

# CYCLOTRON EMISSION FROM AM HERCULIS<sup>1</sup>

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## ABSTRACT

The cyclotron absorption coefficients, in the ordinary and extraordinary modes, are calculated for the shock heated region of AM Her. The equations of radiative transfer are solved and the intensity of the emitted UV radiation determined as a function of angle. The average spectrum is shown to have deviations from the previously predicted Rayleigh-Jeans spectrum and the magnetic field of AM Her is deduced to be roughly  $5 \times 10^7$  gauss.

## INTRODUCTION

The AM Herculis binaries are believed to contain a magnetic white dwarf, accreting matter from a companion star (refs. 1-3). The polarized light observed has been interpreted as being due to cyclotron emission, at the fundamental cyclotron frequency  $\omega_c = eB/mc$ , in a magnetic field  $B \approx 2 \times 10^8$  gauss. It has been suggested that the matter accreting along the field lines forms a shock heated region (height  $h \sim 10^6$ ) cm above the magnetic pole (refs. 4,5). This region was predicted to be a source of strong optically thick cyclotron emission peaking in the ultraviolet. However, the observed flux is much weaker (ref. 6). The theoretical estimates for the self-absorbed cyclotron emission were made using the angle-averaged cyclotron absorption coefficient (refs. 4,5,7). Recent estimates (ref. 8), made using the total cyclotron absorption coefficient and taking angular effects into account, suggest that the Rayleigh-Jeans spectrum would not be filled and that as a result the UV flux would be less than was previously predicted (refs. 4,5). In this paper the absorption coefficients  $\alpha_{\pm}(\omega, \theta)$  for the ordinary (+) and extraordinary (-) modes are separately determined and the total intensity of the emitted radiation deduced as a function of frequency  $\omega$  and the angle  $\theta$  between the direction of the radiation and the magnetic field.

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## CYCLOTRON RADIATION

The cyclotron absorption coefficients  $\alpha_{\pm}(\omega, \theta)$  have been calculated, for a three-dimensional relativistic Maxwell distribution (as in ref. 8) for the electrons, by a modification (ref. 9) of methods previously used (refs. 10, 11). For the shock heated region of AM Her the Faraday rotation angle  $\psi \approx \Lambda(\omega_c/\omega)^2/2\pi$  is  $\gg 1$ , since the dimensionless parameter  $\Lambda \equiv \omega_p^2 h/\omega_c c \sim 10^6$  (see eq. (3)), where  $\omega_p$  is the plasma frequency and  $\omega/\omega_c \sim 10$ . In this case, the transfer equations for the intensities in the two modes decouple and (assuming Kirchhoff's law) take the form (ref. 10)

$$\frac{dI_{\pm}(\omega, \theta)}{dz} + \alpha_{\pm}(\omega, \theta) \cdot I_{\pm}(\omega, \theta) = \alpha_{\pm}(\omega, \theta) I_{RJ} \quad , \quad (1)$$

where  $I_{RJ} = \omega^2 kT/8\pi^3 c^2$  is the Rayleigh-Jeans intensity per polarization mode. For a homogeneous plasma, the solutions are:

$$I_{\pm} = I_{RJ} [1 - \exp(-\alpha_{\pm} L)] \quad (2)$$

where L is the path length of the radiation through the source. The total intensity is then given by  $I = I_+ + I_-$ .

## RESULTS

The shock heated region is treated as a uniform plasma slab which is perpendicular to the magnetic field so that the path length of the radiation is  $L=h/\cos \theta$ . The temperature of the slab is taken to be  $kT = 20$  keV, as may be inferred from the hard X-ray observations (ref. 12), while the dimensionless parameter  $\Lambda$  is given by (refs. 4, 8)

$$\Lambda \approx 1.6 \times 10^6 \left( \frac{M/M_{\odot}}{R/5 \times 10^8 \text{ cm}} \right)^{3/2} \frac{10^8 \text{ gauss}}{B} \quad , \quad (3)$$

where M is the mass of the white dwarf and R its radius.

The intensity of the emitted radiation is plotted as a function of  $\cos \theta$  for several harmonics in figure 1. Consider the radiation at  $\omega/\omega_c = 12$ . For  $\cos \theta \approx 0$ , the plasma is optically thick for both modes and hence the intensity is that of a black body (flat curve). For increasing values of  $\cos \theta$  the plasma first becomes optically thin in the ordinary mode (at  $\cos \theta \approx 0.2$ ) and then in the extraordinary mode (at  $\cos \theta \approx 0.4$ ) giving rise to the decrease in intensity. For lower harmonics the radiation is optically thick for a greater range of  $\cos \theta$  and conversely for higher harmonics. During an orbital cycle of AM Her, the viewing angle  $\theta$  varies.

The total flux  $F(\omega)$  from the plasma slab may be compared to the total Rayleigh-Jeans flux  $B_{RJ}(\omega)$ , if emitted as a black body:

$$\frac{F(\omega)}{B_{RJ}(\omega)} = \frac{\int_0^1 I(\cos \theta) \cos \theta d(\cos \theta)}{\int_0^1 2I_{RJ} \cos \theta d(\cos \theta)} \quad (4)$$

In figure 2,  $F(\omega)$  is plotted as a function of  $\omega/\omega_c$ , for several values of  $\Lambda$ . An important result is that  $F(\omega)$  deviates from the Rayleigh-Jeans flux for  $\omega/\omega_c \gtrsim 6$ . If the angle-averaged absorption coefficient is used the flux would follow the Rayleigh-Jeans curve up to a frequency  $\omega^*$  and be optically thin for  $\omega > \omega^*$ . The value of  $\omega^*$  is  $\approx 12 \omega_c$  for  $\Lambda = 1.0 \times 10^6$  (ref. 4). For  $\omega \gtrsim \omega^*$  also, the angle-averaged results give fluxes higher than  $F(\omega)$ : by a factor  $\approx 3$  for  $\omega \approx 14 \omega_c$  and a factor  $\approx 6$  for  $\omega/\omega_c \approx 30$ . The values of  $F(\omega)$  are in good agreement, for  $\omega/\omega_c \lesssim 12$ , with those obtained using the total cyclotron absorption coefficient (ref. 8), however for  $\omega/\omega_c \gtrsim 12$ ,  $F(\omega)$  is higher (e.g. by a factor of almost 2 for  $\Lambda = 1.0 \times 10^6$ ,  $\omega/\omega_c = 14$ ). This is because of the neglect of optically thin emission for small angles in ref. 8, an approximation which is good at low frequencies.

Raymond et al. (ref. 6) find that the UV continuum consists of a black body ( $kT = 25\text{-}30$  eV) component, which also produces the soft X-rays (ref. 13), and a flat uneclipsed component produced by the X-ray heated secondary or by the accreting gas further up the accretion column. They do not however observe the optically thick cyclotron emission from the hot ( $kT \approx 20$  keV) shock heated region which had been predicted (refs. 4,5). The smallest value for the predicted cyclotron emission consistent with the soft X-ray flux is 20 times the observed value at  $1500 \text{ \AA}$ . This discrepancy could be removed if the mass of the white dwarf ( $M \approx 0.6 M_\odot$ ) and the magnetic field ( $B \approx 3 \times 10^7$  gauss) are lower than had been previously assumed (ref. 14). If angular effects are taken into account, as in this paper, a higher field  $B \approx 5 \times 10^7$  gauss (with the same mass  $M \approx 0.6 M_\odot$ , so that  $\Lambda \approx 6.5 \times 10^5$ ) would suffice, since  $\lambda = 1500 \text{ \AA}$  would correspond to  $\omega/\omega_c \approx 14$  (figure 2).

Recent UV observations of AM Her by Tanzi et al. (ref. 15) confirm the low UV flux observed by Raymond et al. (ref. 6). The former however find that the spectrum from  $1150$  to  $3200 \text{ \AA}$  is well fitted by a power law  $F(\lambda) \propto \lambda^{-2}$ , i.e.,  $F(\omega) \approx \text{constant}$ . These observations are in better agreement with our results than those of ref. 6. The reasons for the differences in the observations are not entirely clear, but may be due to: (a) the observations not being carried out at the same time, (b) the neglect of reddening in ref. 6 and (c) the fit to the UV flux in ref. 15 being made without distinguishing between the eclipsed and uneclipsed flux or subtracting out the soft X-ray component.

In conclusion it is suggested that the magnetic field in AM Her is  $B \approx 5 \times 10^7$  gauss which is a factor of about 4 below the usually adopted value. This lower value is consistent with estimates for the field strength made in understanding the optical polarization observations (ref. 9). The UV flux from the shock heated region is predicted to deviate from the Rayleigh-Jeans spectrum.

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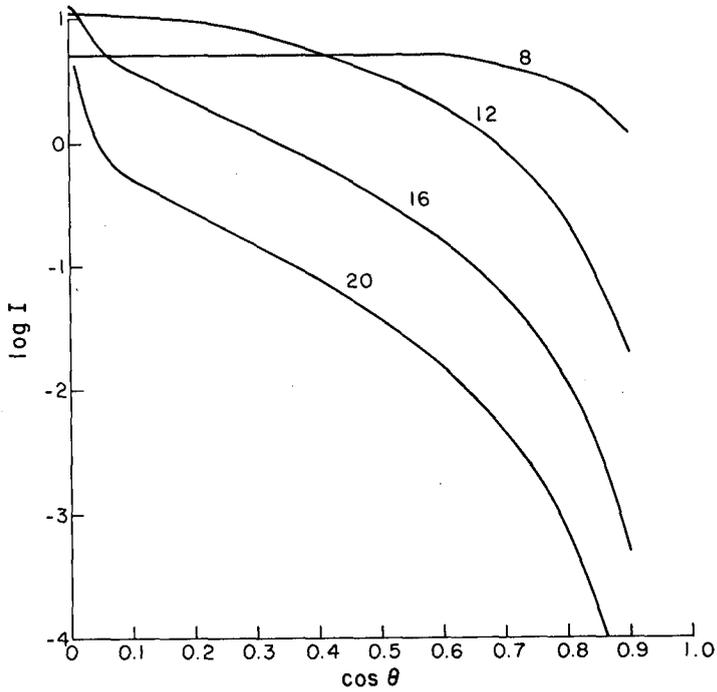


Fig. 1. Plot of the log of the intensity  $I$  vs.  $\cos \theta$  for  $\Lambda = 10^6$ ,  $h = 10^6$  cm,  $kT = 20$  keV and  $\omega/\omega_c = 8, 12, 16$  and  $20$ .

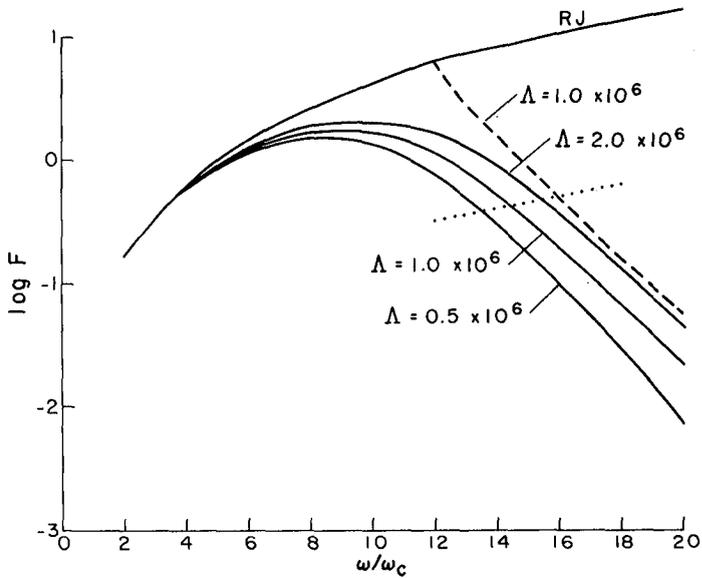


Fig. 2. Plot of the log of the flux  $F(\omega)$ , in arbitrary units, vs.  $\omega/\omega_c$  for  $kT = 20$  keV and  $\Lambda = 0.5 \times 10^6$  cm,  $1.0 \times 10^6$  cm and  $2.0 \times 10^6$  cm. The curve RJ is the Rayleigh-Jeans flux, dashed curve is due to Masters (ref. 4) while the dotted curve corresponds to 0.05 times the Rayleigh-Jeans flux (cf. ref. 6).