THE CYCLOTRON LINES IN THE OPTICAL SPECTRA OF THE STARS OF AM HERCULIS GROUP: OBSERVATIONS AND INTERPRETATION

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1. Introduction

The stars of the AM Herculis group (AM Her, VV Pup, AN UMa and 2A 0311-227) are close binaries containing a mass losing, nondegenerate star and an accreting degenerate dwarf. Their main properties are: the large linear and circular polarization of the optical light, high and low luminosity states, the variable emission line, spectra of H, He and other elements and the identification of these objects with X-ray sources. It is generally accepted that the strong magnetic field of the degenerate dwarf is responsible for these peculiar properties and for the distinction between these objects and the cataclysmic variables (Mitrofanov 1978, 1979a). The polarized optical continuum may be emitted by the accreted magnetized plasma (e.g. Chanmugam and Wagner, 1979), by the magnetized photosphere of the degenerate dwarf (Mitrofanov et al. 1977), or by both sources (Mitrofanov, 1979b). To explain the observed X-rays, Lamb and Masters (1979) showed that a magnetic field about 10^8 gs is necessary. Unfortunately, the basic prediction of their model - the strong ultraviolet continuum in the spectrum of AM Herculis - appears to be absent (Raymond et al. 1979). Chanmugam and Wagner (1979) proposed a rather different estimate for B of $2 \cdot 10^8/m^*$gs ($m^* = 5 \div 25$). For further investigations of the AM Herculis-type stars it seems useful to find a direct observational method for measuring the dwarfs' magnetic fields.

When X-ray pulsars were associated with accreting magnetized neutron stars, Gnedin and Sunyaev (1973) showed that the hot accreted plasma is a possible source of the cyclotron radiation. A spectral feature which may be interpreted as an electron cyclotron line was discovered by Trümper et al. (1977) in the hard portion (~58 kev) of X-ray spectra of Her X-1. The electron cyclotron frequency, ν_{cyc}, corresponding to the magnetic field $B \gtrsim 10^8$gs falls in the region of visual light $\nu_{cyc} = 2.81 \cdot 10^{14} \times (B/10^8\text{gs})$Hz. Consequently, the optical spectra of AM Herculis type stars may possibly contain electron cyclotron features.

In Section II the theoretical results concerning the generation of

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the cyclotron radiation are discussed. The cyclotron interpretation for the strong emission feature, λ3470, discovered by Liebert et al. (1978) in the spectrum of VVPuppis is proposed in Section III. The preliminary results of the search for cyclotron lines in the spectra of AM Herculis and MV Lyrae are considered in Sections IV and V.

II. The Cyclotron Emission from the Heated Magnetized Plasma

The electromagnetic radiation is known to propagate through the magnetized plasma as ordinary and extraordinary waves. If the wave vector $\vec{k}$ is parallel to the direction of the external magnetic field $\vec{B}$, the electric vector $\vec{E}$ of extraordinary wave rotates similarly with the Larmor precession of electrons, but the electric vector of the ordinary wave rotates in the opposite direction. Therefore, the absorption of the extraordinary wave has a resonance for $\nu = \nu_{cyc}$ and is much stronger than the absorption of the ordinary wave. In the simple case ($\vec{k} \,||\, \vec{B}$) the ordinary wave absorption has no resonance and is comparable with the absorption in a plasma without a magnetic field. In all papers known to the author which have dealt with the intensity, spectrum and polarization of the radiation emitted by the hot magnetized plasma (e.g. Fabian et al., 1976; Masters et al., 1977; Chanmugam and Wagner, 1979; Lamb and Masters, 1979) only the extraordinary wave has been taken into account. Details of the ordinary wave absorption are given by Mitrofanov et al., (1979).

In the paper by Mitrofanov et al. (1979) the case of low density and nonrelativistic plasma was considered with $\omega_p^2/\omega_{cyc}^2 << \beta$ and $kT_e/m_e c^2 << 1$. Here ω_p is the plasma frequency, β is V/c and V is the thermal velocity of electrons with the temperature T_e. The temperature T_e was taken to be sufficiently high to ensure the validity of the classical approach $kT_e/\hbar\omega_{cyc} >> 1$. The effects of both the free-free and the cyclotron absorption were included. In the presence of the strong magnetic field the effective collision frequency determining the free-free absorption depends on the mutual orientations of the external magnetic field B and the E-vector of the electromagnetic wave

$$\nu_{||,\perp} = \nu_o \frac{\Lambda_{||,\perp}}{\Lambda_o} \cdot \frac{kT_e}{\hbar\omega}\left(1 - e^{-\frac{\hbar\omega}{kT_e}}\right), \qquad (1)$$

where

$$\nu_o = \frac{4}{3}\left(\frac{2\pi}{m_e}\right)^{1/2} \cdot \frac{N_e^4}{(kT_e)^{3/2}} \cdot \Lambda_o$$

is the effective collision frequency for the plasma without magnetic field, N is the electron density and $\Lambda_{||,\perp}$ are the quantities which for $B \to 0$ become the usual Coulomb logarithm Λ_o. They may be calculated using the formulae of Pavlov and Panov (1976). The differences between $\nu_{\|}$, $\nu_{\perp}$ and ν_o are significant only for $\omega \simeq \omega_{cyc}$. But even for these frequencies the approximation

$$\nu_{\|} \sim \nu_{\perp} \sim \nu_o \simeq 4 \cdot 10^7 \Lambda_o \left(\frac{N}{10^{16}\ cm^{-3}}\right) \cdot \left(\frac{10^6}{T_e}\right)^{3/2} \ \mathrm{Hz} \tag{2}$$

is sufficiently good if the cyclotron absorption is essential.

The absorption coefficients for the each wave were calculated using the dispersion equation method. For the most interesting cases analytical expressions appear to be available. If the mean effective frequency of the electron-proton collisions ν_o is much larger than the Doppler broadening $\beta\omega_{cyc}$ of the cyclotron resonance, the known formulae obtained for the absorption coefficients (Pavlov and Shibanov, 1977) are obtained:

$$k_{1,2} \simeq \frac{\omega_p^2 \nu_{\perp}}{4\omega(\omega+\omega_{cyc})^2}\left[\frac{1}{2}(1 + \cos^2\alpha) \pm P_V\cos\alpha \mp \frac{1}{2}P_Q\sin^2\alpha\right] +$$

$$+ \frac{\omega_p^2 \nu_{\perp}}{4\omega(\omega-\omega_{cyc})^2}\left[\frac{1}{2}(1 + \cos^2\alpha) \mp \frac{1}{2}P_V\cos\alpha \mp \frac{1}{2}P_Q\sin^2\alpha\right] +$$

$$+ \frac{\omega_p^2 \nu_{\|}}{4\omega^3}\sin^2\alpha(1 \pm P_Q), \tag{3}$$

where

$$P_Q = \frac{\omega_{cyc}\sin^2\alpha}{(4\omega^2\cos^2\alpha + \omega_{cyc}^2\sin^4\alpha)^{1/2}}, \quad P_V = \frac{2\omega\cos\alpha}{(4\omega^2\cos^2\alpha + \omega_{cyc}^2\sin^4\alpha)^{1/2}}$$

In this expression the upper sign corresponds to the ordinary ($\iota = 2$) wave and α is the angle between $\vec{k}$ and $\vec{B}$. The formulae (3) are valid also in the case when $\nu_o \ll \beta\omega_{cyc}$, but $\Delta\omega = |\omega - \omega_{cyc}|$ is so large that the cyclotron absorption appears negligible or if the angle $\alpha \to 90^o$ and the linear Doppler broadening becomes so small that $\omega_{cyc}\beta\cos\alpha \ll \nu_o$.

If $\beta\omega_{cyc} \gg \nu_o$, $\omega \sim \omega_{cyc}$ and $\alpha \lesssim \frac{\pi}{2} - \arccos\frac{\nu}{\sqrt{2}\beta\omega_{cyc}}$ the cyclotron absorption is essential and the coefficients $k_{1,2}$ equal

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$$k_1 \simeq \frac{\sqrt{\pi}}{\sqrt{8}} \frac{\omega_p^2}{\omega_{cyc}^2\beta} \cdot \frac{1 + \cos^2\alpha}{2|\cos\alpha|} \cdot \mathrm{Re}W(Z); \qquad (4)$$

$$k_2 \simeq \frac{1}{2\sqrt{2\pi}} \frac{\omega_p^2}{\omega_{cyc}^2}\beta \cdot \frac{\sin^4\alpha(2 + \cos^2\alpha)^2}{|\cos\alpha|(1+ \cos^2\alpha)^3} \cdot \frac{\mathrm{Re}W(Z)}{|W(Z)|^2}, \qquad (5)$$

where

$W(Z) = e^{-z^2} \cdot (1 + \frac{2i}{\sqrt{\pi}}\int_0^z d\,x\, e^{x^2})$ is the Kramp function and $Z = \frac{\omega - \omega_{cyc}}{\sqrt{2}\omega\beta\cos\alpha}$. The expression (4) for k_1 is well known. It has the strong resonance $\sim \omega_p{}^2/\omega_{cyc}\beta$ with the width $\sim \beta\omega_{cyc}$. The expression (5) for k_2 as far as we know had not been obtained elsewhere before for the low density plasma. This coefficient has a much smaller resonance $\sim \beta\omega_p^2/\omega_{cyc}^2$ and broader width. It is clear that this resonance is significant if $\beta >> \nu_o/\omega_{cyc}$. Its magnitude is comparable with the resonance in the absorption coefficients at the second harmonic $\omega = 2\omega_{cyc}$. So, the resonant lines resulting from the ordinary wave and from the second harmonic should be emitted in similar conditions.

To illustrate our results we calculated the spectrum and polarization of the radiation from magnetized homogeneous slabs. The optical depth τ for the extraordinary wave with $\omega = \omega_{cyc}$ and $\vec{k} \parallel \vec{n}$ was used as a parameter ($\vec{n}$ is a normal to the slab's surface). Some examples are presented at the Figure 1. For $\tau \lesssim 1$ the spectrum of outcoming radiation is similar to the resonant profile of k_1. If $\tau >> 1$ but $\lesssim \beta^{-2}$ the broad cyclotron continuum due to extraordinary wave and the narrow line due to ordinary one are emitted. If $\tau >> \beta^{-2}$ and $\omega_{cyc}/\nu_o\beta$ the spectral distribution becomes Planckian. The polarization of radiation disappears when the slab becomes optically thick for ordinary waves because in this case the opposite polarization of the two waves compensate each other.

So, one comes to the conclusion that depending on the optical depth the hot magnetized plasma may radiate a cyclotron line, a broad cyclotron continuum with a narrow line or only the continuum.

III. The Possible Identification of the Emission Feature λ3470 in the VV Puppis Spectra

Although the VV Pup spectrum usually has strong H and He II emission lines, Angel et al. (1977) have observed that sometimes this star has an unusual state of steady low luminosity with no strong H and He II emission. According to a more detailed description of these observations (Liebert et al., 1978), in March and April of 1977 VV Pup was in two different states. In March the magnitude at minimum phase was small, $m_{min} \simeq 17.5$, brightening was large, $\Delta m \simeq 2.5$, and the H and

He II emission lines were strong. The average Hβ flux was about 1% of the continuum 3500-6000Å flux. In April the minimum light was approximately the same, but brightening was small, $\Delta m \simeq 0.5$, and the spectra had no strong H and He II emission (Hβ flux did not exceed 0.02% of the 3500-6000 Å continuum). Liebert et al. (1978) found a strong unidentified emission line near 3470 Å which was statistically significant in spectra obtained both by a single-channel prism scanner of the Steward 2.3 m telescope and by a Kitt Peak 4 m intensified image-dissector scanner. This feature corresponded to an energy flux of about 5-10% of the 3500-6000 Å continuum, i.e. it was very strong. When VV Pup was in the active state (March 1977), we can conclude from Liebert's data (1978) that the emission feature λ3470 was absent.

It seems possible to interpret the strong emission feature λ3470 as a cyclotron line (Mitrofanov, 1979). The magnitude of a magnetic field B corresponding to the wavelength of this line is equal to $3.1 \cdot 10^8$gs. The accuracy of this determination depends on the spectral width of the feature, and the error may be estimated to be $\Delta B = B \cdot \Delta\lambda/\lambda = 10^7$gs.

In April 1977, the continuum source in the 3500-6000 A band was accepted to be the degenerated dwarf's surface with a temperature of about 9000 K (Liebert et al. 1979). The distance of VV Pup is estimated to be about 100 pc. Thus in the state of steady low luminosity $L_{cont} \simeq 10^{30}$ erg/s and $L_{cyc} \simeq 10^{29}$erg/s. It seems natural to assume that the cyclotron continuum was absent and nearly the total gravitational energy released was radiated in the cyclotron line. To provide for the observed L_{cyc}, a weak accretion at a rate of $\sim 10^{12}$g/s $(M_{dwarf}/M_\odot) \cdot (5\ 10^8\text{cm}/R_{dwarf})$ is necessary. The radius of the Alfven surface appears to be much larger than the distance between the VV Pup components. This means that the dwarf's magnetic field at every point determines the dynamics of the transferring plasma. Assuming a dipole field configuration, one can estimate the area S of the dwarfs surface where the accretion occurs. If the radius of the outflowing region on the nondegenerate component is of the order of its radius $2\ \ 10^{10}$ cm and the distance between the dwarf and the outflowing region is about $2.5 \cdot 10^{10}$cm, then $S \simeq 5 \cdot 10^{15}\text{cm}^2$. The hypothesized cyclotron line should arise in the plasma slab heated by the stand-off shock above this area. The electron temperature may be estimated from the condition that the linewidth of λ3470 is not smaller than Doppler broadening $\Delta\lambda/\lambda \simeq 4 \cdot 10^{-2}$. Hence $V \simeq 6 \cdot 10^8$cm/s and $T_e \lesssim 10^6$.

Taking into account the absence of cyclotron continuum one should assume that the heated plasma is optically thick relative to the cyclotron absorption of the extraordinary wave. This condition is satisfied $\tau_1 = 2\omega_{cyc}k_1 d/c \lesssim 1$ if $\langle Nd\rangle \lesssim 10^{15}\text{cm}^2$, where $\langle Nd\rangle$ is the mean product of the electron concentration N and the thickness d of the slab. An increase in the accretion rate leads to an increase in the temperature and density of the heated region. The optical depth τ_1 becomes >> 1 and as a result the cyclotron continuum is emitted. The periodic brightening of VV Pup in the active state is thought to be associated with this continuum. Similarly, increased accretion results in the strong H and He II emission. Thus one may predict

Table 1

Spectral lines	Mean FWHM	Maximal FWHM	Mean equivalent width	Maximal equivalent width	$\frac{\overline{W}}{\overline{W}(4686)}$	$\frac{W_{max}}{W_{max}(4686)}$	$\frac{W^{(1}}{W(4686)}$	$\frac{W^{(2}}{W(4686)}$
He II 4686	13.2	16.5	22.9	35				
He II 4199			0.3	0.6	0.013	0.017	0.007	0.006
He II 4541.6			1.0				0.017	0.010
? 4550	20.3	39.4	4.6	11	0.20	0.30		
H_β	17.1	20.4						

1) in accordance with the Tables of Atomic Spectral Lines

2) in accordance with the theoretical estimations; the local thermal equilibrium and $kT \gg H\nu$ are assumed (ν is the frequency of spectral lines)

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an anticorrelation between the periodic brightening and the strong H and He II emission on the one hand and the presence of the cyclotron line on the other.

For equilibrium between the pressure of the infalling plasma $\dot{M}V_{ff}/2S$ and the thermal pressure inside the hot region $2NkT_e$ it is necessary to have $N \simeq 10^{14}cm^{-3}$ for $T_e \simeq 10^6$. Therefore, d should be about 10 cm. The plasma heated by the standoff shock has to provide the observed luminosity of the cyclotron line

$$L_{cyc} \simeq \frac{B^2}{4\pi}\delta_T\beta^2 cS\langle Nd\rangle \simeq 10^{14}\langle Nd\rangle\left(\frac{B}{3\cdot 10^8 gs}\right)^2 \cdot \left(\frac{T_e}{10^6}\right) \cdot \left(\frac{S}{5\cdot 10^{15}cm^2}\right)\frac{ergs}{s} \qquad (6)$$

where δ_T is the Thomson cross-section of the electron. The value of L_{cyc} estimated from (6) agrees with the observed luminosity $\sim 10^{29}$ergs/s if <Nd> is just the same, i.e. $\sim 10^{15}cm^{-2}$. Some part of the energy emitted in the cyclotron line should be absorbed by the surface of the degenerate dwarf giving rise to a hot spot with the luminosity $L_{sp} \lesssim 10^{29}$ergs/s.

IV. The Possible Cyclotron Line in the Optical Spectra of AM Herculis

The observations of AM Her-type stars were carried out by the A.F. Ioffe Physical Technical Institute, the Special Astrophysical Observatory and the Crimea Astrophysical Observatory. The spectroscopy was performed at the 6-m telescope. The apparatus and the first results were described by Burenkov and Voikhanskaya (1979) and we will discuss only several (about 60) spectra (Figure 2) obtained in 7-8 of July, 1978. Besides the usual emission lines of H (from Hβ to H_{14}), He, C, N, etc., some of the spectra also have strong and broad emission features at 4550 A accompanied by absorption at 4610A. The equivalent width W and the spectral profile of λ4550 depends on the phase of the orbital period. The phases were calculated in accordance with elements used by Priedhorsky et al. (1978). The magnitude of W is very small << 1 Å and the wavelength of the features is rather indeterminate at the phases 0.85-1.0. At the other phases W appears to be much larger ~ (5 ÷ 10) Å. We shall discuss below the interpretation of the feature λ 4550 only at phases for which its equivalent width is sufficiently large.

A large number of atoms and ions (N I, Fe II, Ne I etc.) have weak spectral lines near 4550 Å. Nevertheless they may be rejected because the stronger lines of the same spectral series of these atoms and ions are absent in the observed spectra. The nearest possible atomic line seems to be He II 4541.6. For the identification of λ4550 with this line one should assume that it has the regular red Doppler shift ~8 Å which corresponds $V_{||} \simeq 500$ km/s. This velocity is comparable with the amplitude of the observed velocity curve of He II 4686 (Greenstein et al., 1977), but this curve is quite symmetrical with approximately equal positive and negative shifts. So, it seems difficult to identify λ4550 with He II 4542. Other arguments against this identification are given below.

The full width at half-maxima (FWHM) of λ4550 is approximately twice the FWHM of the strongest line λ4686 of He II. The ratios of the line strengths W(4550)/W(He II 4686) and W(4550)/W(HeII 4199) are approximately an order of magnitude larger than the estimated ratios W(He II 4542)/W(He II 4686) and W(He II 4542)/W(He II 4199). The line strength of λ4550 appears to be much larger than the possible strength of the line He II 4542. The equivalent widths of the all H and He lines depend on the orbital phase and their variations are well correlate with each other. The variation of λ4550 does not correlate with any of them. Finally, one should take into account that the spectral feature λ4550 lies approximately at the spectral boundary ~4500 Å between the polarized red and nonpolarized blue light (Kruzewski 1977).

So, the spectral feature λ4550 is essentially distinguished from the other atomic lines and it may be interpreted as an electron cyclotron line (Voikhanskaya and Mitrofanov, 1979). It seems to be emitted by the heated slab of the magnetized plasma above the surface of the degenerate dwarf. The absorption feature λ4610 is likely to be due to cyclotron absorption in the higher and colder regions of the accretion column with a smaller magnetic field. The wavelength and the linewidth correspond to a magnetic field $B = (2.3 \pm 0.1) \cdot 10^8$ gs in the emitting region, i.e. near the pole of the magnetic degenerate dwarf.

In contrast to VV Puppis the cyclotron line and the polarized cyclotron continuum seem to be present in the optical spectra of AM Herculis. This is possible (see Section II) if the optical depth τ_1 of the plasma slab for the extraordinary wave is >> 1 and for the ordinary wave $\tau_2 \sim \tau_1 \beta^2 \lesssim 1$. The electron temperature T_e and the parameter β may be estimated from the condition that the Doppler broadening is smaller than the mean observed linewidth of λ4550-4610. They appear to be $\beta \lesssim 10^{-2}$ and $T_e \lesssim 3 \cdot 10^5$. If the observed cyclotron line was emitted almost perpendicularly to the magnetic field the linewidth is proportional to $\beta^2 \omega_{cyc}$. In this case β and T_e may be as much as $\sim 3 \cdot 10^{-2}$ and $\sim 10^6$, respectively. The parameter <Nd> of the emitting region is estimated about $10^{18} \div 10^{19}$ cm^{-2}.

V. The Possible Broad Cyclotron Feature in the Spectrum of MV Lyrae

The novalike star MV Lyrae is a possible member of the AM Herculis group (Voikhanskaya et al., 1978). The variable linear and circular polarization of its light achieved ~1.5% and ~4%, respectively. In the spectrum of MV Lyr Greenstein (1954) reported broad hydrogen and faint λ4471 He I emission lines. Current observations indicate that these lines have very variable strengths and profiles (Voikhanskaya 1979).

Among all spectra of MV Lyrae obtained in 1977-78 two large groups were picked out. The spectra of the first group had strong emission

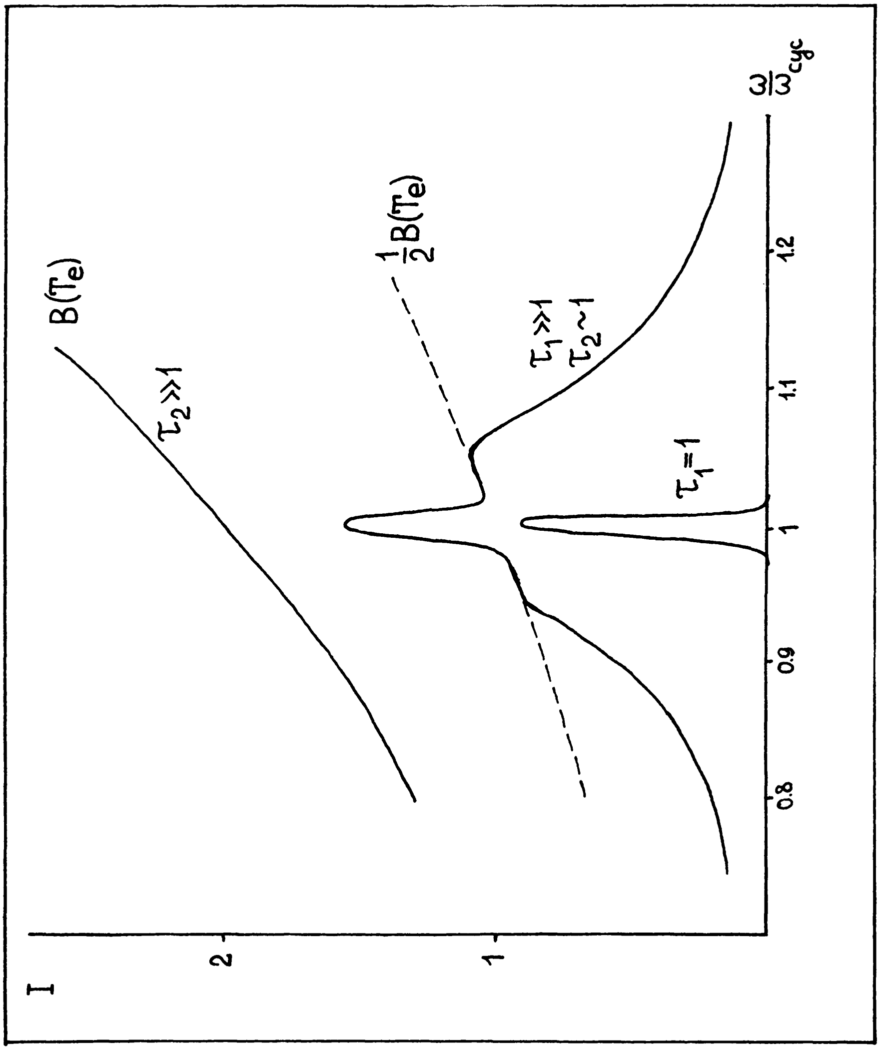

Fig. 1. The spectrum of radiation from a magnetized homogeneous slab with $\vec{n} \| \vec{B}$, $kT_e/\hbar\omega_{cyc} = 5$, $\beta = 0.01$, $\nu_o/\omega_{cyc} = 10^{-4}$ and $\alpha = 60^o$; $B(T_e)$ is the Planck function.

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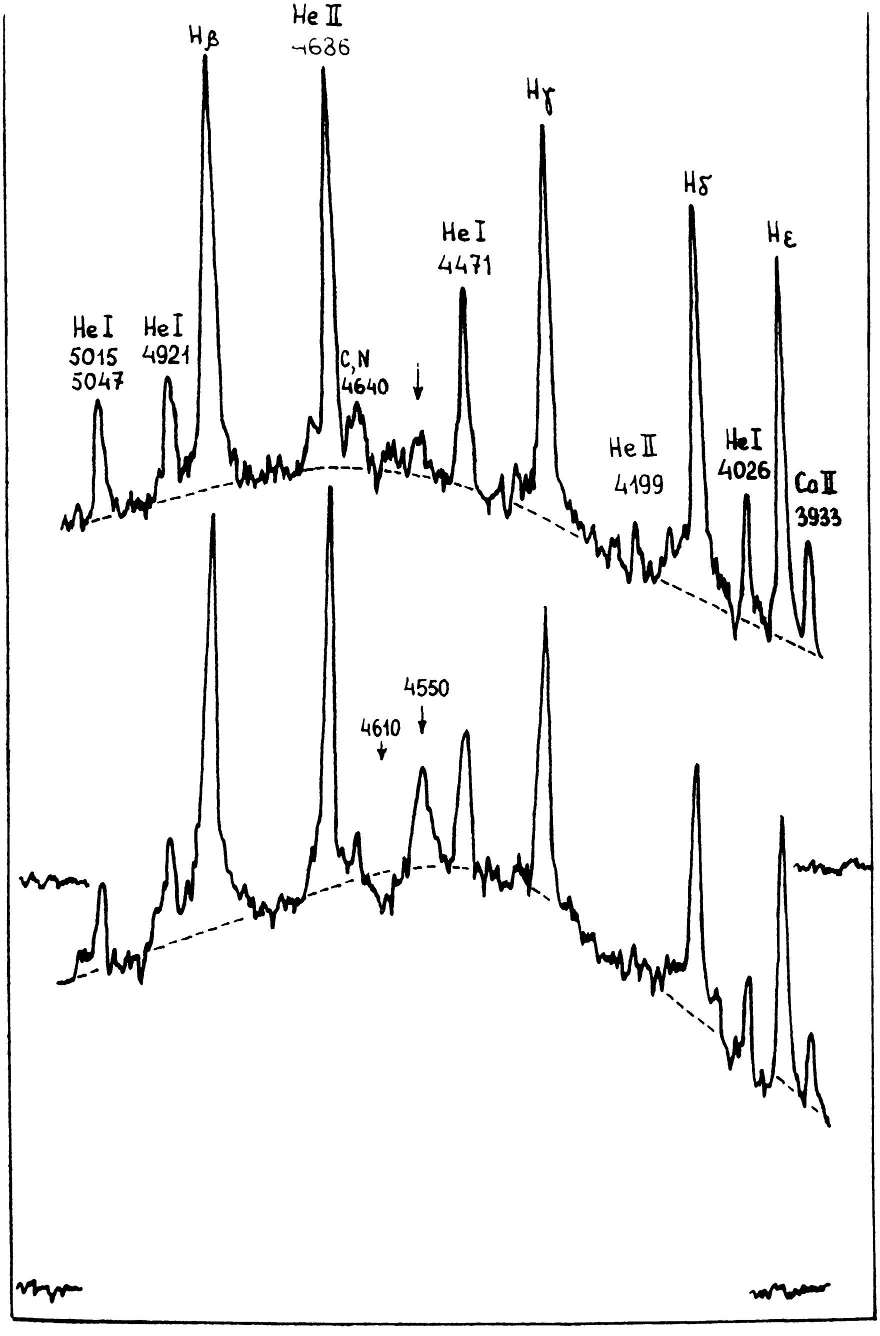

Fig. 2. Two spectra of AM Herculis obtained on June 7/8, 1978. Dashed are the continua. Noise levels are indicated at left and right.

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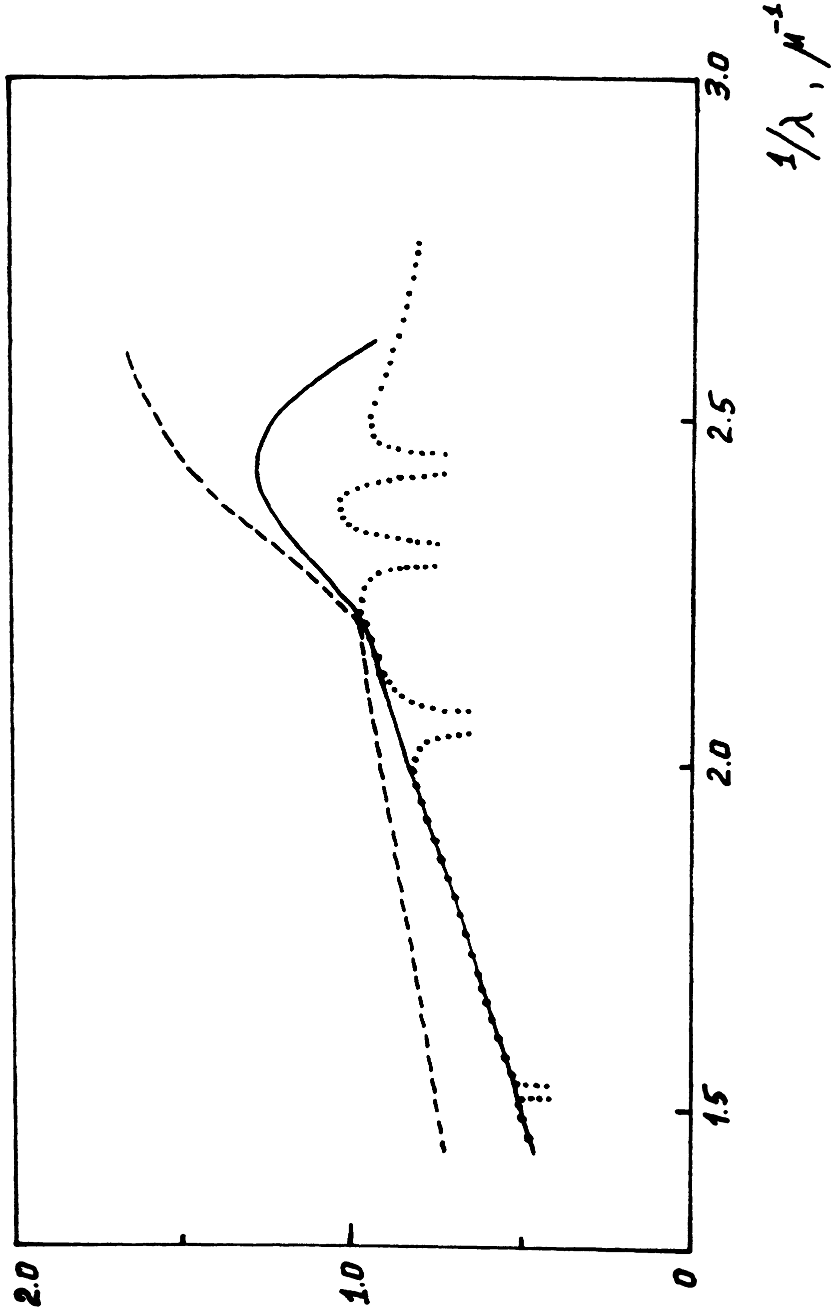

Fig. 3. The generalized spectra of MV Lyrae at the states with strong hydrogen lines (dashed) and without them. The dotted line represents the model spectrum of a DA dwarf.

lines and the second one contained spectra without any noticeable emission lines. In Figure 3 the solid and dashed lines correspond to the generalized spectra from the second and first groups, respectively. In the state with strong lines the spectrum of MV Lyrae has a significant excess in the ultraviolet region. In the state without atomic emission lines the spectrum of MV Lyrae fits with the model spectrum of DA-dwarf ($T_{eff} \simeq 2 \cdot 10^4$) (Voikhanskaya, 1979) but with two distinctions: the absence of the absorption hydrogen lines and the presence of the broad emission feature λ4200 which has an equivalent width ~140 Å and a FWHM of about 450 Å.

It seems natural to suppose that this feature is also the electron cyclotron line (Voikhanskaya and Mitrofanov, 1979). Using the line-width one can estimate the electron temperature to be ~10^6. The corresponding magnetic field is about $(2.6 \pm 0.2) \cdot 10^8$ gs.

MV Lyrae is known to be a spectral binary with a period ~2^h (Walker, 1968). It undergoes irregular light variations up to 0.4 mag in the ultraviolet band. As the wavelength increases the amplitude decreases. The characteristic time scale of the light variations is $2\text{-}5^{min}$. Walker (1954) supposed the light increases to be due to the brightening of the some parts of the dwarf's surface, i.e. due to the origin of a number of hot spots. The peculiarity of MV Lyrae may result from the nonstationary regime of the accretion into the strong magnetic field of the degenerate dwarf. The variable and multicomponent profiles of the emission lines indicate that the plasma is accreted as separated drops. Every falling drop heats a local region onto the dwarf's surface and a bright spot appears. This may lead to the irregular variations of light and polarization and to the broadening of the cyclotron line.

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