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Effects of electromagnetic interaction in the polarization of light scattered by cometary and other types of cosmic dust

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ABSTRACT

Context. We study how the electromagnetic interaction between the monomers in aggregates affects the polarization of cosmic dust.
Aims. We aim to show that the electromagnetic interaction depends on the porosity and composition of the aggregates and contributes significantly to the spectral gradient of polarization (polarimetric color). The results may explain the observations of some comets that demonstrated atypical negative polarimetric color in the visible and also a reverse of the positive polarimetric color to the negative one in the near-infrared.
Methods. We performed computer simulations of the light scattering by aggregates consisting of spheres made of a variety of materials: transparent, absorptive, and the material similar to that of the dust in comet Halley. We studied how the number of monomers covered by the electromagnetic wave at a single period (on the light path equal to one wavelength) affects their interaction by considering linear clusters of 2 and 10 monomers of radius of 0.1 μm.
Results. Electromagnetic interaction between the monomers in aggregates depolarizes the light. The interaction becomes stronger if more monomers are covered by the electromagnetic wave at a single period. Thus, the porosity of aggregates influences their polarization. The electromagnetic interaction also depends on composition and is stronger for transparent materials.
Conclusions. Electromagnetic interaction between the monomers in aggregates may explain why the polarimetric color of comet dust decreases as observations move from the visible to the near-infrared since a longer wavelength covers more monomers. It may also explain why some comets exhibit negative polarimetric color even in the visible; these comets may have more compact dust. Strong electromagnetic interaction resulted either from compactness or transparency of the material can explain the negative polarimetric color of interplanetary dust and debris disks and contribute to the polarization of asteroids. In general, the spectral dependence of polarization is a promising tool for studying the properties of cosmic dust particles, particularly their porosity.

Key words. scattering – techniques: polarimetric – methods: numerical – comets: general – minor planets, asteroids: general – interplanetary medium

1. Introduction

The angular dependence of polarization is similar for comets (Kolokolova et al. 2004), interplanetary dust (Leinert et al. 1981), asteroids (Goidet-Devil et al. 1995), the Moon (Dollfus & Bowell 1971), and debris disks (Graham et al. 2007). It is characterized by a bell-shaped positive branch with the maximum at 65−85° and, for larger scattering angles, a negative branch within 155−180°. For different objects, it differs only in the position of the maximum and minimum polarization and their values. Unlike the angular dependence, the spectral gradient of polarization, often called polarimetric color, differs for different objects: in the visible, polarization increases with wavelength for comets (Kolokolova et al. 2004) but decreases for interplanetary dust (Levasseur-Regourd et al. 2001), asteroids (Kiselev et al. 1999; Ishiguro et al. 1997), and the Moon (Dollfus & Bowell 1971). For debris disks, both tendencies were observed (Tamura et al. 2006).

For asteroidal and lunar regolith particles, whose dominating size is dozens and even hundreds of microns (see, e.g., Clark et al. 2002), the light scattering occurs in the geometrical optics regime. In this case, the spectral change of the light-scattering characteristics is mainly defined by the spectral change in their refractive index. For the vast majority of asteroids, the absorption decreases with wavelength in the visible producing a corresponding increase in their albedo that defines their red color. This should cause the decrease in polarization (negative polarimetric color) in accordance with the inverse albedo/polarization rule (Dollfus & Zellner 1979).

The situation differs for comets. The angular and spectral behavior of comet polarization is most consistent with the model of dust particles as aggregates of submicron monomers (Kolokolova et al. 2004; Kimura et al. 2003, 2006). For submicron monomers in the visible, as the wavelength becomes longer, the size parameter $2\pi r/\lambda$ (r is the radius of the monomer and λ is the wavelength) becomes smaller. This brings the monomers closer to the Rayleigh scattering regime characterized by high polarization. Thus, polarization increases with wavelength resulting in a positive polarimetric color.

However, observations show that some comets exhibit "asteroidal" dependence of polarization characterized by negative polarimetric color (Kiselev et al. 2008). The negative polarimetric color in the visible was found for comets C/1999 S4 LINEAR, 73P/Schwassman-Wachmann 3, 9P/Tempel 1, 21P/Giacobini-Zinner, and C/1989 X1 Austin. Kiselev et al. (2008) also confirmed that comet polarization tends to decrease with wavelength in the near-infrared, as previously reported for comet C/1995 O1 Hale-Bopp (Jones & Gehrz 2000). These observational findings require a reconsideration of the aggregate model of comet dust.

The light scattering characteristics of aggregates are determined by two factors: (1) the properties of the individual monomers and (2) their electromagnetic interaction. Although the properties of individual monomers often dominate the formation of the light scattering characteristics as described above, the effects of interaction also play a noticeable role. In this paper, we study how the electromagnetic interaction between the monomers affects the polarization of light scattered by aggregates.

2. Modeling the electromagnetic interaction between monomers in aggregates

Electromagnetic interaction (also called coupling) between particles in an aggregate means that each monomer scatters the light in a way that depends on the scattering of all other monomers. In other words, the scattered electromagnetic wave is not the incident electromagnetic wave transformed by the interaction with each monomer separately but also includes electromagnetic waves resulted from exchange by electromagnetic waves between the monomers. One can roughly consider this as if the light scattered by any monomer then gets scattered by all other monomers and the net observed scattered light becomes formed by both the light scattered by all monomers in the aggregate and by multiple scattering of light between the monomers. An example of the electromagnetic interaction can be the scattering by two dipoles. As shown in Jackson (1965), the interaction energy between two dipoles $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ or, in other words, their mutual potential energy is

$$W_{12} = (\boldsymbol{p_1} \cdot \boldsymbol{p_2} - 3(\boldsymbol{n} \cdot \boldsymbol{p}_1)(\boldsymbol{n} \cdot \boldsymbol{p_2}))/|\boldsymbol{x_1} - \boldsymbol{x_2}|^3, \tag{1}$$

where $\boldsymbol{n}$ is a unit vector in the direction $\boldsymbol{x}_1 - \boldsymbol{x}_2$. Qualitatively, this should be similar if the light is scattered not by dipoles but by small particles, e.g., monomers in an aggregate. This is supported by the computations presented in Kimura & Mann (2004), which showed that the dipole terms play an important role in the interaction between monomers. Notice that according to Eq. (1) the interaction becomes stronger as the distance between the dipoles decreases. For aggregates, this should produce a dependence of the interaction and its effects on the aggregate compactness.

The electromagnetic interaction was not studied specifically for astronomical applications. However, the results presented by Chen et al. (1988); Mishchenko et al. (1995); Petrova et al. (2000); Kimura & Mann (2004); Tishkovets et al. (2004); Kolokolova et al. (2006) demonstrate the influence of the electromagnetic interaction on the light scattering characteristics of aggregates, in particular, the depolarizing effect of the electromagnetic interaction. Both Mishchenko et al. (1995) and Tishkovets et al. (2004) showed that the polarization decreases as monomers in the aggregate become closer, and, thus, the interaction between them increases. Kimura & Mann (2004) pointed out that if the wavelength is close to the size of monomers, then only interaction between the neighbors (touching monomers) affects the scattering whereas in case of longer wavelengths more distant monomers become involved that increases the influence of interaction on the light scattering characteristics. Kolokolova et al. (2006) described this effect by assuming that the strength of the electromagnetic interaction depends on the number of the monomers covered by the electromagnetic wave at a single period (on the light path equal to one wavelength). In accordance with this, Chen et al. (1988) found that the depolarization of the light scattered by aggregates increased with wavelength, i.e., with the number of monomers covered by a single wavelength. The depolarizing effect of interaction can be understood if one keeps in mind that the interaction between monomers in some sense is equivalent to the multiple scattering that also depolarizes the light. Multiple scattering depolarizes light more as the order of scattering, defined by the number density of the particles and their absorption, increases. Similar effects can be expected in the case of light scattering by aggregates.

Table 1. Maximum polarization (%) for 2- and 10-monomer aggregates.

Composition, wavelength, and refractive index	10-monomer aggregate	2-monomer aggregate
Cometary (Halley-like) dust		
0.45 μm, $m = 1.88 - i0.47$	59.2	56.9
0.6 μm, $m = 1.98 - i0.48$	87.2	87.0
2.2 μm, $m = 2.36 - i0.457$	91.7	97.2
$m = 1.9 - i0.5$		
0.45 μm	58.0	55.0
0.6 μm	89.0	88.6
2.2 μm	94.4	98.3
$m = 1.5 - i0.001$		
0.45 μm	92.9	94.5
0.6 μm	96.9	98.1
2.2 μm	98.5	99.5

To check the depolarizing effect of the interaction between monomers in aggregates, we tested the case in which the wavelength covered the same number of monomers as it increased and the case in which it covered more particles as it increased. Since our goal was to apply our results to the comet dust, we considered the monomers of radius 0.1μm that provided the best fit to the comet photometric and polarimetric data (Kimura et al. 2003, 2006). We first performed computations for the most realistic comet material, Halley-like dust, consisting of silicates, iron, organics refractory, and amorphous carbon. We refer to Kimura et al. (2003) for details and references to the refractive indices of the constituent materials. The refractive indices of the Halley-like dust are listed in Table 1.

To separate the effect of the number of particles that a wavelength covers from other effects that may influence the polarization, we considered light scattering by two linear clusters, one consisting of 2 spheres and the other of 10 spheres. In these calculations, we used the T-matrix method for a randomly oriented cluster of spheres (Mackowski & Mishchenko 1996). We performed the calculations for the three wavelengths 0.45, 0.6, and 2.2 μm to simulate comet observations described by Kiselev et al. (2008) and Jones & Gehrz (2000). Thus, for the 2-monomer cluster the wavelength always covered the same number of monomers, whereas for the 10-monomer cluster the number of covered monomers increased with wavelength. The results are presented in Fig. 1 and Table 1. Even though the polarization increases with wavelength in all cases confirming the strong effect of monomer size, the polarization of the 2-monomer cluster is lower than for the 10-monomer cluster at shorter wavelengths but at longer wavelengths (in the near-infrared) it becomes higher than the polarization of the larger, 10-monomer, cluster. This demonstrates the depolarizing effect of the interaction that increases as a larger number of monomers are covered by the wavelength.

To eliminate the influence of the spectral change in the refractive index, we repeated the computations using the refractive index m = 1.9–0.5 that is close to that of the Halley-like

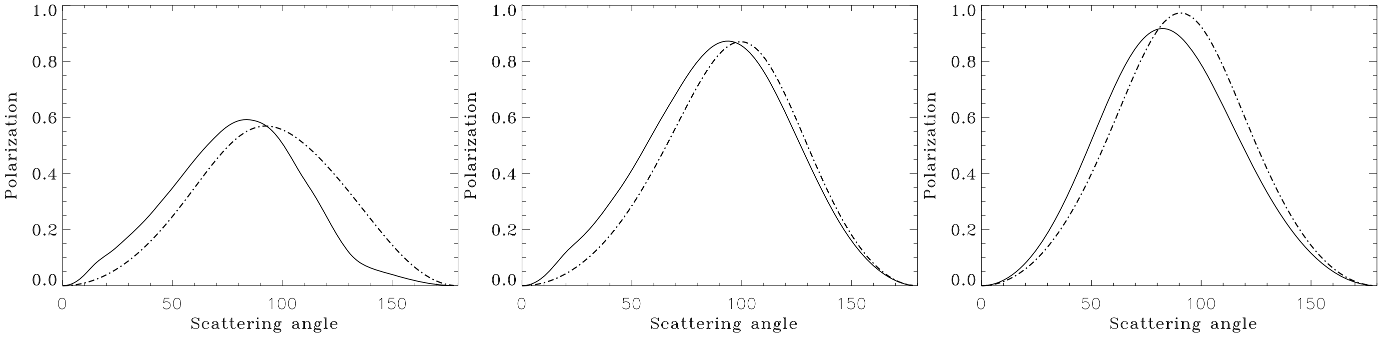

Fig. 1. Polarization vs. scattering angle calculated for 2-monomer (dashed line) and 10-monomer (solid line) aggregates made of the Halley-like material. The figures are (from left to right) for the wavelengths 0.45, 0.6, and 2.2 μm.

material but does not change with wavelength. Table 1 shows these results. One can see that the polarization changes the same way: a 10-monomer cluster produces more polarized light than a 2-monomer cluster at shorter wavelengths but less polarized light at longer wavelengths. This confirms that the number of monomers per single wavelength is the characteristic that defines the relative polarization of these two clusters, and not the spectral change in their refractive index.

However, the electromagnetic interaction should also depend on the absorption of the material and be stronger in the case of transparent materials for which more orders of scattering are possible. We checked this effect by computing light scattering of the same aggregates but made of some transparent, silicate-like material ($m = 1.5 - i0.001$). The results shown in Table 1 confirm that as the transparency of the material increases, the electromagnetic interaction strengthens and the depolarizing influence of the interaction causes the polarization of the 10-monomer particle to become lower than the polarization of the 2-monomer particle at all wavelengths.

3. Role of electromagnetic interaction in the spectral properties of polarization

The results of the previous section demonstrate that for typical cometary values of absorption, the number of monomers per single wavelength is the main factor that defines the interaction and, thus, its depolarizing effect. An important consequence of this is the dependence of polarization on the arrangement of monomers in aggregates, particularly, aggregate porosity. This was already noted by Kimura & Mann (2004) and Kolokolova et al. (2006). This tendency is also evident in the results of Lumme et al. (1997) and Petrova et al. (2000), where in all cases the maximum polarization is greater for more porous aggregates. A strong confirmation of these results can be found in Shen et al. (2009), where it was shown that an important parameter in defining the quantitative characteristics of the angular dependence of polarization is R/λ, where R is the characteristic radius of aggregate. Shen et al. (2009) showed that at $R/\lambda \ll 1$ the structure of the aggregate does not affect the polarization much; this is expected as in this case the wavelength always covers the entire aggregate. For $R/\lambda \geq 1$, the results are very complex and indicative of some interplay between the size of monomer, their number, porosity, and refractive index. However, the higher porosity of aggregates always resulted in greater values of polarization supporting the idea that lowering the number of monomers covered by a single wavelength decreases the interaction and thus also decreases the depolarization of the scattered light. The explanation of this tendency is that in compact aggregates the wavelength covers more particles than in the porous ones. Thus, the strength of the electromagnetic interaction is greater for compact particles that, in turn, results in stronger depolarization of the light scattered by more compact particles. This is illustrated by Fig. 2. For a very porous aggregate, an increase in wavelength may not provide any increase in the number of covered monomers. The situation is different for compact aggregates for which an increase in the wavelength always provides an increase in the number of the covered monomers if the monomers are smaller than the wavelength, which is the case for the cometary aggregates.

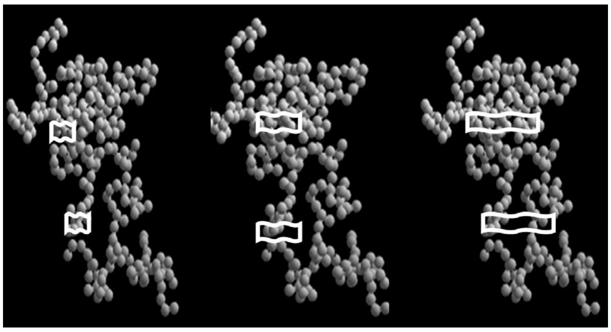

Fig. 2. The difference in the number of monomers that defines the strength of the electromagnetic interaction for porous (bottom part of the figure) and compact (top part of the figure) aggregates. At short wavelengths (*left* image), the number of the monomers covered in the porous and compact aggregates is the same. For longer wavelengths (*middle* image), the wavelength still covers the same number of particles in the porous aggregate (no change in the electromagnetic interaction) but many more in the compact aggregate (stronger interaction). Finally, at some longer wavelengths, even in the porous aggregate, the number of covered monomers increases, thus increasing the interaction (*right* image). As a result, depolarization of the scattered light is the same for the porous and compact aggregates at short wavelengths, increases for the compact aggregate at longer wavelengths, and at some wavelength also increases for the porous aggregate.

As described in the introduction, comets typically exhibit an increase in their polarization in the visible that can be easily explained by decreasing the size parameter of the submicron monomers as the wavelength increases. However, at some porosity not individual monomers but the interaction between them dominates the light scattering. For each porosity, there is a critical wavelength after which the number of monomers per single wavelength is sufficient to produce a strong interaction. At a wavelength longer than the critical one, the polarization can decrease with wavelength. This may explain why the cometary polarimetric color changes sign as the observations move from the visible to the near infrared.

4. Conclusions

We have shown that the electromagnetic interaction between the monomers in aggregates plays a significant role in the formation of the polarization of the light that they scatter. The strength of the electromagnetic interaction increases when more monomers are involved in the light-scattering process and/or the material is characterized by lower absorption. This leads us to draw the following conclusions for the cometary and other types of cosmic dust particles:

1. Cometary dust particles are porous aggregates of submicron particles. This causes the positive polarimetric color in the visible. However, porosity is not high enough to keep this trend at longer wavelengths and the polarimetric color reverses from being positive to negative in the near-infrared.
2. The negative polarimetric color in the visible observed for some comets may be caused by higher compactness of the particles in their dust. It is worth mentioning that for all ecliptic, Jupiter-family comets for which a spectral gradient of polarization in the visible has been measured (9P/Tempel 1, 73P/Schwassman-Wachmann 3, 21P/Giacobini-Zinner), the polarimetric color appears to be negative. This may be one more indication (in addition to others described in Kolokolova et al. 2007) of the higher compactness of the dust particles in old comets.
3. The depolarizing effect of the strong electromagnetic interaction may also play a role producing the negative polarimetric color observed for the asteroid regolith. As predicted by Worms (2003) and concluded from some meteoritic studies (Consolmagno & Britt 2002), the regolith particles may be rather fluffy, but compact in comparison with the comet dust.
4. A strong interaction caused by either compactness or composition can be the crucial factor that determines the polarimetric properties of interplanetary dust, particularly its negative polarimetric color.
5. Both negative and positive spectral gradients of polarization measured by Tamura et al. (2006) for the Beta Pictoris disk may result from different porosity or composition or a combination of these two factors for particles in different parts of the disk.

The major conclusion of this study is that the spectral dependence of polarization can be an important property for studying porosity of cosmic dust. In particular, the wavelength at which the positive polarimetric color changes to a negative value indicates the conditions in which the electromagnetic interaction between monomers overpowers the effect of their size parameter change. Thus, it can provide a way of determining porosity of the dust aggregates.

The difference in the refractive index (as well as the spectral change in the refractive index) also plays some role in providing different spectral gradients of polarization. We are planning a comprehensive computer modeling of the spectral behavior of polarization to ascertain the role of each factor contributing to the interplay between monomer composition, size, and arrangement of particles in aggregates.

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