A dust model to explain cometary polarization

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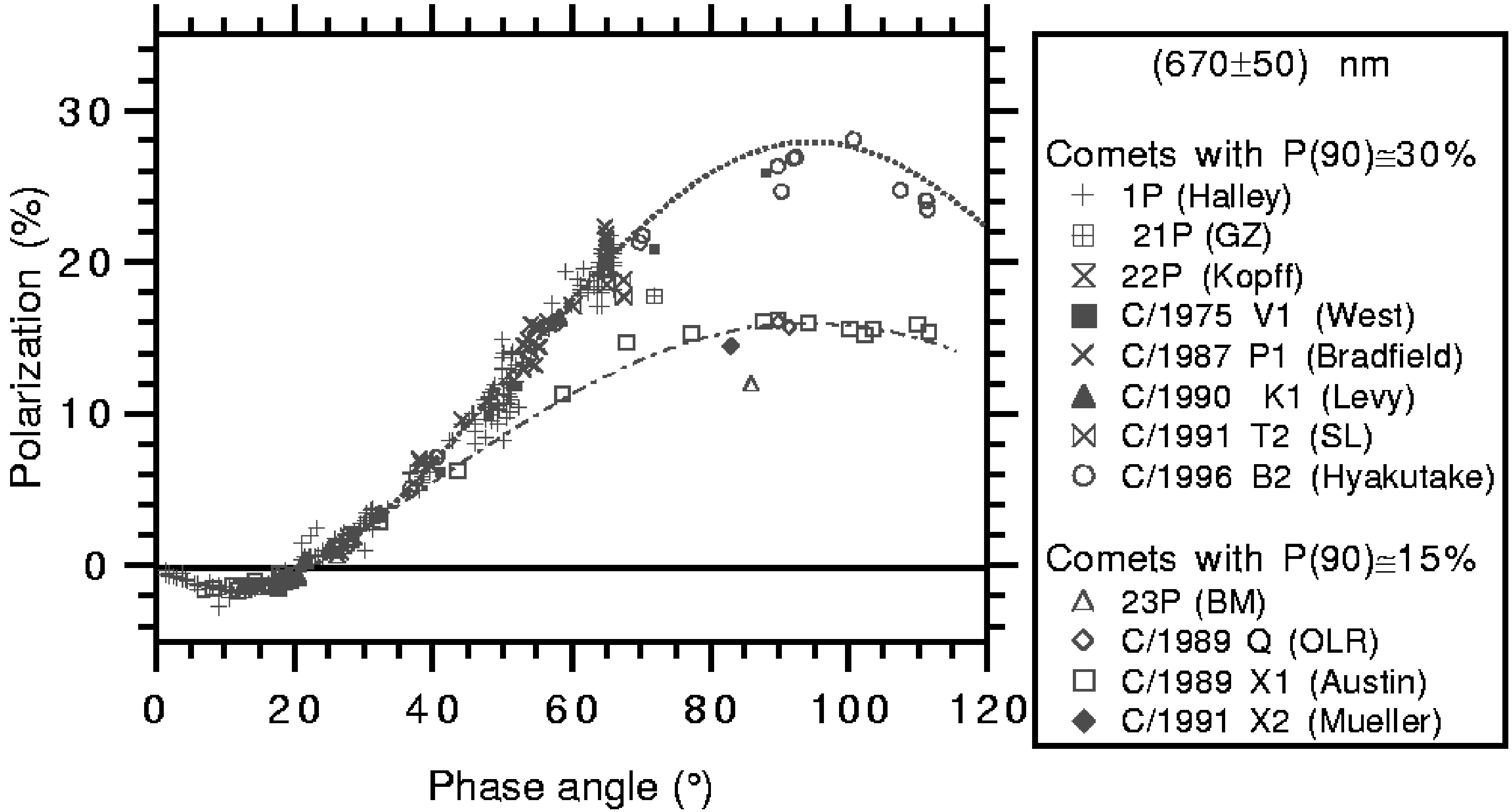


from Levassuer-Regourd, Space Science Reviews ***90: 163–168, 1999***

- Comets are known to exhibit high amount of polarization, caused due to scattering of sun-light by dust grains present in the coma of comets.

- P_{max} (~ 20 -25 %) is observed at scattering angle close to 90. As the phase angle becomes very low (<20 degrees), almost all the comets exhibit negative polarization with P_{min} (~2%).

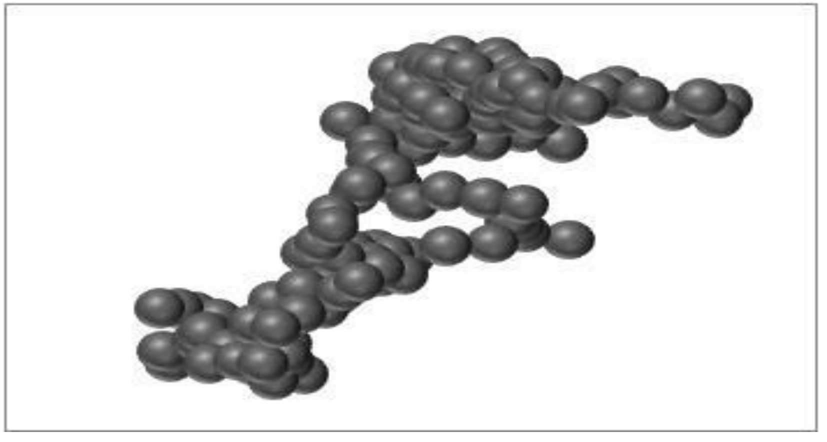
- It has been found that, the observed cometary polarization data can be explained fairly well, by assuming the grains to be Mie spheres with a specific dust size distribution (for Halley from Spacecraft observation, Mazets et al. 1987) and compositions characterized by complex refractive indices (Mukai et al. 1987, Sen et al. 1991). The best-fit refractive index values were not consistent with any known real material.

- However, the naturally occurring cometary grains cannot be ideal compact spheres, as required by Mie theory. The Mie theory was used, as it is more convenient and direct, with fewer numbers of free parameters required for modeling.

How do cometary grains look like ?

- Size : They are micrometer and nanometer size particles ?
- Shape : sphere ? Spheroids ? Fractals ?
- Structures: Compact ? Porous ? Fractals ?
- Size distribution ? Singe Size ?
- Compositions : silicates (Pyroxene / Olivine), water ice ? Organics ?

- Pyroxene $Mg_x Fe_{(1-x)}SiO_3$ Olivine $Mg_{2y} Fe_{(2-2y)}SiO_4$



- For comet Levy (1990XX), considering the grains to be prolate (aspect ratio of 0.48), the observed polarization data was fitted more closely (Kerola and Larson 2001, Icarus; Das and Sen. 2006, A&A), as compared to the work done previously with Mie sphere .

- However, the above procedure, could NOT improve the case of comets Halley, Hale-Bopp etc.

- STARDUST spacecraft mission on comet wild 2 suggested grains to be mixtures of COMPACT and AGGREGATE

- Assuming an individual cometary grain to be an aggregate of several monomers (FRACTALS), we performed calculations by Superposition T-matrix method (Mackowski and Mishchenko 1996).

- The momomer radius and (n+ik) were used as free parameters.

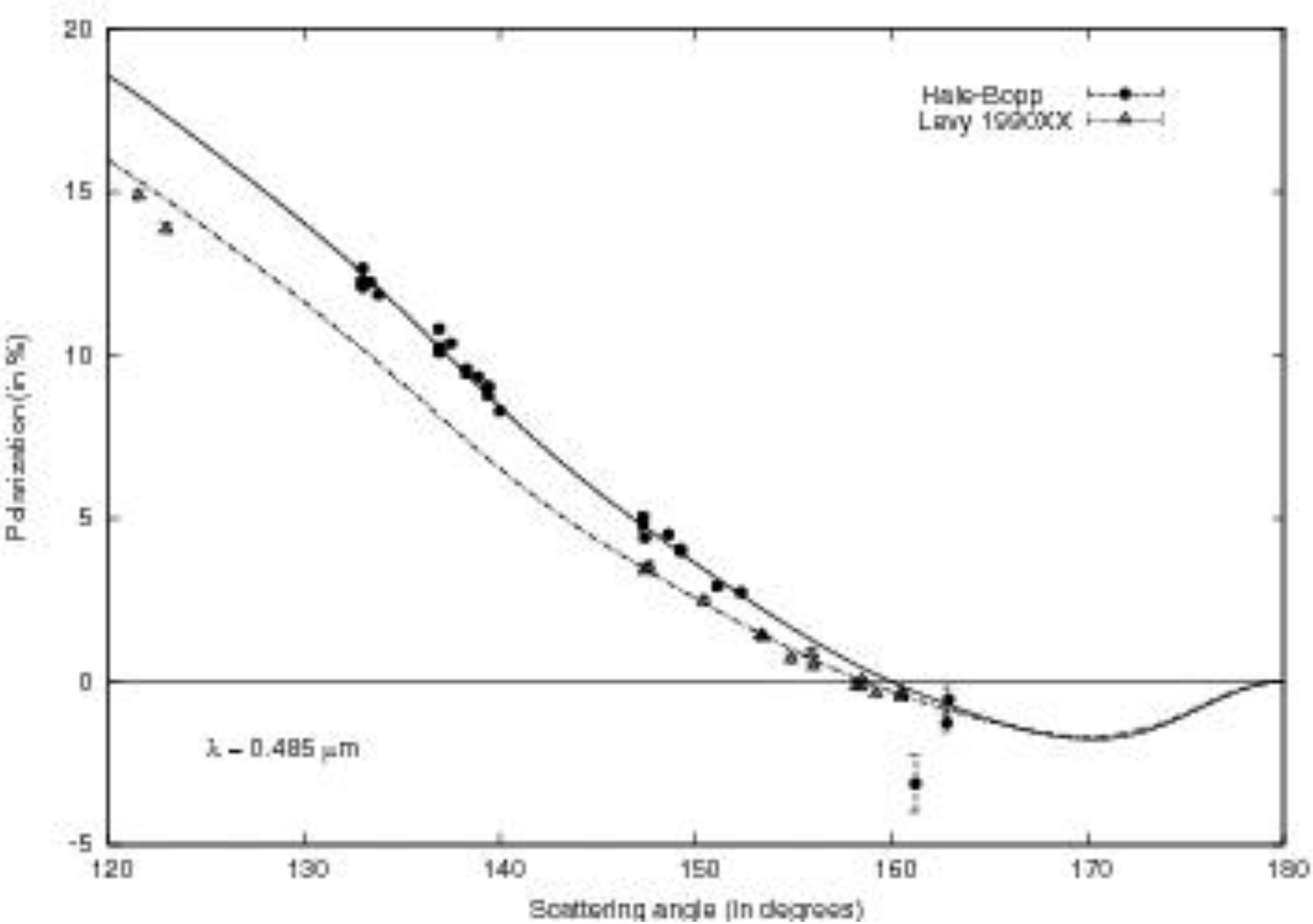
With the polarization data of comet Levy at 0.485 µm , by $\varkappa^2$ minimisation, a theoretical fit was made by choosing N (number of monomers)=128 and initially taking an refractive index value close to that of olivine, we could fit the observed data with a refractive index of (1.783, 0.052) and *a*=0.12 µm very well and the fit was better than that with prolates (Das et al. 2008, MNRAS 38)

- Similarly for HaleBopp at λ = 0.485 µm and 0.684 µm, data were fitted with two different values of monomer radius (*a*)(Das et al. 2008, MNRAS 390)

- At 0.485 µm, for Hale Bopp the monomer radius was *a* = 0.12 µm, which was same as that obtained for Levy, but with different refractive index value (1.778, 0.059). For Levy the corresponding value was (1.783, 0.052).

- At 0.684 µm, with *a* =0.17 µm and refractive index value (1.755, 0.080) the best fit was obtained for Hale Bopp.

- BCCA structure gave better fit to the observed data.



……from the above studies

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- Compared to Mie spheres , the prolate and then the aggregate grains, gave much closer fit to the observed cometary polarization data,. But with monomer radius (*a*) and refractive index (n+ik) as free parameters, the fitting procedure demanded different values of *a* at different wavelengths.

- Since this gives rise to an unrealistic situation, it can be indicative of a situation which is more complex than just having one single aggregate population and that too composing of one single size of monomers of same material.

- STARDUST space mission had suggested cometary (comet 81P/Wild 2) grains to be *mixture* of compacts and aggregates (Hortz et al. 2006, Science; Berchell et al. 2008)

- Very recently two major works have been reported with such *mixture* model :

1. Lasue, Levasseur-Regourd, Hadamcik and Alcoufee, 2009, Icarus, **199**

2. Kolokolova and Kimura, 2010, Earth, Planet and Space , **62**, No.1

Lasue et al. 2009

Considered two components (1) COMPACT and (2) AGGREGATE

- COMPACT : Spheroid – with a power law size distribution with index -3 and lower and the upper limit as 0.2 micron and 40 micron (HaleBopp). The compact spheroids again had two different populations in terms of compositions :

- (i) organic (n+ik=1.88+i0.1 at λ =0.55 µm and 75% in vol of the total compact grains.)

- (ii) Silicates (Mg-rich Pyroxene with n+ik=1.62 +i0.003).

- AGGREGATE : Within one aggregate, the constituents are spheroids and have a fixed size (0.1 µm), but with above two compositions . However, an aggregate contains from 16 to 256 grains (monomers). Thus they generated different sizes of aggregates.

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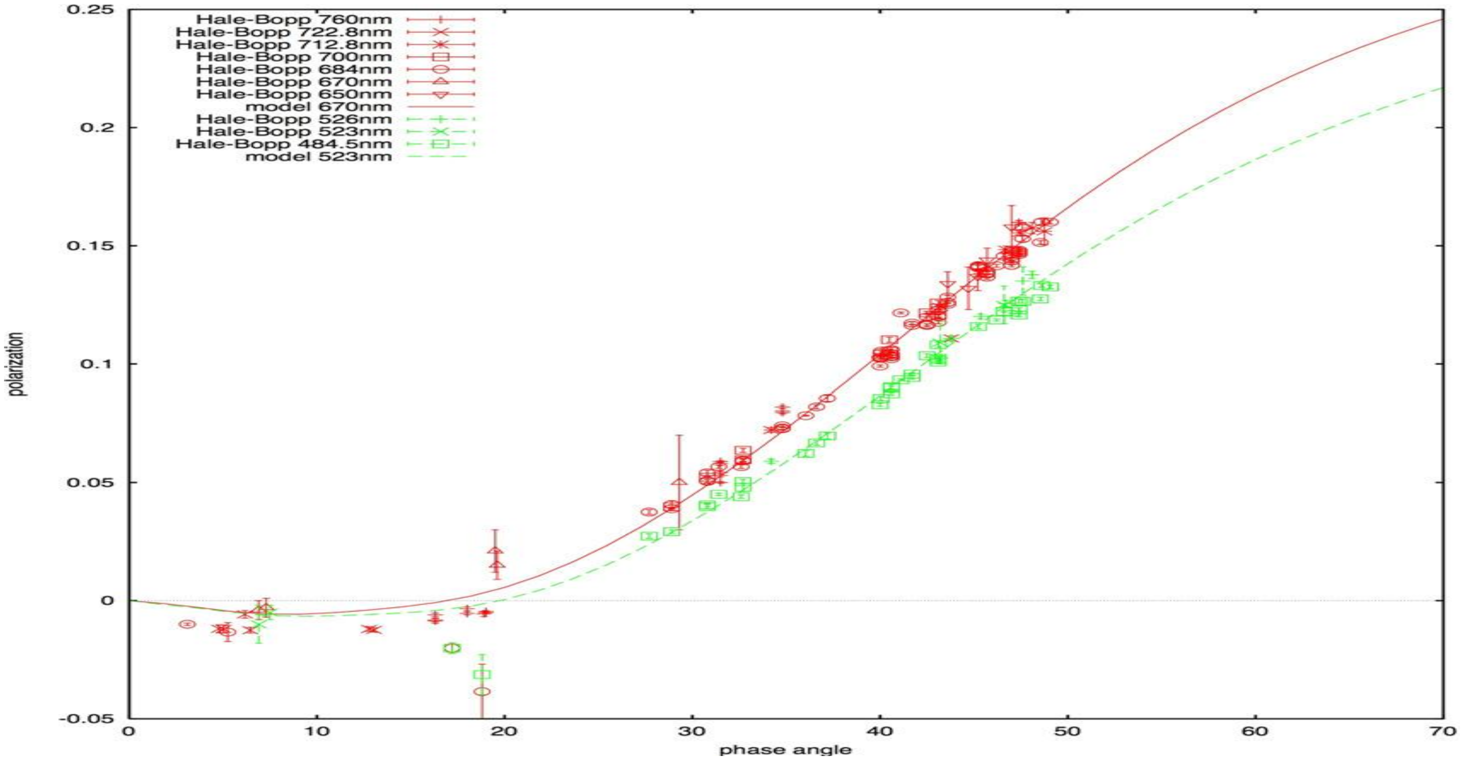

Halley and Hale-Bopp polarization data were fitted by Lasue et al(2009) with 5 free parameters:

- – The power-law index, *s.*
- – The minimum and maximum volume-equivalent diameter of the particles,
- – The ratio between compact and aggregate particles.
- – The ratio between non-absorbing (silicates) and more absorbing (organic) materials.

Kolokolova and Kimura 2010 (Earth, Planet and Space,62)

considered a three component dust model

1) Silicate (n+ik=1.6 +i0.001; pyroxene) : compact multishaped, polydisperse mixture of spheroids were considered, with a size distribution with the power law index -3, average radius r=1.5 and sigma=1.5.

2) Aggregate (BCCA) of 256 number of organic monomers (0.1 μm size sphere) were considered with refractive index value taken from Li and Greenberg (1997).

3) Aggregate (BCCA) of 256 number of monomers (0.1 μm size sphere), with composition of Halley like composites . The refractive index was estimated by using Maxwell Garnet mixing rule for a mixture of 32% Silicate, 2.6% iron and 66% carbonaceous material (in terms of volume) . (Kimura et al 2003, A&A and n+ik= 1.88+i0.47 for λ =0.45 μm and =1.98+i0.48 for λ =0.6 μm).

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As it appears from above…

- To explain cometary polarization data with a model containing compact and aggregates, there are a number of free parameters and the fit may not be unique:
- **Compact** : different populations with different compositions, shapes and their size distribution
- **Aggregate :** size , shape/ structures and composition of monomers. Distribution in sizes of monomers ? Number of monomers in an aggregate
- **Mixing ratio of Compact and Aggregate**
- **Ratio of compositions (Silicate : Organics)**

In our work reported here, we fit the polarization data of comet Halley at λ = 0.365, 0.485, 0.670 and 0.684 μm (details in Das and Sen 2011 JQSRT; Das et al. 2011, MNRAS).

Two types of particles were considered

(1) Compact with size *a* (volume equivalent radius) = 0.1 – 10.0 μm with axial ratio 0.8 -1.2,

Power law size distribution $n(a) \sim a^{-2.6}$

(-2.6 obtained from a reanalysis of Giotto data by Fulle et al. 2000)

Composition: silicate - pyroxene (n +ik = 1.692+i0.049)

Organic = (1.842,0.459) at λ = 0.485

(Dorschner et al. 1995 AA; Jenniskens et al. 1993 AA)

(2) Aggregates with monomer size range 0.05 – 0.20 μm, with above the power law distribution and compositions .

All together 128 monomers were considered $a_v = a_m N^{1/3}$

- The aggregates had two populations BCCA and BAM2, mixed in ratio taken as a free parameter
- BAM2 (Shen et al. ApJ 2008, 2009) Ballistic Agglomerates with two Migrations

- For BCCA (128 monomers) porosity 0.9
- For BAM2 (64 monomres) porosity 0.5

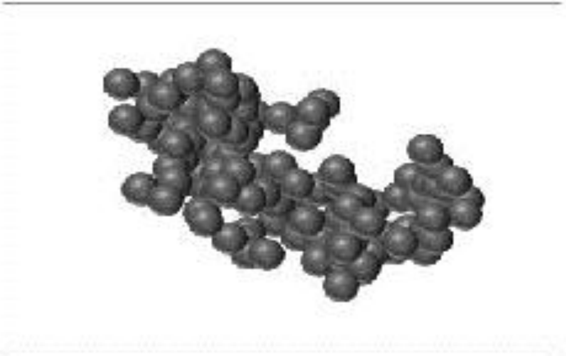
- The COMPACT : AGGREGATE ratio was taken as 65:35 from STARDUST spacecraft mission on comet wild (Berchell et al. 2008)

- Two free parameters were considered for modeling :

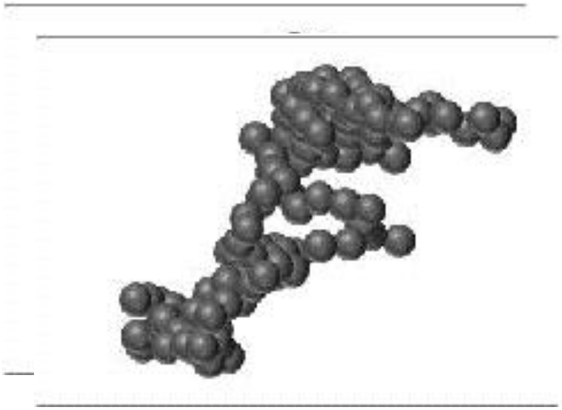
SILICATE : ORGANIC ratio

and

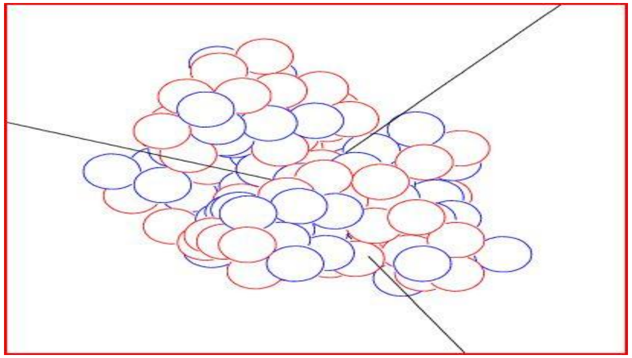
BCCA: BAM2 ratio



BPCA

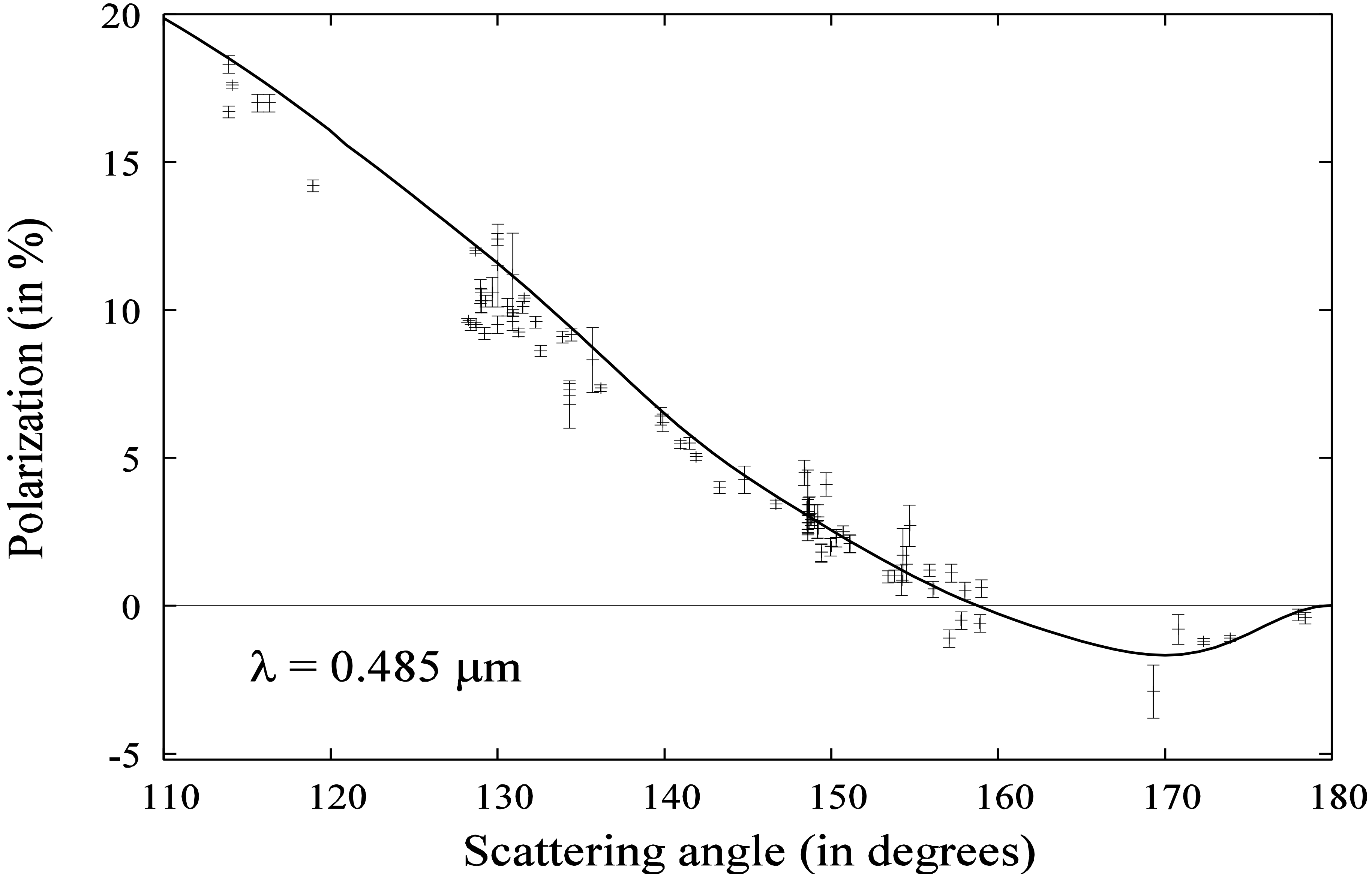


BCCA 128 monomers



BAM2

The polarization data of comet Halley at 0.485 μm fitted with a model containing Compact and Aggregate (BAM2+BCCA) . The fitted parameters are BCCA:BAM2 =1:1 and SILICATE : ORGANIC =78:22 by volume .



Comet Halley data at 0.485 µm fitted against a model containing compact and aggregates. The contribution from individual components are shown.

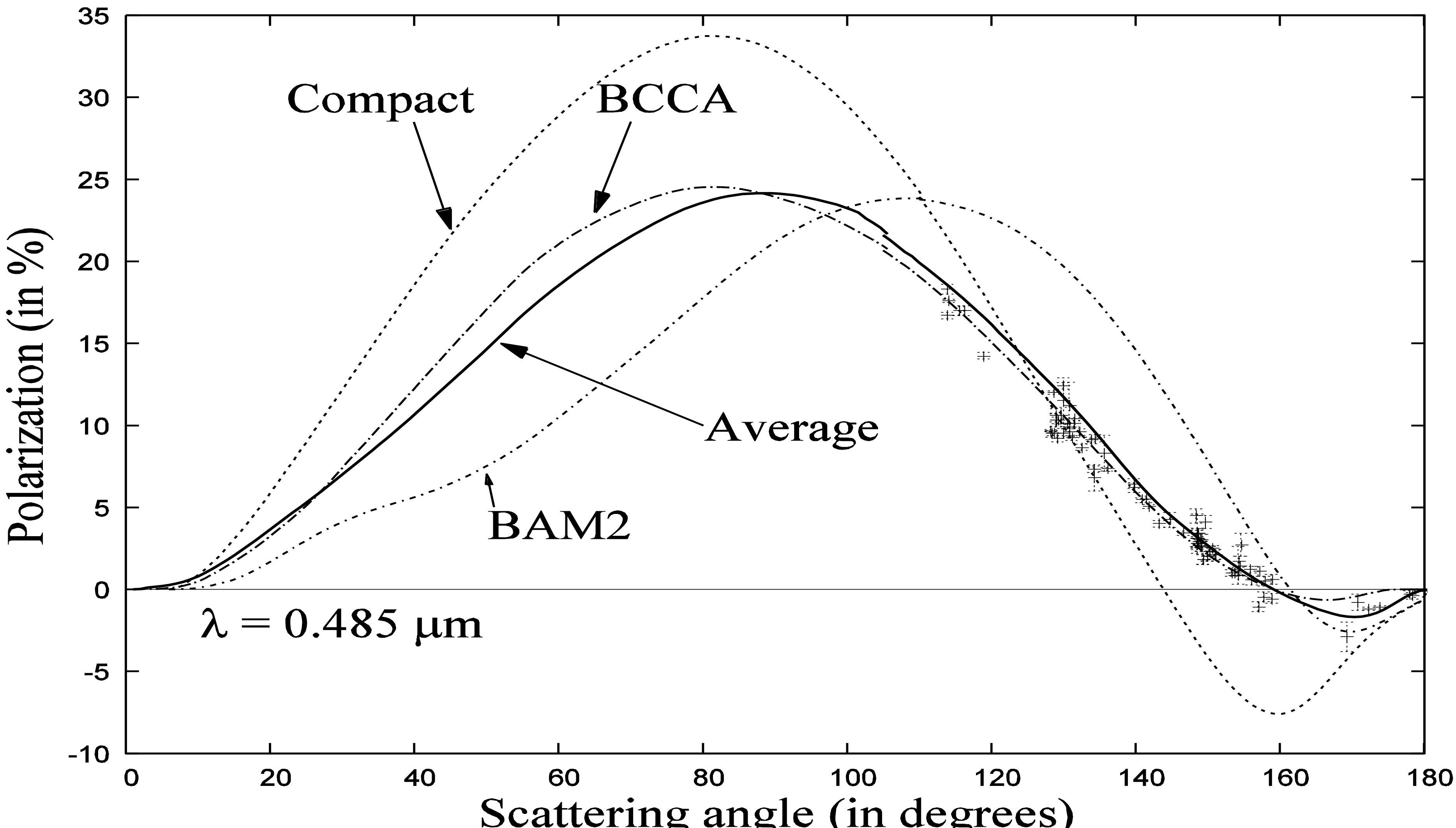


Table 1
Different combinations of BCCA:BAM2 and SILICATE:ORGANIC ratios along with P_{min} values (with corresponding scattering angle values) and χ^2 values are shown.

BCCA:BAM2	SILICATE:ORGANIC (volume)	P_{min} (scat. angle)	χ^2
1:1	78:22	−1.70 (170°)	56.7
3:1	3:1	−0.51 (165°)	123.6
1:3	1:3	−1.89 (168°)	221.3
3:2	1:1	−0.63 (165°)	302.5

The refractive indices of the amorphous pyroxene ($Mg_xFe_{1-x}SiO_3$, *where* $x = Mg/(Mg + Fe)$, *and* $x = 0.4, 0.5, 0.6, 0.7, 0.8, 0.95$ and 1.0) are reported by Dorschner for different values of *x.*

We select x = 0.5 to have an equal number of Mg and Fe in the pyroxene formula.

By linearly interpolating the data obtained from laboratory studies, we get he refractive indices for pyroxene (1.722, 0.101) at 0.365 μm, (1.692, 0.0492) at 0.485 μm, (1.673, 0.0198) at 0.670 μm and (1.672, 0.0185) at 0.684 μm.

The refractive indices of the organic are taken from Jenniskens (1993): (1.679, 0.536) at 0.365 μm, (1.842, 0.459) at 0.485 μm, (1.942, 0.357) at 0.670 μm and (1.949, 0.349) at 0.684 μm.

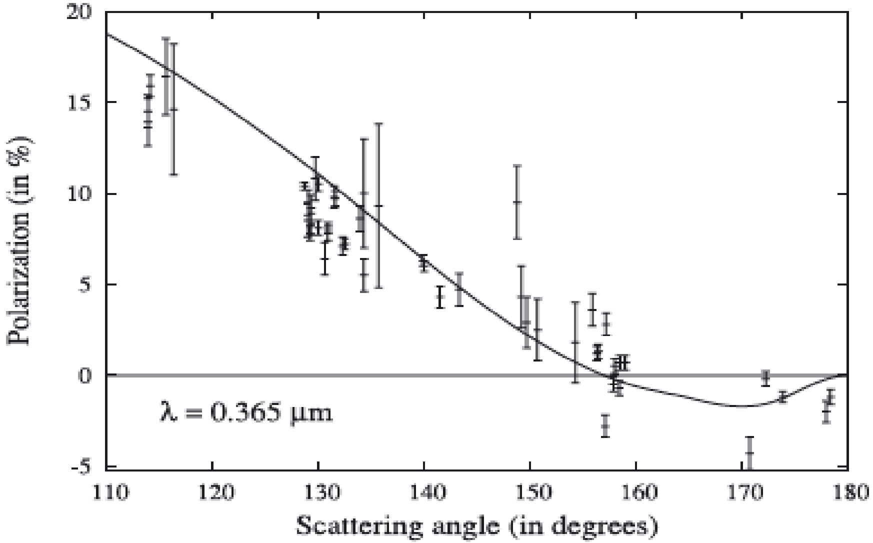


Figure 2. Polarization values as observed at the wavelength $\lambda = 0.365$ μm for Comet 1P/Halley by Bastien et al. (1986), Gural'Chuk et al. (1987), Kikuchi et al. (1987), Le Borgne et al. (1987), Sen et al. (1991) and Chernova et al. (1993). The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2) for the size distribution $n(a) \sim a^{-2.6}$ at $\lambda = 0.365$ μm.

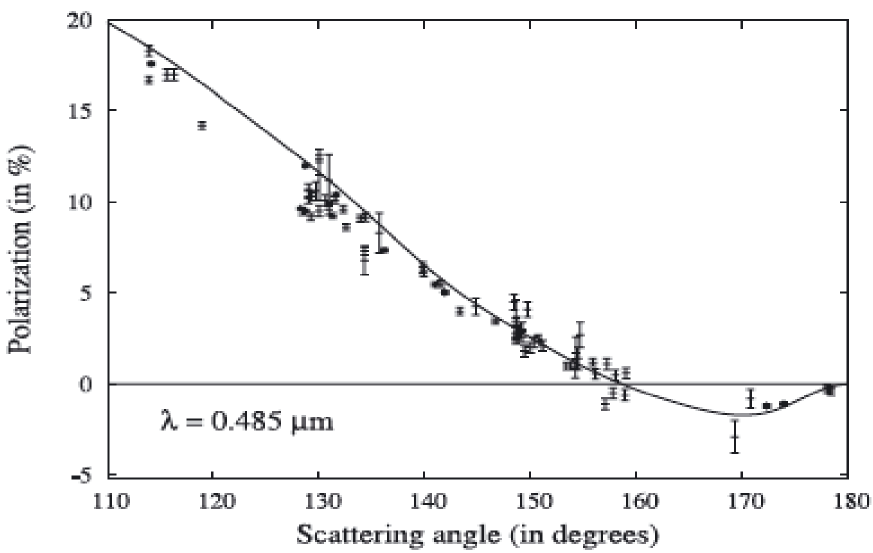


Figure 3. The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2)

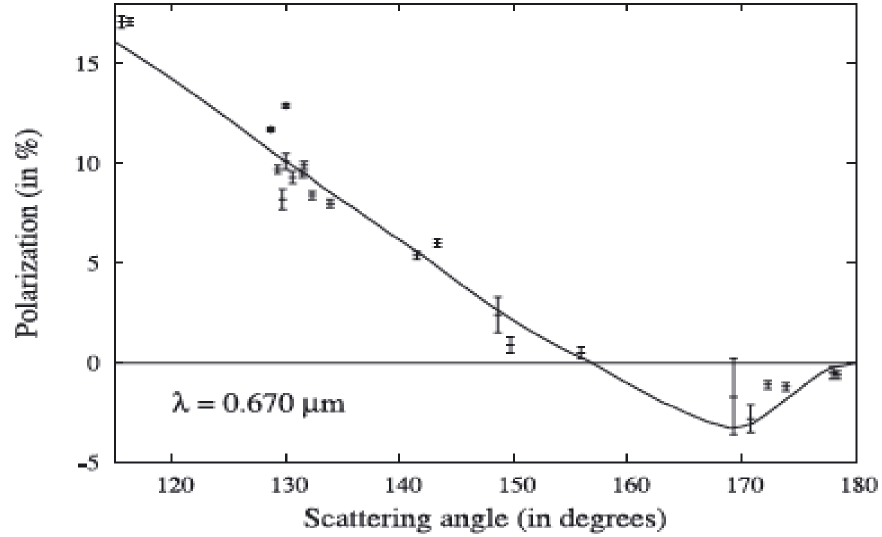


Figure 4. The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2) for the size distribution $n(a) \sim a^{-2.6}$ at $\lambda = 0.670$ μm.

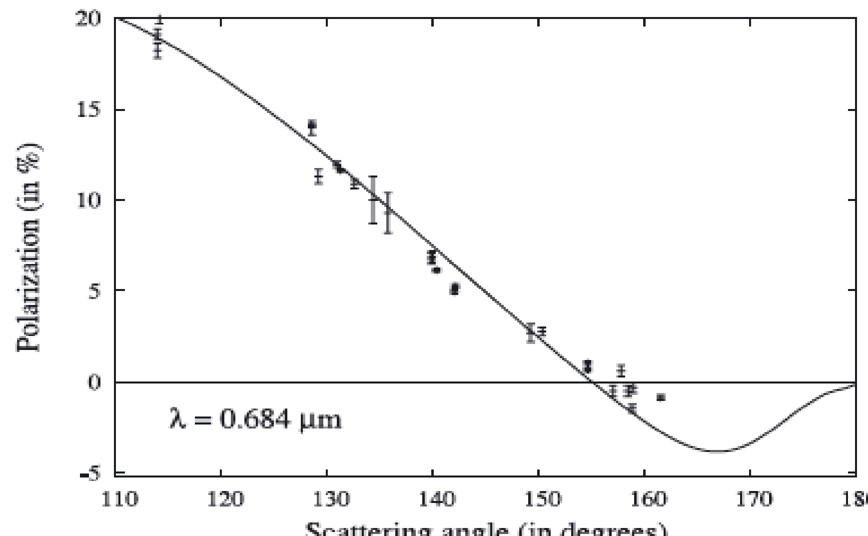


Figure 5. The solid curve represents the best-fitting average polarization curve obtained for compact particles and aggregates (BCCA and BAM2) for the size distribution $n(a) \sim a^{-2.6}$ at $\lambda = 0.684$ μm.

ducing a negative polarization branch. The negative branch is deeper

conclusions

1. A mixture of compact and aggregate definitely explains the cometary polarization data better, as compared to pure aggregate model (*in order, we first tried with compact sphere, spheroids, pure aggregate*).

2. However, there are a number of free parameters and fit may not be unique.

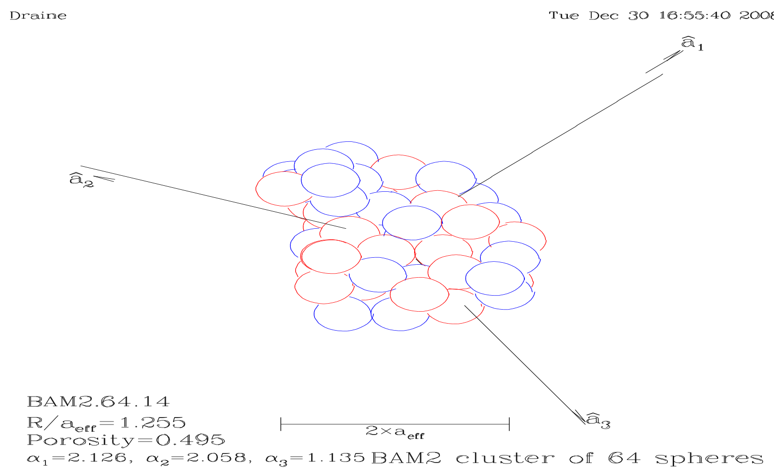
3. The best fit was obtained at 0.485 μm wavelength with SILICATE : ORGANIC and BCCA:BAM2 ratios as 78:22 and 1:1. These best fitted values are then used to match the observed data at 0.365, 0.670 and 0.684 μm.

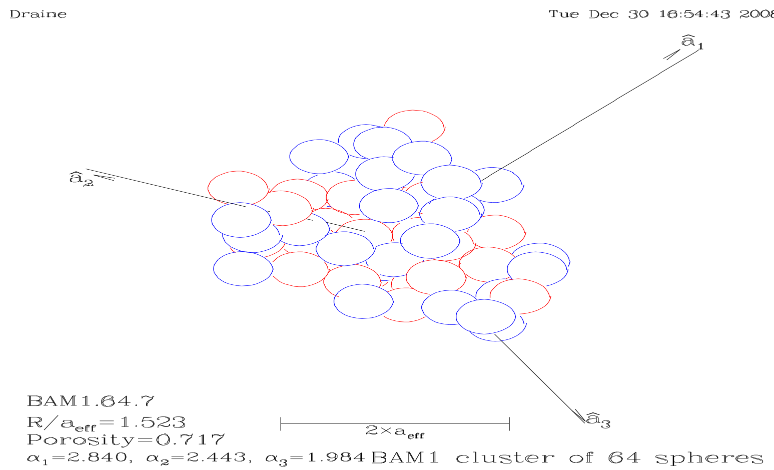
4. Distribution in monomer sizes and introducing a new structure BAM2 (more compact structure than BCCA) can help the modeling especially negative polarization branch.

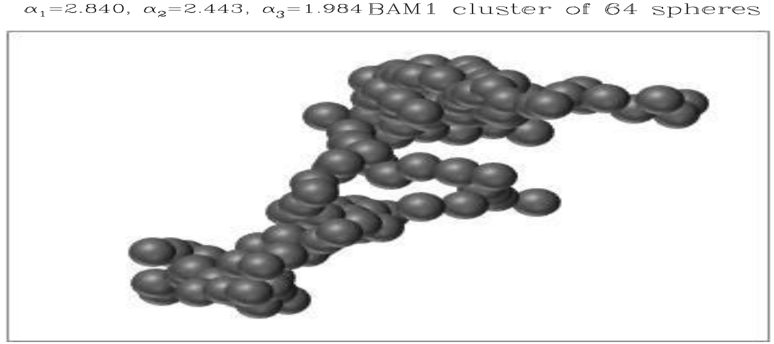
5. A proper grain model for comets, should finally in addition to polarization, also explain optical and IR photometric data including COLOR.

…………………Thank You

Possible structures of different cometary grains generated through simulations







- BAM1 (“ballistic agglomeration with one migration”) clusters are produced by requiring arriving monomers $j \geq 3$, after making first contact with a monomer $k < j$, to “migrate” to make contact with another monomer, by rolling or sliding over the first-contacted monomer, along the shortest possible trajectory. If there is more than one candidate for this second contact, the nearer is chosen. BAM1 clusters with $N \geq 3$ have every monomer in contact with at least two other monomers; for $N \geq 4$ some of the monomers are in contact with three or more other monomers.

- BAM2 clusters are constructed as follows: monomers $j = 2$ and 3 are added randomly just as for the BAM1 clusters. Monomers $j \geq 4$ arrive on random rectilinear trajectories; after first contact they make two migrations. The first migration is the same as for constructing BAM1 clusters: “rolling” along the shortest possible trajectory to make a second contact. This is followed by a second migration, now rolling over both the first and second sphere contacted to contact a third neighbor, again choosing the shortest trajectory if there is more than one candidate. BAM2. clusters with $N \geq 4$ have every monomer in contact with at least three neighbors, with some incontact with four or more neighbors.

- The observed optical polarizations for comets have been explained in past assuming cometary grains to be compact spheres, such that Mie Theory could be applied to simulate the observed polarizations. However, from a realistic point of view, recently other shapes like spheroids and aggregates of monomers have been considered for cometary grains, to explain the observed polarizations. For this purpose T- matrix or DDA based light scattering technique was mostly used to simulate the observed polarizations. A number of authors have used T-matrix, DDA and various other techniques, along with aggregate grain model to explain the polarizations of comets like Halley, Hale-Bopp, Levy and Hyakutake etc. Recent STARDUST mission had suggested cometary grains to be mixtures of compact and porous aggregates. Accordingly, recently attempts have been made to reproduce cometary polarization with mixture of various compositions, shapes and porosity.

- The work that will be presented contains a model for cometary grains which contains (1) solid grains of pyroxine (silicate) with various sizes and shapes of sphere, prolates and oblates and (2) aggregates of monomers with various sizes, with composition of carbon and having structures defined by BCCA and BAM2 codes. It is found that the present model can explain the observed polarization data, especially the negative branch, for comet Halley at 485 $¥mu m$, more effectively as compared to other work done in past. Among the aggregates the BAM2 structure was found to play a major role, in deciding the cross-over angle and depth of negative polarization branch.