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Faraday rotation and polarization of light scattered in magnetized stellar wind

N.A. Silant'ev[1], **Yu.N. Gnedin**[2], **and T.Sh. Krymski**[2]

[1] Instituto Nacional de Astrofísica, Óptica y Electrónica, Apartado Postal 51 y 216, Z.P. 72000, Pue., México (silant@inaoep.mx)
[2] Main Astronomical Observatory of Russian Academy of Sciences, 196140, St. Petersburg, Russia

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Abstract. We consider the single scattering of nonpolarized radiation of central star on the electrons of plasma outflow (stellar wind). We assume that such stellar wind is magnetized. It is shown that the scattered radiation acquires the integral linear polarization due to nonhomogeneous distribution of the Faraday rotation angles even for spherical stellar winds. For nonspherical winds, Faraday's rotation changes the spectrum of integral polarization drastically compared with the nonmagnetized case. The numerical calculations of the polarization spectra are presented for Parker's spherical model of magnetized stellar wind. Such spectra allow us to estimate the values of magnetic field and electron number density in stellar winds.

Key words: polarization – scattering – stars: mass-loss – stars: magnetic fields

1. Introduction

There is much observational data about the existence of stellar winds and envelopes for stars of very different types (see for example, Hartmann 1983; Willis 1991; Owocki 1994; Schulte-Ladbeck 1995; Babel 1995; Paatz & Camenzind 1996). The main parameters which are determined from observations are the terminal velocity v_∞ and the mass-loss rate $\dot{M}$. The value of v_∞ may be very large, for example, $v_\infty \approx (1-3)10^3$ km s^{-1} for some O-stars (Chlebowski & Garmany 1991). Mass-loss rate $\dot{M}$ changes in very vast limits. Thus, for stars type A and B $\dot{M} \leq 10^{-16} M_\odot$ yr^{-1} (Babel 1995); for T Tauri stars $\dot{M} \sim 10^{-9} M_\odot$ yr^{-1} (Paatz & Camenzind 1996); for the Herbig Ae/Be stars with $M \leq 2.6 M_\odot$ one observes $\dot{M} \sim 10^{-8} M_\odot$ yr^{-1} (Böhm & Catala 1995). Some red giants have extremely large outflow $\dot{M} \sim (10^{-5} - 10^{-4}) M_\odot$ yr^{-1} (Jiang & Huang 1997).

To determine estimations of magnetic field in stars and theirs winds is considerably more difficult than to estimate the fact of the mass outflow. Magnetic fields may be estimated from the observation of Zeemann's splitting of spectral lines (see for example, Giampapa & Worden 1983; Landstreet 1992; and Stenflo 1994) and by observation of circular polarization of light (Mathys 1995a,b). For hot stars and winds these methods are rarely available due to difficulties with the choice of the spectral lines needed. For this reason, full data about the magnetic field have been obtained for Ap stars (Mathys 1995a,b; Leroy 1995; Wade et al. 1996). One of the largest values of magnetic field B=17500 G is found for the star HD 47103 (Babel et al. 1995).

Theoretical investigations of stellar winds were first published by Parker (1958), in which the hydrodynamic theory of outflow was developed. The theory of stellar winds for O and B supergiants was proposed by Lucy & Solomon (1970). The driving mechanism in this theory is the radiative pressure as a result of continuum radiation absorption in some spectral lines. Later, this theory was improved by Castor et al. (1975) (see also, Owocki & Rybicki 1984,1991 and Cassinelli 1991). Gradually, the stellar wind theories were improved to take into account the dynamic influence of magnetic and centrifugal forces, and the compressibility of the gas (see, Böhm & Catala 1995; and Lovelace et al. 1991). These investigations have shown that the structure of stellar winds depends strongly on the particular conditions at the stellar surface and near the star (see, Lamers & Cassinelli 1999).

The anisotropy of the stellar wind outflow gives rise to the existence of integral polarization of radiation scattered by wind's particles. Usually, one considers this polarization as a result of single scattering of unpolarized light of the central star on free electrons of the wind, i.e. one supposes that the wind is hot, as, for example, is the solar wind. The general formulae for integral polarization of light scattered in nonspherical envelopes are given in Gnedin et al. (1973), Dolginov & Silant'ev (1974), and in Brown & McLean (1977). It should be noted that the observed integral polarization also includes the polarization from the central star if it has nonspherical atmosphere or nonhomogeneous distribution of the surface temperature. The estimations of polarization for these cases are presented in Gnedin & Silant'ev (1976), and Gnedin et al. (1976). The data about intrinsic polarization of star's light are very numerous (see, for example, Leroy 1995; Bagnulo et al. 1995; Mathys 1995a,b; Drissen & Robert 1992; Schulte-Ladbeck et al. 1992).

The observation of the light polarization gives additional information about the conditions at stellar surface and its environment, particularly, about the anisotropy of the scattering particles distribution in stellar winds and envelopes. The existence

Send offprint requests to: N.A. Silant'ev of magnetic fields gives rise to the anisotropy of the extinction and propagation of light even in spherical atmospheres and envelopes. If magnetic field is not extremely large ($B < 10^5 G$), the optical anisotropy is determined only by the action of Faraday's rotation of the polarization plane. The angle of the Faraday rotation ψ may be written in the form (Gnedin & Silant'ev 1997):

$$\psi(\mathbf{n},\mathbf{B}) = \frac{1}{2}\delta\tau\cos\Theta,$$

$$\delta = \frac{3\lambda}{4\pi r_e}\cdot\frac{\omega_B}{\omega} \simeq 0.8\lambda^2(\mu m)B(G), \quad (1)$$

where $\mathbf{n}$ is the direction of wave propagation, Θ is the angle between $\mathbf{n}$ and magnetic field $\mathbf{B}$, τ is the Thomson optical length ($\tau = N_e\sigma_{Th}l$), N_e is the density number of free electrons, l is the geometric path, $\sigma_{Th} = 8\pi r_e^2/3$ is the Thomson cross-section, $r_e = e^2/mc^2 \approx 2.82\cdot 10^{-13} cm$ is classic radius of electron, $\omega_B = \mid e \mid \cdot B/mc$ is the cyclotron frequency, $\omega = 2\pi c/\lambda = kc$ is cyclic frequency of radiation ($\omega_B/\omega \cong 0.93\cdot 10^{-8}\lambda(\mu m)B(G)$).

It is seen from Eq. (1), that the angle of Faraday's rotation is sufficiently large even for small magnetic fields $B \geq 10G$, if the optical depth τ is not extremely small. For $\psi \geq 2\pi$ the integral radiation being the sum of radiations with very different Faraday's rotations, becomes depolarized.

The integral polarization from the surfaces of some type stars with dipole magnetic field was calculated by Silant'ev (1993). It was shown that the spectra of polarization $p(\lambda)$ have a peak-like form with a maximum near wavelength $\lambda \sim 1\mu m$ and value $p_{\max} \leq 0.05\%$. The polarization practically disappears for the surface magnetic fields $B > 100G$ due to the Faraday depolarization. The small values of $p_{\max}$ may be explained by multiple scattering of photons in optically thick photospheres and by small value of the scattering extinction as compared with the absorption one. In this paper the models of photospheres were taken from the paper Kurucz et al. (1974).

In the case of optically thin stellar winds and envelopes one may expect that $p_{\max}$ will be considerably greater because here depolarizing action of the multiple scattering is absent. First calculations of integral linear polarization from optically thin spherical envelopes with the dipole magnetic field were made by Gnedin & Silant'ev (1984). The form of $p(\lambda)$ was also peak-like with the maximum at $\delta_{equator}\tau_{envelope} \sim 1$, where $\delta_{equator}$ is determined by magnetic field at star's equator. The values $p_{\max}$ reach some per cents at $\tau_{envelope} = 0.5$. Here the region of magnetic field values, corresponding to sufficiently large polarization, is more vast than that for the case of optically thick photospheres. The characteristic form of the polarization spectrum $p(\lambda)$ allows us to estimate the value of magnetic field when other usual methods are invalid.

The goal of the present paper is to demonstrate that for the stellar magnetized winds the Faraday rotation also gives rise to considerable integral polarization. This polarization, depending on the number density of electrons and the magnetic field distribution in the wind, allows us to check the particular forms of stellar wind models. The existence of an azimuthal component of magnetic field, which is the characteristic feature of magnetized stellar winds, changes even asymptotic behavior of $p(\lambda)$ as compared with simple dipole model of magnetic field in stellar envelopes.

The particular calculations of integral polarization of radiation, presented in the paper, are concerned with the most simple, spherical stellar wind model of Parker (1958). For such a model only the existence of the magnetic field gives rise to integral linear polarization. Thus, we study the influence of the Faraday rotation in its pure form.

For anisotropic stellar winds the Faraday rotation changes the form of spectrum $p(\lambda)$ in such a way that for small characteristic angles of rotation the polarization may be greater or smaller than the value, calculated without taking into account the influence of magnetic field, depending on the particular geometry of field. However, for the case of large characteristic angles of rotation, the value $p(\lambda)$ always tends to zero. The asymptotic form of $p(\lambda)$ for this case characterizes the electron number density and magnetic field geometry far from the central star.

The statement of the problem and simple general formulae are available for calculation of the spectrum of integral polarization $p(\lambda)$ and the inclination angle χ of the polarization plane for any optically thin stellar winds, if the distributions of the electron number density $N_e(\mathbf{r})$ and the magnetic field $\mathbf{B}(\mathbf{r})$ are known.

2. Basic formulae

For the calculation of integral linear polarization of the radiation single scattered by the electrons of stellar wind we use the general formulae (see Gnedin & Silant'ev 1984, 1997) for observed radiative flux F_I and corresponding Stokes parameters F_Q and F_U:

$$F_I(\mathbf{n}) = \frac{L}{4\pi R^2}\cdot\frac{3\sigma_{Th}}{16\pi}\int dV\frac{N_e(\mathbf{r})}{r^2}(1+\cos^2\vartheta), \quad (2)$$

$$F_Q(\mathbf{n}) = -\frac{L}{4\pi R^2}\cdot\frac{3\sigma_{Th}}{16\pi}\int dV\frac{N_e(\mathbf{r})}{r^2}\sin^2\vartheta\cos 2(\varphi+\psi), \quad (3)$$

$$F_U(\mathbf{n}) = -\frac{L}{4\pi R^2}\cdot\frac{3\sigma_{Th}}{16\pi}\int dV\frac{N_e(\mathbf{r})}{r^2}\sin^2\vartheta\sin 2(\varphi+\psi). \quad (4)$$

Here, L(erg s^{-1}Hz^{-1}) is the luminosity of the central star, R is the distance from the star to the telescope, the angles ϑ and φ determine the direction of the radius-vector $\mathbf{r}(r,\vartheta,\varphi)$ (see Fig. 1), σ_{Th} is the Thomson cross-section, $N_e(\mathbf{r})$ is the electron number density in the wind; the direction of the light propagation $\mathbf{n}$ coincides with the z-axis. The Faraday rotation angle $\psi(\mathbf{r},\mathbf{n})$ is determined, according to (1), by the integration along the line of sight from the initial point **r** - the place of the radiation scattering:

$$\psi(\mathbf{r},\mathbf{n}) = 0.4\sigma_{Th}\lambda^2(\mu m)\int dl N_e(\mathbf{r}')\mathbf{n}\mathbf{B} \quad (5)$$

One can conclude from Fig. 1 that at the line of sight $\varphi = \varphi'$ and $r\sin\vartheta = r'\sin\vartheta'$. This gives the relation $dl =$

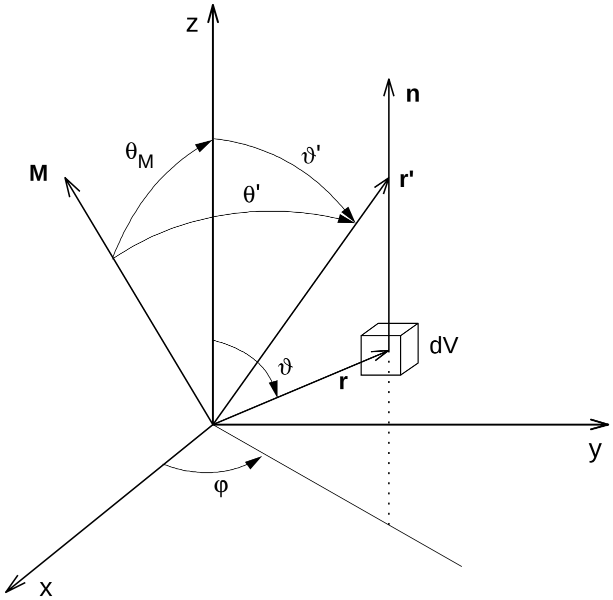

Fig. 1. Scheme of the single scattering of nonpolarized radiation from central star in magnetized stellar wind. Detailed description of the scheme is given in the text.

$d\vartheta r\sin\vartheta/(\sin\vartheta')^2$. The vector $\mathbf{r}'$ runs along the line of sight $\mathbf{n}$. Remember also, that the value F_Q(erg s^{-1}cm^{-2}Hz^{-1}) is equal to the difference of linearly polarized fluxes $F_x - F_y$, and analogously $F_U = F_{x'} - F_{y'}$, where the axes x' and y' are received from x and y by the positive (right-hand screw) rotation at the angle of $45°$.

We have assumed in (2)-(4) that the central star is a point-like source of nonpolarized radiation. This approximation is valid practically for distances $r \geq 2R_s$ (Dolginov et al. 1995). Here R_s is the radius of the star. Besides, it should be noted that near the star surface the polarized component of scattered radiation is small, since the incident photons have very different directions of propagation inside the solid angles of about 2π sterad (the isotropic part of intensity $I(\mu) \approx I_0 + I_1\mu$ does not give any contribution to polarized scattered component, and the anisotropic part $I_1\mu$ gives the polarized radiation which is proportional to $\sin^2\vartheta \equiv 1-\mu^2$, but is 6 times smaller then its contribution to nonpolarized part of scattered light). Below we shall see that for large values of the Faraday rotation angle ψ the integral linear polarization is determined mostly by those parts of stellar wind, which are located far from the star (in these regions the Faraday depolarization of light is smaller than that near the star). So, for these remote regions our assumption that the star is point-like source of radiation is indeed a valid. For the case of small characteristic angles of Faraday's rotation this assumption leads to some overestimated values of integral polarization.

The basic value by calculation of integral polarization is the Faraday angle of rotation $\psi(\mathbf{r},\mathbf{n})$. Here we describe more detailed expression for this value. The symmetry properties of magnetic field $\mathbf{B}(\mathbf{r})$ may be described most simply in some spherical frame of reference, characterized by the unit vectors $\mathbf{e}_r, \mathbf{e}_\vartheta^{(M)}$ and $\mathbf{e}_\varphi^{(M)}$, with z-axis along some physically distinguished vector $\mathbf{M}$ (the magnetic dipole moment, etc.). Without any restrictions we can assume that the vector $\mathbf{M}$ lies in the plane (z,x), as is shown in Fig. 1. Using the representation $\mathbf{B}(\mathbf{r}) = B_r\mathbf{e}_r + B_\vartheta\mathbf{e}_\vartheta^{(M)} + B_\varphi\mathbf{e}_\varphi^{(M)}$, one can write:

$$\psi(\mathbf{r},\mathbf{n}) = 0.4\sigma_{Th}\lambda^2(\mu m)\int\limits_0^{\vartheta} d\vartheta' \frac{r\sin\vartheta}{(\sin\vartheta')^2} N_e(\mathbf{r}')\Big[B_r(\mathbf{r}')\cos\vartheta'$$

$$+B_\varphi(\mathbf{r}')\frac{\sin\theta_M}{\sin\theta'}\sin\vartheta'\sin\varphi + B_\vartheta(\mathbf{r}')\frac{\cos\theta'\cos\vartheta' - \cos\theta_M}{\sin\theta'}\Big]. \quad (6)$$

Here, θ_M is the angle between $\mathbf{M}$ and z-axis, θ' is the angle between current radius-vector $\mathbf{r}'$ and $\mathbf{M}$ ($\cos\theta' = \cos\vartheta'\cos\theta_M + \sin\vartheta'\sin\theta_M\cos\varphi$; remember, that $\varphi' = \varphi$ along the line of sight).

The direct radiative flux from the star $L/4\pi R^2 \gg F_I$ and one can assume

$$p(\lambda) = \sqrt{F_Q^2 + F_U^2}\cdot\left(\frac{L}{4\pi R^2} + F_I\right)^{-1}$$

$$\cong \sqrt{F_Q^2 + F_U^2}\cdot\left(\frac{L}{4\pi R^2}\right)^{-1}. \quad (7)$$

The angle of inclination of the polarization plane χ is determined from the relation: $\tan 2\chi = F_U/F_Q$.

All the above formulae are general. In the absence of magnetic field they describe the integral polarization of scattered radiation from stellar envelopes and winds and coincide with the formulae of Dolginov & Silant'ev (1974), and Brown & McLean (1977) (note, that in the latter paper, in the basic formula (23), factor 2 is omitted).

It is of interest to consider in more detailed the case of small angles of Faraday's rotation $\psi \ll 1$. In this case formulae (3) and (4) gives:

$$F_Q(\mathbf{n}) = -\frac{L}{4\pi R^2}\cdot\frac{3}{16\pi}\sigma_{Th}\int\limits_{R_s}^{\infty} dr\int\limits_0^{\vartheta_1} d\vartheta\sin^3\vartheta\int\limits_0^{2\pi} d\varphi N_e(\mathbf{r})\times$$

$$\left[\cos 2\varphi - 2\psi\sin 2\varphi - 2\psi^2\cos 2\varphi\right], \quad (8)$$

$$F_U(\mathbf{n}) = -\frac{L}{4\pi R^2}\cdot\frac{3}{16\pi}\sigma_{Th}\int\limits_{R_s}^{\infty} dr\int\limits_0^{\vartheta_1} d\vartheta\sin^3\vartheta\int\limits_0^{2\pi} d\varphi N_e(\mathbf{r})\times$$

$$\left[\sin 2\varphi + 2\psi\cos 2\varphi - 2\psi^2\sin 2\varphi\right]. \quad (9)$$

Here, $\vartheta_1 = \pi - \arcsin(R_s/r)$ excludes from the integration the invisible part of the wind.

The terms without ψ and ψ^2 describe integral polarization of light scattered in nonmagnetized stellar envelopes and winds. For spherical envelopes and winds ($N_e(\mathbf{r}) = N_e(r)$) integral polarization does not exist. For envelopes and winds possessing some axial symmetry the plane of integral polarization lies either in the plane "the symmerty axis-line of sight" or is perpendicular to this plane.

The existence of magnetic field makes the situation more complicated. Generally, the linear term with $\psi \sim \lambda^2$ always gives the contribution and the spectrum of polarization $p(\lambda) \sim \lambda^2$ for $\psi \ll 1$. However, sometimes, due to special symmetry of the problem, only the terms with ψ^2 give the contribution, and $p(\lambda) \sim \lambda^4$. Sometimes, the λ-region of the asymptotic $p(\lambda) \sim \lambda^2$ is very narrow and one must to consider the contribution of terms with ψ^2.

3. Calculations in the frame of simplified Parker's model

To demonstrate, that the Faraday rotation really changes the spectra of integral polarization $p(\lambda)$ from stellar winds, is sufficient to perform the calculations for the most simple model of stellar wind. This is, without doubt, Parker's model (Parker 1958), where $N_e(\mathbf{r}) = N_e(r)$ is assumed, i.e. the stellar outflow is spherical. We shall use the simplified Parker's model, when magnetic dipole field is carried away directly from the stellar surface $r = R_s$. By this assumption, the Parker formulae give

$$B_r = B_0 \left(\frac{R_s}{r}\right)^2 \cos\theta,$$

$$B_\varphi = B_0 \left(\frac{\Omega R_s}{v_\infty}\right) \left(\frac{r}{R_s} - 1\right) \left(\frac{R_s}{r}\right)^2 \cos\theta \sin\theta,$$

$$B_\vartheta = 0. \tag{10}$$

Here, B_0 is the surface polar magnetic field ($\theta = 0$), Ω is cyclic angular velocity of the star, v_∞ is terminal velocity of the stellar wind, θ is the angle between the dipole axis $\mathbf{M}$ and the radius-vector $\mathbf{r}$. Assuming $N_e(r) = N_0(R_s/r)^2$, one can receive from (6):

$$\psi(\mathbf{r}, \mathbf{n}) = \psi_r + \psi_\varphi, \tag{11}$$

$$\psi_r = 0.05\lambda^2(\mu m)\tau \frac{B_0}{\rho^3 \sin^3\vartheta} \left[\left(\vartheta - \frac{\sin 4\vartheta}{4}\right)\cos\theta_M + 2\sin\theta_M \sin^4\vartheta \cos\varphi\right], \tag{12}$$

$$\psi_\varphi = 0.4\lambda^2(\mu m)\tau \frac{C_0 \sin\theta_M \sin\varphi}{\rho^3 \sin^3\vartheta} \left[\left(\frac{\rho}{3} - \frac{1}{4}\right)\cos\theta_M \sin^4\vartheta + \rho \sin\theta_M \sin\vartheta \cos\varphi \left(\frac{\cos^3\vartheta}{3} - \cos\vartheta + \frac{2}{3}\right) - \sin\theta_M \cos\varphi \left(\frac{3\vartheta}{8} - \frac{\sin 2\vartheta}{4} + \frac{\sin 4\vartheta}{32}\right)\right]. \tag{13}$$

Here, $\rho = r/R_s$ is a dimensionless distance from star's centre, $\tau = N_0 \sigma_{Th} R_s$ is the Thomson optical thickness of stellar wind, $C_0 = B_0(\Omega R_s/v_\infty)$ is parameter characterizing the azimuthal magnetic field.

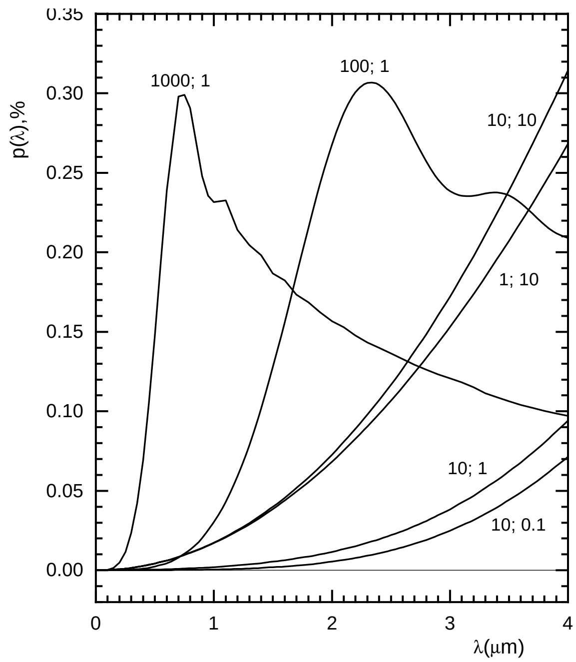

Fig. 2. The spectrum of integral linear polarization of the radiation scattered in magnetized stellar wind (Parker's model of spherical outflow with dipole stellar magnetic field). The Thomson optical depth of the wind is equal to $\tau = 0.05$; the axis of magnetic dipole $\mathbf{M}$ is perpendicular to the line of sight $\mathbf{n}$ ($\theta_M = 90°$). The numbers near the curves denote the values of magnetic field parameters B_0 and C_0, correspondingly.

The particular forms of ψ_r and ψ_φ give rise, according to (8) and (9), to the following asymptotic expansions for F_Q and F_U at $\psi \ll 1$:

$$F_Q = \frac{L}{4\pi R^2}\left[0.006846\lambda^2(\mu m) C_0 \tau^2 \sin^2\theta_M + 0.000238\lambda^4(\mu m) B_0^2 \tau^3 \sin^2\theta_M - 0.000099\lambda^4(\mu m) C_0^2 \tau^3 \sin^2\theta_M \cos^2\theta_M\right] \tag{14}$$

$$F_U = \frac{L}{4\pi R^2}\left[0.00072\lambda^4(\mu m) B_0 C_0 \tau^3 \sin^2\theta_M \cos\theta_M\right]. \tag{15}$$

It is seen that asymptotic spectrum $p(\lambda) \sim \lambda^2$ for $\psi \ll 1$ and this is solely due to existence of the azimuthal component B_φ of magnetic field in the stellar wind. So we see that even asymptotic behavior of polarization spectrum gives us very important qualitative information about the magnetic field. For the envelopes with pure dipole magnetic field (Gnedin & Silant'ev 1984) the azimuthal component is absent and one has $p(\lambda) \sim \lambda^4$ for $\psi \ll 1$. However, for $C_0 \ll B_0$ the asymptotic expansion $p(\lambda) \sim \lambda^2$ has very narrow region of validity and transforms, by increasing of λ, to the expression $\sim \lambda^4$. The asymptotic expressions are valid for $0.05\lambda^2(\mu m)\tau B_0 \ll 1$ and $0.4\lambda^2(\mu m)\tau C_0 \ll 1$. In the $\lambda-$region, where $F_Q \sim \tau^2\lambda^2$, one can neglect by $F_U \sim \tau^3\lambda^4 \ll F_Q$ meaning that the polarization plane is parallel to the plane $(\mathbf{M}, \mathbf{n})$.

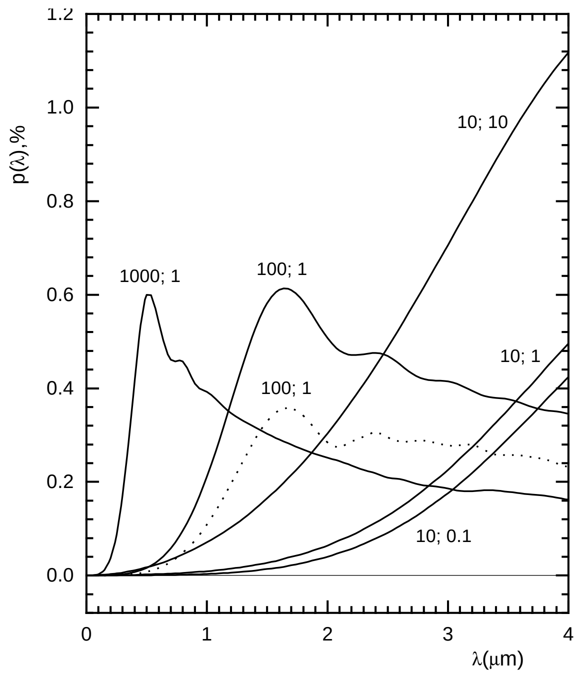

Fig. 3. The same as in Fig. 2., but for the case $\tau = 0.1$. The dotted curve represents the case $\theta_M = 45°$.

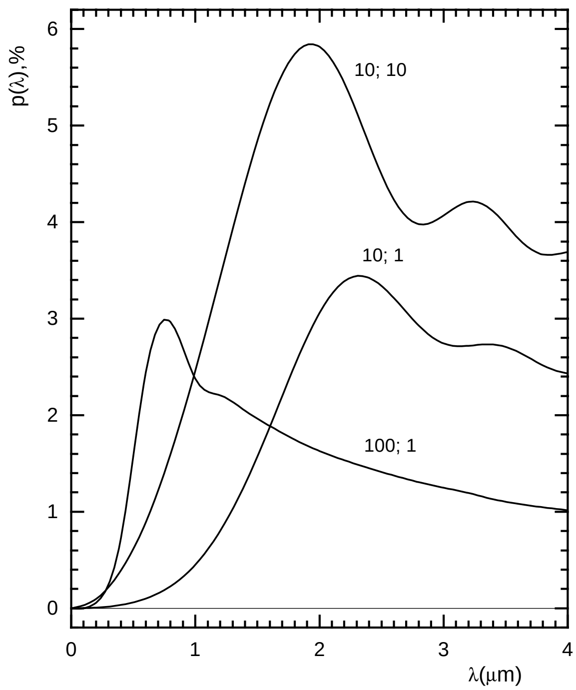

Fig. 4. The same as in Fig. 2., but for the case $\tau = 0.5$.

Some results of numerical calculations of the polarization spectra $p(\lambda)\%$ for various values of parameters τ, B_0, C_0 and θ_M are presented in Figs. 2, 3, and 4. It is seen that all the spectra have the asymptotic behavior for small wave length, first as $\sim \lambda^2$ and then $\sim \lambda^4$. The polarization maximum takes place when the sum of the Faraday rotation angles $\psi_r + \psi_\varphi$ acquires the value $\approx \pi$ ($\lambda^2(\mu m)[0.1B_0 + 0.4C_0]\tau \approx \pi$). Further, by increasing of the angle ψ, polarization decreases. First, this decreasing has some oscillating character, corresponding to characteristic values $2\pi, 3\pi, 4\pi$ for the Faraday angle of rotation. Very complicated form of functions ψ_r and ψ_φ do not allow us to receive any general asymptotic expansion for $p(\lambda)$ in the case of large characteristic Faraday's angles, $\psi \gg 1$. The estimations of integrals for the case $\lambda^2(\mu m)\tau B_0 \gg 1$ lead to estimations of the type:

$$F_Q \approx C_1 \left(\frac{\tau}{\lambda B_0^2}\right)^{2/3} \left(1 + C_2 \frac{\sin(a\lambda^2 B_0 \tau - \pi/4)}{(a\lambda^2 B_0 \tau)^{7/6}}\right), \quad (16)$$

where the values C_1, C_2 and a weakly depend on the ratio C_0/B_0. The asymptotic dependence $p(\lambda) \sim \lambda^{-2/3}$ occurs for comparatively large values of λ. In our figures, only the cases $B_0 = 1000$ and 100 at $C_0 = 1$ show the approach to this asymptotic law.

It is seen from expressions (12) and (13) for ψ_r and ψ_φ, that the case of very large angles of Faraday's rotation $\psi \gg 1$ first occurs for small values of the distance $\rho = r/R_s \geq 1$(here we take into account that for small ϑ the polarization of scattered radiation is small). Far from the star, $\rho \gg 1$, the Faraday rotation angles, as before, can be small. This means, that the asymptotic law $p(\lambda) \sim \lambda^{-2/3}$ is determined by the contribution of remote acts of the photon scattering. The structure of stellar winds and its magnetic field is known mostly just for far distances from the central star as it is in Parker's model. So, the observation of the polarization spectra, corresponding to asymptotic behaviour at $\psi \gg 1$, allow us to receive the additional information about the distant parts of stellar winds.

Of course, the asymptotic form of $p(\lambda)$ for $\psi \gg 1$ depends strongly on particuar forms of the distributions of $N_e(\mathbf{r})$ and $\mathbf{B}(\mathbf{r})$ in remote regions of stellar wind. It can serve, for these reasons, as an additional way for the estimation of these characteristics of stellar winds.

4. Conclusion

There are many types of stellar winds. Many of them present the plasma outflow from the stars and take away the frozen magnetic field. The single scattering of nonpolarized star's light in optically thin winds gives rise to partially linearly polarized scattered radiation. If the stellar wind is not spherical, then scattered radiation integrally is also polarized. In magnetized winds the scattered radiation, by its propagation in the wind, undergoes the action of the Faraday rotation of the polarization plane. For every light ray the Faraday rotation does not change the degree of polarization. However, integral polarization, being the sum of such rays with very different Faraday's rotations of the polarization plane, acquires the new features of its polarization spectrum as compared with the case of nonmagnetized wind. The flat spectrum of single Thomson scattered radiation transforms to peak-like spectrum with $p_{\max}(\lambda)$ corresponding to the characteristic value of the Faraday rotation angle $\psi \approx \pi$. For large values of ψ the polarization spectrum $p(\lambda)$ tends to zero. The asymptotic expansion of $p(\lambda)$ for $\psi \gg 1$ depends on the magnetic field and number density of electrons in the remote parts of the wind. All the features of polarization spectrum $p(\lambda)$ can serve to receive the estimations of the magnetic field and the number density values for magnetized stellar winds.

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