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POLARIZED RADIATION FROM AM HERCULIS BINARIES

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ABSTRACT: Is the accretion column of AM Herculis binaries a circular or a flattened cylinder? We show that polarization data can answer this question. We evaluate the polarized radiation emitted by a circular cylinder accretion column and compare it with a flattened cylinder as a function of: 1) the angle of observation with respect to the axis of the accretion column, 2) the magnetic field, 3) the thickness of the column, 4) the temperature of the plasma, and 5) the observed radiation frequency.

Key words: AM Herculis binaries, polarized radiation, accretion column.

I INTRODUCTION

The principal characteristics of the AM Herculis binaries are remarkable optical properties discovered by Tapia (1977) who found linear and circular polarization at a high level. The linear polarization of the binary AM Herculis is in the form of a narrow pulse repeated every 3.1 hours. Chanmugam and Wagner (1977, 1978) and Stockman et al. (1977) proposed a model in which the magnetic white dwarf is locked into synchronous rotation with the orbital period. In this scenario, material is channeled along magnetic field lines from the inner Lagrangian point directly onto a magnetic pole of the white dwarf without the formation of an accretion disc (see Fig. 1). There are about 10 such binaries known. The observed linear polarization reaches $\sim$ 16% (CW 1103+254) (Stockman et al. 1983) and the circular polarization reaches $\sim$ 35% (AN UMa) (Krzeminski and Serkowski 1977).

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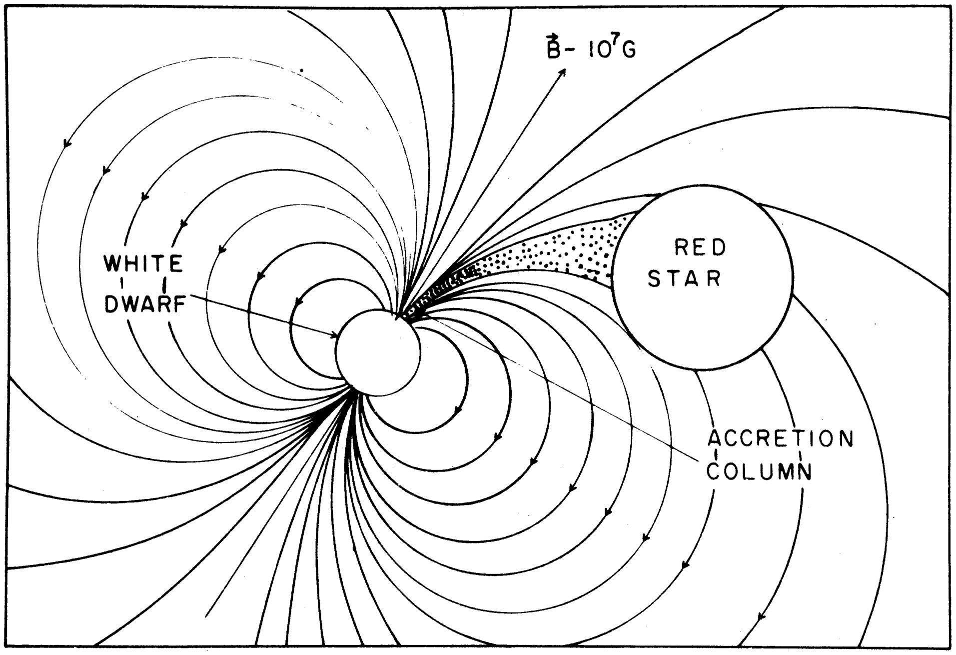

Fig. 1 - The schematic geometry of AM Herculis binaries.

We study the following problem: when observing the radiation from an accretion column (such as that of a AM Herculis binary), are we observing the radiation from a circular cylinder or a flattened cylinder? We do not have cylindrical symmetry about the accretion column and there is thus no necessity to have a circular accretion column (see Fig. 2).

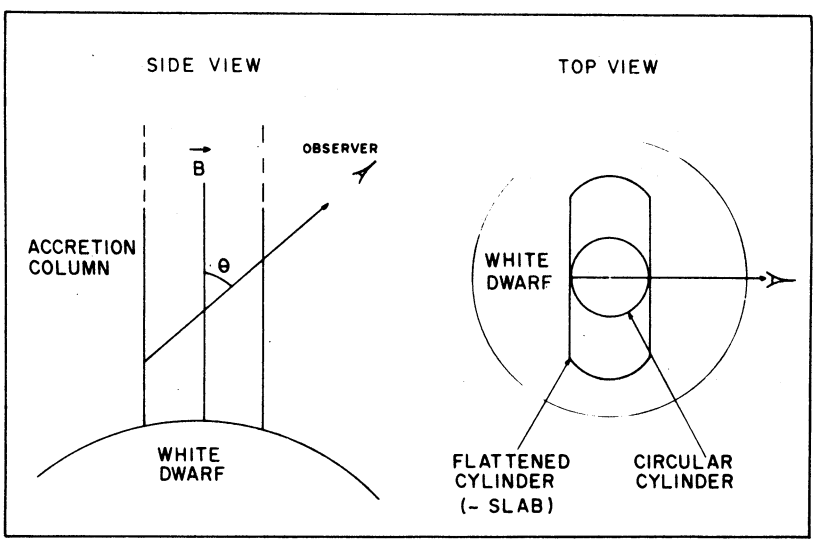

Fig. 2 - Circular and flattened cylinder accretion columns.

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We obtain simplified analytic expressions for the absorption coefficients $\mu_{\pm}(\Theta)$ for the extraordinary (+) and ordinary (-) modes of the radiation and use these simplified analytic expressions to evaluate the polarized radiation as a function of Θ for a circular cylinder accretion column and a flattened cylinder ($\sim$ slab) accretion column, where Θ is the angle of observation with respect to the magnetic field.

II. ABSORPTION OF RADIATION IN A HOT MAGNETIZED PLASMA

One of the most detailed calculations performed recently of the polarized radiation emitted by an accretion column is that of Barrett and Chanmugam's (1984) (hereafter BC) where they approximated the accretion column as a slab. Their absorption coefficients are based on the analysis of Pavlov et al (1980) who start from the expression for the complex dielectric tensor of a hot magnetized plasma.

The absorption coefficients used by BC for the extraordinary mode (+) and ordinary mode (-) have the form:

$$\mu_{\pm}(\Theta) = 2\frac{\omega}{c}\mathrm{Im}(N_I \pm (N_C^2 + N_L^2)^{1/2}) \tag{1}$$

where

$$N_I = 1 + (\varepsilon_{yy} + \varepsilon_{xx}\cos^2\Theta - \varepsilon_{xz}\sin2\Theta + \varepsilon_{zz}\sin^2\Theta - 2)/4 \tag{2}$$

$$N_L = (\varepsilon_{yy} - \varepsilon_{xx}\cos^2\Theta + \varepsilon_{xz}\sin2\Theta - \varepsilon_{zz}\sin^2\Theta)/4 \tag{3}$$

$$N_C = i(\varepsilon_{xy}\cos\Theta + \varepsilon_{yz}\sin\Theta)/2 \tag{4}$$

The coefficients ε_{xx}, ε_{yy}, etc are the components of the complex dielectric tensor of a hot magnetized plasma that have the form:

$$\varepsilon_{xx} = 1 + \frac{i\sqrt{\pi}v\, e^{-\chi}}{\beta|\cos\Theta|\chi} \sum_{s=-\infty}^{\infty} s^2\, I_s\, W_s(z_s) \tag{5}$$

$$\varepsilon_{yy} = \varepsilon_{xx} - \frac{2\, i\sqrt{\pi}v\, \chi\, e^{-\chi}}{\beta|\cos\Theta|} \sum_{s=-\infty}^{\infty}(I_s' - I_s)\, W_s(z_s) \tag{6}$$

etc, where

$$v = (\omega_p/\omega)^2,\ \chi = (\beta\omega\sin\Theta/\omega_B)^2/2,\ \beta = \sqrt{2\, k_BT/(mc^2)} \tag{7}$$

ω is the radiation frequency, ω_p is the plasma frequency, ω_B is the cyclotron frequency, ν_c is the collision frequency, ν_D is the Doppler width, I_s' is the

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modified Bessel function, $I'_s = dI_s/d\chi$, and

$$W_s(z_s) = \frac{i}{\pi} \int_{-\infty}^{\infty} (z_s - t)^{-1} \exp(-t^2)dt \qquad (8)$$

$$z_s = X_s + iY_s \ , \ X_s = (\omega - s\omega_B)/\nu_D \ , \ Y_s = (\nu_c + \nu_r)/\nu_D \qquad (9)$$

$$\nu_r = 2\ \omega^2\ e^2/(3\ m\ c^3) \qquad (10)$$

III. SIMPLIFIED ANALYTIC EXPRESSIONS FOR $\mu_\pm(\Theta)$

We use the form

$$\mu^S_\pm(\Theta) = \mu^G_\pm(\Theta) + (\mu^B + \mu^T)(1 + M_\pm(\Theta)) \qquad (11)$$

where $\mu^G_\pm(\Theta)$ is the pure gyroresonance absorption coefficient (no collisions) derived by Engelamnn and Curatolo (1973) (with the corrections noted by Chanmugam 1980), the term μ^B is the inverse thermal bremsstrahlung absorption coefficient, μ^T is the Thomson scattering term and $M_\pm(\Theta)$ is our correction factor which has the form:

$$M_\pm(\Theta) = A_\pm\ (1 - \Theta/90)^{\alpha_\pm} \qquad (12)$$

where $A_\pm$ and $\alpha_\pm$ are independent of Θ. In general, $M\ (0^o) < 1$ and $M\ (90^o) = 0$.

The determination of the left side of Equation (11) is done using the expression of BC and then resolving a system of two equations and two unknowns (A, α) using two values of Θ (e.g. $\Theta = 5^o, 30^o$). Figure 3 shows the comparison between our simplified expressions for the absorption coefficients and that of BC, for three typical sets of data. One can see that there is good agreement in the range $0^o \lesssim \Theta \lesssim 85^o$.

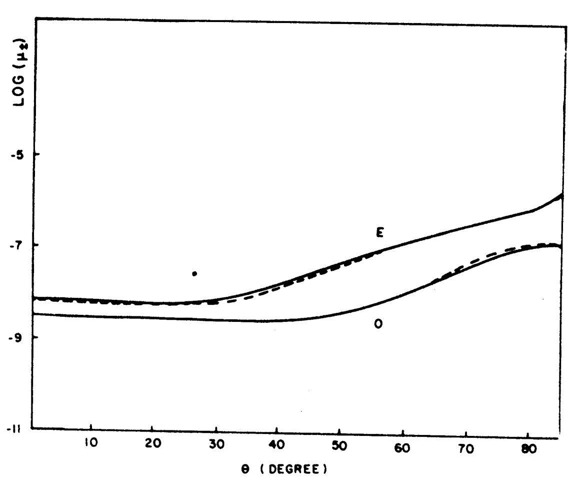

Fig. 3a

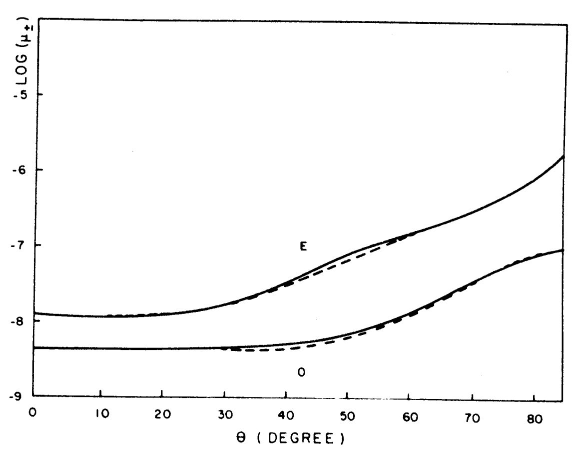

Fig. 3b

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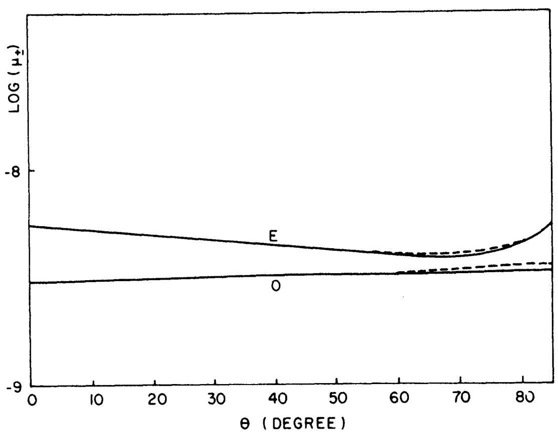

Fig. 3c

Fig. 3 - Comparison of the simplified (dashed curve) and BC (solid curve) absorption coefficients for: a) kT = 1.0 keV, B = 3.0 x 10^7 G, D(Diameter) = 10^8 cm and X = ω/ω_B = 5; b) kT = 0.2 keV, B = 3.0 x 10^7 G, D = 10^8 cm and X = 4; c) kT = 1.0 keV, B = 3.0 x 10^7 G, D = 10^8 cm and X = 7. The absorption coefficients are plotted in units of $\omega_p^2/(\omega_B c)$.

IV. POLARIZATION OF THE RADIATION FROM A CIRCULAR CYLINDER AND A FLATTENED CYLINDER

The cross section of the accretion column, making an angle Θ with the magnetic field, is an ellipse in the case of a circular cylinder and a rectangle in the case of a flattened cylinder, as one can see in Fig. 4. We assume the accretion column to be homogeneous. From Fig. 4, the intensity of the emitted radiation from the flattened cylinder is proportional to

$$\bar{I}^{\pm}_{FC}(\nu) = \frac{1}{2L} \int_{-L}^{L} (1 - \exp(-\tau^{\pm}_{\nu}(Y_f)))dx \cong 1 - \exp(-\tau^{\pm}_{\nu}) \quad (13)$$

where $\tau^{\pm}_{\nu} = \mu^{s}_{\pm}(\Theta)2R_0/\sin\Theta$, (14)

whereas the intensity of the emitted radiation from the circular cylinder is proportional to

$$\bar{I}^{\pm}_{CC}(\nu) = \frac{1}{2R_0} \int_{-R_0}^{R_0} (1 - \exp(-\tau^{\pm}_{\nu}(Y_f)))dx = 1 - \frac{1}{2} \int_0^{\pi} \sin\phi \exp(-\tau^{\pm}_{\nu}\sin\phi)\, d\phi \quad (15)$$

We define the factor $R_{\pm}$ as:

$$R_{\pm} = \int_0^{\pi} \frac{\sin\phi \exp(-\tau^{\pm}_{\nu} \sin\phi)\, d\phi}{2\exp(-\tau^{\pm}_{\nu})} \quad (16)$$

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Using the expressions for circular and linear polarizations of BC, the circular polarization of a flattened cylinder can be written as

$$CP_{FC} = \left[\frac{1 - A^2}{1 + A^2}\right]\left[\frac{\exp(-\tau_-) - \exp(-\tau_+)}{2 - \exp(-\tau_-) - \exp(-\tau_+)}\right] \quad (17)$$

and for a circular cylinder as

$$CP_{CC} = \left[\frac{1 - A^2}{1 + A^2}\right]\left[\frac{R_- \exp(-\tau_-) - R_+ \exp(-\tau_+)}{2 - R_- \exp(-\tau_-) - R_+ \exp(-\tau_+)}\right] \quad (18)$$

The linear polarization for a flattened cylinder can be written as

$$LP_{FC} = \left[\frac{2A}{1 + A^2}\right]\left[\frac{\exp(-\tau_-) - \exp(-\tau_+)}{2 - \exp(-\tau_-) - \exp(-\tau_+)}\right] \quad (19)$$

and for a circular cylinder as

$$LP_{CC} = \left[\frac{2A}{1 + A^2}\right]\left[\frac{R_- \exp(-\tau_-) - R_+ \exp(-\tau_+)}{2 - R_- \exp(-\tau_-) - R_+ \exp(-\tau_+)}\right] \quad (20)$$

where $A = t/((1 + t^2)^{1/2} - 1)$ and $t = 2\omega \cos\Theta/(\omega_B \sin^2\Theta)$ (21)

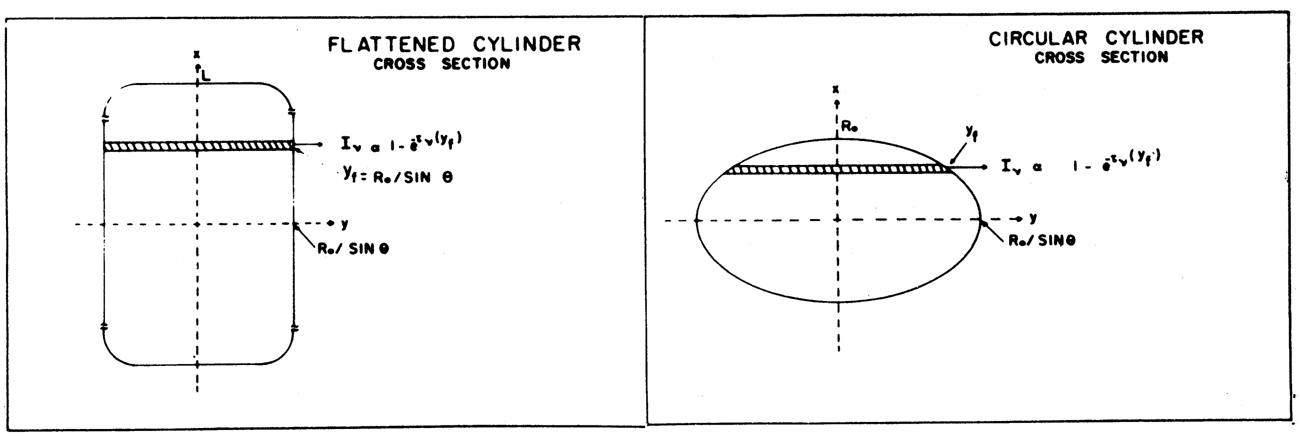

Fig. 4 The optical depth geometries and the emitted radiations from circular and flattened cylinder accretion columns.

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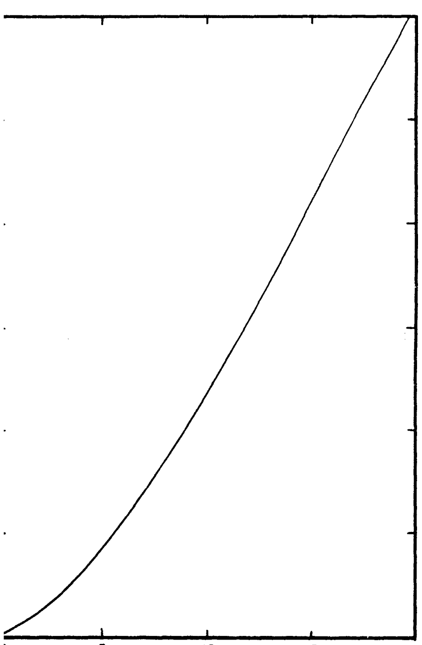
We note that the prime difference between the polarization from a ircular cylinder and from a flattened cylinder is the factor $R_{\pm} = R_{\pm}(\tau_{\pm})$. This actor is an increasing function of $\tau_{\pm}$, as one can see in Fig. 5. Examples of he above relations are given in Fig. 6. We have in Fig. 6a the circular olarization for kT = 0.2 keV, $B = 3.0 \times 10^7$ G, $X = \omega/\omega_B$ = 6 and 8, and $D/10^8$ = , 4 and 8; in Fig. 6b we have the circular polarization for kT = 1.0 keV, = 3.0×10^7 G, X = 9 and $D/10^8$ = 1, 4 and 8; and in Fig. 6c we have the inear polarization for kT = 1.0 keV, $B = 3.0 \times 10^7$ G, X = 7 and 9, and $D/10^8$ = , 4 and 8.



g. 5 Log (R) (Eq. 16) as a function of τ.

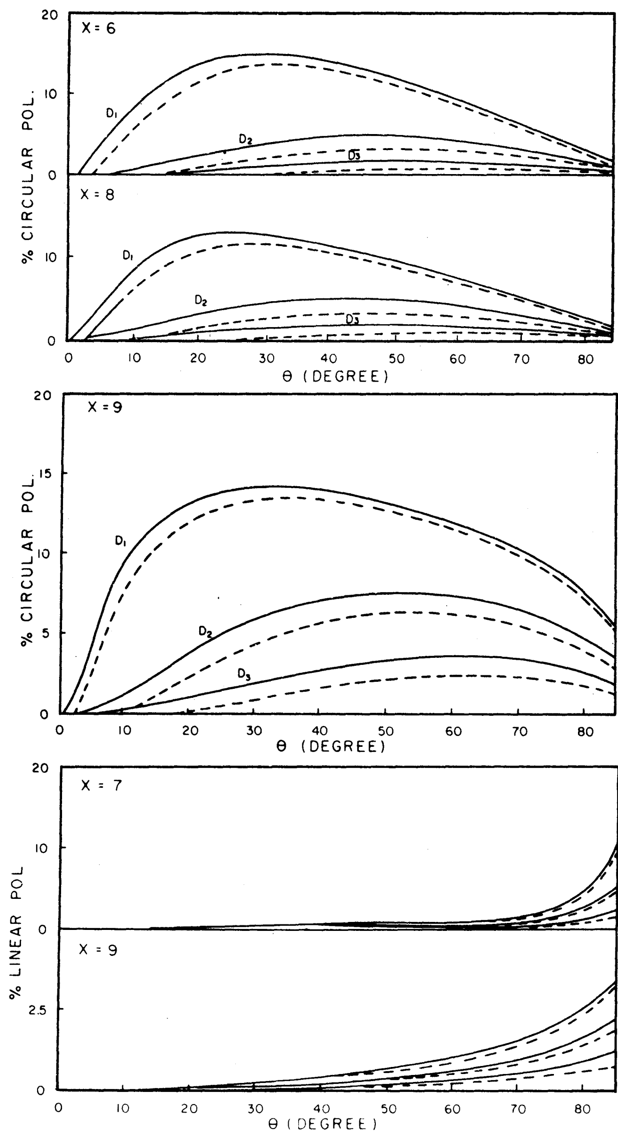


Fig. 6 Polarized radiation emitted from circular and flattened cylinder accretion columns: 6a) circular polarization for kT = 0.2 keV, $B = 3.0 \times 10^7$ G, and X = ω/ω_B = 6 and 8; 6b) circular polarization for kT = 1.0 keV, $B = 3.0 \times 10^7$ G, and X = 9, and 6c) linear polarization for kT = 1.0 keV, $B = 3.0 \times 10^7$ G, X = 7 and 9. In the figures, D_1, D_2, D_3 are equal to 1, 4, 8 x 10^8 cm, respectively. The solid curves are for circular cylinder and the dashed curves are for flattened cylinder accretion columns.

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V. CONCLUSIONS

1) The circular cylinder accretion column, in general, gives more linear and circular polarization than the flattened cylinder.

2) There is a large difference in the circular polarization between the circular cylinder and the flattened cylinder for small angles. This is due to the fact that small Θ corresponds to large τ, and large τ gives large values for R (see Fig. 5).

3) The difference between the polarizations from the circular and flattened cylinder are greater at lower frequencies.

From the above we conclude that good polarization data can determine the accretion column geometry of AM Herculis binaries.

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