

DUST GRAINS IN REFLECTION NEBULAE

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Abstract. Observations and Mie theory calculations of colors and polarization in several reflection nebulae are compared.

A new study of light scattering in reflection nebulae was begun in 1968. Details of the observations and of the theoretical treatment are given elsewhere (Zellner, 1970, 1973). Briefly, observations of color and polarization were made in a few selected regions of NGC 2068, NGC 7023, and IC 5067 with the two-channel digital polarimeter described by Coyne and Gehrels (1967). Most of the data were taken at the 154-cm Catalina reflector of the Lunar and Planetary Laboratory. About 40 h of integration time were invested per region, in six filters ranging in effective wavenumber from 1.21 to 3.03 per micron. The color data were generally in good agreement with previous results, but polarizations in NGC 2068 and NGC 7023 were found to be systematically larger than those reported by Elvius and Hall (1966).

The observations were compared with single-scattering Mie calculations for a wide variety of complex refractive indices $m^* = m' - im''$. Two types of broad size distributions were used, namely the Oort-van de Hulst distribution as modified by Greenberg (OHG distribution) (Greenberg, 1966), $n(a) = n_0 \exp -5[a/a_0]^3$, and the exponential distribution, $n(a) = n_0 \exp -5[a/a_0]$. The factor of 5 is introduced in order to make the scale radius a_0 roughly comparable with the equivalent single radius a in the absence of a size distribution. Wavelength-independent refractive indices were assumed, so that a_0 could be left as a free parameter to be determined by the agreement between theory and observation. In most theoretical studies of reflection nebulae, the dust cloud has been assumed to be homogeneous and bounded by a simple geometrical figure such as a sphere or a plane-parallel slab. As illustrated in Figure 1, my models are free of geometrical constraints; in each separate nebular region, the extreme scattering angles θ_1 and θ_2 are independently adjusted to best match the observations. The computed polarization is very sensitive both to the scattering geometry and to the scale radius. The color data, being more perturbed by internal and foreground extinction, are only indicative.

Reflection nebula polarizations usually decrease linearly with wavenumber from the infrared into the ultraviolet. This behavior is characteristic of forward-scattering dielectric grains, but can be produced by particles with a large m'' only under contrived conditions of internal attenuation. Thus pure graphite or metallic grains are immediately ruled out. It has been stated (Hanner, 1971) that silicate grains ($m' = 1.5$ to 1.7) would give negative polarization at short wavelengths, contrary to all observations. Figure 2, however, shows this statement to be a halftruth. With an appropriate shift

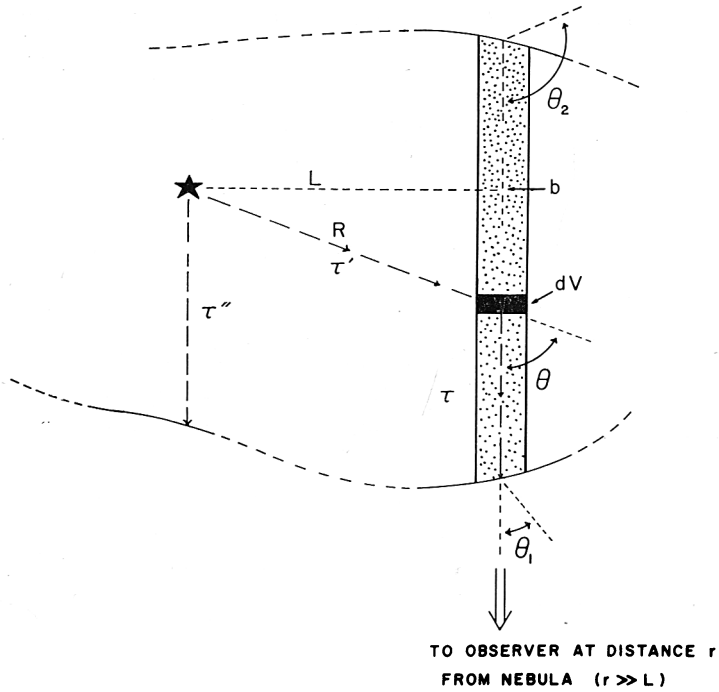


Fig. 1. The scattering plane.

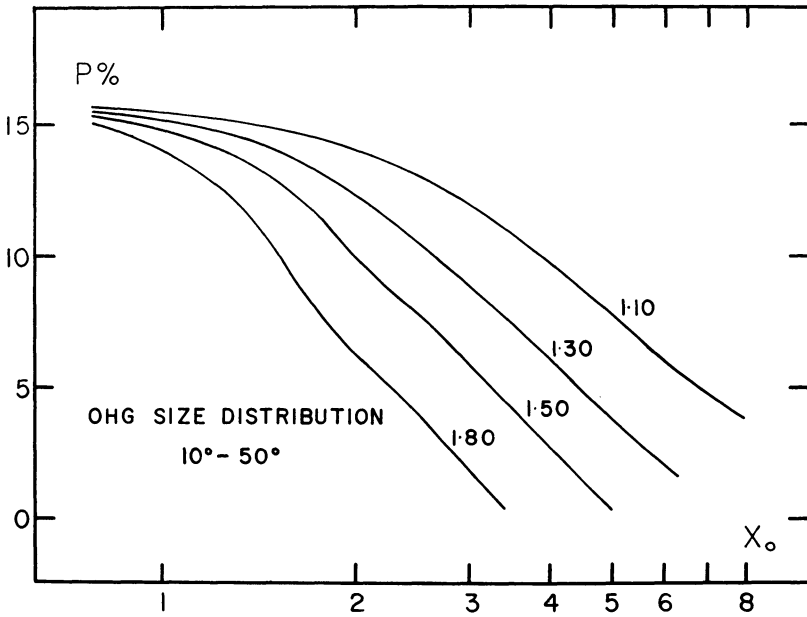


Fig. 2. Polarization vs $x_0 = 2\pi a_0/\lambda$ for single scattering by spherical grains of various refractive indices in the OHG size distribution.

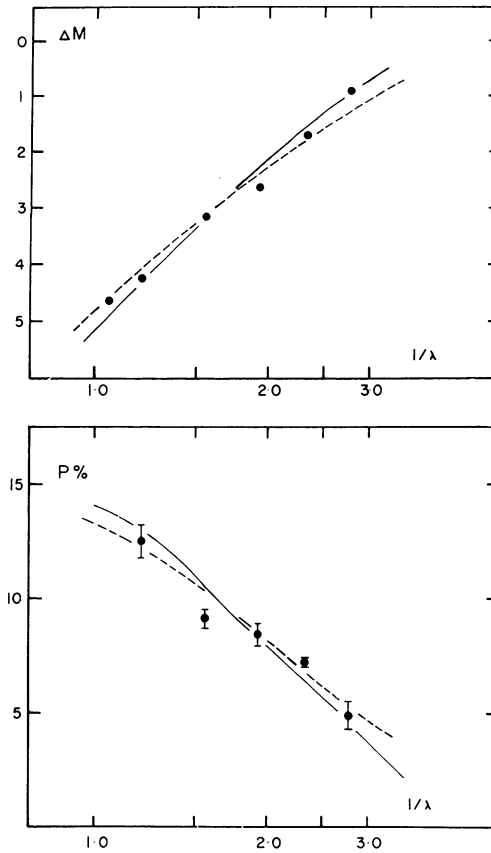


Fig. 3. Observations of color (top; $\Delta M = M_{\text{nebula}} - M_{\text{star}}$) and polarization (bottom) for a region in NGC 2068. The curves are computed for the OHG distribution with range of scattering angles 10° to 50° . Solid curve: refractive index $m^* = 1.50$, $a_0 = 0.19 \mu$; dashed curve: $m^* = 1.10$, $a_0 = 0.38 \mu$.

in radius, ices and silicates have almost identical scattering properties, and I doubt that they can be clearly distinguished by other than spectroscopic methods.

In bright reflection nebulae the optical depths are high*, so that single-scattering models are of doubtful validity. The agreement between observed and computed colors and polarizations, however, is in many cases quite good. Examples are given in Figures 3 and 4 for a region of NGC 2068, and in Figure 5 for a region in IC 5076. The fits become progressively worse as the imaginary component m'' is increased above 0.05 for $m' = 1.30$, or above 0.10 for $m' = 1.65$.

The derived grain properties are summarized in Table I for three fashionable refractive indices. The radii come out to be surprisingly small, smaller by a factor of 2 or 3 than are appropriate for the interstellar extinction curve. The meaning of this result is unclear. While the models are crude, an a_0 as large as the classical value of

* The conclusion by Gehrels (1967) that NGC 7023 is optically thin was based on an incorrect surface brightness, taken from Martel (1958).

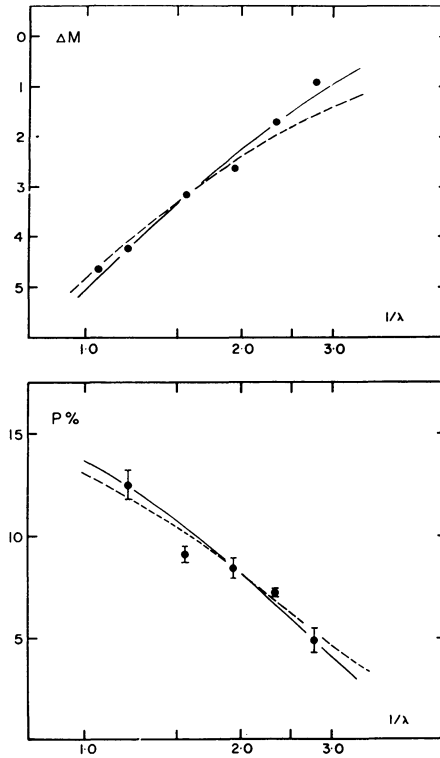


Fig. 4. As in Figure 3, except the solid curve is for $m^* = 1.30$, $a_0 = 0.26 \mu$, and the dashed curve $m^* = 1.30 - 0.10i$, $a_0 = 0.29 \mu$.

TABLE I

Derived grain sizes. The listed values are scale radii a_0 in the OHG size distribution

m^*	Nebula	a_0 microns	Mean a_0
1.30	2068 I	0.26	0.20 ± 0.04
	2068 II	0.15	
	5076	0.17	
	7023 NE	0.22	
	7023 N	0.16	
$1.30 - 0.05i$	2068 I	0.27	0.22 ± 0.05
	2068 II	0.20	
	5076	0.16	
	7023 NE	0.26	
	7023 N	0.17	
$1.65 - 0.10i$	2068 I	0.18	0.15 ± 0.02
	2068 II	0.13	
	5076	0.14	
	7023 NE	0.14	
	7023 N	0.12	

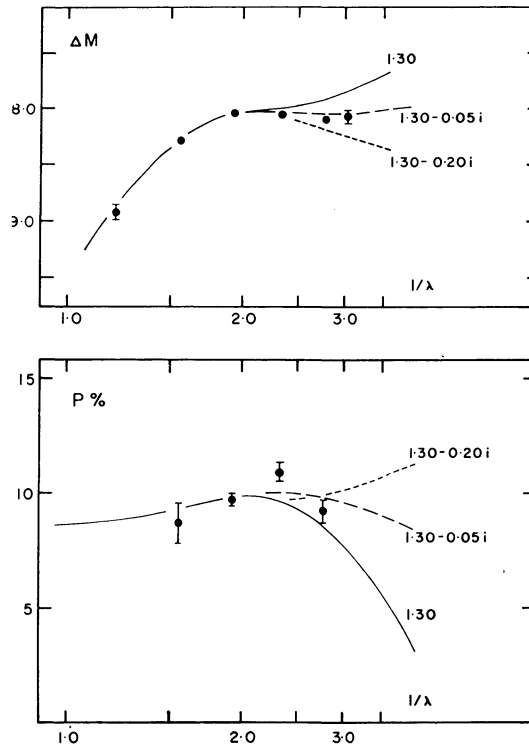


Fig. 5. Observations of color (top) and polarization (bottom) in a region of IC 5076. The scale radii are 0.17μ for $m^* = 1.30$, 0.16μ for $m^* = 1.30 - 0.05i$, and 0.15μ for $m^* = 1.30 - 0.20i$. The nebula is backscattering at $150^\circ < \theta < 165^\circ$.

0.6μ for ices is certainly excluded since, as noted above, negative polarizations would inevitably be produced. Even smaller grains, with radii near 0.1μ , are implied by the polarizations produced in circumstellar dust shells (Zellner, 1971; Shawl, 1972). It is possible that we are seeing a failure of the Mie theory, in that the extinction and angular-scattering properties of the interstellar grains cannot be modeled by smooth spheres with a unique radius. More extensive polarimetry, together with a theory able to handle arbitrarily high optical depths, is needed to resolve this dilemma.

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