs along field lines which are offset from the magnetic pole (Lamb, 1985). With increasing $\dot{M}$, the accretion stream penetrates further along the single-particle trajectory in the orbital plane, causing accretion to occur along a range of field lines and to produce an arc of emission on the white dwarf which forms what may be termed an "X-ray auroral oval".

The emitting areas display a hierarchy in the sense that $A_{cyc} > A_{brems}$ with A_{bb} falling somewhere inbetween. In EF Eri, $L_{brems} \simeq 5\ L_{cyc}$ while $A_{brems} < A_{cyc}$ (Beuermann et al., 1986). As a consequence, the specific accretion rate in the cyclotron halo is much less than in

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the intensely emitting bremsstrahlung core or cores. While the specific accretion rate in the bremsstrahlung core may correspond to ≳ 10% of the Eddington limit, it is lower in the cyclotron halo by several orders of magnitude. The comparison with the terrestrial aurora may, in fact, be illustrative: aurorae sometimes show a fluctuating ribbon of intense emission and a general faint glow of the sky.

References:

Bailey, J., et al., 1985, Mon. Not. R. astr. Soc. **215**, 179

Beuermann, K., Stella, L., and Krautter, J., 1985, Proc. Symposium "X-Ray Astronomy 84", Bologna, eds. M. Oda and R. Giacconi, p. 27

Beuermann, K., and Stella, L., 1985, Space Sci. Rev. **40**, 139

Beuermann, K., Stella, L., and Patterson, J., 1986, submitted to Astrophys. J.

Cropper, M., 1985, Mon. Not. R. astr. Soc. **212**, 719

Cropper, M., 1986, this conference

Hameury, J.M., King, A.R., and Lasota, J.P., 1986, Mon. Not. R. astr. Soc. **218**, 695

King, A.R., and Shaviv, 1984, Mon. Not. R. astr. Soc. **215**, 1P

Kylafis, N.D., Lamb, D.Q., 1982, Astrophys. J. Suppl. **48**, 239

Lamb, D.Q., 1985, in Cataclysmic variables and Low-Mass X-Ray Binaries, eds. D.Q. Lamb and J. Patterson, D. Reidel Publ. Co., p. 179

Liebert, J., and Stockman, H.S., 1985, in Cataclysmic Variables and Low-Mass X-Ray Binaries, eds. D.Q. Lamb and J. Patterson, D. Reidel Publ. Co., p. 151

Piirola, V., Coyne, G.V., and Reiz, A., 1986, this conference

Schmidt, G.D., Stockman, H.S., and Grandi, S.A., 1986, Astrophys. J. **271**, 735

Szkody, P., Liebert, J., and Panek, R.J., 1985, Astrophys. J. **293**, 321

Watson, M.G., King, A.R., Williams, G., Heise, J., and Beuermann, K., 1985, Workshop: Recent Results on Cataclysmic Variables, ESA SP-236, p. 169

Wickramasinghe, D.T., and Meggitt, S.M.A., 1985, Mon. R. astr. Soc. **216**, 875

https://doi.org/10.1017/S0252921100105421 Published online by Cambridge University Press