The relationship between grain shape and interstellar polarization

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We analyze the effects of grain shape and orientation on parameters of interstellar linear polarization curve. The consideration is performed for partially aligned prolate and oblate spheroidal particles with aspect ratios $a/b = 1.1 - 10.$ radiation.

LINEAR POLARIZATION: OBSERVATIONS

The phenomenon of interstellar linear polarization is caused by the linear dichroism of the interstellar medium due to the presence in it of non-spherical oriented grains. Non-spherical particles produce different extinction of light depending on the orientation of the electric vector of incident radiation relative to the particle axis. The spectral dependence of polarization in the visible part of spectrum $P(\lambda)$ is described by Serkowski empirical formula (see, e.g., [1])

$$P(\lambda)/P_{\max} = \exp[-K \ln^2(\lambda_{\max}/\lambda)], \quad (1)$$

where K is the coefficient, $P_{\max}$ the maximum degree of polarization and $\lambda_{\max}$ the wavelength corresponding to it. From the analysis of observational data for several hundred stars it has been found the upper limit on the ratio of $P_{\max}$ to the colour excess $E(\mathrm{B-V})$ [1]

$$P_{\max}/E(\mathrm{B-V}) \lesssim 9\%/\mathrm{mag}\,. \quad (2)$$

This ratio determines the polarizing efficiency of the interstellar medium towards a particular star.

It was established a relation between the total-to-selective extinction ratio R_{V} and $\lambda_{\max}$ ($R_{\mathrm{V}} = (5.6 \pm 0.3)\,\lambda_{\max}$, $\lambda_{\max}$ in μm), and regional variations of R_{V} and $\lambda_{\max}$ (see Fig. 4.13 in [2]). The increase of R_{V} and $\lambda_{\max}$ is usually attributed to the growth of grain size although both parameters also depend on the degree and direction of grain alignment [3].

In [3] there was noted the anticorrelation between the observed polarizing efficiency and $\lambda_{\max}$, i.e., the larger value of $\lambda_{\max}$ corresponds to the smaller value of $P_{\max}/E(\mathrm{B-V})$. Using the model of infinite cylinders this fact was interpreted as the decrease of the angle between the line of sight and the magnetic field direction Ω.

To test this hypothesis, we used the recent data of Efimov [4] who fitted the multi-wavelength polarimetric observations for 105 stars. We chose 76 stars located in the galactic plane ($|b| \lesssim 20°$) with distances $D \lesssim 1$ kpc. The observed values of $P_{\max}/E(\mathrm{B-V})$ versus $\lambda_{\max}$ (we used the Whittet fit from [4]) are plotted in Fig. 1 (left panel). It can be seen that any correlation is absent. However, for stars more or less closely located on the sky a systematic trend toward smaller polarizing efficiency for larger $\lambda_{\max}$ is obvious (right panel of Fig. 1).

To interpret the observations one needs to utilize a model of rotating partially aligned non-spherical grains. Such a model was recently developed and applied for the simultaneous interpretation of the observed interstellar extinction and polarization curves for

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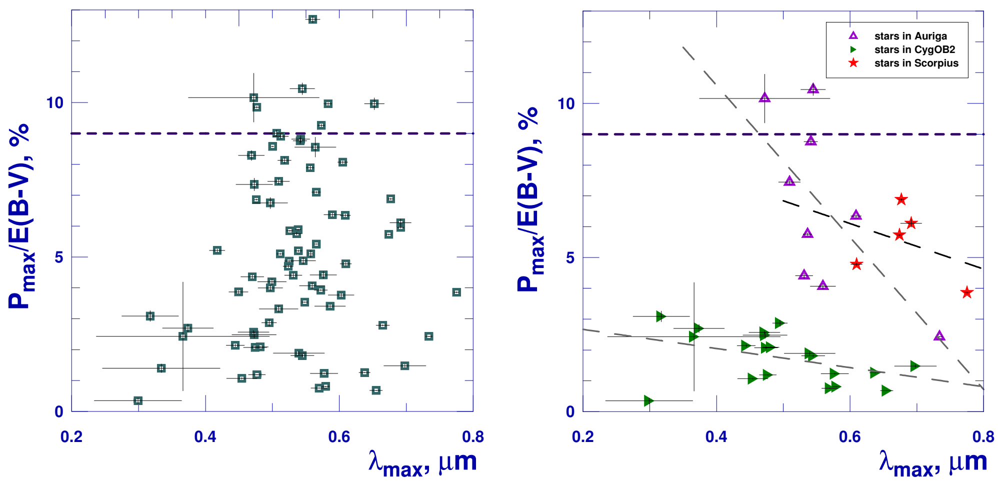

Figure 1. Polarizing efficiency of the interstellar medium in dependence on wavelength where interstellar linear polarization has maximum. Data are shown for 76 stars located not far than 1000 pc (left) and separately for stars in Auriga, Cygnus and Scorpius (right). The horizontal line is the observational upper limit as given by Eq. (2). Dashed lines are linear fits. Data were taken from [4].

certain stars [5, 6]. The shape of grains in the spheroidal model is characterized by the only parameter — the ratio of the major to minor semi-axis a/b. Note that previous modelling of interstellar polarization with spheroids included non-rotating particles with $a/b \lesssim 2$ (see [7, 8, 9]).

SPHEROIDAL MODEL OF INTERSTELLAR DUST

We use the model of homogeneous spheroids with a power-law size distribution ($n(r_V) \propto r_V^{-q}$) with imperfect Davis–Greenstein (IDG) orientation (see [5, 6] for details). Spheroids are characterized by their type (prolate or oblate), the aspect ratio a/b and size parameter r_V (radius of a sphere whose volume is equal to that of a non-spherical particle). For a given wavelength λ, the extinction and polarization cross sections $\langle C_{\rm ext}\rangle_\lambda$ and $\langle C_{\rm pol}\rangle_\lambda$ are obtained by averaging of the cross sections over the size distribution and grain orientations. The direction of grain orientation is described by the angle Ω (angle between the line of sight and the magnetic field direction, $0° \le \Omega \le 90°$). The value $\Omega = 90°$ corresponds to the case when the particle rotation plane contains the light propagation vector k, which gives the maximum degree of linear polarization. For $\Omega = 0°$, the light falls perpendicular to the particle rotation plane and from symmetry reasons the net degree of polarization produced is zero.

The IDG mechanism is described by the function $f(\xi, \beta)$ depending on the alignment parameter ξ and the precession angle β

$$f(\xi,\beta) = \frac{\xi \sin\beta}{(\xi^2\cos^2\beta + \sin^2\beta)^{3/2}}. \quad (3)$$

The parameter ξ depends on the particle size r_V, the imaginary part of the grain magnetic susceptibility χ'', gas density $n_{\rm H}$, the strength of magnetic field B, and temperatures of dust $T_{\rm d}$ and gas $T_{\rm g}$

$$\xi^2 = \frac{r_V + \delta_0 (T_{\rm d}/T_{\rm g})}{r_V + \delta_0}, \qquad \delta_0 = 8.23 \times 10^{23} \frac{\varkappa B^2}{n_{\rm H} T_{\rm g}^{1/2} T_{\rm d}}, \ \mu{\rm m}. \tag{4}$$

Our model has the following main parameters: minimum and maximum radii of grains $r_{V,\rm min}$ and $r_{V,\rm max}$, the power index q and the degree (δ_0) and direction (Ω) of grain alignment.

RESULTS AND DISCUSSION

We made calculations for polydisperse ensembles of spheroids consisting of astronomical silicate (astrosil [10]) and amorphous carbon (AC-Be [11]). Size distribution parameters were chosen so as to give the ratio $R_{\rm V} \approx 3.1 - 3.2$ for particles with $a/b \approx 1$. This occurs if $r_{V,\rm min} = 0.010\mu$m, $r_{V,\rm max} = 0.25\mu$m and $q = 2.5$ for particles from astrosil and $r_{V,\rm min} = 0.001\mu$m, $r_{V,\rm max} = 0.25\mu$m and $q = 4.0$ for particles from AC-Be. Some results are plotted in Figs. 2, 3. They show the polarizing efficiency $P_{\rm max}/E({\rm B-V})$ in dependence on the angle Ω and the degree of alignment δ_0. The colour excess $E({\rm B-V})$ was found by averaging over the B and V filter passbands taken from [12].

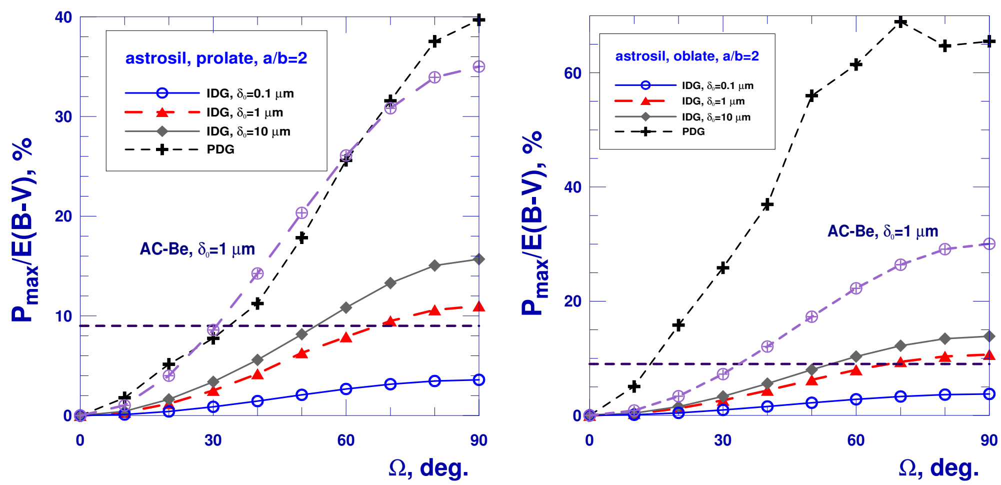

Figure 2. Polarizing efficiency dependence on angle between the line of sight and the magnetic field. The results are plotted for prolate (left) and oblate (right) spheroids from astrosil with imperfect (IDG) and perfect (PDG) Davis–Greenstein orientation. The horizontal line shows the observational upper limit as given by Eq. (2).

As expected, the polarizing efficiency grows with the increase of Ω, δ_0 and a/b (Figs. 2, 3). At the same time, it is seen the difference between polarizing properties of the prolate and oblate spheroids. Partially aligned oblate particles only slightly polarize transmitted radiation if $\Omega \lesssim 40^\circ - 50^\circ$ (Fig. 2, right panel). This is true for silicate and carbon particles. If the aspect ratios of prolate and oblate particles are the same then similar polarization can be reached if the degree of alignment of oblate particles is more in comparison with prolate particles.

Note that $\lambda_{\rm max}$ is mainly determined by grain size and shape and weakly depend on the alignment parameters. The resulting relationships will be applied for detailed comparison of the theory with observations.

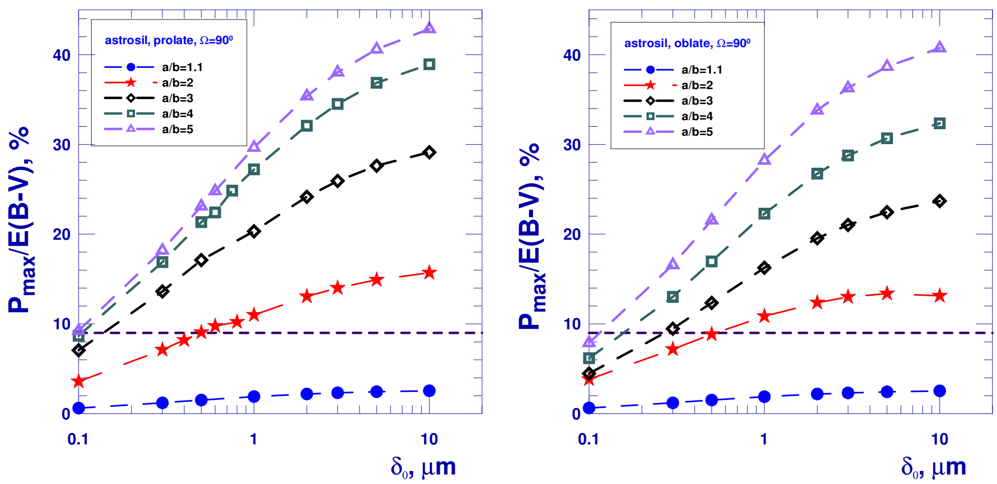

Figure 3. Polarizing efficiency dependence on the degree of alignment. The results are plotted for prolate (left) and oblate (right) spheroids from astrosil with IDG orientation. The horizontal line shows the observational upper limit as given by Eq. (2).

Acknowledgments

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