Aggregate dust model to study the polarization properties of comet C/1996 B2 Hyakutake

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Received [year] [month] [day]; accepted [year] [month] [day]

Abstract
In our present study, the observed linear polarization data of comet Hyakutake are studied at wavelengths $\lambda = 0.365 \mu m$, $0.485 \mu m$ and $0.684 \mu m$ through simulations using Ballistic Particle-Cluster Aggregate and Ballistic Cluster-Cluster Aggregate aggregates of 128 spherical monomers. We first investigated that the size parameter of the monomer, $x \sim 1.56 - 1.70$, turned out to be most suitable which provides the best fits to the observed dust scattering properties at three wavelengths $\lambda = 0.365 \mu m$, $0.485 \mu m$ and $0.684 \mu m$. Thus the effective radius of the aggregate ($r$) lies in the range $0.45 \mu m \leq r \leq 0.49 \mu m$ at $\lambda = 0.365 \mu m$; $0.60 \mu m \leq r \leq 0.66 \mu m$ at $\lambda = 0.485 \mu m$ and $0.88 \mu m \leq r \leq 0.94 \mu m$ at $\lambda = 0.684 \mu m$. Now using superposition T-MATRIX code and the power-law size distribution, $n(r) \sim r^{-3}$, the best-fitting values of complex refractive indices are calculated which can best fit the observed polarization data at the above three wavelengths. The best-fitting complex refractive indices $(n, k)$ are found to be $(1.745, 0.095)$ at $\lambda = 0.365 \mu m$, $(1.743, 0.100)$ at $\lambda = 0.485 \mu m$ and $(1.695, 0.100)$ at $\lambda = 0.684 \mu m$. The refractive indices coming out from the present analysis correspond to mixture of both silicates and organics, which are in good agreement with the in situ measurement of comets by different spacecraft.

Key words: comets: general – dust, extinction – scattering – polarization

1 INTRODUCTION

The study of cometary polarization, over various scattering angles and wavelengths, gives valuable information about the nature of cometary dust. The numerical and experimental simulations of polarization data gives information about the physical properties of the cometary dust, which include size distribution, shape and complex refractive indices. Several investigators (Kikuchi et al. 1987; Lamy et al. 1987; Sen et al. 1991a, 1991b; Chernova et al. 1993; Xing & Hanner 1997; Petrova et al. 2004; Kimura et al. 2006; Das et al. 2004; Kolokolova et al. 2007, Bertini et al. 2007 etc.) have studied linear and circular polarization measurements of many comets. These studies help us to understand the dust grain nature of comets.

Comet Hyakutake (C/1996 B2) was the brightest comet appeared in the sky in the year 1996. Its passage near the Earth was one of the closest cometary approaches of the previous 200 years which passed within 0.1 AU of the Earth in March 1996. Comet Hyakutake was bright enough to make high precision polarimetric observations during pre-perihelion phase. Observations for the linear polarization of comet Hyakutake were carried out at three different wavelengths: $0.365 \mu m$, $0.485 \mu m$ and $0.684 \mu m$ by different investigators (Joshi et al. 1997; Kiselev & Velichko 1998 and Manset & Bastien 2000).

Greenberg and Hage (1990) first suggested that cometary particles are not spherical and porous. They originally proposed the presence of large numbers of porous grains in the coma of comets to
explain the spectral emission at 3.4\( \mu \text{m} \) and 9.7\( \mu \text{m} \). Dollfus (1989) discussed the results of laboratory experiments by microwave simulation and laser scattering on various complex shapes with different porosities. The results of in situ measurements carried out on the Giotto spacecraft at Comet Halley (Fulle et al. 2000) and the analysis of the infrared spectra of Comet Hale-Bopp (Moreno et al. 2003) also agree with the model of aggregates. It is clear from recent modeling of optical (Xing & Hanner 1997; Kimura 2001; Kimura et al. 2006; Petrova et al. 2004; Tishkovets et al. 2004; Lasue et al. 2006; Kolokolova et al. 2007; Bertini et al. 2007; Levasseur-Regourd et al. 2007, 2008; Das et al. 2008a; 2008b etc.), thermal-infrared observations (Lisse et al. 1998; Harker et al. 2002), laboratory studies (Wurm & Blum 1998; Gustafson & Kolokolova 1999; Hadamcik et al. 2002 etc.), and especially from the ‘Stardust’ returned samples (Hörz et al. 2006), that cometary dust consists of irregular, mostly aggregated particles.

Das & Sen (2006) studied the non-spherical dust grain characteristics of Comet Levy 1990XX using the T-matrix theory. They found that compact prolate grains as compared to spherical grains can better explain the observed linear polarization data. Recently, Das et al. (2008a) have again analyzed the observed polarization data of Comet Levy 1990XX and successfully reproduced the polarization curve through simulations using aggregate dust model, where the fit was still better. It has been found from their analysis that aggregate particles can produce a still better fit to the observed data as compared to compact prolate grains. Recently, using aggregate dust model, Das et al. (2008b) successfully explained the polarization characteristics of comet Hale-Bopp at \( \lambda = 0.485 \mu \text{m} \) and 0.684 \( \mu \text{m} \). Lasue et al. (2009) have explained successfully the polarization properties of comet Hale-Bopp and Halley by using a model of light scattering through a size distribution of aggregates (spherical or spheroidal) mixed with single spheroidal particles.

In the present work, the aggregate dust model is proposed to study the observed polarization data of Comet Hyakutake at \( \lambda = 0.365 \mu \text{m}, 0.485 \mu \text{m} \) and 0.684\( \mu \text{m} \).

2 AGGREGATE MODEL OF COMETARY DUST:

The aggregates are built by using ballistic aggregation procedure. Two types of aggregates are considered here- BPCA (Ballistic Particle-Cluster Aggregate) and BCCA (Ballistic Cluster-Cluster Aggregate). In actual case, the BPCA clusters are more compact than BCCA clusters (Mukai et al. 1992). A systematic explanation on dust aggregate model is already discussed in our previous work (Das et al. 2008a). Laboratory diagnosis of particle coagulation in the solar nebula suggests that the particles grow under BCCA process. It is also found that the morphology of dust particles does not play a major role in determining the shape of polarization (Kimura 2001; Kimura et al. 2003, 2006; Kolokolova et al. 2006; Lasue & Levasseur-Regourd 2006; Bertini et al. 2007; Das et al. 2008a, 2008b). The size of the individual monomer in a cluster plays an important role in scattering calculations. These have been confirmed by the results of previous work on dust aggregate model (Kimura et al. 2003; Kimura et al. 2006; Petrova et al. 2004; Hadamcik et al. 2006; Bertini et al. 2007) and also from our previous work (Das et al. 2008a).

3 COMPOSITION

The in situ observations of comets, laboratory analysis of samples of Interplanetary Dust Particles (IDP) and remote infrared spectroscopic study of comets give useful information about the composition of cometary dust. The in situ measurement of impact-ionization mass spectra of Comet Halley’s dust, has suggested that the dust consists of magnesium-rich silicates, carbonaceous materials, and iron-bearing sulfides (Kissel et al. 1986; Jessberger et al. 1988 and Jessberger 1999). Actually, the first evidence for carbonaceous material in comets comes from the study of Vega spacecraft data by Kissel et al. (1986). These materials are also known to be the major constituents of IDPs (Brownlee et al. 1980). The studies of comets and IDPs have shown the presence of amorphous and crystalline silicate minerals (e.g. forsterite, enstatite) and organic materials (Hanner & Bradley 2004). Laboratory studies have shown that majority of the collected IDPs fall into the spectral classes defined by their 10 \( \mu \text{m} \) feature profil.
These observed profiles indicate the presence of pyroxene, olivine and layer lattice silicates. This is in good agreement with results obtained from Giotto and Vega mass spectrometer observations of Comet Halley (Lamy et al. 1987). The infrared (IR) measurement of comets has also provided important information on the silicate compositions in cometary dust. The spectroscopic studies of silicates have shown the predominance of both crystalline and amorphous silicates consisting of pyroxene or olivine grains (Wooden et al. 1999; Hayward et al. 2000, Bockelée - Morvan et al. 2002 etc.). Mg-rich crystals are also found within IDPs and are predicted by comparing the IR spectral features of Comet Hale-Bopp with synthetic spectra obtained from laboratory studies (Hanner 1999; Wooden et al. 1999, 2000). ‘Stardust’ samples have also confirmed a variety of olivine and pyroxene silicates in Comet 81P/Wild 2 (Zolensky et al. 2006).

Levasseur-Regourd et al. (1996) studied a polarimetric data base of several comets and from the nature of phase angle (α) dependence, they concluded that there is a clear evidence for at least two classes of comets according to the values of polarization at α ≈ 80° − 100°: comets with a high maximum in polarization, of about 25% for one group and smaller than 15% for the other group. The two classes of comets are distinct only for α > 35°. It has been also observed that there is a very good correlation between the existence of a high maximum in polarization and a strong silicate emission feature (Levasseur-Regourd 1999). The observed polarization data of comet Hyakutake showed a high maximum in polarization. The polarization at a given phase angle larger than 30° most often increases linearly with increasing wavelength in the visible domain and this increase being steeper for larger phase angles (Levasseur-Regourd & Hadamcik 2003). Recent studies have provided useful information about the two groups of polarimetrically different comets (Kiselev et al., 2001; Kiselev et al., 2004; Jewitt 2004; Jockers et al., 2005).

It has been already found that the silicate composition can best reproduce the observed polarization data of Comet Levy 1990XX and Comet Hale-Bopp (Das et al. 2008a,b).

4 NUMERICAL SIMULATIONS:

The scattering calculations for BCCA & BPCA particles have been done by the Superposition T-matrix code, which gives rigorous solutions for ensembles of spheres (Mackowski & Mishchenko 1996). The observed linear polarization data of comet Hyakutake at λ = 0.365μm, 0.485μm & 0.684μm are taken from Joshi et al. (1997), Kiselev & Velikhco (1998), Manset & Bastien (2000).

The linear polarization is given by

\[ P(\theta) = \frac{S_{21}}{S_{11}} \]

For modeling comet Hyakutake, we will use a power-law size distribution, \( n(r) = \frac{dn}{dr} \sim r^{-3} \). For a particular type of aggregate with fixed N, the size distribution is just \( \frac{dn}{da_m} \sim a_m^{-3} \). Thus the averaged polarization is (Shen et al. 2009):

\[ \bar{P} = \frac{\int_{a_{\text{min}}}^{a_{\text{max}}} \frac{dn}{da_m} p(a_m, \theta) S_{11}(a_m, \theta) n(a_m) da_m}{\int_{a_{\text{min}}}^{a_{\text{max}}} S_{11}(a_m, \theta) n(a_m) da_m} \]

where \( a_{\text{min}} \) and \( a_{\text{max}} \) are the minimum and maximum values of the monomer size in our size distribution.

The radius of an aggregate particle can be described by the radius of a sphere of equal volume given by \( r = a_m N^{1/3} \), where N is the number of monomers in the aggregate. In the present work, \( N = 128 \) is taken. The size parameter of the monomer is given by \( x = \frac{2\pi a_m}{\lambda} \). We first investigated that \( x \sim 1.56 \) − 1.70 turned out to be most suitable which may provide the best qualitative fits to the observed dust scattering properties at three wavelengths \( \lambda = 0.365\mu m, 0.485\mu m \) and \( 0.684\mu m \). This correspond to \( 0.090\mu m \leq a_m \leq 0.098\mu m \) at \( \lambda = 0.365\mu m \); \( 0.120\mu m \leq a_m \leq 0.131\mu m \) at \( \lambda = 0.485\mu m \) and \( 0.174\mu m \leq a_m \leq 0.186\mu m \) at \( \lambda = 0.684\mu m \). Thus the effective radius of the aggregate \( r \) lies in
the range 0.45μm ≤ r ≤ 0.49μm at λ = 0.365μm; 0.60μm ≤ r ≤ 0.66μm at λ = 0.485μm and 0.88μm ≤ r ≤ 0.94μm at λ = 0.684μm.

We start calculations considering the refractive indices for amorphous pyroxene and amorphous olivine at λ=0.365μm, 0.485μm & 0.684μm. The refractive indices of the materials are calculated by linearly interpolating the data obtained from laboratory studies (Dorschner et al. 1995). Olivines and pyroxenes are described by Mg_{2y}Fe_{2-2y}SiO_{4}, with y = 0.4, 0.5 and Mg_{y}Fe_{1-y}SiO_{4}, with y = 1.00, 0.95, 0.8, 0.7, 0.6, 0.5 and 0.4.

It has been already investigated that the choice of the above values of refractive indices can’t match the observed polarization data of Comet Levy 1990XX and Hale-Bopp (Das et al. 2008a,b). The same set of refractive indices is now chosen to fit the observed polarization data of Comet Hyakutake. The calculations have been done for BCCA aggregates. But no such good fit has been observed using the above value of refractive indices. Next, the calculation has been repeated for carbonaceous materials, but none of them could match the observed data well.

We now use $\chi^2$ minimization technique to evaluate the best-fitting values of $(n, k)$, which can fit to the observed polarization data. We have already used this minimization technique to fit the observed linear polarization data of Comet Levy 1990XX at λ = 0.485μm and Comet Hale-Bopp at λ = 0.485μm and 0.684μm (Das et al. 2008a,b), with aggregate models of dust.

The error in the fitting procedure can be defined as

$$\chi^2_{pol} = \sum_{i=1}^{J} \left| \frac{P_{obs}(\theta, \lambda) - P_{model}(\theta, \lambda)}{E_p(\theta, \lambda)} \right|^2$$

Here, $P_{obs}(\theta, \lambda)$ is the degree of linear polarization observed at scattering angle $\theta_i$ (i = 1, 2, ..., J) and wavelength $\lambda$, $P_{model}(\theta, \lambda)$ is the polarization values obtained from model calculations and $E_p(\theta, \lambda)$ is the error in the observed polarization at scattering angle $\theta_i$ and wavelength ($\lambda$).

We now introduce a quantity $\chi^2 = \chi^2_{pol}/J$, where J is the number of data points. The values of $(n, k)$ are varied over a large range simultaneously with $a_m$ and we find for a particular value of $(n, k)$, $\chi^2$ becomes minimum. This particular value of $(n, k)$ is our best fitted $(n, k)$ value and the corresponding minimum value of $\chi^2$ is denoted as $\chi^2_{min}$. It is also observed that this technique of minimization of $\chi^2$ is quite unique. The value of $\chi^2_{min}$ gives the confidence level on our best fit values of $(n, k)$ and also in the overall fitting procedure.

We need to fine-tune the free parameters $(n, k)$ in the model to make the best fit to the observed linear polarization data of Comet Hyakutake. The real part of the refractive index is increased from $n = 1.4$ to $2.0$ with 0.001 steps, while the imaginary part of the refractive index is increased from $k = 0.001$ to $1.0$ with 0.001 steps. The same range has been already used for Comet Levy 1990XX and Comet Hale-Bopp (Das et al. 2008a,b).

Now we analyze the observed data of comet Hyakutake at 0.365μm. We calculate $\bar{P}$ averaged over the size distribution $n(r) \sim r^{-3}$ with $r_{min} = 0.45μm$ and $r_{max} = 0.49μm$ ($a_{min} = 0.090μm$, $a_{max} = 0.098μm$). The best fitting refractive index at 0.365μm is found to be $n = 1.745$, $k = 0.095$. The simulated polarization curve at 0.365μm is shown in Fig. 1.

We now extend our calculation further to fit the observed polarization data at $\lambda = 0.485μm$ and 0.684 μm. Here we also calculate $\bar{P}$ averaged over the size distribution $n(r) \sim r^{-3}$ with $r_{min} = 0.60μm$ and $r_{max} = 0.66μm$ ($a_{min} = 0.120μm$, $a_{max} = 0.131μm$) at $\lambda = 0.485μm$ and $r_{min} = 0.88μm$ and $r_{max} = 0.94μm$ ($a_{min} = 0.174μm$, $a_{max} = 0.186μm$) at $\lambda = 0.684μm$. The best fitting refractive indices are obtained from the present analysis are found to be (1.743, 0.100) at $\lambda = 0.485μm$ and (1.695, 0.100) $\lambda = 0.684μm$. The simulated polarization curve for comet Hyakutake at $\lambda = 0.485μm$ and 0.684 μm for BCCA aggregates are shown in Fig. 2 and Fig. 3.

5 DISCUSSION:

The negative polarization behaviour of comet is one of the major features observed in comets. Several comets show negative polarization beyond 157° scattering angle (Kikuchi et al., 1987; Chernova et al.,
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Fig. 1 Polarization values as observed at wavelength $\lambda = 0.365 \mu m$ for comet Hyakutake by Joshi et al. (1997) and Kiselev & Velichko (1998). The solid curve represents the best-fitting polarization curve obtained for BCCA particles with 128 monomers for a size distribution $n(r) \sim r^{-3}$ for $0.45 \mu m \leq r \leq 0.49 \mu m$ at $\lambda = 0.365 \mu m$. Here $n = 1.745$, $k = 0.095$.

1993; Ganesh et al., 1998 etc.). Interestingly, all comets show very similar characteristics of negative polarization (minimum value of polarization $\sim -2\%$ near $170^0$ and inversion angle at $20-22^0$). Comet Hyakutake was observed over a wide scattering angle range ($68.6^0-143.1^0$), but there was no observation recorded beyond $143.1^0$ (Joshi et al., 1997; Kiselev & Velichko 1998 and Manset & Bastien 2000). In the present work, it is interesting to observe that the used dust aggregate model reproduce the negative polarization behaviour beyond $157^0$.

The strength of the silicate feature is defined as the ratio of the flux between 10 and 11 $\mu m$ to that of the underlying continuum (Lisse 2002; Sitko et al., 2004; Kolokolova et al., 2007). The silicate feature strength of Comet Hyakutake is $>1.5$ (Lisse 2002) whereas the values for Comet Levy 1990XX and Comet Hale-Bopp are given by 1.8 (Harker et al., 1999) and 2.16 (Sitko et al., 2004). Comet Hale-Bopp is an intrinsically bright comet, with polarization values much higher than those of other comets. It has been found that Comet Hale-Bopp shows the highest silicate feature strength. The strong silicate feature indicates high abundance of silicates in the dust. It can be seen that the refractive indices coming out from the present calculation is closed to the refractive indices of silicates and organics. Again the in situ measurements of comet Halley (Lamy et al. 1987) and the ‘Stardust’ returned samples of comet Wild 2 (Zolensky et al., 2006) showed the presence of a mixture of silicates and organic refractory in cometary dust. Thus, our model calculations represent the more realistic type of grains which may be considered as a mixture of silicates and carbonaceous materials. It is to be noted that the presence of negative polarization in the backscatter domain has been commonly attributed to silicates or dirty ice grains (Kimura et al., 2006).

It has been investigated that the aggregate dust model can well fit the observed polarization data of comet Hyakutake when the size parameter of the monomer, $x \sim 1.56 - 1.70$. Thus the size ranges of the
monomer differ for three wavelengths which is unlikely. The proposed model can be further developed if we take a mixture of compact spheroidal grains and aggregates over a wide size range which Lasue et al. (2009) used in their paper. They studied comet Halley and comet Hale-Bopp using a mixture of fluffy aggregates and compact solid grains and successfully explained the observed polarization characteristics of two comets. In a follow-up paper, we also plan to model cometary dust as a mixture of aggregates and compact particles.

6 CONCLUSIONS

1. The size parameter of the monomer, $x \sim 1.56 - 1.70$, turned out to be most suitable which provides the best fits to the observed polarization data of comet Hyakutake at three wavelengths $\lambda = 0.365 \mu m$, $0.485 \mu m$ and $0.684 \mu m$. This correspond to $0.090 \mu m \leq a_m \leq 0.098 \mu m$ at $\lambda = 0.365 \mu m$; $0.120 \mu m \leq a_m \leq 0.131 \mu m$ at $\lambda = 0.485 \mu m$ and $0.174 \mu m \leq a_m \leq 0.186 \mu m$ at $\lambda = 0.684 \mu m$.
2. The best fit refractive indices coming out from the present analysis are $n = 1.745$ and $k = 0.095$ for $N = 128$ at $\lambda = 0.365 \mu m$; $n = 1.743$ and $k = 0.100$ for $N = 128$ at $\lambda = 0.485 \mu m$ and $n = 1.695$ and $k = 0.100$ for $N = 128$ at $\lambda = 0.684 \mu m$. These values resemble the mixture of silicates and carbonaceous compounds.
3. The negative polarization values have been successfully generated for $\theta > 157^0$ at three wavelengths.
4. We plan a follow-up paper where computations will be made considering a mixture of aggregates and compact spheroidal particles over a wide size range of the particles.
Fig. 3  Polarization values as observed at wavelength $\lambda = 0.684 \mu m$ for comet Hyakutake by Joshi et al. (1997), Kiselev & Velichko (1998) and Manset & Bastien (2000). The solid curve represents the best-fitting polarization curve obtained for BCCA particles with 128 monomers for a size distribution $n(r) \sim r^{-3}$ for $0.88 \mu m \leq r \leq 0.94 \mu m$ at $\lambda = 0.684 \mu m$. Here $n = 1.695$, $k = 0.100$.

ACKNOWLEDGMENTS

The authors HSD and AKS acknowledge Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune for its associateship programme. The authors acknowledge T. Mukai and Y. Okada for help on the execution of BPCA and BCCA codes. The authors are thankful to D. Mackowski, K. Fuller, and M. Mishchenko, who made their superposition T-matrix code publicly available. The authors highly acknowledge the referee of the paper for his valuable suggestions and comments for which the quality of the paper has been improved.

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