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Evolution of non-spherical porous dust grains in galaxies

T. Kondratieva

Saint-Petersburg State University of Aerospace Instrumentation, 67 Bolshaya Morskaya, St. Petersburg, 190000 Russia

Abstract. Recent research has examined the evolution of interstellar dust grain size distribution over time scales of up to 10 Gyr, focusing on the primary grain growth and destruction mechanisms present in both the diffuse and dense interstellar medium. The grains were modeled as porous spheres, and for the first time, the porosity was considered to depend on the particle size and time. In this work, it is proposed in the first approximation that non-spherical dust grains have a comparable mass distribution to that of spherical ones. The use of porous spheroids facilitates the calculation of the time evolution of both the interstellar polarization curve and the interstellar extinction curve. As the polarization curve is known to be a critical test for porous dust grain models, the results obtained for spheroids are important for a further understanding of the dust grain evolution in galaxies.

Keywords: ISM: general, dust, extinction, evolution; polarization

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1 Introduction

Interstellar (IS) dust consists of small solid particles, usually within the sub-micron size range, and is present in various objects throughout the Universe, including comets and early galaxies. The origin and physical properties of dust grains, including their size and shape distributions, as well as related questions, continue to be areas of active research and discussion.

Information about dust properties can be obtained by modeling the wavelength dependencies of IS extinction and polarization and comparing these models with observations. The recent paper by Hirashita & Il'in (2022) examines variations in the grain size distribution throughout the evolution of galaxies over a period of up to 10 billion years. The particle porosity was assumed to depend on the grain size and change with time. IS extinction curves were constructed for different size and porosity distributions, assuming that the grains are spheres. The curves were compared with observations for our Galaxy.

However, the IS extinction curves do not accurately characterize the porosity of dust grains. The interstellar polarization curves are more sensitive to porosity, as it shifts the IS polarization maximum to the UV wavelengths. Therefore, the aim of this work was to calculate the IS polarization curves by replacing spheres with spheroids that have mass and porosity distributions based on findings of Hirashita & Il'in (2022).

2 Model

We assume that IS dust grains are homogeneous oblate spheroids of a fixed semiaxis ratio a/b ($a \geq b$). An increase in porosity p of the equal mass M particles leads to an increase in their volume, expressed as $V = \dfrac{M}{\rho\,(1-p)} = \dfrac{4\pi a^2 b}{3(1-p)}$. Consequently, the semiaxes maintain a constant ratio, where ρ is the density of the particle material. The grain porosity $p(M,t)$ and mass $n(M,t)$ distributions at various evolution times t are sourced from Hirashita & Il'in (2022). Following that work, we consider amorphous silicate and carbon particles with the standard (same as those of Hirashita & Il'in 2022) refractive indices $m^{\rm sil}(\lambda)$ and $m^{\rm amC}(\lambda)$ respectively.

It is assumed that a fraction $f(M)$ of silicate grains is aligned, whereas the remaining silicate and all carbon grains have a random orientation (Hensley & Draine 2023). The IS extinction $A(\lambda)$ at the wavelength λ is proportional to the mean extinction cross-section $\langle C_{\rm ext}\rangle$ of scatterers, while the IS polarization $P(\lambda)$ relates to the mean polarization cross-section $\langle C_{\rm pol}\rangle$. For spheroids, the cross-sections are influenced by the particle semiaxes a, b, the refractive index m, the incidence angle, α, and the polarization state of radiation, including TE and TM modes which are oriented perpendicularly. To calculate the cross-sections for spheroids, we apply the code developed by N. V. Voshchinnikov[1]

So, we use the following formulae to find the mean cross-sections:

$$\langle C_{\rm ext}\rangle(\lambda, a/b, \alpha, t) = \int\limits_{M_{\rm min}}^{M_{\rm max}} \left[\bar{C}_{\rm ext}\,\left(1 - f(M)\right) + C_{\rm ext}\, f(M)\right]\, n(M,t)\, dM, \qquad (1)$$

$$\langle C_{\rm pol}\rangle(\lambda, a/b, \alpha, t) = \int\limits_{M_{\rm min}}^{M_{\rm max}} C_{\rm pol}\, f(M)\, n(M,t)\, dM, \qquad (2)$$

where $C_{\rm ext} = \left(C_{\rm ext}^{\rm TE} + C_{\rm ext}^{\rm TM}\right)/2$, $C_{\rm pol} = \left(C_{\rm ext}^{\rm TE} - C_{\rm ext}^{\rm TM}\right)$, and $\bar{C}_{\rm ext}$ is the cross-section averaged over all spheroid orientations (Hensley & Draine 2023).

The cross-sections of our porous spheroids have more parameters:

$$C_{\rm ext}^{\rm TE,\,TM}\left[x_V(\lambda, M, t),\; a/b,\; m(m_0(\lambda), M, t),\; \alpha\right]. \qquad (3)$$

Here the diffraction parameter x_V related to the particle volume V is equal to

$$x_V(\lambda, M, t) = \frac{2\pi r_V}{\lambda} = \frac{2\pi}{\lambda}\left(\frac{3\,M}{4\pi\rho\,[1 - p(M,t)]}\right)^{1/3}. \qquad (4)$$

The refractive index reduced by the particle porosity is calculated with the Effective Medium Theory for material with the refractive index $m_0(\lambda)$

$$m(m_0(\lambda), M, t) = g^{\rm EMT}[m_0(\lambda), p(M,t)]. \qquad (5)$$

The fraction of aligned spheroidal particles $f(M)$, is characterized by two parameters: $M_{\rm crit}$ and ΔM, within the interval $[M_{\rm crit} - \Delta M, M_{\rm crit} + \Delta M]$, a transition occurs from the random orientation to the perfect alignment. In the IS dust grain alignment theory, $M_{\rm crit}$ is associated with a mean particle size of approximately 0.1 μm, as noted by Tram & Hoang (2022).

3 Numerical results

We have conducted calculations of the IS extinction and polarization curves based on the model described in Section 2, utilizing the results of galactic evolution of grain size and porosity distributions as outlined by Hirashita & Il'in (2022).

Calculations indicate that commonly used small values of ΔM (a sharp transition from randomly oriented silicate grains to perfectly aligned ones) result in an artifact in the polarization curve $P(\lambda)$ at $\lambda \sim 0.2$ μm.

[1] http://www.astro.spbu.ru/staff/ilin2/SOFTWARE/svm.html

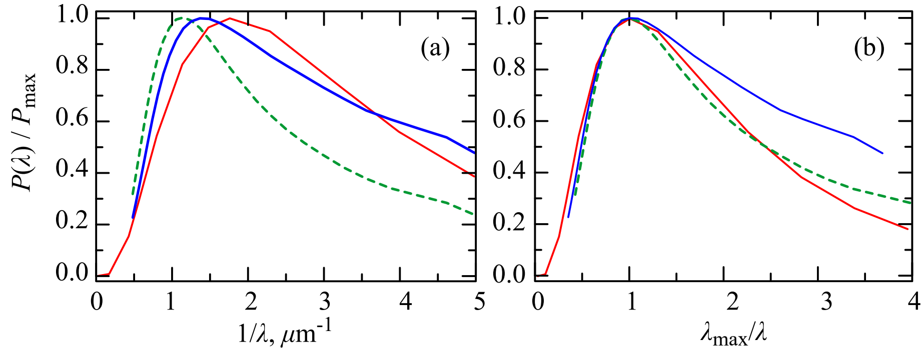

Fig. 1. Interstellar polarization curves: the standard Serkowski law with $\lambda_{\max} = 0.55\ \mu$m (red line) and curve obtained by us for the mass distribution from Hirashita & Il'in (2022) at $t = 10$ Gyr for compact (blue line) and porous (green line) oblate spheroidal grains (the aspect ratio $a/b = 2$).

For models with reasonable values of ΔM, we obtain IS polarization curves that are generally in agreement with those observed. Despite Hirashita & Il'in (2022) predict highly porous grains, p reaches 0.7 at the effective size $r_V \approx 0.03\ \mu$m, but being as low as 0.2 at $r_V \sim 0.002\ \mu$m and 0.2 μm. This does not too significantly shift the IS polarization curve maximum as can be seen in Fig. 1a.

The large values of $\lambda_{\max}$ obtained by us are caused by excess (in comparison to MRN) massive grains (size about 0.1–0.4 μm) that are consistently forming in evolved stars, as outlined in the scenario proposed by Hirashita & Il'in (2022). The width of the polarization curve for porous grains is found to well agree with the standard one (see Fig. 1b).

4 Conclusions

In conclusion, a spheroidal grain model has been developed to analyse the changes in the IS extinction and polarization curves during the evolution of ISM of the Galaxy. We applied the model to the findings of Hirashita & Il'in (2022), which assumed that the grain porosity depends on time and particle size. It has been shown that despite the significant porosity identified by Hirashita & Il'in (2022), their results yield IS polarization curves that generally align with the observed data.

References

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