On the polarizing efficiency of the interstellar medium

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Abstract

We consider the wavelength dependence of the ratio of the linear polarization degree to extinction (polarizing efficiency) for aligned spheroidal particles. Size/shape/orientation effects are analyzed. The comparison of the theory with the polarizing efficiency of the interstellar medium observed in several directions permits to restrict the range of the model parameters.

1 Interstellar extinction and polarization

The reddening and linear polarization of stellar radiation occurs when it passes through interstellar clouds. Interstellar extinction grows with the radiation wavelength decrease while interstellar linear polarization reaches a maximum in the visual part of spectrum and declines at shorter and longer wavelengths (see [1], [2] and Fig. 1, left panel). Interstellar linear polarization indicate that non-spherical grains aligned in large-scale magnetic fields are present in the Galaxy. These data contain information about the interstellar magnetic fields and properties of dust grains. A correlation between observed interstellar extinction and polarization shows that the same particles are responsible for both phenomena.

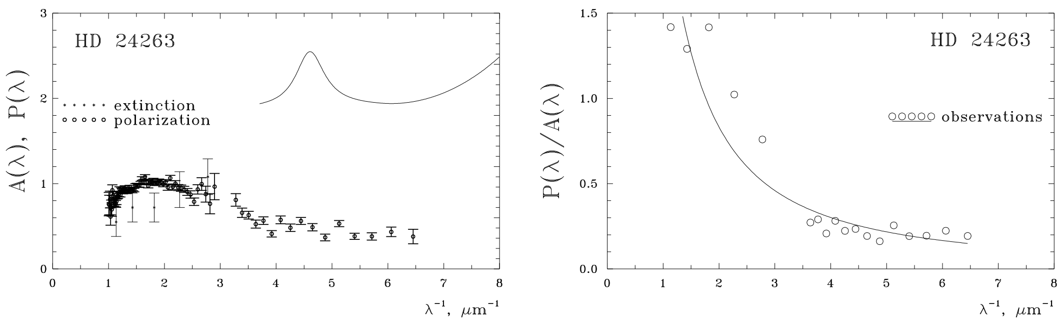

Figure 1: Interstellar extinction and polarization curves for star HD 24263 (left panel) and the polarizing efficiency of the interstellar medium in the direction of this star (right panel; solid curve shows the power-law approximation $P/A \propto \lambda^{1.47}$.). Observational data were taken from [3] (extinction) and [4] (polarization).

The modelling of these phenomena usually includes the consideration of normalized extinction $E(\lambda - \mathrm{V})/E(\mathrm{B}-\mathrm{V})$ and normalized polarization given by Serkowski's curve $P(\lambda)/P_{\max} = \exp[-K \ln^2(\lambda_{\max}/\lambda)]$ (see, e.g., [5] and discussion in [1], [2]). In such case, it is difficult to apply the dust-phase abundances and alignment theory for restriction of grain properties. It seems better to compare with observations the absolute extinction and theoretical polarizing efficiencies.

The *polarizing efficiency* of the diffuse interstellar medium is defined as the ratio of the percentage polarization (P) to the extinction (A) observed at the same wavelength $P(\lambda)/A(\lambda)$. There exists an empirically found upper limit on this ratio

$$P_{\max}/A(\mathrm{V}) \lesssim 3\%/\mathrm{mag}\,, \tag{1}$$

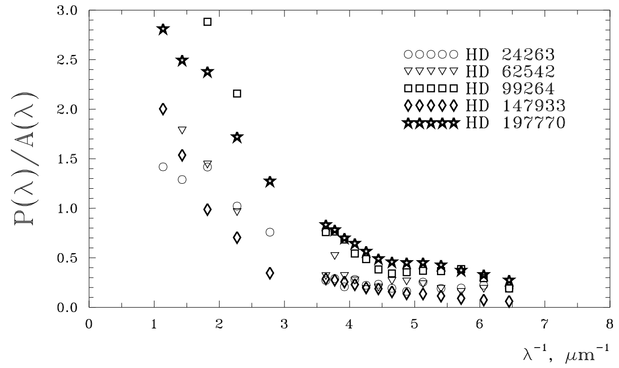

Figure 2: Polarizing efficiency of the interstellar medium in the direction of five stars. Observational data were taken from [3] (extinction) and [4] (polarization).

where $P_{\max}$ is the maximum degree of linear polarization which is reached near the wavelength $\lambda_{\max} \approx 0.55\,\mu$m (see [1], [2] for more discussion).

As a preliminary we chose five stars located not far than 500 pc[1] with measured UV polarization [4], then found the extinction (data published in [3] were mainly used) and calculated the ratio $P(\lambda)/A(\lambda)$. The obtained polarizing efficiencies are shown in Fig. 2. Note that, apparently, first presentation of the observational data in the similar form was made by Whittet [6, Fig. 9] who gave the average normalized dependence $P(\lambda)/A(\lambda) \cdot A_{\rm V}/P_{\max}$.

Here, we compare the observed polarizing efficiencies with the theoretical ones produced by rotating spheroidal grains of different composition, size, shape and porosity for various degrees and directions of grain alignment.

2 Modelling

Let us consider non-polarized light passing through a dusty cloud of rotating spheroidal grains. Rotating interstellar grains are usually partially aligned (see, e.g., [7]). Imperfect alignment is also supported by the fact that values of the polarizing efficiencies calculated for non-rotating or perfectly aligned particles are generally higher than the empirically estimated upper limit given by Eq. (1) [2, 8].

The extinction in stellar magnitudes and polarization in percentage can be found as [2]

$$A(\lambda) = 1.086 N_{\rm d} \langle C_{\rm ext} \rangle_\lambda\,, \qquad P(\lambda) = N_{\rm d} \langle C_{\rm pol} \rangle_\lambda 100\%\,, \tag{2}$$

where $N_{\rm d}$ is the dust grain column density and $\langle C_{\rm ext} \rangle_\lambda$ and $\langle C_{\rm pol} \rangle_\lambda$ are the extinction and linear polarization cross sections, respectively, averaged over the grain orientations

$$\langle C_{\rm ext} \rangle_\lambda = \left(\frac{2}{\pi}\right)^2 \int_0^{\pi/2} \int_0^{\pi/2} \int_0^{\pi/2} \pi r_V^2\, Q_{\rm ext}\, f(\xi,\beta)\, d\varphi d\omega d\beta\,, \tag{3}$$

$$\langle C_{\rm pol} \rangle_\lambda = \frac{2}{\pi^2} \int_0^{\pi/2} \int_0^{\pi} \int_0^{\pi/2} \pi r_V^2\, Q_{\rm pol}\, f(\xi,\beta)\, \cos 2\psi\, d\varphi d\omega d\beta\,. \tag{4}$$

Here, r_V is the radius of a sphere with the same volume as spheroidal grain, β is the precession-cone angle for the angular momentum $\mathbf{J}$ which spins around the magnetic field direction $\mathbf{B}$, φ the spin angle, ω the precession angle (see Fig. 1 in [8]). Quantities $Q_{\rm ext} = (Q_{\rm ext}^{\rm TM} + Q_{\rm ext}^{\rm TE})/2$ and $Q_{\rm pol} = (Q_{\rm pol}^{\rm TM} - Q_{\rm ext}^{\rm TE})/2$ are the efficiency factors for the non-polarized incident radiation, $f(\beta, r_V)$ is the cone-angle distribution.

We consider so-called imperfect Davies–Greenstein (IDG) orientation described by the function $f(\xi,\beta)$ which depends on the alignment parameter ξ and the angle β

$$f(\xi,\beta) = \frac{\xi \sin\beta}{(\xi^2 \cos^2\beta + \sin^2\beta)^{3/2}}. \tag{5}$$

[1]We suggest that these stars are seen through one interstellar cloud.

The parameter ξ is a function of the particle size r_V, the imaginary part of the grain magnetic susceptibility χ'' ($= \varkappa\omega_{\rm d}/T_{\rm d}$, where $\omega_{\rm d}$ is the angular velocity of grain), gas density $n_{\rm g}$, the strength of magnetic field B and dust ($T_{\rm d}$) and gas ($T_{\rm g}$) temperatures

$$\xi^2 = \frac{r_V + \delta_0(T_{\rm d}/T_{\rm g})}{r_V + \delta_0}, \quad \text{where} \quad \delta_0^{\rm IDG} = 8.23\,10^{23}\,\frac{\varkappa B^2}{n_{\rm g} T_{\rm g}^{1/2} T_{\rm d}}\,\mu\text{m}. \tag{6}$$

The angle ψ in Eq. (4) is expressed via the angles φ, ω, β and Ω (angle between the line of sight and the magnetic field, $0^\circ \leq \Omega \leq 90^\circ$). Note that for the case of the perfect DG orientation (PDG, perfect rotational or 2D orientation) the major axis of a non-spherical particle always lies in the same plane. For PDG, integration in Eqs. (3), (4) is performed over the spin angle φ only.

3 Results and discussion

The calculations have been made for prolate and oblate rotating spheroids of several sizes and aspect ratios consisting of astronomical silicate (astrosil) and amorphous carbon (AC1). Some results for prolate particles are plotted in Figs. 3 and 4. They show the polarizing efficiency in the wavelength range from the infrared to far ultraviolet. The observational dependence $P(\lambda)/A(\lambda)$ for two stars is given for comparison. The value of δ_0 for IDG orientation is typical of diffuse interstellar medium [8]. Calculations for porous grains are made using the Bruggeman mixing rule for refractive index and particles of same mass as compact ones. Note that calculated efficiencies can be considered as upper limits because some populations of grains (spherical, non-oriented) may give the contribution into extinction but not to polarization.

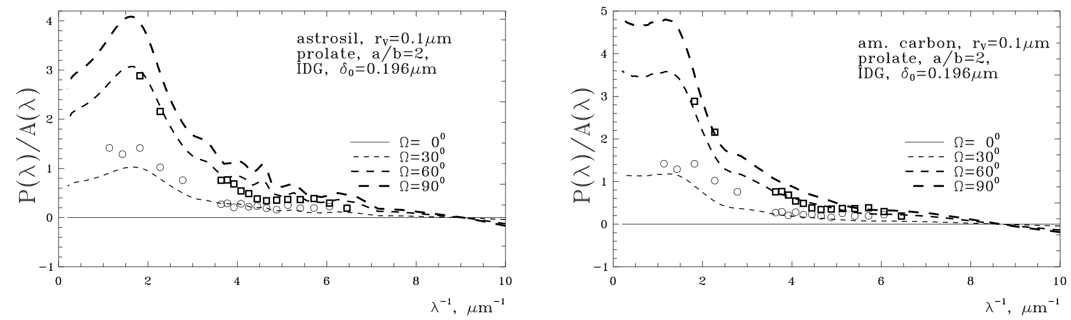

Figure 3: Wavelength dependence of polarizing efficiency for homogeneous rotating spheroidal particles of astronomical silicate and amorphous carbon. The effect of variations of particle composition and direction of alignment is illustrated. The open circles and squares show the observational data for stars HD 24263 and HD 99264, respectively.

From Figs. 3, 4 one can conclude that the wavelength dependence of polarizing efficiency is mainly determined by the particle composition and size. Variations of other parameters influence on the value of efficiency (the dependence of P/A is scaled). The growth of the efficiencies $P(\lambda)/A(\lambda)$ takes the place if we increase angle Ω (direction of alignment), parameter δ_0 (degree of alignment) or aspect ratio a/b (consider more elongated or flattened particles) and decrease particle porosity P or particle size r_V.

The resulting relationships will be applied for detailed comparison of the theory with observations.

Acknowledgments

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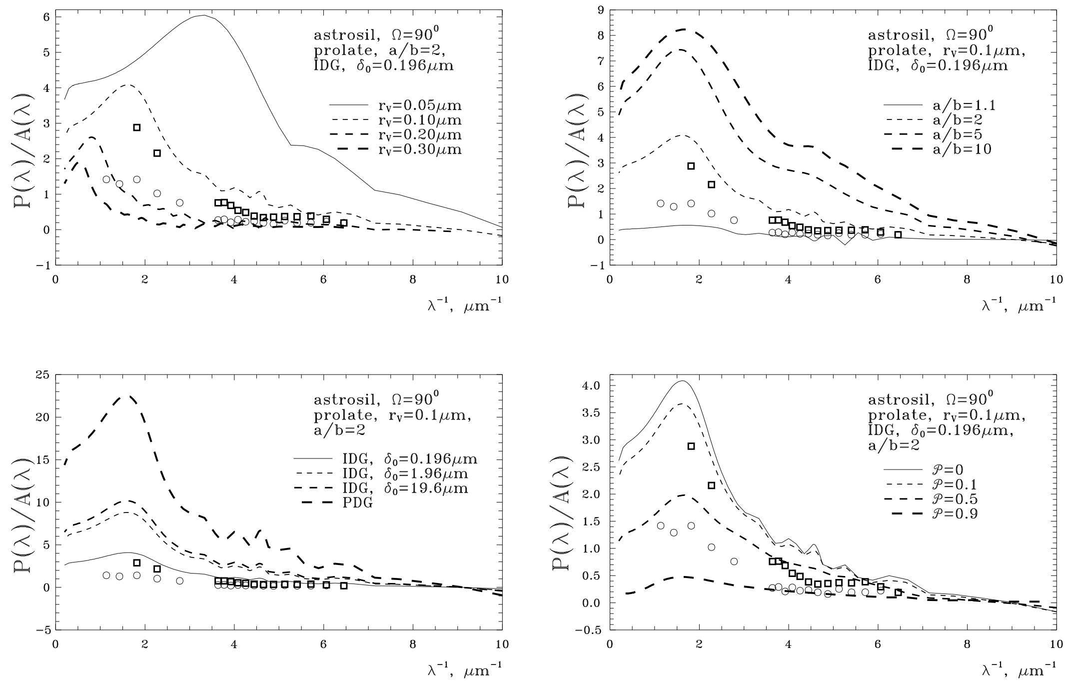

Figure 4: Wavelength dependence of polarizing efficiency for homogeneous rotating spheroidal particles of astronomical silicate. The effect of variations of particle size, shape, porosity and degree of alignment is illustrated. The open circles and squares show the observational data for stars HD 24263 and HD 99264, respectively.

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