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THE WAVELENGTH DEPENDENCE OF LINEAR AND CIRCULAR POLARIZED RADIATION FROM THE MAGNETIC WHITE DWARF Grw+70°8247

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ABSTRACT

The wavelength dependence of linear polarization from the magnetic white dwarf Grw+70°8247 is investigated. The gray-body magnetoemissive linear polarization is corrected for radiative transfer by the use of a model white-dwarf atmosphere. The wavelength dependence found by this method does not fit the wavelength dependence of the observed linear polarization. Also the wavelength dependence of the circular polarization from Grw+70°8247 is reexamined in the light of new observations.

Subject headings: magnetic stars — polarization — stars, individual — white dwarf stars

I. INTRODUCTION

The gray-body magnetoemission theory of Kemp (1970) predicted that thermal radiation in the presence of a large magnetic field possesses a continuous circular polarization along the magnetic field direction. A search for circular polarization in white dwarfs (Kemp *et al.* 1970) revealed that the radiation from the white dwarf Grw+70°8247 was in fact circularly polarized. However, the wavelength dependence of the circular polarization did not fit that predicted by the model proposed by Kemp, which was an optically thin gray-body radiating system in the presence of a large magnetic field. Shipman (1971) showed that if one considers an optically thick gray-body radiating system, i.e., considering radiative transfer in Kemp's model, then the observed wavelength dependence of the *circular* polarization from Grw+70°8247 could be explained in the optical region. Thus we are motivated to apply Shipman's method to the *linear* polarization. We also reproduce Shipman's results for the circular polarization as a check on our program and discuss these results in the light of new observations (Angel, Landstreet, and Oke 1972).

II. THE CALCULATION OF THE LINEAR AND CIRCULAR POLARIZATIONS

The linear and the circular polarizations were calculated using a method based on the proposal (Shipman 1971) that the magnetoemission phenomenon can be considered as being produced by a difference in the continuous absorption coefficients for the different senses of the polarizations. Thus, for example, for circular polarization with the magnetic field along the line of sight we have

$$\frac{j_R - j_L}{j_R + j_L} = \frac{\kappa_R - \kappa_L}{\kappa_R + \kappa_L} = q_{\text{thin}} , \tag{1}$$

where q_{thin} is the fractional circular polarization predicted by the optically thin magnetoemission theory, j_R and j_L are the intensities of the right and left sense of the polarization, respectively and κ_R and κ_L are the continuous absorption coefficients corresponding to the right and left sense of the polarization, respectively. For the optically thick model the fractional circular polarization is obtained (Shipman 1971) as follows:

$$q = \frac{H_R - H_L}{H_R + H_L}, \tag{2}$$

where H_L and H_R refer to the left and right circularly polarized flux, respectively, obtained from a model atmosphere.

A similar analysis can be carried out for the fractional linear polarization. For this case the π-component is compared to the sum of the σ-components of the linear polarization. Thus for the optically thin case, with the magnetic field perpendicular to the line of sight, the fractional linear polarization, q^*_{thin} say, is given by

$$q^*_{\text{thin}} = \frac{\frac{1}{2}(j_{\sigma_+} + j_{\sigma_-}) - j_\pi}{\frac{1}{2}(j_{\sigma_+} + j_{\sigma_-}) + j_\pi} = \frac{\frac{1}{2}(\kappa_{\sigma_+} + \kappa_{\sigma_-}) - \kappa_\pi}{\frac{1}{2}(\kappa_{\sigma_+} + \kappa_{\sigma_-}) + \kappa_\pi}. \tag{3}$$

The factor $\frac{1}{2}$ is a normalization factor that arises as follows. The total σ-intensity j_σ is the sum of the σ_+ intensity j_{σ_+} and σ_- intensity j_{σ_-}. Chanmugam, O'Connell, and Rajagopal (1972*a*, *b*) found that for an electron oscillating in a magnetic field, the intensities of the σ-components of the radiation are

$$j_{\sigma_+} \simeq \frac{1}{\omega - \Omega}, \qquad j_{\sigma_-} \simeq \frac{1}{\omega + \Omega}, \tag{4}$$

for $\omega > 2\Omega$, where $\Omega \equiv$ Lamor frequency $= eB/2mc$. However, the total σ-intensity, j_σ, in the absence of the magnetic field ($j_{\sigma_+} + j_{\sigma_-} \simeq 2/\omega$) is equal to the total π-intensity, j_π, which was shown to be proportional to $1/\omega$. Thus the need for the normalization constant of $\frac{1}{2}$. Substituting equation (4) into equation (3), we see that

$$q^*_{\text{thin}} \simeq \tfrac{1}{2}(\Omega/\omega)^2. \tag{5}$$

To lowest order in B, equations (1) and (3) also hold at an arbitrary observing angle θ, if $B_\parallel = B \cos\theta$ and $B_\perp = B \sin\theta$, are used to calculate the magnetic-field–dependent quantities in equations (1) and (3), respectively.

For the optically thick case, the fractional linear polarization q^* is

$$q^* = \frac{\frac{1}{2}(H_{\sigma_+} - H_{\sigma_-}) - H_\pi}{\frac{1}{2}(H_{\sigma_+} + H_{\sigma_-}) - H_\pi}. \tag{6}$$

The polarized fluxes are obtained as follows. The flux at each frequency is determined once with the normal zero-magnetic-field continuous absorption coefficients and then for the continuous absorption coefficients corrected for the magnetic field. The magnetic-field–corrected continuous absorption coefficients, κ_p, can be related to the zero field coefficients, κ_0, as follows:

$$\kappa_p = \kappa_0(\kappa_p/\kappa_0) = \kappa_0(j_p/j_0), \tag{7}$$

where j_p and j_0 are the polarized and zero magnetic field intensities predicted by the various magnetoemission models. The ratios are then expanded to lowest order. The three models to be considered for the fractional linear polarization are:

Model A.—An exact harmonic oscillator model with a constant density of oscillator states (Chanmugam *et al.* 1972*a*, *b*).

Model B.—An exact harmonic oscillator model with the density of states corrected for the magnetic field (Chanmugam *et al.* 1972*a*, *b*).

Model C.—A bremsstrahlung model (Kemp 1970) correct to the first nonzero order in the magnetic field B.

Thus the continuous absorption coefficients corrected for the magnetic field for the different models of the linear polarization are

Model A:

$$\kappa_{\sigma_+} = \kappa_0\left(1 + \frac{\Omega_\perp}{\omega} + \frac{\Omega_\perp^2}{\omega^2}\right), \tag{8a}$$

$$\kappa_{\sigma_-} = \kappa_0\left(1 - \frac{\Omega_\perp}{\omega} + \frac{\Omega_\perp^2}{\omega^2}\right), \tag{8b}$$

$$\kappa_\pi = \kappa_0\,; \tag{8c}$$

Model B:

$$\kappa_{\sigma_+} = \kappa_0\left(1 + \frac{\Omega_\perp}{\omega} + \frac{3}{2}\frac{\Omega_\perp^2}{\omega^2}\right), \tag{9a}$$

$$\kappa_{\sigma_-} = \kappa_0\left(1 - \frac{\Omega_\perp}{\omega} + \frac{3}{2}\frac{\Omega_\perp^2}{\omega^2}\right), \tag{9b}$$

$$\kappa_p = \kappa_0\,; \tag{9c}$$

Model C:

$$\kappa_{\sigma_+} = \kappa_0\left(1 + \frac{8\Omega_\perp}{\omega} + 24\frac{\Omega_\perp^2}{\omega^2}\right), \tag{10a}$$

$$\kappa_{\sigma_-} = \kappa_0\left(1 - \frac{8\Omega_\perp}{\omega} + 24\frac{\Omega_\perp^2}{\omega^2}\right), \tag{10b}$$

$$\kappa_\pi = \kappa_0\,; \tag{10c}$$

where $\Omega_\perp = eB_\perp/2mc$. For the fractional circular polarization we have reproduced Shipman's results (model C). The continuous absorption coefficients used are

$$\kappa_R = \kappa_0(1 - 8\Omega_\parallel/\omega)\,, \tag{11a}$$

$$\kappa_L = \kappa_0(1 + 8\Omega_\parallel/\omega)\,, \tag{11b}$$

where $\Omega_\parallel = eB_\parallel/2mc$.

We have used the program ATLAS (Kurucz 1969) to calculate the model white-dwarf atmospheres, as did Shipman. The model atmospheres used were $T_{\text{eff}} = 12{,}000°$ K, $\log g = 8$, H = 0.9, He = 0.1, and $T_{\text{eff}} = 14{,}000°$ K, $\log g = 8$, H = 0.0, He = 1.0. Both models are in LTE and radiative equilibrium, and have solar metal content. The basis for this choice of models may be found in Shipman (1971). The magnetic fields were determined by fitting the theoretical models to the observations at a particular wavelength. For the circular polarization, the wavelength chosen was 5000 Å, whereas for model C in the linear polarization, 4300 Å, was chosen. Since models A and B could not be fitted to the observations, the choice of the magnetic field was made as follows. In the optically thin case models A and B are equivalent to model C if the magnetic field in models A and B is scaled by a factor of ~5 over that of model C. The origin of the scaling factor is apparent when we compare the values of q^*_{thin} as obtained by use of equation (3) for the different models. We have seen that for model A

$q^*_{\rm thin} \sim \frac{1}{2}(\Omega/\omega)$. Substituting equation (10) into equation (3), we see that for model C $q^*_{\rm thin} \sim 12(\Omega/\omega)^2$. Thus if the magnetic field for model A is about 5 times that of model C, the $q^*_{\rm thin}$ values would be equal. This choice of the magnetic field produces the correct magnitude of the fractional linear polarization; however, the polarization is π-like rather than σ-like. Varying the magnetic field from this value produces even poorer agreement with the observations.

III. RESULTS AND DISCUSSION

In figure 1 the wavelength dependence of the circular polarization predicted using the model atmosphere is shown. Our results confirm those of Shipman (1971) except that we obtain a magnetic field twice that of Shipman since we used the Larmor frequency (Kemp 1970) rather than the cyclotron frequency, which Shipman used. Also shown for comparison are the broad-band observations of the circular polarization (Kemp *et al.* 1970; Angel and Landstreet 1970; Angel *et al.* 1972) and the circular polarization predicted by the optically thin model of Kemp (1970). New narrow-band observations of the circular polarization (Angel *et al.* 1972) have also been made and show the same basic wavelength dependence as the new broad-band observations.

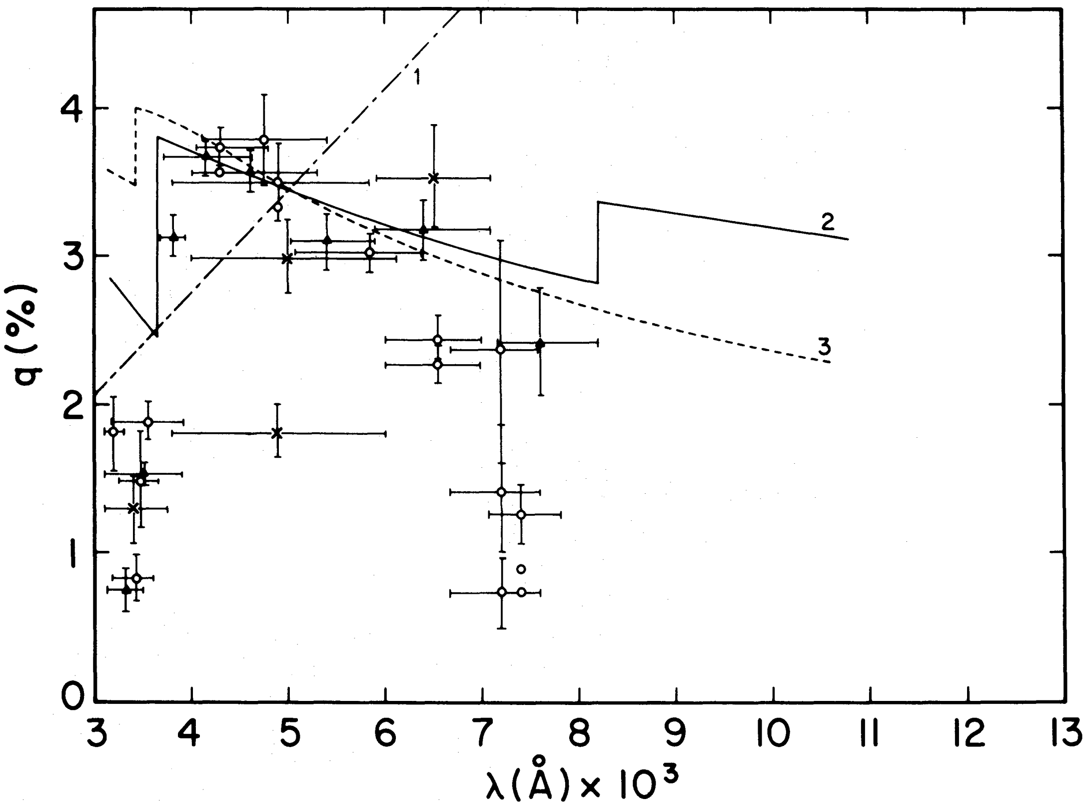

FIG. 1.—Wavelength dependence of the predicted circular polarization for the various models. Curve 1 corresponds to the optically thin model of Kemp (1970). Curve 2 corresponds to Model C with the parameters $T = 12{,}000°$ K, $\log g = 8$, H $= 0.9$, He $= 0.1$, $B = 1.2 \times 10^7$ gauss. Curve 3 corresponds to Model C with the parameters $T = 14{,}000°$ K, $\log g = 8$, H $= 0.0$, He $= 1.0$, $B = 2 \times 10^7$ gauss. The observed circular polarizations are indicated by the following: *Crosses*, Kemp *et al.* (1970); *triangles*, Angel and Landstreet (1970); *open circles*, Angel *et al.* (1972). Where observational points are clustered together, error bars were omitted from several points for clarity. The error bars of these points may be found in their corresponding references.

However, fine-scale wavelength structure, possibly due to molecules (Angel 1972), is also apparent in the narrow-band observations. Since such molecules are not incorporated in the model atmosphere program, we have not considered this fine-scale spectral structure here. Note that Shipman's results are in good agreement with the observations of Angel and Landstreet (1970) but not with those of Kemp and Swedlund (1970). The recent observations of Angel *et al.* (1972) have shown a large change in the circular polarization at wavelengths greater than 6000 Å. The reason for this change is not yet known. However, the agreement of Shipman's results for the circular polarization with these new observations is somewhat less striking than the agreement with Angel and Landstreet's 1970 observations. The decrease in the predicted circular polarization beyond 6000 Å is not large enough when compared to these new observations. Not shown in our figure 1 nor in Shipman's figure 1 are the two broad-band observational points in the infrared of Kemp and Swedlund (1970). The reason for the omission of these two points of large circular polarization (~10 percent) is that they have not been verified in recent narrow-band observations of Angel *et al.* (1972).

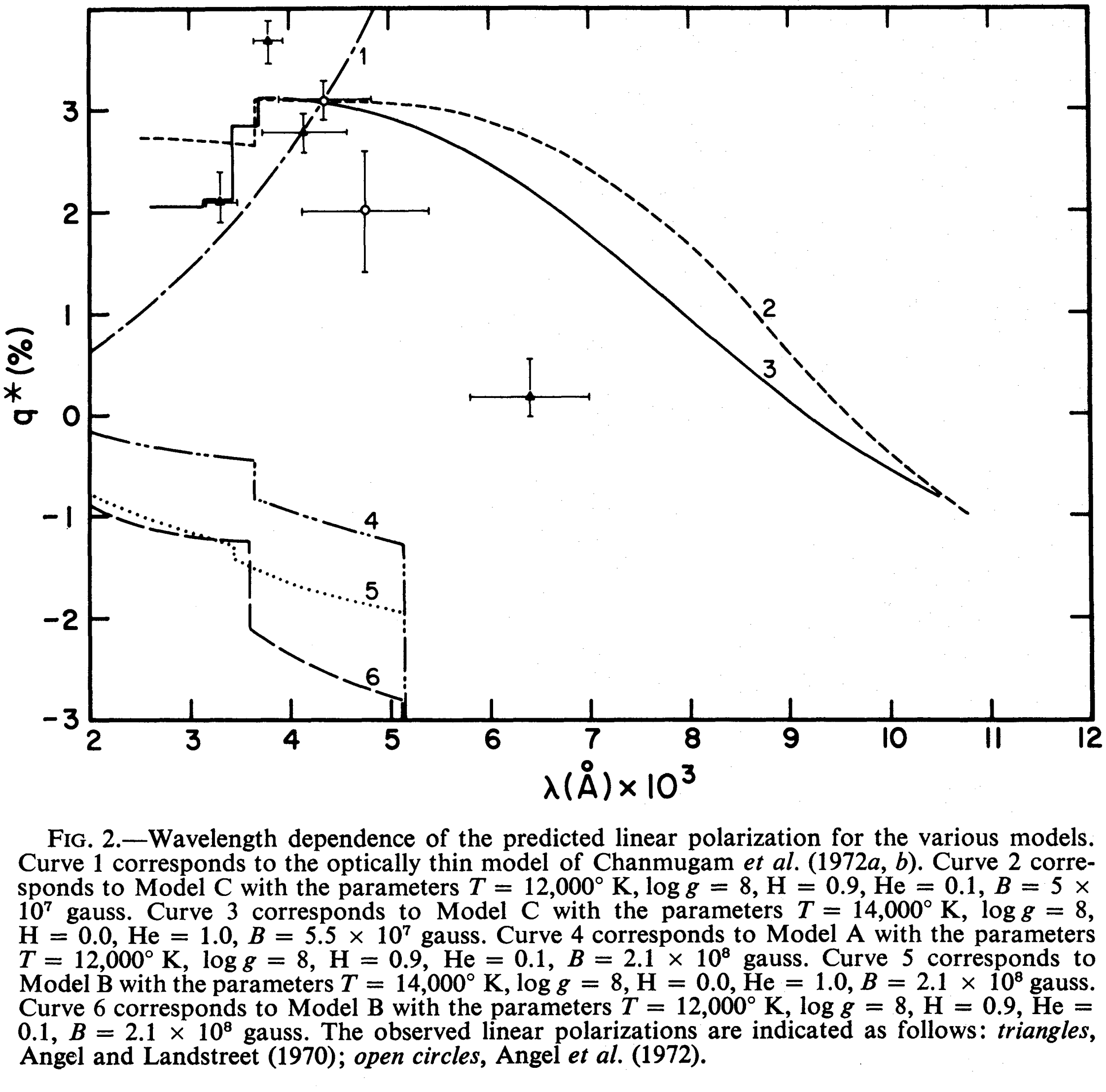

FIG. 2.—Wavelength dependence of the predicted linear polarization for the various models. Curve 1 corresponds to the optically thin model of Chanmugam *et al.* (1972*a*, *b*). Curve 2 corresponds to Model C with the parameters $T = 12{,}000°$ K, $\log g = 8$, H = 0.9, He = 0.1, $B = 5 \times 10^7$ gauss. Curve 3 corresponds to Model C with the parameters $T = 14{,}000°$ K, $\log g = 8$, H = 0.0, He = 1.0, $B = 5.5 \times 10^7$ gauss. Curve 4 corresponds to Model A with the parameters $T = 12{,}000°$ K, $\log g = 8$, H = 0.9, He = 0.1, $B = 2.1 \times 10^8$ gauss. Curve 5 corresponds to Model B with the parameters $T = 14{,}000°$ K, $\log g = 8$, H = 0.0, He = 1.0, $B = 2.1 \times 10^8$ gauss. Curve 6 corresponds to Model B with the parameters $T = 12{,}000°$ K, $\log g = 8$, H = 0.9, He = 0.1, $B = 2.1 \times 10^8$ gauss. The observed linear polarizations are indicated as follows: *triangles*, Angel and Landstreet (1970); *open circles*, Angel *et al.* (1972).

In figure 2 the wavelength dependence of the linear polarization predicted using the model atmosphere is shown for the three models. For comparison, the linear polarization predicted by the optically thin model (Chanmugam *et al.* 1972*a*) and the observations of the linear polarization (Angel and Landstreet 1970; Angel *et al.* 1972) are also shown. The observations show a general increase in the linear polarization as the wavelength is increased from 3300 Å until a maximum is reached at 3800 Å. Beyond this maximum the linear polarization decreases with wavelength as did the circular polarization. However, this decrease of the observed linear polarization is more rapid than that of the circular polarization. The optically thick models A and B give very poor agreement with the observations, being unable to even produce a σ-like linear polarization in the optical region of the spectrum. The large decrease in the linear polarization at $\lambda = 5124$ Å (corresponding to $\omega = 2\Omega_\perp$) occurs because the transition probability for the σ_+ transition is zero for $\omega < 2\Omega$ and thus there is no σ_+ component of the flux. The bremsstrahlung model (model C) for the circular polarization best fits the observations, but it suffers from the same problem as does the circular polarization in that it also fails to predict *correctly* the observed decrease in the polarization.

To summarize, we conclude that for the *linear* polarization there is a significant discrepancy between all observations and the theoretical predictions of the three models. In addition, the *circular* polarization predicted by Shipman (1971) does not agree as well with the new circular polarization observations (Angel *et al.* 1972) as it did with the older observations (Angel and Landstreet 1970). As a result, we feel that, although a radiative-transfer correction to Kemp's model does drastically change and greatly improve the correlation between the theoretical wavelength dependence of the circular and linear polarization and their observed wavelength dependence, the significant discrepancy which still remains makes it desirable to develop a new model for the polarized radiation which will discuss the behavior of atoms in magnetic fields. An approach along these lines has now been initiated (Rajagopal *et al.* 1972; Smith *et al.* 1972; Smith *et al.* 1973; O'Connell 1973*a*, *b*; Surmelian and O'Connell 1973).

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