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POLARIZATION OF THE RADIATION OF MAGNETIC STARS

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The polarization of the radiation of magnetic stars arising from the Zeeman effect cannot exceed 1%. The wavelength dependence of the polarization in the range 4152-4262 Å has been computed for ε UMa.

In 1961 Thiessen [1] reported observations of linear polarization in the magnetic variable star HD 71886. Two years later Polosukhina [2] detected a comparatively high level of linear polarization (up to 2%) in the magnetic variable star HD 215441, which has a very strong magnetic field, as high as 30 kG. Both authors considered the polarization to be associated with the magnetic field of the star, and the variations in the polarization with variations in the magnetic field.

These results were subsequently disputed by other authors [3, 4], who have claimed that there is no evidence for synchronous variations of the polarization and magnetic field. In other magnetic stars the radiation generally is very little polarized – by no more than 1%.

First of all, one should recognize that in measurements of the polarization and the magnetic field, different components of the field are in fact being measured. In the case of the magnetic field, its absolute value is measured, but in splitting comparable to the linewidth only the longitudinal field component is measured.

At any rate it is the longitudinal component that is responsible for changes in the sign of the field. Linear polarization, on the other hand, is wholly governed by the transverse field component. Thus there is no reason to believe a priori that the polarization ought to vary synchronously with the field. In particular, even with the simplest model for a magnetic star (an oblique rotator) the polarization should not vary synchronously with the magnetic field; if the axis of the rotator has certain angles of inclination to the line of sight, the polarization will exhibit very weak variations. One can conceive of other models for the magnetic structure of a star such that strong field variations will be accompanied only by very weak variations in the observed polarization, and the period of the latter variations will not coincide with the period of the longitudinal-field variations.

The question arises whether it might be at all possible for the Zeeman effect in the lines to account for a total percentage polarization of up to 2%. When observations are made over a wide spectral range, the Zeeman circular polarization will vanish but the linear polarization will maintain a finite value. The maximum linear polarization will depend on the strength of the line. In a field strong enough for the Zeeman components to be completely resolved, we will have in the case of a simple triplet

$$p \sim W_\pi(\eta_0) - 2W_\sigma(\eta_0/2). \qquad (1)$$

Here p represents the degree of linear polarization in the line; W_π and W_σ are the equivalent widths of the π and σ components, respectively; and η_0 is the ratio of the opacity at the line center to the opacity in the continuum. For weak lines the equivalent linewidth is approximately proportional to η_0, and the polarization is nearly zero. For lines located in the middle part of the curve of growth, the polarization reaches a maximum. As η_0 continues to increase, damping begins to play a role, the dependence of the equivalent width on η_0 becomes more significant again, and the polarization diminishes.

A second parameter on which the amount of polarization depends strongly is the ratio of the Zeeman splitting to the width of the line absorption: $v_H = \Delta\lambda_H/\Delta\lambda_L$. For very rough estimates we may take the polarization p in broad lines to be proportional to v_H^2. In the case of weak fields or broad lines the polarization diminishes sharply. The amount of this polarization can be calculated from any of the several available theories of line formation in an atmosphere with a magnetic field. Since our calculations are intended only as an estimate we may take the simplest theory, that of Unno [5], which was developed for lines formed through the true-absorption mechanism. Similar calculations have been performed by Leroy [6] for the sun in the wavelength range 4400-4900 Å. In view of the broad lines in the spectra of type A0 stars we would expect, according to Leroy's graphs, a polarization of $\approx 10^{-2}$ for fields of ≈ 10 kG.

Some difficulty arises in connection with the broad and deep hydrogen lines. These lines are described neither by Unno's theory nor by any of the other existing theories. However, simply because of the great width and strength of these lines we would expect in view of the remarks above that, even in the most intense magnetic fields attainable in stars, these lines would not be significantly split and accordingly would exhibit little polarization. At any rate their contribution to the polarization may be neglected when observing over a wide wavelength range.

In order to carry out some actual computations we have used a spectrum of the star ε Ursae Majoris obtained by V. M. Pavlova on May 16, 1967, with the 50-inch telescope of the Crimean Astrophysical Observatory, at a dispersion of 14 Å/mm. We have selected the region λλ 4152-4262 Å, which is free from hydrogen lines. The total polarization in this part of the spectrum has been computed from the expression

$$p = \frac{\Sigma p_L W_L}{\Delta l - \Sigma W_L}. \tag{2}$$

Here Δl is the length of the spectral region, W_L represents the equivalent width of an absorption line, and P_L is the degree of linear polarization in the absorption line. The summation extends over all lines occurring in the given spectral region.

Unno's theory gives

$$p_L = \int_{-\infty}^{\infty} \frac{\eta_Q}{(1+\eta_I)^2 - \eta_Q^2 - \eta_V^2}\, dv$$

$$\times \left(\int_{-\infty}^{\infty} \left[1 - \frac{1+\eta_I}{(1+\eta_I)^2 - \eta_Q^2 - \eta_V^2} \right] dv \right)^{-1}, \tag{3}$$

where

$$\eta_I = \frac{\eta_p}{2}\sin^2\psi + \frac{\eta_l+\eta_r}{4}(1+\cos^2\psi), \qquad \eta_r = \eta_0 e^{-(v+v_H)^2},$$

$$\eta_Q = \left(\frac{\eta_p}{2} - \frac{\eta_l+\eta_r}{4}\right)\sin^2\psi, \qquad \eta_l = \eta_0 e^{-(v-v_H)^2},$$

$$\eta_V = \frac{\eta_r-\eta_l}{2}\cos\psi, \qquad \eta_p = \eta_0 e^{-v^2},$$

$$v = \Delta\lambda/\Delta\lambda_D,\ v_H = \Delta\lambda_H/\Delta\lambda_D,\ \Delta\lambda_H = 4.67\cdot 10^{-5}\ g\lambda^2 H.$$

It is assumed here that the lines have pure Doppler profiles; ψ is the angle between the magnetic field and the line of sight. We have adopted η_0 so as to yield the observed equivalent width, we have taken the theoretical values for the Landé g factors, and the Doppler width $\Delta\lambda_D$ of the absorption coefficient has been assumed equal to 0.07 Å.

For our rough estimate we have considered that all the lines are formed in the same purely transverse field H (ψ = 90°).

Figure 1 shows the behavior of the polarization in our selected wavelength region for field strengths H = 5, 10, and 20 kG. Individual points correspond to the polarization in wavelength bands 10 Å wide. The mean values of the polarization are 0.44, 0.83, and 0.99% for fields of 5, 10, and 20 kG, respectively. The total polarization should have approximately the same value if the star is observed in integrated light.

The following conclusions may be drawn from our calculations and Fig. 1.

1. In principle the Zeeman effect can explain the observed polarization, at least for stars where the polarization (as observed) does not exceed 1%. One should recognize, however, that because of various assumptions our calculations provide only an

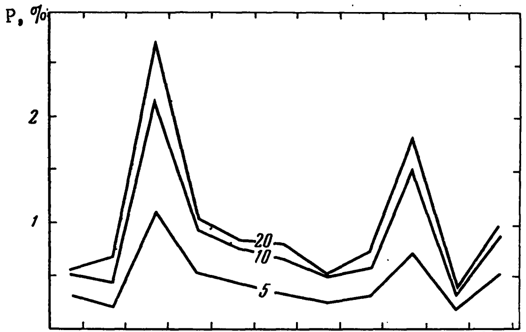

Fig. 1

upper estimate. A particularly important assumption is that the field is strictly transverse, for the degree of polarization depends strongly on the angle ψ. The polarization may also diminish sharply if the azimuth of the magnetic field varies strongly at different points of the disk.

2. The percentage polarization shows major variations along the spectrum, and at some wavelengths is two to three times its average value. Thus observations of the polarization at different wavelengths should enable one to distinguish between polarization associated with the magnetic field of the star and polarization due to interstellar absorption.

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