Modelling the polarization properties of Comet 1P/Halley using a mixture of compact and aggregate particles

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ABSTRACT

Both the in situ measurement of Comet 1P/ Halley and the Stardust-returned samples of Comet Wild 2 showed the presence of a mixture of compact and aggregate particles, with both silicates and organic refractory being in the composition of the cometary dust. Results obtained recently from the Stardust mission suggest that the overall ratio of compact to aggregate particles is 65:35 (or 13:7) for Comet 81P/Wild 2. In the present work, we propose a model that considers cometary dust as a mixture of compact and aggregate particles, with a composition of silicate and organic. We consider compact particles as spheroidal particles and aggregates as both ballistic cluster–cluster aggregate (BCCA) and ballistic agglomeration with two migrations (BAM2) aggregate with a certain size distribution. The mixing ratio of compact to aggregate particles is taken to be 13:7. For modelling Comet 1P/Halley, the power-law size distribution \( n(a) \sim a^{-2.6} \), obtained from a re-analysis of the Giotto spacecraft data, for both compact and aggregate particles, is used. We consider a mixture of BAM2 and BCCA aggregates with a lower cut-off size of about 0.20 \( \mu m \) and an upper cut-off of about 1 \( \mu m \). We also consider a mixture of prolate, spherical and oblate compact particles with an axial ratio (\( E \)) of 0.8–1.2 where a lower cut-off size of about 0.1 \( \mu m \) and an upper cut-off of about 10 \( \mu m \) are considered. Using a \( T \)-matrix code for polydisperse spheroids (0.1 \( \mu m \leq a \leq 10 \mu m \)) and superposition \( T \)-matrix code for aggregates (0.2 \( \mu m \leq a_v \leq 1 \mu m \)), the average simulated polarization curves are generated, which can best fit the observed polarization data at the four wavelengths: \( \lambda = 0.365, 0.485, 0.670 \) and 0.684 \( \mu m \). The suitable mixing percentages of aggregates obtained from the present modelling are 50 per cent BAM2 and 50 per cent BCCA particles, and the silicate-to-organic mixing percentages are 78 per cent silicate and 22 per cent organic, in terms of volume. The present model successfully reproduces the observed polarization data, especially the negative branch, for Comet 1P/Halley at the above four wavelengths, more effectively as compared to other work done in the past. It is found that among the aggregates, the BAM2 aggregate plays a major role in deciding the cross-over angle and depth of the negative polarization branch.

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

1 INTRODUCTION

The study of polarization of the scattered radiation from comets, over various scattering angles and wavelengths, gives valuable information about the nature of cometary dust. The analysis of polarization data gives information about the physical properties of the cometary dust, which include size distribution, shape and complex refractive indices.

The in situ dust measurement of Comet 1P/Halley was the first direct account of grain mass distribution (Mazets et al. 1986). Mukai, Mukai & Kikuchi (1987) and Sen et al. (1991) analysed the polarization data of Comet 1P/Halley using power-law dust distribution (Mazets et al. 1986), and using Mie theory they derived a set of refractive indices of cometary grains. The dust distribution function derived by Mazets et al. (1986) is actually based only on the Vega 2 results, while Lamy, Grün & Perrin (1987) derived the grain size distribution function for Comet 1P/Halley by comparing data from the spacecraft Vega 1, Vega 2 and Giotto. Much later this dust distribution function was used by Das, Sen & Kaul (2004) to analyse the polarization data of a number of comets including Comet 1P/Halley.

Several investigators made useful polarimetric measurements of Comet 1P/Halley through International Halley Watch (IHW) filters (Bastien, Menard & Nadeau 1986; Kikuchi et al. 1987; Le Borgne,
Leroy & Arnaud 1987; Sen et al. 1991; Chernova, Kiselev & Jockers 1993). The polarization data of Comet 1P/Halley were analysed by several investigators using the Mie theory, which assumes the dust particles to be spherical (Mukai et al. 1987; Sen et al. 1991; Das et al. 2004). However, the naturally occurring cometary grains cannot be ideal compact spheres, as required by the Mie theory. The Mie theory was used, as it is more convenient and direct, with a small number of free parameters required for modelling. Das & Sen (2006) studied the non-spherical dust grain characteristics of Comet C/1990 K1 Levy using the T-matrix theory. They found that compact prolate grains (with axial ratio = 0.486) as compared to spherical grains better explain the observed linear polarization data. Assuming an individual cometary grain to be an aggregate of several monomers, Das et al. (2008a) again analysed the observed polarization data of Comet C/1990 K1 Levy and successfully reproduced the polarization curve through simulations, where the fit was still better. The $X_{\text{max}}$ value for the aggregates was found to be 4.2 whereas the value obtained by Das & Sen (2006) for compact prolate grains was 5.22. Thus it was concluded that aggregate particles can produce a still better fit to the observed data as compared to compact prolate grains. Again, Das, Das & Sen (2008b) successfully explained the polarization characteristics of Comet C/1995 O1 Hale-Bopp at $\lambda = 0.485$ and 0.684 $\mu$m using an aggregate dust model. However, the aggregate dust model used in the previous work was restricted to a single size of the monomer with the same size parameter at different wavelengths. More recently, Das et al. (2010) included the size distribution for aggregates and studied the observed polarization data of Comet C/1996 B2 Hyakutake at $\lambda = 0.365, 0.485$ and 0.684 $\mu$m.

It is now well accepted from the in situ measurements of comets and Stardust–returned samples of Comet Wild 2 that cometary dust consists of a mixture of compact particles and aggregates (Lamy et al. 1987; Fomenkova et al. 1999; Hörz et al. 2006; Zolensky et al. 2006, Burchell et al. 2008 etc.). Lasue et al. (2009) studied Comet 1P/Halley and Comet C/1995 O1 Hale-Bopp using a mixture of fluffy aggregates and compact solid grains. They developed a model of light scattering by a size distribution of aggregates of up to 256 submicron-sized grains (spherical or spheroidal) mixed with single spheroidal particles. They obtained a good fit of the positive polarization observations of 1P/Halley with a power-law size distribution ($a^{-2.8}$ with a lower cut-off of 0.26 $\mu$m and an upper cut-off of 38 $\mu$m) with a mixture of silicates (between 40 and 67 per cent in volume) and more absorbing organic material (between 33 and 60 per cent in volume). The fits deduced from their model show that the negative polarization branch is not deep enough to match the observed polarization data, especially for Comet 1P/Halley, although the fits are found to be good for the positive part of the polarization. Recently, Kolokolova & Kimura (2010) modelled cometary dust as a mixture of compact particles (made of silicate) and aggregates (made mainly of organics and presenting a 1P/Halley-like composition). Using a size distribution function $a^{-3}$ for compact particles and 256 number of ballistic cluster–cluster aggregates (BCCAs), they reproduced the polarimetric data, including negative polarization at small phase angles and the positive polarization with the maximum value less than 30 per cent at the phase angle around 90° and a red polarimetric colour. However, their model reproduced a feature common to ‘dusty comets’ polarization curves but they did not use a chi-squared fitting procedure to compare with the observed data for a given comet.

In the present work, a model for cometary dust with a mixture of compact spheroidal particles and aggregates with size distribution is proposed to study the observed polarization data of Comet 1P/Halley at $\lambda = 0.365, 0.485, 0.670$ and 0.684 $\mu$m.

## 2 DUST MODEL

The in situ measurement of Comet 1P/Halley and the Stardust–returned samples of Comet Wild 2 showed the presence of a mixture of compact and aggregate particles with a composition of silicates and organic refractory. Moreno et al. (2007) adopted a systematic approach to test whether a collection of compact particles can reproduce the observed properties of cometary dust. Using a model of spheroidal particles, they found that the axial ratio should be either $E = 2$ (oblate) or $E = 0.5$ (prolate). The refractive indices lie within a range of $n = 1.6$–1.7 and $k = 0.05$–0.1. They also studied a more complex model based on size distributions of irregularly shaped particles composed of a varying number of cubes as elementary units. Their models, which considered irregularly shaped and compact particles with different structures, showed results close to the observations. However, the weakness of their model of compact structures was that the maximum in the linear polarization values did not occur in the 90°–100° phase angle region as observed. Recently, Kolokolova & Kimura (2010) modelled cometary dust as a mixture of compact spheroidal and aggregate particles. They considered the compact particles to be a mixture of oblate and prolate spheroids with the axial ratio being within the range of 1–2.5 and aggregates were taken to be BCCAs.

In the present work, we propose a model that considers cometary dust as a mixture of compact and aggregate particles. Since the in situ analysis of dust samples exhibits the overall ratio of compact to aggregate particles to be 65:35 (Burchell et al. 2008), we use the same value in our analysis. For modelling Comet 1P/Halley, we will use a power-law size distribution, $n(r) = dr/dr \sim a^{-2.6}$, for both compact particles and aggregates, obtained from a re-analysis of the Giotto data by Fulle et al. (2000).

We consider compact spheroidal particles with a size distribution of 0.1–10 $\mu$m. The particles are represented by multishaped, polydisperse mixture of spheroids. We consider a mixture of prolate, spherical and oblate compact particles with an axial ratio ($E$) of 0.8–1.2. Computations of light scattering by plain and coated particles are made through codes adapted from the T-matrix code (Mishchenko & Travis 1998).

We build the aggregates using the ballistic aggregation procedure (Meakin 1983, 1984). Two different models of cluster growth are used: first via single-particle aggregation and then through cluster–cluster aggregation. These aggregates are built by random hitting and sticking particles together. The first one is called ballistic particle–cluster aggregate (BPCA) when the procedure allows only single particles to join the cluster of particles. If the procedure allows clusters of particles to stick together, the aggregate is called a BCCA. Actually, the BPCA clusters are more compact than BCCA clusters (Mukai et al. 1992). The porosity of BPCA and BCCA particles of 128 monomers has the values 0.90 and 0.94, respectively, and the fractal dimension of BPCA and BCCA is $D = 3$ and 2, respectively. A systematic explanation of the dust aggregate model has been presented in our previous work (Das et al. 2008a).

Recently, Shen, Draine & Johnson (2008) considered three different classes of clusters distinguished by aggregation rules. These are ballistic agglomeration (BA), ballistic agglomeration with one migration (BAM1) and ballistic agglomeration with two migrations (BAM2). They developed a set of parameters to characterize the irregular structure of these aggregates. Actually a BA cluster is identical with a BPCA cluster. The geometry of a BAM1 cluster and that of a BAM2 cluster are random but less porous than BA clusters. The effective porosity ($P$) increases in the order BAM2 $\rightarrow$ BAM1 $\rightarrow$ BA. The porosity of a BAM2 structure having 64
monomers is $P \approx 0.5$ and the fractal dimension is $D \approx 3$ (Shen et al. 2008). The aggregates are taken from Bruce T. Draine’s webpage.

In our model, we take the same cloud of particles, i.e. the same type of particles [compact spheroidal and porous (BCCA + BAM2) particles] and the same size distribution [$\rho(r) = dn/da \sim a^{-2.6}$], to fit the observed data at all wavelengths.

In our simulation, we divide the present work into the following two phases.

(i) We first take the BCCA aggregates and then mix them with compact spheroidal particles in a 65:35 mixing ratio. The result obtained from this modelling will be discussed in Section 4.

(ii) We then consider the more compact aggregate BAM2 [having porosity ($P$) $\sim 0.50$ approximately] which is mixed with highly porous BCCA clusters ($P \sim 0.9$) with a variable mixing ratio ($\beta$). Then the aggregate mixture is mixed with compact particles in a 65:35 mixing ratio. Here we consider the composition of both silicate and organic to have a variable mixing ratio ($\gamma$).

The free parameters used in the model are as follows:

(i) the mixing ratio ($\beta$) between BCCA and BAM2;

(ii) the mixing ratio ($\gamma$) between silicate and organic.

We use the $\chi^2$-minimization technique to evaluate the best-fitting values of the above free parameters by the following equation:

$$
\chi^2_{\text{best}} = \sum_{i=1}^{N} \frac{|P_{\text{obs}}(\theta_i, \lambda_i) - P_{\text{theo}}(\theta_i, \lambda_i)|^2}{E^2_{\text{pol}}(\theta_i, \lambda_i)}.
$$

Here, $P_{\text{obs}}(\theta_i, \lambda_i)$ is the degree of linear polarization observed at scattering angle $\theta_i$ ($i = 1, 2, \ldots, N$) and wavelength $\lambda$; $P_{\text{theo}}(\theta_i, \lambda_i)$ are the polarization values obtained from model calculations; and $E_{\text{pol}}(\theta_i, \lambda_i)$ is the error in the observed polarization at scattering angle $\theta_i$ and wavelength $\lambda$. It is also observed that this technique of minimization of $\chi^2$ is quite unique. The value of $\chi^2_{\text{min}}$ gives the confidence level on our best-fitting values of $\beta$ and $\gamma$ and also in the overall fitting procedure. Some preliminary work on the combined dust model has already been reported in Das & Sen (2011).

3 COMPOSITION

The in situ observation of comets, laboratory analyses of samples of interplanetary dust particles (IDP), and remote infrared spectroscopic studies of comets give useful information about the composition of cometary dust. The in situ measurement, of impact-ionization mass spectra of Comet 1P/Halley’s dust, has suggested that the dust consists of magnesium-rich silicates, carbonaceous materials and iron-bearing sulfides (Jessberger, Christoforidis & Kissel 1988; Jessberger 1999). 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 in one of the three spectral classes. 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 1P/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, Hanner & Sekanina 2000, Bockelée-Morvan et al. 2002, etc.). Mg-rich crystals are also found within IDPs and are predicted by comparing the infrared (IR) spectral features of Comet C/1995 O1 Hale-Bopp with the 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).

It is to be noted that though we used only two free parameters $\beta$ and $\gamma$ in our model, the refractive indices of silicate and organic can be used as other free parameters. However, we have limited ourselves to the value taken from standard references, because with many free parameters the computational time becomes very long. In our computation, we take the refractive indices of silicate (especially amorphous pyroxene) from Dorschner et al. (1995). The refractive indices of the amorphous pyroxene ($\text{MgFe}_{1-x}$Si$_2$O$_6$, where $x$ is the Mg number, $x = \text{Mg}/(\text{Mg} + \text{Fe})$, and $x = 0.4, 0.5, 0.6, 0.7, 0.8, 0.95$ and 1.0) are reported by them for different values of $x$. We select $x = 0.5$ to have an equal number of Mg and Fe in the pyroxene formula. However, we do not claim that the choice of $x = 0.5$ is unique. The values are calculated by linearly interpolating the data obtained from laboratory studies. The refractive indices are $(1.722, 0.101)$ at 0.365 $\mu$m, $(1.692, 0.0492)$ at 0.485 $\mu$m, $(1.673, 0.0198)$ at 0.670 $\mu$m and $(1.672, 0.0185)$ at 0.684 $\mu$m. The refractive indices of the organic are taken from Jenniskens (1993): $(1.679, 0.536)$ at 0.365 $\mu$m, $(1.842, 0.459)$ at 0.485 $\mu$m, $(1.942, 0.357)$ at 0.684 $\mu$m and $(1.949, 0.349)$ at 0.684 $\mu$m. The refractive indices of silicate and organic at 0.485 $\mu$m have already been used by Das & Sen (2011) to model the optical polarization of comets.

4 NUMERICAL SIMULATION

For modelling Comet 1P/Halley, we use a power-law size distribution, $n(a) = dn/da \sim a^{-2.6}$, for both compact particles and aggregates, obtained from a re-analysis of the Giotto data by Fulé et al. (2000). The observed linear polarization data of Comet 1P/Halley are taken from Bastien et al. (1986), Gural’Chuk, Kiselev & Mo-rozhenko (1987), Kikuchi et al. (1987), Le Borgne et al. (1987), Sen et al. (1991) and Chernova et al. (1993) at $\lambda = 0.365, 0.485, 0.670$ and 0.684 $\mu$m.

We calculate the scattering properties of spheroidal compact particles using the T-matrix code (Mishchenko & Travis 1996) for 0.1 $\leq a \leq 10$ $\mu$m, where $a$ is the equal volume sphere radius of the particle. The step-size used to integrate the size distribution is 0.01 $\mu$m. We also calculate the scattering properties of the BCCA and BAM2 clusters using the superposition T-matrix code, which gives rigorous solutions for the ensembles of spheres (Mackowski & Mishchenko 1996).

The size of an individual monomer in a cluster plays an important role in scattering calculations. These have been confirmed by the results of the previous work on the dust aggregate model (Petrova, Tishkovets & Jockers 2004; Hadamcik et al. 2006; Kimura, Kolokolova & Mann 2006; Bertini, Thomas & Barberi 2007; Das et al. 2008a). The radius of an aggregate particle can be described by the radius of a sphere of equal volume given by $a_r = a_m N^{1/3}$, where $N$ is the number of monomers in the aggregate. In the present work, BCCA with 128 monomers and BAM2 with 64 monomers are taken. As we had computational limitation and as the BAM2 cluster takes a longer computational time compared to BCCA particles, we had to restrict the number of monomers only to 64 for the BAM2 particles. In our calculation, averages of three random realizations are considered for both BCCA and BAM2. The size of the monomer is taken from the range $0.05$ $\mu$m $\leq a_m \leq 0.20$ $\mu$m.
Thus the lower cut-off radius of the cluster is 0.2 μm and the upper cut-off is 1 μm. It is to be noted that since the number of monomers is fixed in each type of aggregate, the distribution in monomer sizes is essentially the size distribution of aggregates. For a particular type of aggregate with a fixed N, the size distribution is just \( dn/da \sim a^{-2.6} \). The step-size used to integrate the size distribution is 0.01 μm.

We start the calculation only considering the BCCA particles and then mix them with compact spheroidal particles in a 13:7 mixing ratio. It has been checked that the mixing of compact spheroidal grains and aggregates will not help much in producing a deeper negative polarization branch beyond 157°. It has also been noted from Lasue et al. (2009) that the fits deduced from their modelling do not show a deep negative polarization branch for Comet 1P/Halley.

Using the aggregate dust models with BAM2 geometry and a moderate porosity (\( P \approx 0.6 \)), Shen, Draine & Johnson (2009) reproduced albedo and polarization for cometary dust, including negative polarization observed at scattering angles beyond 160°. To study the effect of the BAM2 structure, we now start the computation at \( \lambda = 0.485 \mu m \) with BCCA and BAM2 particles in different mixing ratios (\( \beta \)) and then finally mix with compact spheroidal particles having a mixing ratio of 65:35 (or 13:7), where \( \gamma \) is taken to be 3:1. In Fig. 1, the polarization curves are generated for \( \beta = 1:3 \) and 1:1, which actually correspond to 25 per cent BCCA + 75 per cent BAM2 particles and 50 per cent BCCA + 50 per cent BAM2 particles for a size distribution \( n(a) \sim a^{-2.6} \). The size ranges for the aggregates (BCCA and BAM2) and the compact spherical particles are taken to be 0.2 ≤ \( a \) ≤ 1.0 μm and 0.1 ≤ \( a \) ≤ 10 μm, respectively. We also generate the polarization curves separately with BCCA and BAM2 particles. Fig. 1(a) shows the average polarization curve obtained from the mixing of compact spheroidal particles and aggregates (BCCA and BAM2). The mixing ratio between BCCA and BAM2 is 1:3. In Fig. 1(b), curve 1 corresponds to the average polarization curve in the range of 150°–180° obtained from the mixing of compact and BAM2 particles only, curve 2 with \( \beta = 1:3 \), curve 3 with \( \beta = 1:1 \) and curve 4 is obtained from the mixing of compact spheroidal particles and BCCA particles only.

It is clear from Fig. 1 that the existence of the BAM2 structure (which is more compact than BCCA) is crucial in producing the deeper negative polarization branch. Thus the introduction of BAM2 aggregate in the aggregate mixture will help in reproducing the negative polarization well, which was not possible in previous studies on Comet 1P/Halley by several investigators. Actually, IDP may contain both porous and compact aggregates. So it will be more realistic that we consider aggregates to be a mixture of more compact BAM2 (\( P \sim 0.5 \)) and more porous BCCA (\( P \sim 0.9 \)) clusters with a certain mixing ratio \( \beta \).

We now use the \( \chi^2 \) minimization technique to evaluate the best-fitting values of \( \beta \) and \( \gamma \) which can fit to the observed polarization data. We have already used this minimization technique to fit the observed linear polarization data of some comets (Das et al. 2008a, Das et al. 2b, 2010; Paul et al. 2010), with aggregate models of dust. We need to fine-tune the free parameters \( \beta \) and \( \gamma \) in the model to make the best fit to the observed linear polarization data of Comet 1P/Halley. Some preliminary work on the combined dust model has been reported by Das & Sen (2011) where they used the same technique to simulate the observed polarization data of Comet Halley at 0.485 μm. However, their work is limited to a single wavelength.

The best-fitting values of \( \beta \) and \( \gamma \) are found to be 1:1 and 78:22 at \( \lambda = 0.365, 0.485, 0.670 \) and 0.684 μm. The \( \chi^2 \) values obtained from the present analysis are 14.8, 47.2 and 32.5 at \( \lambda = 0.365, 0.670 \) and 0.684 μm, respectively, whereas the value obtained by Das & Sen (2011) for \( \lambda = 0.485 \mu m \) is 56.7. The best-fitting average polarization curves at four wavelengths are shown in Figs 2–5.

5 DISCUSSION

The in situ impact-ionization mass spectra of Comet 1P/Halley’s dust suggest that the dust consists of magnesium-rich silicates, carbonaceous materials and iron-bearing sulfides (Jessberger et al. 1998; Jessberger 1999). In our modelling we consider cometary dust as a mixture of compact and porous particles with the composition of silicates and organic refractory. The silicate-to-organic ratio obtained in the present work is 39.11 or 78 per cent silicate and 22 per cent organic by volume. Thus it can be concluded that the silicate composition is dominating in Comet 1P/Halley as compared to organic refractory.

The negative polarization feature of comets is one of the important features observed in them. Many comets show negative polarization beyond 157° ((Kikuchi et al. 1987; Chernova et al. 1993; Ganesh et al. 1998 etc.). Several investigators (Greenberg & Hage 1990; Muinonen et al. 1996, 2007; Petrova et al. 2004; Tishkovets, Petrova & Jockers 2004; Hadamick et al. 2007 etc.) have discussed the cause of negative polarization in comets. Actually, it is important to fit the observed polarization data in the positive part as well as in the negative branch. Using the aggregate dust model, Das et al. (2008a, Das et al. 2b; Paul et al. 2010) successfully reproduced the polarization curves including a negative branch observed for the comets C/1990 K1 Levy, C/1995 O1 Hale-Bopp, C/1996 B2 Hyakutake and C/2001 Q4 NEAT. But it is now well accepted that cometary dust consists of compact and porous particles. Several investigators studied comets using a mixture of highly porous aggregates and compact solid grains. It has been observed that the plots show good fit to the positive part of the polarization, but do not show a deeper negative polarization branch beyond 157°.

In our present work, we take a mixture of aggregates (highly and moderately porous) and then mix it with compact spheroidal grains in a 13:7 ratio. It may be noticed from Figs 2–5 that our modelling
Figure 2. Polarization values as observed at the wavelength $\lambda = 0.365 \mu m$ for Comet 1P/Halley by Bastien et al. (1986), Gural’Chuk et al. (1987), Kikuchi et al. (1987), Le Borgne et al. (1987), Sen et al. (1991) and Chernova et al. (1993). The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2) for the size distribution $n(a) \sim a^{-2.6}$ at $\lambda = 0.365 \mu m$.

Figure 3. The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2) for the size distribution $n(a) \sim a^{-2.6}$ at $\lambda = 0.485 \mu m$, taken from Das & Sen (2011).

can successfully reproduce the positive part as well as the negative branch of the polarization at three different wavelengths. However, if we just withdraw the BAM2 structure from our model, the negative polarization branch will not be reproduced at proper scattering angle values. So it appears that the existence of BAM2 particles (which is more compact than BCCA) is very important in our grain model as it can reproduce a deeper negative polarization branch. Thus our modelling can help in explaining the polarization characteristics of Comet 1P/Halley successfully at different wavelengths.

The angular dependence of brightness and linear polarization of compact and porous clusters has been investigated by Tishkovets et al. (2004). They found that porous clusters are brighter almost in the whole angular range due to the larger cross-section, and these clusters produce smoother polarization curves with a higher maximum. The negative branch in the backscattering direction is shallower, because the wave interference and near-field effects are weaker within the aggregates. However, in compact clusters, both the interference and the near-field effects play a major role in producing a negative polarization branch. The negative branch is deeper for compact clusters as compared to porous clusters. The minimum is deeper, and the inverted angle is shifted to smaller scattering angles. The negative polarization is mostly generated by particles below the surface layer of the cluster, where the radiation field is inhomogeneous, and the amplitude, phase, and propagation direction of the wave change randomly (Tishkovets et al. 2004). It has been demonstrated by Petrova et al. (2004) that the external layer of the clusters plays an important role in forming the polarization phase curve. Both the appearance of the negative polarization branch and its shape strongly depend on the sizes of the scattering elements and on the structure of the particle ensemble. In a subsequent work, Shen et al. (2009) studied the phase curve and polarization values, as produced by BAM1 and BAM2 and it was found that a more compact BAM2 cluster shows a deeper negative polarization branch as compared to BAM1 and BCCA.

Before we conclude we may note that the $\chi^2$ values reported earlier for Comet C/1990 K1 Levy showed improvement in the fit in Das et al. (2008a) with aggregate grains ($\chi^2$ value 4.2) as compared to Das & Sen (2006) with compact prolate grains ($\chi^2$ value 5.22).
It is true that these two $\chi^2$ values for Comet C/1990 K1 Levy are much lower than the $\chi^2$ value we obtained in the present work for Comet Halley. It may be noted here that in the present work the fit was made on the data points of Comet Halley collected from various sources as observed by different groups of observers (for example at 0.485 $\mu$m, we have 86 data points collected from six different groups of observers). Such data points collected from diverse groups of observers will always have some inherent scatter in their values, as those observations are made with different aperture sizes and different sets of filters (with different central wavelengths and full width at half-maximum). Besides, different groups of observers use different instruments, with different spectral responses. When we club such data points taken from various sources, ideally all the observed data points should be calibrated so as to take into account the above effects. But that is a tedious job; normally such corrections are never made and they were not in the present case as well.

On the other hand, in the two earlier work (Das & Sen 2006 and Das et al. 2008a) on Comet C/1990 K1 Levy, the fit was made on data values collected from a single source, viz. Chernova et al. (1993). Therefore, it is quite natural to expect that the $\chi^2$ value in the present work on Halley will be higher than what has been obtained earlier for C/1990 K1 Levy. And this is due to the diversities in the sources of data points for Halley. For example at $\lambda = 0.670$ $\mu$m, if we exclude the data point (position angle, polarization) = (130.0, 12.9), the $\chi^2$ value just drops from 47.2 to 15.6.

For Comet C/1990 K1 Levy the data points were only 16 as compared to 86 for Halley at the wavelength 0.485 $\mu$m. Also, for Comet Halley we considered a much wider range of phase angle values as compared to Levy, which constrained our grain model further and increased the $\chi^2$ value. What is important here to note is that for Comet Halley no other grain model can generate a lower $\chi^2$ value (indicating a better fit) than what we have reported in the present work.

6 CONCLUSION

(i) A mixture of compact spheroidal grains and aggregates successfully explains the observed polarization data of Comet 1P/Halley at $\lambda = 0.365, 0.485, 0.670$ and 0.684 $\mu$m.

(ii) The positive part as well as the negative polarization have been successfully generated using the proposed combined model of cometary dust.

(iii) With the introduction of a distribution of monomer sizes and BAM2 cluster (more compact than BCCA), one can fit the observed polarization data much better, as compared to the previous work on Comet 1P/Halley. It is also observed that the existence of the BAM2 structure is important in reproducing the deeper negative polarization branch.

(iv) The best-fitting mixing ratio between BCCA and BAM2 ($\beta$) is found to be 1:1 (or 50 per cent BAM2 + 50 per cent BCCA). Thus it can be concluded that porous grains in Comet 1P/Halley are composed of both highly and moderately porous particles.

(v) The best-fitting mixing ratio between silicate and organic particles ($\gamma$) is found to be 39:11 (or 78 per cent silicate and 22 per cent organic in volume).

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