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Magnetic Fields of Stars with Strong Outflows: Testing by Polarimetry

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Abstract. We have developed the method that allows to estimate the magnetic field strengths of stars with strong outflows. The magnetic fields of these objects are estimated in the context of a theory that includes the Faraday rotation of the polarization plane on the mean free path of a photon in the outflow (stellar wind). As a result we have determined the optical thickness and strengths of radial and toroidal stellar magnetic fields.

1 Introduction

Many stars with magnetic fields are sources of both thermal and non–thermal emission. Thermal radiation is the free–free emission from thermal electrons in the ionized stellar outflow–wind (Loo et al., 2006). It is well known that all hot stars have winds, and they are all expected to have thermal emission. A significant fraction of hot stars also emits non–thermal radiation, which is generally explained as attributed to synchrotron emission from relativistic electrons. It means that these stars have magnetic fields.

Wright & Barlow (1975) developed an elegant formalism for thermal radio emission from hot stars. They assumed isothermal, spherically symmetric outflow and showed that the expected flux is in the form $F_\nu \sim \nu^\alpha$, where the spectral index $\alpha = 0.6$. It allows a star's mass–loss rate to be derived from its thermal radio flux.

The basic goal of this paper is to demonstrate that the polarization of stellar radiation produced by scattering in the stellar wind allows also to derive a star's mass–loss rate. We show that the scattered radiation acquires integral linear polarization due to non–homogeneous distribution of Faraday rotation angles even for the spherical stellar wind. Therefore, the appearance of broadband linear polarization is a signature of stellar wind outflows of early type–O and B stars, including the He–strong B_p stars.

Recently, Smith & Groote (2001) have provided the detailed analysis of spectral lines to determine conditions in the co–rotating plasma clouds, attached to rotating magnetic B stars. They used ultraviolet lines, obtained with the IUE satellite. For these purposes, they have chosen the four stars: σ Ori E, HD 184927, β Cep and HD 6684, which are rotating, magnetic He–strong stars with magnetic wind properties.

Their basic goals were: (a) to estimate the physical parameters of the attached clouds, including temperature, density, extent, metallicity and turbulence; (b) to study the surface chemical composition; (c) to examine the processes, responsible for resonance line emission, etc.

It is commonly accepted that He–strong B_p stars are a separate subclass of early–type B stars with special properties, basic among which are their oblique dipolar magnetic fields, magnetically controlled winds, and chemical surface anomalies (see, for instance, Bohlender et al., 1987; Bohlender, 1994; Bolton, 1994; Shore et al., 1990; Shore and Brown, 1990). These properties provided the demonstration of several peculiarities in the UV spectrum of these stars that can be explained by the circumstellar clouds, forced into co–rotation over the magnetic equator (Groote & Hunger, 1997).

Smith & Groote (2001) have made a more detailed analysis of the UV spectral lines of these He–strong stars, and investigated accurately the behaviour of the blue–wing absorption from winds in these lines. Firstly, they have found that the variations of the UV and probably optical lines are due to absorption in the cloud that has a torus–like shape. Secondly, they have remarked that the blue wings of the Si III, Si IV and C IV resonance lines remain constant with rotational phase for all the program stars. The last fact means that the wind originates not only from the magnetic pole surface but also in the equatorial region (probably, the so–called exo–magnetospheric wind from the outer edge of the torus, Groote & Hunger, 1997). Their numerical analysis of line strength variations indicates that the cloud line component forms in an extended environment with column density of roughly $10^{23}\,\mathrm{cm}^{-2}$. Another important conclusion they made claims that at least a part of emission originates from the wind–cloud interface.

Smith & Groote (2001) claim that the conditions of the environment of He–strong stars provide a rich test bed for the study of magnetic and hydrodynamical processes in these stars.

The basic goal of our paper is to demonstrate the possibilities of a new tool for investigations of the above mentioned conditions. We believe that polarimetric observations of these stars in the continuum and in the lines can provide new important information on wind and cloud properties in the environment of these stars.

One can find the following three basic sources of the intrinsic polarization with slightly various mechanisms of its generation.

Firstly, it is the star itself. The continuum radiation of a magnetic star can be polarized due to the effect of magnetic intensification (Leroy, 1990; Huovelin, 1990; Gnedin & Natsvlishvili, 2000). Broadband linear polarization (BLP) can appear as a result of the transverse Zeeman effect of spectral lines (so–called, π–components). Leroy (1990) and Huovelin (1990) have developed a theory of broadband linear polarization of magnetic star radiation via overlapping the magnetically–broadened spectral lines. In this case the net polarization is a consequence of a different amount of saturation in orthogonally–polarized π and σ components of spectral lines. The wavelength variation of this effect is an important feature allowing one to distinguish magnetic intensification from other polarizing mechanisms.

The following results were obtained from various models of BLP. Wavelength dependence varies with spectral type and luminosity. Sharp features can be found in the spectral slopes in different spectral intervals. These features can be observed in late spectral type stars (see Huovelin, 1990; Gnedin & Natsvlishvili, 2000). A common feature of the behaviour of a polarization curve is a rise of net polarization to UV spectral range. The value of polarization itself is quite low and does not exceed $p_l \sim 0.1\%$. Numerous model calculations have shown that even this relatively low–polarization value can be reached only for the magnetic field strength of $\geq 1\,\mathrm{kG}$ since the effect of saturation of spectral lines requires quite large strengths of magnetic fields on the stellar surfaces.

Secondly, it is the Thomson scattering of stellar light in wind and clouds that provides a net polarization (see in detail below).

Thirdly, the region where the wind and clouds are interacting can also be responsible for the appearance of polarized radiation. In this case the main mechanism is the so–called impact polarization due to the excitation of ion lines by the stellar wind particles (Kazantsev & Henoux, 1995). In this case the line emission becomes polarized.

2 Net Polarization Produced by Stellar Light Scattering into Magnetically–Driven Clouds

This situation is quite close to the case, considered by Gnedin & Silant'ev (1980, 1997, 2000). They solved the problem of generation of polarized radiation of a magnetic star, surrounded by an envelope, consisting of magnetized plasma. The plasma is driven by the dipole magnetic field of a star. The radiation of such star acquires linear polarization as a result of scattering on the electrons in the envelope. This scattered radiation undergoes Faraday rotation via propagation in the magnetized plasma of the envelope. The base of determination of the resulting net polarization is to calculate the integral polarization value, taking into account the Faraday rotation angle of the polarization plane for various directions of scattered light.

The above mentioned authors have shown that the basic parameter in the considered situation is

$$\tau_T\delta = \frac{3}{4\pi}\frac{c\omega_B\tau_T}{r_e\nu^2} = 0.8\lambda^2(\mu)B(G)\tau_T, \tag{1}$$

where λ and ν are the wavelength and frequency of scattered light, respectively, $\omega_B = eB/m_ec$ is the cyclotron frequency, $r_e = e^2/m_ec^2$ is the classical radius of an electron and τ_T is the optical thickness of the circumstellar envelope (a cloud).

The physical meaning of Eq. (1) is the magnitude of the angle of Faraday rotation at the length of two mean free paths of light with respect to Thomson scattering.

The Stokes parameters of scattered radiation is determined by the expressions (Gnedin & Silant'ev, 1984, 1997; Silant'ev et al., 2000):

$$\begin{aligned}
F_I(\vec{n}) &= \frac{L}{4\pi R^2}\frac{3\sigma_T}{16\pi}\int dV\frac{N_e(\vec{r})}{r^2}(1+\cos^2\vartheta) \\
F_Q &= -\frac{L}{4\pi R^2}\frac{3\sigma_T}{16\pi}\int dV\frac{N_e(\vec{r})}{r^2}\sin^2\vartheta\cos 2(\varphi+\psi) \\
F_U &= -\frac{L}{4\pi R^2}\frac{3\sigma_T}{16\pi}\int dV\frac{N_e(\vec{r})}{r^2}\sin^2\vartheta\sin 2(\varphi+\psi),
\end{aligned} \tag{2}$$

where L is stellar spectral luminosity ($\mathrm{erg\,s\,Hz^{-1}}$), ϑ and φ are polar and azimuthal angles of the radius–vector $\vec{r}$ in the frame reference with the z–axis directed along the line of sight (see Fig. 12 from Gnedin & Silant'ev, 1997), $N_e(\vec{r})$ is the electron density in an envelope, R is the distance from the star to an observer, $\psi \equiv \psi(\vec{n},\vec{r})$ is the Faraday angle value, corresponding to the travel of a ray of light from point $\vec{r}$.

The Faraday rotation angle $\psi(\vec{n},\vec{r})$ was determined by Silant'ev et al. (2000) with the integration along the line of sight from the initial point $\vec{r}$ — the place of the radiation scattering:

$$\psi(\vec{n},\vec{r}) = 0.4\sigma_T\lambda^2(\mu m)\int dl N_e(\vec{r})\vec{n}\vec{B} \tag{3}$$

The calculations of (3) were made by Silant'ev et al. (2000).

The value of polarization due to this mechanism may be rather large. Thus, the maximum integral polarization from even the spherical envelope with the electron density $N_e(\vec{r}) \sim 1/r^2$ may reach magnitude $P_e \approx 10\%\,\tau_{env}$.

We use the results by Gnedin & Silant'ev (1980, 1997) for the estimation of expected value of polarization of stellar light, scattered by circumstellar gas clouds forced into co–rotation with He–strong stars in the situation, considered by Smith & Groote (2001). We start with the case of a spherically–symmetric circumstellar cloud, and then estimate the deviations from spherically symmetry.

The numerical analysis of line strength variations for He–strong stars made by Smith & Groote (2001) indicates that the cloud line components form in an external environment of column density $\sim 10^{23}\,\mathrm{cm}^{-2}$. It corresponds to the Thomson optical thickness $\tau_T \sim 0.1$. For this value of density, and the stellar magnetic field strength $B_S \approx 100\,\mathrm{G}$, the corresponding values of the parameter $\delta_S \tau_T \approx 12$ and the function $f(\delta_S \tau_0, \vartheta_m = 90°) \approx 0.05$ if we use the visual band. The resulting net polarization is given at the level $p_e \approx 0.5\%$ that can be easily detected with modern polarimetric devices.

Of course, the circumstellar envelope can have a non–spherical shape. In this case the net polarization can increase. The most important thing is that the degree of polarization acquires the wavelength dependence opposite to the case of pure Thomson scattering in a medium without magnetic field. One can find the characteristic shapes of wavelength dependencies of net polarization in the case of magnetized circumstellar environment in Gnedin & Silant'ev (1980) (spherically symmetrical envelope) and Gnedin & Silant'ev (1997) (non–spherically symmetrical envelope).

3 Net Polarization of Stellar Light Scattered in Magnetized Stellar Wind

Smith & Groote (2001) have interpreted the behaviour of the blue–wing absorption in He–strong stars as an evidence of existence of winds in these objects. Shote & Brown (1990) have found that a dipolar field of only a few hundred gauss can suffice to guide a polar wind from the surface to its equatorial regions via the closed magnetic loops. They claim that the wind particles are abruptly halted near the magnetic equator, where they establish a quasi–state torus-shape structure.

One of remarkable results of Smith & Groote (2001) is that the blue wings of the Si III, Si IV and C IV resonance lines remain constant with rotational phase for all the program stars. The phase–independent nature of wind allows us to consider at the first approximation the more simple, spherical stellar wind model of Parker (1958). We shall show that such kind of approximate model gives rise to integral linear polarization if we shall take into account the influence of the Faraday rotation effect in its pure form.

The common solution of the problem of single scattering of non–polarized light of the central star on the electrons of magnetized stellar wind have been given by Silant'ev et al. (2000). Here we are considering a specific situation that is to be close to a real case with the program stars from Smith & Groote (2001). Silant'ev et al. (2000) and Piotrovich et al. (2010) used the simplified Parker's model, when magnetic dipole is carried away directly from the stellar surface. In this case, Parker's magnetic field takes a form:

$$B_r = B_0 \left(\frac{R_S}{r}\right)^2 \cos\theta; \qquad B_\theta = 0$$
$$B_\varphi = B_0 \left(\frac{\Omega R_S}{V_\infty}\right)\left(\frac{r}{R_S} - 1\right)^2 \cos\theta \sin\theta \tag{4}$$

where B_0 is the surface polar magnetic field ($\theta = 0$), Ω is cyclic angular velocity of a star, V_∞ is terminal velocity of the stellar wind, θ is the angle between the dipole axis and the radius–vector $\vec{r}$.

The qualitative analysis of this picture presents the following picture. The spectrum of polarized light has a maximum, the position of which is determined approximately by the condition

$$\lambda^2(\mu m) B(G) \tau_T \geq 1. \tag{5}$$

If the left part of (5) largely exceeds unity, the position of maximum does not radically change, but the net polarization sometimes increases.

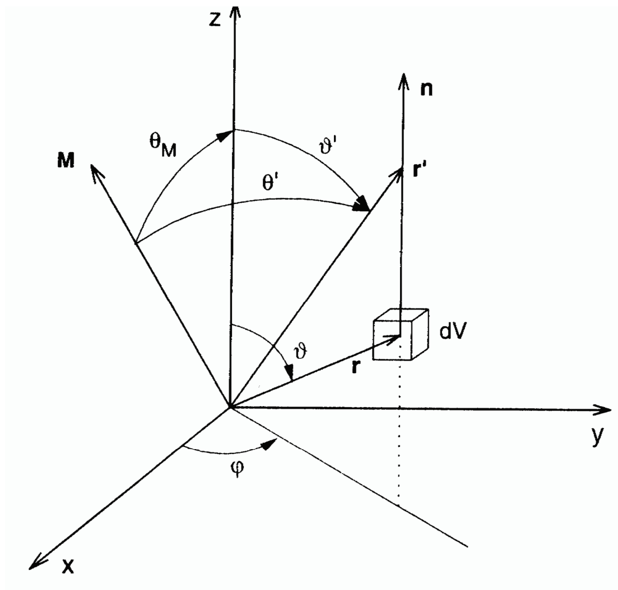

Figure 1: The scheme of calculation of integral polarization

If the dipole component of the wind magnetic field increases, the position of the maximum is shifted to the short wavelength band. With the increase of the toroidal component the maximum is shifted to the long wavelength band. For the wavelength region $\lambda \ll \lambda_{max}$ the relation $P_e(\lambda \ll \lambda_{max}) \sim B_\perp / B_U$ exists, that is saturated for $B_\perp \sim B_U$, where B_U is the dipole component of the stellar magnetic field, and $B_\perp$ is the toroidal component.

These results demonstrate that measurements of linear intrinsic polarization of He–strong stars can provide significant additional data on the structure of circumstellar environment, and partially about the wind circulations in these stars and its interaction with the co–rotating circumstellar clouds.

The Faraday rotation angle $\psi(\vec{n}, \vec{r})$ forms the basis for calculating integral polarization. A convenient form for the numerical calculation of (3) was derived by Silant'ev et al. (2000):

$$\psi(\vec{r}, \vec{n}) = 0.4\sigma_T \lambda^2(\mu m) \int_0^{\vartheta} d\vartheta' \frac{r \sin\vartheta}{(\sin\vartheta')^2} N_e(\vec{r}') \times \\ \times \left[B_r(\vec{r}') \cos\vartheta' + B_\varphi(\vec{r}') \frac{\sin\theta_m}{\sin\theta'} \sin\vartheta' \sin\varphi + \right. \\ \left. + B_\vartheta(\vec{r}') \frac{\cos\theta' \cos\vartheta' - \cos\theta_m}{\sin\theta'} \right] \quad (6)$$

Here, we used the relation $\vec{B}(\vec{r}) = B_r \vec{e}_r + B_\vartheta \vec{e}_\vartheta^{(M)} + B_\varphi \vec{e}_\varphi^{(M)}$, where $\vec{e}_r$, $\vec{e}_\vartheta^{(M)}$ and $\vec{e}_\varphi^{(M)}$ are unit vectors in the coordinate system with the z–axis directed along the magnetic dipole moment $\vec{M}$. We also assume that the vector $\vec{M}$ lies in the (z, x) plane, as follows from Fig. 1. θ_m is the angle between the direction of the poloidal magnetic field moment $\vec{M}$ and the z–axis, θ' is the angle between $\vec{M}$ and the radius vector $\vec{r}$ ($\cos\theta' = \cos\vartheta' \cos\theta_m + \sin\vartheta' \sin\theta_m \cos\varphi$). Along the line of sight $\varphi = \varphi'$.

The Faraday rotation effect actually changes the polarization spectrum $P_e(\lambda)$ of the accretion disk radiation, scattered in the disk wind. The broad emission line region can arise precisely at the base of the disk wind.

The main problem in ascertaining the degree and distribution of polarized radiation as a function of radiation wavelength, is to take into account the magnetic field topology. We use Parker's popular model that describes the magnetic field structure arising in a plasma outflow similar to a stellar disk wind. We suggest here the disk wind outflow being spherically symmetric.

In this case we obtain the following expression for the Faraday rotation angle from (6):

$$\begin{aligned}
&\psi(\vec{r},\vec{n}) = \psi_r + \psi_\varphi;\\
&\psi_r = 0.05\lambda^2(\mu m)\tau\frac{B}{\rho^3\sin^3\theta}\times\\
&\qquad\times\left[\left(\vartheta - \frac{\sin 4\vartheta}{4}\right)\cos\theta_m + 2\sin\theta_m\sin^4\vartheta\cos\varphi\right];\\
&\psi_\varphi = 0.4\lambda^2(\mu m)\tau\frac{C\sin\theta_m\sin\varphi}{\rho^3\sin^3\vartheta}\times\\
&\qquad\times\left[\left(\frac{\rho}{3} - \frac{1}{4}\right)\cos\theta_m\sin^4\vartheta + \right.\\
&\qquad\qquad+\rho\sin\theta_m\sin\vartheta\cos\varphi\left(\frac{\cos^3\vartheta}{3} - \cos\vartheta + \frac{2}{3}\right) -\\
&\qquad\qquad\qquad\left. -\sin\theta_m\cos\varphi\left(\frac{3\vartheta}{8} - \frac{\sin 2\vartheta}{4} + \frac{\sin 4\vartheta}{32}\right)\right]
\end{aligned} \tag{7}$$

Here, $\rho = r/R_0$ is the dimensionless distance measured from the stellar surface, $\tau = N_e\sigma_T R_0$ is the Thomson scattering optical depth of the outflowing wind plasma, and $C = B(\Omega R_0/V_\infty)$ is a parameter that characterizes the toroidal component of the Parker magnetic field, V_∞ is the wind velocity.

The system of equations (1)–(7) provides a basis for numerical calculation of the intrinsic polarization of stars with outflows. The results of the numerical calculations may be compared with those of spectropolarimetric observations of stars.

Fig. 2 presents the wavelength dependence of polarization from the magnetized wind with the parameters of magnetic field and optical thickness of the wind itself. The last parameter allows to estimate the outflow rate $\dot{M}_{out}$:

$$\dot{M}_{out} = 4\pi\rho R_W^2 V_W = 4\pi\frac{m_p}{\sigma_T}\tau_t R_W V_W, \tag{8}$$

where m_p is the proton mass, $\sigma_T = 6.65\cdot 10^{-25}\,\mathrm{cm}^2$ is the Thomson cross–section, R_W is the characteristic radius of a stellar wind and V_W is the wind velocity. As the wind density is radically decreased with respect to the distance from the stellar surface, one can consider the case when $R_W \approx R_S$, where R_S is the radius of a star.

For $\tau_T = 0.4$, $R_W \approx R_S = 10^{12}\,\mathrm{cm}$, $V_W = 300\,\mathrm{km/s}$ we obtain $\dot{M} = 2\cdot 10^{-5}\,M_\odot/\mathrm{yr}$ that is the typical value for the outflow rate for giant and supergiant stars.

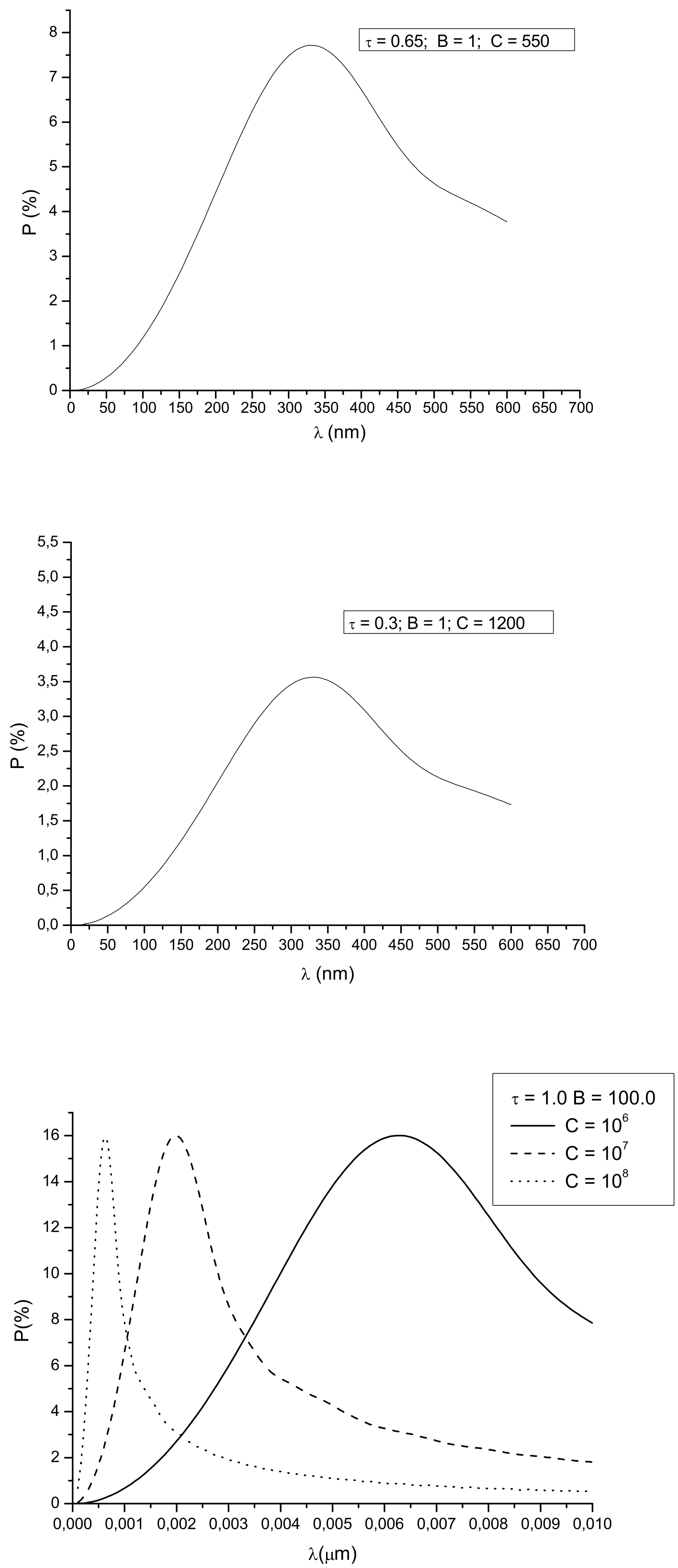

Figure 2: The wavelength dependence of polarization from the magnetized wind with the parameters of magnetic field and optical thickness of the wind

Table 1: The results of our calculations

Star	τ_T	$B_l = 100$ G	$B_l = 10$ G
ζ Puppis	0.2	$P_l = 0.4\%$	0.02%
ε Ori	0.17	0.17%	0.01%
Deneb	0.03	0.01%	$\ll 0.01\%$
P Cyg	1	0.1%	0.3%
WR 40	3.4	0.1%	0.3%

4 Polarization of Radiation of Some Stellar Objects with Outflows

4.1 Polarization of Radiation of Cataclysmic Variables with Outflows

In the accretion disks of the cataclysmic variables (CVs) there is the power outflow from the disk's surface. The existence of P Cyg profiles of strong UV carbon lines (C IV λ 1549) proves such outflows (Proga, 2004). It means that the radiation of this line will be polarized as a result of electron scattering by the disk outflow.

For the radiation–driven disk wind the typical values of outflow rates are $\dot{M} = 10^{-11} \div 10^{-8}\, M_\odot/\mathrm{yr}$ for the typical ratios of bolometric luminosity to the Eddington one $L_{bol}/L_{Edd} = 0.01 \div 0.1$. The typical velocities of stellar wind are at the level of $V \sim 10^3$ km/s. For this case, the optical thickness of the disk wind with respect to electron scattering can be estimated as

$$\tau_T = 0.2 \left(\frac{\dot{M}_W}{10^{-8} M_\odot/yr} \right) \left(\frac{10^5 km}{R_{WD}} \right), \tag{9}$$

where R_{WD} is the radius of a white dwarf. For the poloidal magnetic field, the polarization of UV radiation of $P_e \approx (3\tau_T \sin^2 i)\%$ corresponds to the depolarization factor of $\delta_S \tau_{env} \approx 35$. For the wavelength of CN λ 1549 Å the magnetic field strength on the white dwarf's surface appears to be $B_S \cong 3.35 kG$ for $L_{bol}/L_{Edd} = 0.1$ and $i \approx 90°$.

If the UV luminosity of a white dwarf reaches the Eddington limit of $L_{bol} \approx L_{Edd}$ and $\dot{M} \geq 5 \cdot 10^{-8}\, M_\odot/\mathrm{yr}$, the disk wind becomes optically–thick ($\tau_T > 1$). In this case the maximal polarization degree $P_e \approx 0.3\%$ reaches the magnitude of the depolarization parameter $\delta_S \approx 1.5$. For the wavelength $\lambda = 1519$ Å it allows to determine the dipole magnetic field strength at the WD surface at the level $B_S \approx 10^2$ G. This value is approximately 10 times smaller than in the case of the optically–thin disk wind. In the latter case, the polarization magnitude is approximately twice higher. Thus, the polarimetric observations of CVs allow us to estimate the magnetic field strength at the WD surface, and to determine also the value of Eddington factor of the accretion process.

For the Parker–type magnetic field the maximum of the polarization spectrum is really shifted into the UV spectral range, and the polarization value can reach $\sim 5\%$ at the toroidal magnetic field $B_\varphi \sim (1 \div 10)$ kG. It means that the Parker–type magnetic field produces a higher polarization degree, compared to the dipole magnetic field (Fig. 2, bottom). This result also means that polarization measurements allow us to estimate the topology of magnetic fields of CVs, as well as the intermediate polars.

4.2 Intrinsic Polarization of Hot Stars

Hot stars are characterized by extremely high $\dot{M} \geq 10^{-5}\, M_\odot/\mathrm{yr}$ outflows in the form of dense stellar winds. The optical thickness of this wind is $\tau < 1$ for ζ Puppis and Deneb, and $\tau > 1$ for P Cyg, WR 40 (Chesneau et al., 2003). Zeeman spectropolarimetric observations of these stars do not allow

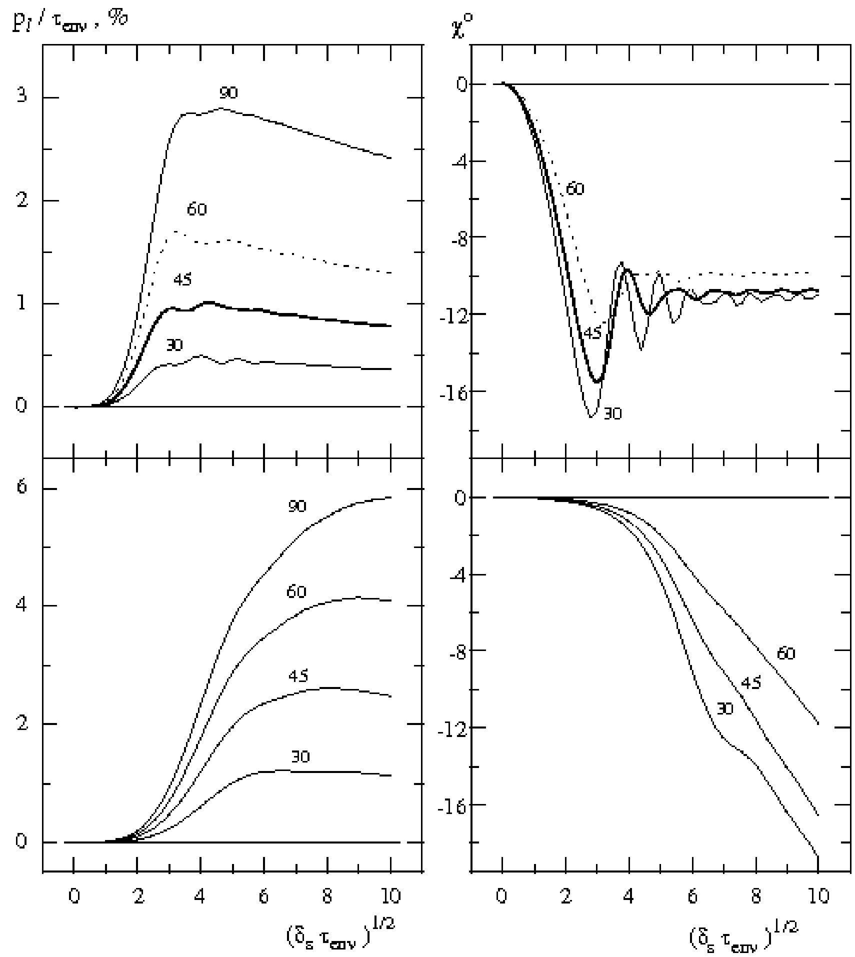

Figure 3: The wavelength dependence of polarization from the magnetized wind with the parameters of magnetic field and optical thickness of the wind

to determine their magnetic fields. Our calculations allow to estimate the degree of broadband polarization (in V–band) for these objects. The results of our calculations are presented in Table 1. We adopt the value of the inclination angle as $i = 90°$. Another target of our calculations is the Oef star HD 192281. The basic parameters of this star are: the mass $M_S = (70 \div 93)\, M_\odot$, effective temperature $\log T_e = 4.67$, radius $R_S = (15 \div 19)\, R_\odot$, distance to the star $D = 1.78$ kpc and the rotation velocity $V_{rot} \sin i = 270$ km/s. The radial wind velocity, determined via the H_β Doppler shift, is $V_r(H_\beta) = 65.8$ km/s.

The basic outflow magnitude for this type of stars is $\dot{M} = 10^6\, M_\odot$/yr. The estimate of the optical thickness of the stellar wind from Eq. (9) gives $\tau_T = 0.4\ (15\, R_\odot / R_S)$.

Now we estimate the polarization degree of rotation scattering in the region of spherical stellar wind. We suggest the dipole topology of stellar magnetic field. The calculations are made for three magnitudes of magnetic field: $B = 1$ G, 10 G and 100 G and for V–band with effective wavelength $\lambda_e = 0.55 \mu m$. The inclination angle is $i = 90°$.

The depolarization factor for the magnetic field $B_S = 1$ G is equal to $\delta = 0.24$. The value of parameter $(\delta_S \tau_{env})^{1/2} = 0.31$ and from Fig. 3 one can obtain $P_e/\tau_{env} \leq 0.1$, and the maximal value of polarization degree at the level $P_e \leq 0.3\%$.

For $B = 10$ G the parameter $(\delta_S \tau_{env})^{1/2} \approx 0.98$ and $P_e/\tau_{env} \approx 0.2\%$ and $P_e \approx 0.8\%$.

For $B = 10^3$ G the depolarization parameter $(\delta_S \tau_{env})^{1/2} \approx 3.1$ and estimated value of intrinsic

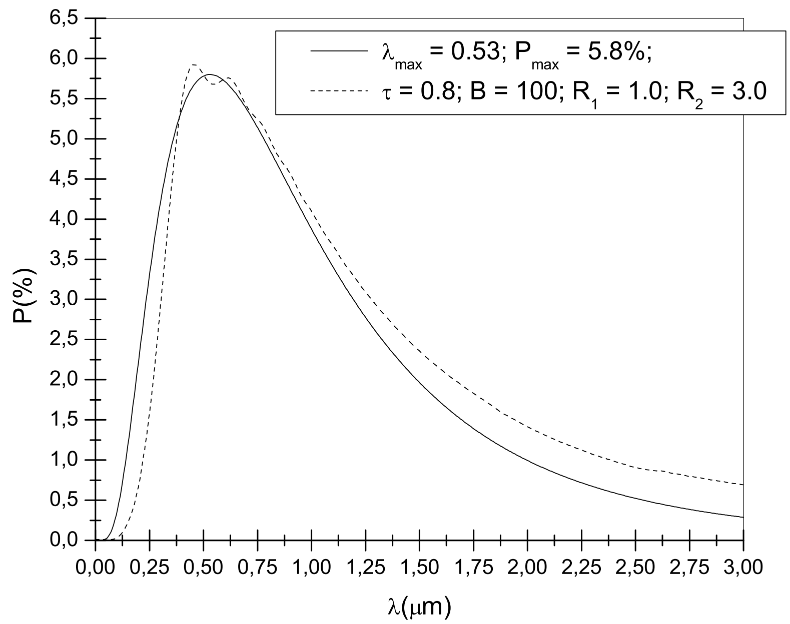

Figure 4: The results of comparison of our calculations with the real distribution of interstellar polarization around HD 147933–4

polarization is $P_e \approx 1.1\%$. The same estimations for the magnetic field strengths $B = 30$ G and 50 G give $P_e = 0.16\%$ and $P_e = 0.4\%$, respectively.

For the other two stars, HD 14442 and HD 14434, our calculations were produced only for the magnetic field strength $B_S = 100$ G. As a result, the values of polarization are $P_e = 1.24\%$ and $P_e = 1.8\%$ for HD 14442, and HD 14434, respectively.

Let us consider now the case when the stellar wind transforms the dipole magnetic field into the Parker–type one. For this case, the results of our calculations are presented in Fig 2. For the Parker–type topology of magnetic field, the maximal polarization degree can reach the value of $P_e \geq 5\%$, that is higher than for the dipole magnetic field.

It is important that for the constant ratio B/C of the radial and toroidal components of magnetic field the maximum of spectral distribution of polarization is shifted to the short wavelength range via an increase of the toroidal component.

4.3 Intrinsic Polarization of Stellar Light Can Simulate the Serkowski Law

We demonstrate a real situation, when the wavelength dependence of the intrinsic linear polarization of a star can mimic the wavelength dependence of interstellar linear polarization described by the Serkowski law.

It appears that the scattering of radiation in the spherical envelope, surrounding a star with an approximately constant density, and a dipole magnetic field produces a specific wavelength dependence of the polarization degree, that is surprisingly similar to that in the Serkowski law. Figure 4 presents the results of comparison of our calculations with the real distribution of interstellar polarization around HD 147933–4. It means that for stars in our Galaxy there is a possibility of existence of intrinsic polarization that disguises real interstellar polarization. This result explains also the famous “super-Serkowski” behaviour of the wavelength dependence of the polarization degree in some observed stars in our Galaxy.

5 Radiation Polarization in Stars, Scattered in Anisotropic Outflows

In many cases, the outflow from stars can have an anisotropic form of a cone–like outflow. The results of numerical calculations of linear polarization from the magnetized cone–like optically–thin plasma envelopes have been presented by Gnedin et al. (2006). Figures 5–7 present the polarization and position angle of the total radiation from magnetized optically–thin conical envelopes versus the parameter $(\delta_S \tau_{env})^{1/2}$. The numbers near the curves mean the inclination angle i (in degrees) of the cone axis $\vec{h}$ to the line of sight $\vec{n}$. Cases (a), (b) and (c) correspond to the cone opening half–angles $\vartheta = 7.5°$, 15° and 30° respectively.

For an optically thin cone without a magnetic field the degree of polarization P was calculated by Dolginov et al. (1995):

$$P = \frac{3}{16} \tau_{env} \cos\vartheta \sin\vartheta \sin^2 i \quad (10)$$

The plane of preferential oscillations of the electric vector of scattered radiation is perpendicular to the plane, containing the cone axis and the line of sight. Figures 6 and 7 present the polarization of radiation scattered in the cone–like envelope with a radial magnetic field.

If a conical envelope consists of radially–ejected charged ion particles and electrons, then inside the envelope there is a regime, where an electron current exists. The presence of a current leads to am azimuthal magnetic field. Fig. 7 presents the polarization from a conical envelope with an azimuthal magnetic field. In this case, the magnetic field is antisymmetric relative to the $(\vec{n}\vec{h})$ plane, where $\vec{n}$ and $\vec{h}$ are the directions of the line of sight and the cone axis, respectively. Then the Faraday rotation here leads only to a change in the polarization degree. The direction of the electric vector oscillation is perpendicular to the $(\vec{n}\vec{h})$ plane, as in the absence of a magnetic field.

The basic result of these calculations is a strong wavelength dependence of polarization and position angle.

6 Impact Polarization of Ion Lines as a Result of Collisions of Stellar Wind Beam with Circumstellar Clouds

Another very important result of Smith and Groote's work concerns the problem of the emission lines strength. Authors were led to the conclusion that it is impossible to explain the total line emission of program stars if one does not only expect that these emissions are caused by the wind–cloud interaction. And in this case, the line emission becomes polarized due to the so–called impact polarization mechanism.

Linear polarization of atomic an ion lines are readily used as a diagnostic of accelerated particle beams. Three different mechanisms of interactions can lead to the polarization emission (see for details Kazantsev et al., 1994, and Kazantsev & Henoux, 1995). The first is the impact excitation by energetic particles with an anisotropic velocity distribution function (for example, a type of stellar wind). The second is the drift alignment, resulting from the exchange of population between the sublevels of the upper states of transition under the effect of anisotropic collisions with low–energy particles. The third is the charge exchange. All these mechanisms are close to the situation considered here.

Unfortunately, the basic calculations and physical experiments have been made only for the hydrogen and helium targets, and can be used for explicit estimations of the expected net polarization of UV ion lines of Si III, Si IV, and C IV. But the energy range of electron and ion beams, used in these experiments and calculations corresponds quite well to the energy range of the typical stellar wind, e. g. $\sim 1 \div 100$ KeV.

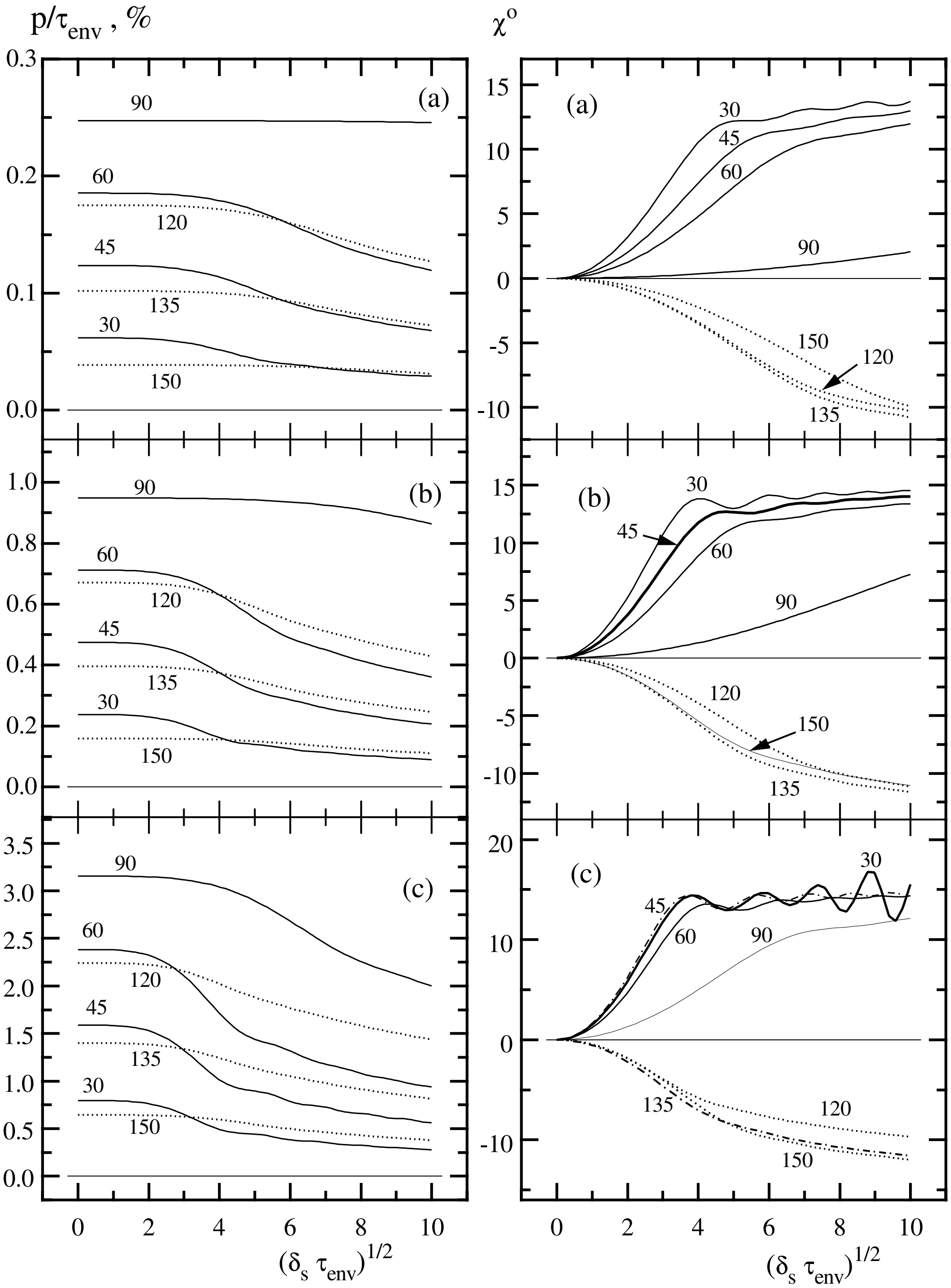

Figure 5: The dependence of polarization and position angle of the radiation, scattered by a magnetized optically–thin conical envelope versus the depolarization parameter and the envelope optical thickness.

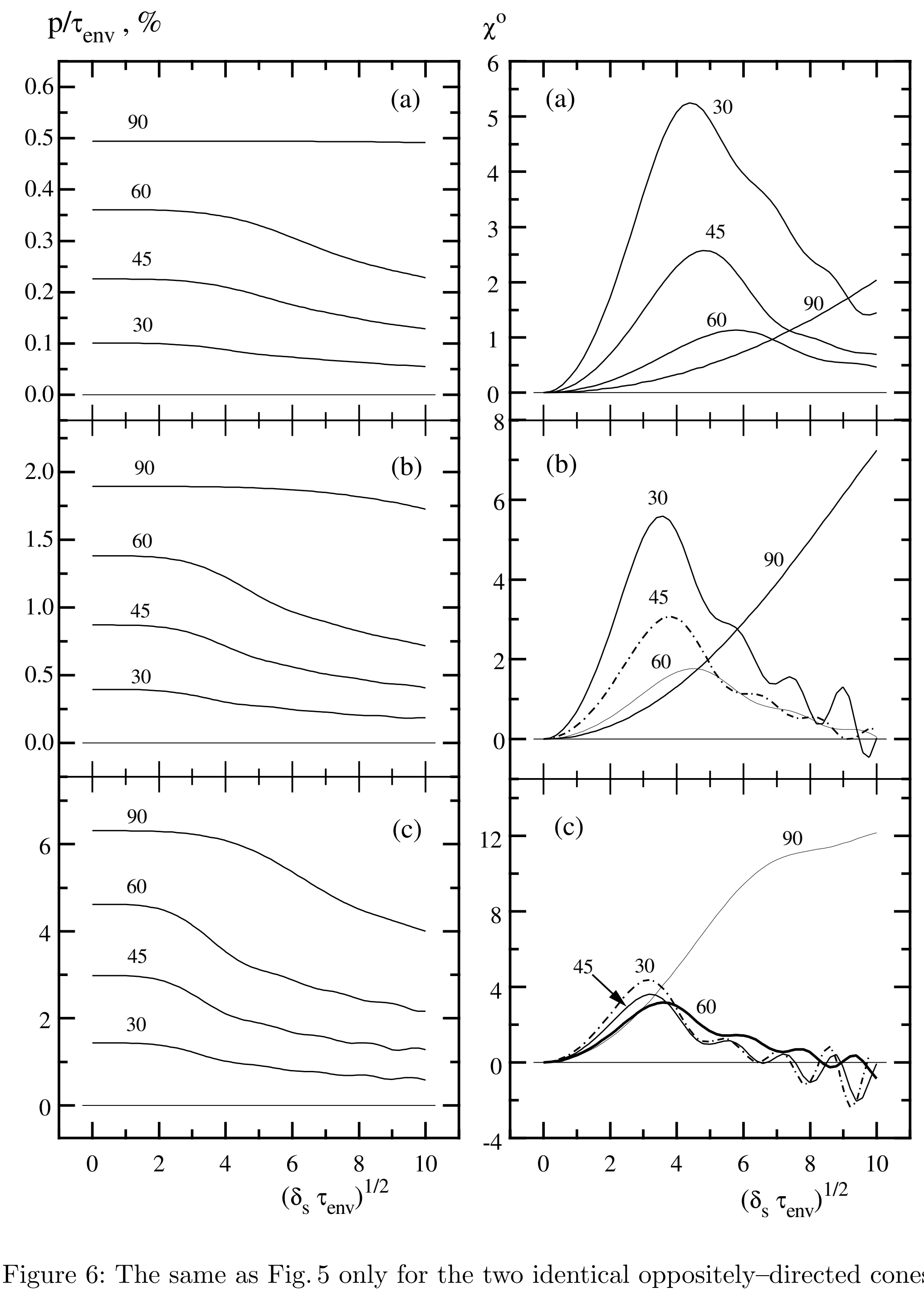

Figure 6: The same as Fig. 5 only for the two identical oppositely–directed cones.

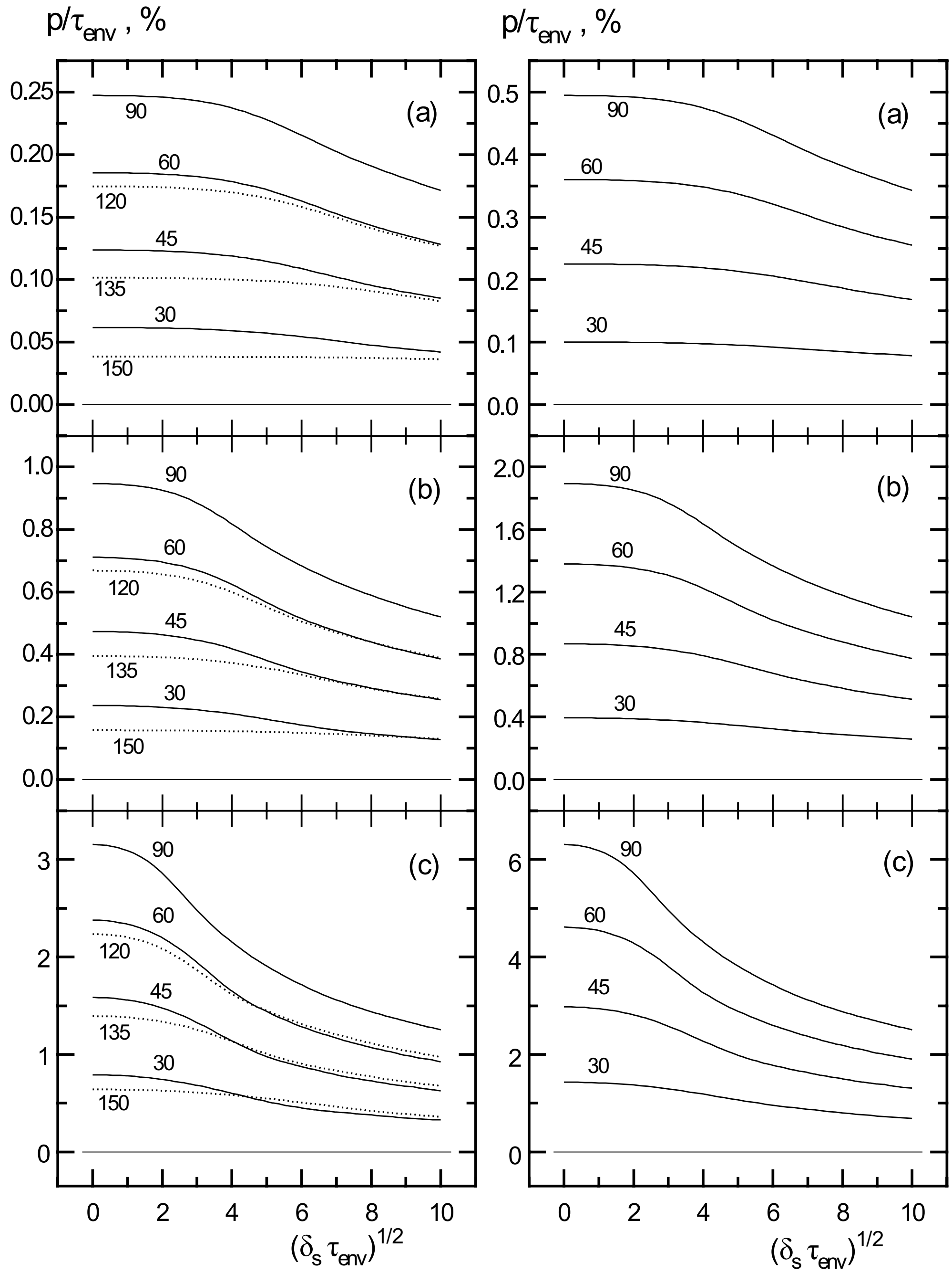

Figure 7: Polarization for a conical envelope with an azimuthal magnetic field. The polarizations from the opposite cones are given in the right–hand part.

Kazantsev & Henoux (1995) indicated that spectropolarimetric effects in the spectrum of optical emission are connected not only with the distribution of resonance radiation, but also to the anisotropy of the fast–excited electrons and photons, and to the anisotropy in the relative velocity space of the colliding atomic particles. They practically have analysed the drift self–alignment of ions, and shown the diagnostic applications of this effect for the study of ionized gas.

Their expression for the degree of polarization in the case of omnidirectional particle beam is

$$P = \frac{\cos^2\vartheta\cos 2\varphi}{A - \sin^2\vartheta}, \tag{11}$$

where ϑ is the angle between the directions of the beam and the line of sight, φ is the azimuthal angle, and $1/A$ is the polarization degree, calculated in the reference frame, connected to the symmetry axis of the collision excitation process. If the stellar wind is isotropic, one should average the Eq. (11) on φ. Evidently, the resulting net polarization is then null. Nonzero net polarization requires anisotropy in stellar wind. The latter can arise via the stellar magnetic field distribution. For example, the stronger stellar wind flux can be produced namely from the region of the magnetic pole, when it was suggested by Vauclair et al. (1991) (see also Groote & Hunger, 1997).

Kazantsev & Henoux (1995) computed various proton energies and slit positions, and obtained the real values of $P \sim 5\%$. The result of integration in the stellar or envelope surface decreases, of course, this magnitude: $P \sim \alpha \times 5\%$, where α is the parameter, characterizing the value of anisotropy of stellar wind and the degree of asphericity of the circumstellar envelope. Even this magnitude is no higher than 10%, one can expect the value of the observable polarization at the level of 0.5%. There is no problem to measure such polarization level with the modern polarimetric technique.

7 Conclusions

We calculated the net intrinsic polarization that can be produced in a result of Thomson scattering of light of a rotating magnetic early B stars in their circulation winds. The existence of such kind of winds for these stars has been proposed by Smith & Groote (2001) from the analysis of the UV spectral lines. We claim that production of intrinsic polarization of the He–strong early B stars is another signature of existence of circulation winds. Our estimations of the intrinsic integral linear polarization are based on our previous calculations of Faraday rotation and polarization of light, scattered in the magnetized stellar envelopes and winds (Gnedin & Silant'ev, 1980, 1984, 1997; Dolginov et al., 1995; Silant'ev et al., 2000). We estimated the expected net polarization at the level of $\sim 0.5\%$.

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