DEPOLARIZATION EFFECT IN REFLECTION NEBULAE

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Abstract. The depolarization effects in reflection nebulae are caused by the size distribution, multiple scattering and irregularity of the grains. In the following abbreviated version of a study of the depolarization effect it is shown that the multiple scattering in reflection nebulae can lead to considerable decrease of the linear polarization. A sample of results obtained by the Monte Carlo method is tabulated.

Several attempts have been made to estimate the nature of dust grains in reflection nebulae by comparison of the observed data with the scattering pattern computed for composite models of polydisperse media using the assumed properties of particles likely to exist in the circumstellar and interstellar space.

Usually some simplifying assumptions for the refractive index and size distribution function for small spherical particles are introduced into the computer program and the Mie theory is used to determine the normalized scattering functions. This method has limits in application as well as in the interpretation of the results, since it gives an exact solution only for homogeneous spherical particles.

On the other hand, the scattering pattern of polydisperse media determined experimentally in the laboratory cannot provide any better guarantee for representing reliable models. The use of high-speed computers made the somewhat idealized polydisperse hypothetical media a relatively efficient tool for this kind of investigation. An excellent discussion of this problem is given in Deirmendjian's monograph (Deirmendjian, 1969).

The computation of scattering properties of optically thin media for this or similar purpose was carried out by several authors. Hanner (1971) compared extensive computations for silicate-like grains with the observed color and polarization in the Merope Nebula. She found that the complex refractive index $m = 1.65 - 0.05i$ may be more representative of the physical properties of submicron grains than pure dielectrics.

The polarization pattern of the computed models seems to be a suitable tool for estimating the physical properties of real dust grains.

There are, however, large discrepancies between the computed degree of polarization and observed values in reflection nebulae.

Polarimetric data obtained for reflection nebulae show that the degree of polarization is generally less than 20% in the visual spectral region and slightly increases with wavelength (see Martel, 1958; Elvius and Hall, 1967; Zellner, 1973). There is only one special case when the linear polarization found by Herbig (1972) in the circumstellar nebula of VY CMa is 60 or 70%.

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The computed models usually show large polarization, especially for models where the star is in front of the nebula (relative to the observer). It is obvious that some depolarization effect must be taken into consideration.

The degradation of the degree of polarization is due to the size distribution, multiple scattering or irregularities in the grain shape. The heterogeneity in the chemical composition of the grains (which cannot be excluded in the vicinity of a star's radiation field) can also lead to considerable depolarization of the scattered light.

The behavior of the polarization pattern for media containing absorbing particles differs significantly from those containing dielectric material. A positive polarization is to be found for absorbing clouds (even with moderate absorbers) with the maximum of polarization degree between phase angles $\vartheta = 60°$ to $90°$ (Greenberg and Hanner, 1970). The shift and increase of the maximum value towards 'forward scattering' (i.e. to lower phase angles) with an increase of the imaginary part of the refractive index is very typical.

The negative polarization (i.e. electric vector parallel to the polarization plane) near phase angles 150°–170° is typical of models containing dielectric particles (Greenberg and Hanner, 1970; Vanýsek, 1970). (These differences, of course, disappear, when the dominant size approaches the Rayleigh scattering domain where the polarization is always positive.)

From analysis of the available models it is evident that the large change of polarization degree with the phase angle together with the unknown geometry of the nebula may cause significant errors in the interpretation because the range of scattering angles along the line of sight is one of the unknown parameters. For instance, only positive polarization was detected in the scattered light of reflection nebulae. This may be due to the simple fact that the forward scattering is dominant in every studied case, and not to the nature of grains.

The depolarization effect caused by multiple scattering must be taken into consideration for dense clouds and the depolarization factor is a function of the optical thickness of the nebula.

In our recent study, the depolarization effect depending on the optical thickness was estimated by the Monte Carlo method. The best approach to the real conditions requires a method which is somewhat heterogeneous in the computing procedure. The phase function which determines the probability of photon propagation after the scattering event was computed for a polydisperse medium with a polynomial size distribution function. Because the determination of linear (and further elliptical) polarization caused by the subsequent scattering involves the difference in the dimensionless components of the Mie scattering complex amplitudes S_1 and S_2 (in van de Hulst's notation), the size distribution is then limited to the Γ function. Therefore the cross-sections and polarization pattern are computed for a *single* particle of some dominant parameter while the phase function follows the polydisperse pattern. This has led to results representing the depolarization effect which is due to the multiple scattering only. However, the photons' trajectory remains the same as in the polydisperse medium.

Table I presents one sample from the set of our results obtained for slightly absorbing silicate particles 0.15 μm in diameter and $m = 1.55-0.02i$ (albedo 0.84 for $\lambda =$ 5500 Å) in a spherical nebula which may be typical of a nebula where the multiple scattering plays a significant role. The Monte Carlo procedure involving 10^3 photons shows that the multiple scattering may be neglected up to the total optical thickness of the nebula 0.4, when it contributed 15% of the total photon output from the nebula.

TABLE I

Polarization of light in a spherical nebula[a] (Monte Carlo results)

$\rho\backslash\tau$	0.37	0.74	1.10	1.47	1.84	2.21
0.1	9.2	6.4	5.2	4.7	4.3	4.0
0.2	18.7	12.8	10.6	9.4	8.5	7.9
0.3	27.1	19.2	15.7	14.1	12.8	11.9
0.4	38.2	26.0	21.1	18.6	16.8	15.7
0.5	47.0	34.4	26.4	23.4	20.9	19.5
0.6	53.9	38.4	31.7	27.7	25.1	23.3
0.7	66.5	44.0	37.1	31.6	28.4	26.2
0.8	72.8	50.8	39.6	35.8	33.5	30.0
0.9	72.8	56.3	46.7	39.6	35.2	34.0
1.0	91.5	63.1	51.1	45.6	40.5	37.0

[a] Computed for grains with diameter $a = 0.15\ \mu$, refractive index $m = 1.55-0.02i$, $\lambda = 5500$ Å, size parameter $x_0 = 2\pi a/\lambda = 1.8$, albedo $= 0.84$. The phase function was assumed to be given by a polydisperse model with the size distribution $(x/x_0)^{-4}$ and limits $0.5 < x < 10$.
ρ = projected distance from the star relative to the radius of the nebula.
τ = optical thickness.

The polarization decreases considerably with increasing optical thickness. For instance, when τ increases from 0.4 to 1.5 the value of the polarization is approximately one half of the original value at the same distance from the star. The depolarization effect following from Table I is not combined with the depolarization caused by the size distribution and therefore for optically thin nebulae the values are high. The integration processes over particle sizes lead to the depolarization effect. The probability that the linear polarization in a polydisperse cloud at a given phase angle remains the same as the polarization of dominant size particles is very low. Even a relatively narrow size distribution can lead to a considerable depolarization. However, if both effects are combined then the resulting linear polarization for a moderately thick nebula might be less than 15% in the visual spectral region.

Conclusions

The above-mentioned results for one typical sample of various sets of models indicate that multiple scattering cannot be neglected in the interpretation of the observed linear polarization in reflection nebulae. Consequently, the interpretation of measured values of optically thick nebulae (as for instance NGC 7023) may be seriously misleading if based only on the polarization by single scattering.

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