A porous model for cosmic dust and its application in comets :

How cometary studies (space and ground based) help us to understand the origin and evolution of solar system ……………………

Asoke K Sen

Department of Physics

Assam University, Silchar 788001, India

Email : asoke.kumar.sen@aus.ac.in

asokesen@yahoo.com

What comets are .....

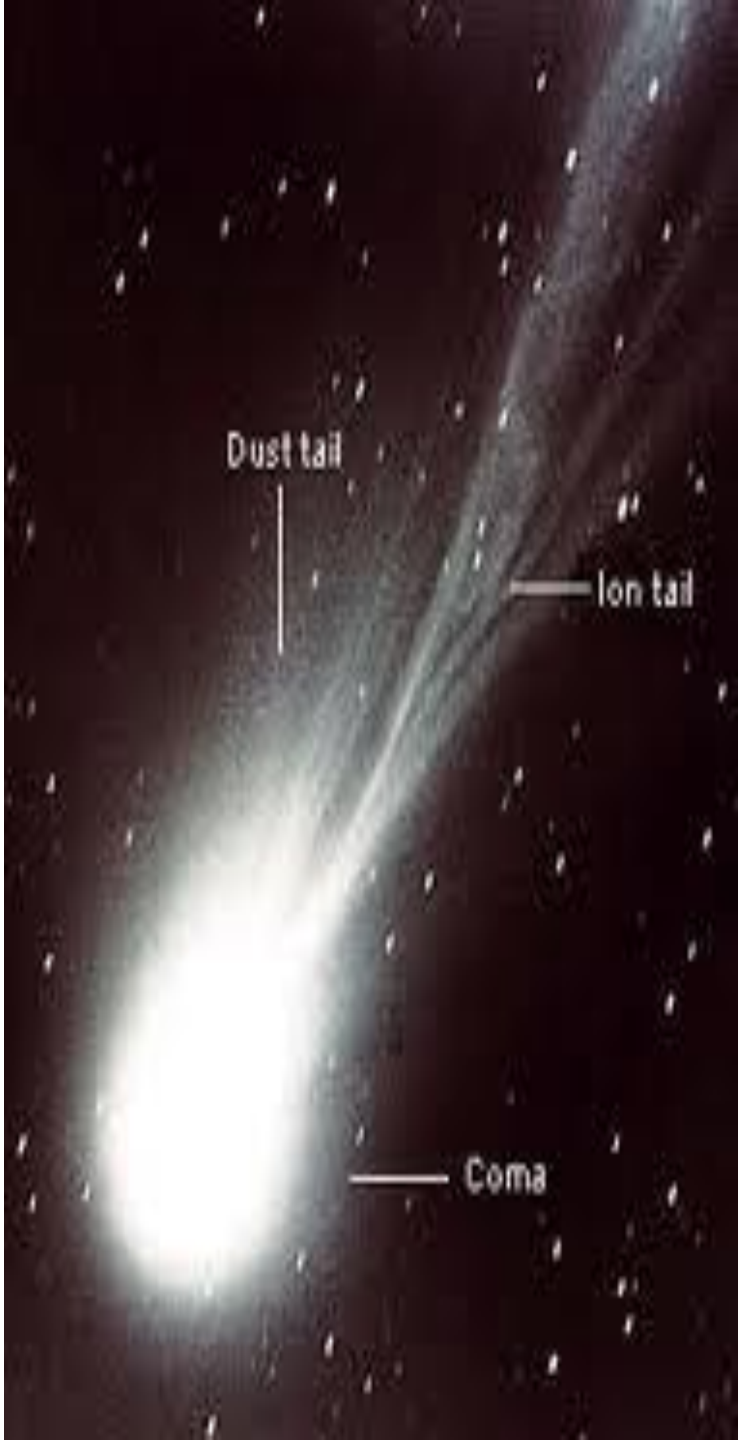
- Small (km sized) objects orbiting the Sun

- Have higher gas content compared to asteroids. So when come closer to Sun

(1 AU= 1.5 x10^{8} km), a gaseous atmosphere is developed (COMA).

- Come from all directions in the solar system, not contained in the ecliptic plane.

- Have aphelion distance ~ $10^{5} – 10^{6}$ AU (there is a spherical reservoir called Oort cloud)



NEW ERA IN COMETARY SCIENCE BEGINS DURING 1985:

Sep 1985 : ICE (NASA) flew at a distance of 7800 km from the comet Giacobini-Zinner.

Mar 1986 : Vega 1 and Vega 2, Giotto (596 km close) , Suisei and Sakigake flew close to Halley

- nucleus ~ single body (Albedo ~4%); ~10% of the sunlit surface is active (mostly refractory)
- ~30% (by mass) of dust are organic compounds (C, H, O, and N); ~80 % of coma is H_2O
- Dust mass distribution & elemental composition were determined by onboard instrument.
- Dust size distribution was established through ground based polarimetry (Mukai et al. 1987, Le Borgne et al. 1987, Sen et al. 1990AA)
- Ground based Imaging Polarimetry work revealed the existence of dust jets from nucleus (Eaton et al. 1988 , Sen et al. 1990 Icarus)

- Space missions on comets and asteroids are aimed at understanding
  - ▼ the surface properties and inner structures of nucleus
  - ▼ different gas composition of coma
  - ▼ nature of gas productions rates
  - ▼ rotations of nucleus
  - ▼ composition, size distribution and other properties of dusts.

The long period comets (P>100 yrs) are believed to come from Oort cloud (50,000 to 100,000 AU).
The short period ones (P <100 yrs) come from a region called Kuiper Belt (extending from orbit of Neptune at 30 AU to 50 AU) (KB is almost 100 times more massive than asteroid belt - confirmed in 1992 by IRAS).
Most short-period comets (period < 20 years) called Jupiter-family comets are believed to originate in the Kuiper belt

Combined with astrometric measurements and other ground based observations = >

(i) the extent of our solar system
(ii) origin of comets and asteroids - planet formations
(iii) information about the early phases of solar system

Apart from Halley missions (Giotto, Vega 1, Vega 2, Sakigake and Suisei) in recent past we had :

1)DEEP SPACE 1 – Borrelly (Oct1998/ Sep2001),

2)STAR DUST –Wild2 (Feb1999 / Jan2006)

→ STAR DUST NExT flew to Tempel 1 on Feb 14, 2011

3)DEEP IMPACT –Tempel 1 (Jan 2004 / Jul 2005, hit the comet with a 370 kg impactor).

→ EPOXI - Hartley 2 (Nov 2010) (an extended mission of DEEP IMPACT)

4)Also we had the Japanese (JAXA) Hayabusa sample return mission on asteroid 25143 Itokawa. **MUSES-C** was launched on 9 May 2003 and rendezvoused with Itokawa in mid-September 2005.

On Nov 2005 it landed on the asteroid and sample was returned to earth on 13 June 2010, with capsule containing asteroid dust.

5)ROSETTA sample mission on comet 67P/C-G, Nov 2014

- **67P/Churyumov–Gerasimenko**

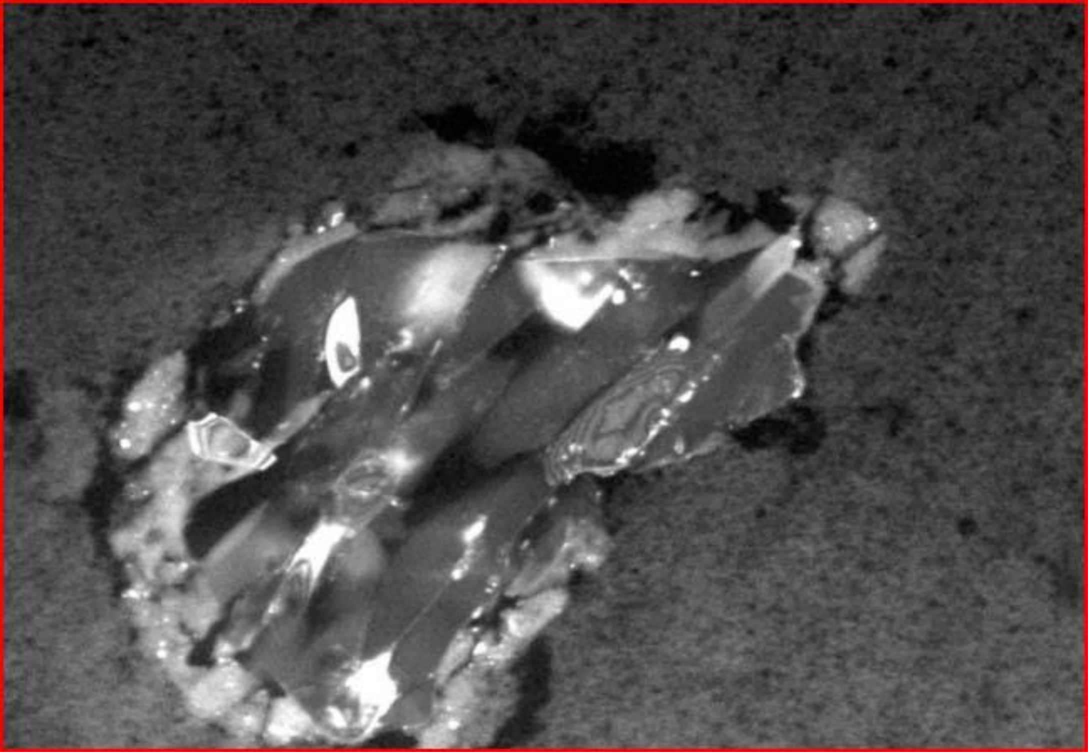
- It was first observed on photographic plates in 1969 by Soviet astronomers Klim Ivanovych Churyumov and Svetlana Ivanovna Gerasimenko, after whom it is named. It came to perihelion (closest approach to the Sun) on 13 August 2015.

- Churyumov–Gerasimenko was the destination of the European Space Agency's *Rosetta* mission, launched on 2 March 2004.

- **Stardust:** Launched in February 1999. It is NASA’s comet sample return mission .

- On January 2, 2004, Stardust flew close to comet Wild-2 and collected cometary particles for analysis. On January 15, 2006, samples of comet were delivered in a return capsule that landed in the Utah desert.

- The mixture of high and low temperature minerals in the coma dust samples collected by the *Stardust mission provides clear evidence of extensive mixing in the* solar nebula prior to comet formation.



← comet wild2 particle
(2 μm in size)

This image shows a comet particle collected by the Stardust spacecraft. The particle is made up of the silicate mineral forsterite, also known as peridot in its gem form.. The particle is about 2 micrometers across.

Particles collected by STARDUST mission from Comet Wild 2, contain olivine, pyroxene and osbornite – minerals which are supposed to form at high temperatures – instead of the cold volatiles expected for an object from the outer solar system.

STAR DUST RESULTS =>

The comet contains an **abundance of silicate (most abundant is crystalline) grains that are much larger than predictions of interstellar grain models**, and many of these are **high-temperature minerals** that **appear** to have formed in the **inner regions** of the solar nebula. Their presence in a comet proves that the **formation of the solar system included mixing on large scales** *in the* solar nebula prior to comet formation.

This **mixing must be taken into account in any theory of our solar system.** The most abundant minerals are the crystalline silicate minerals which are common in planetary materials. Finding them in comet is **somewhat surprising** because **cometary material would be similar to interstellar material**, in which most silicates are believed to be amorphous.

Stardust mission had also suggested that the cometary grains are mixtures of aggregates (porous particles) and compacts. (Hortz et al. 2006, Science; Berchell et al. 2008)

ESA- ROSETTA mission

Launched : 2 Mar 2004 by an Ariane-5 G+ from Kourou, French Guiana..

- Rosetta's main objective was to rendezvous with and enter orbit around, comet 67P/Churyumov-Gerasimenko and to perform observations of the comet's nucleus and coma and drop a lander *Philae* on comet in Nov, 2014.
- Deep space hibernation (June 2011- Jan 2014).

- The first picture of target on 21Mar 2014.
- Philae landed in Nov 2014.

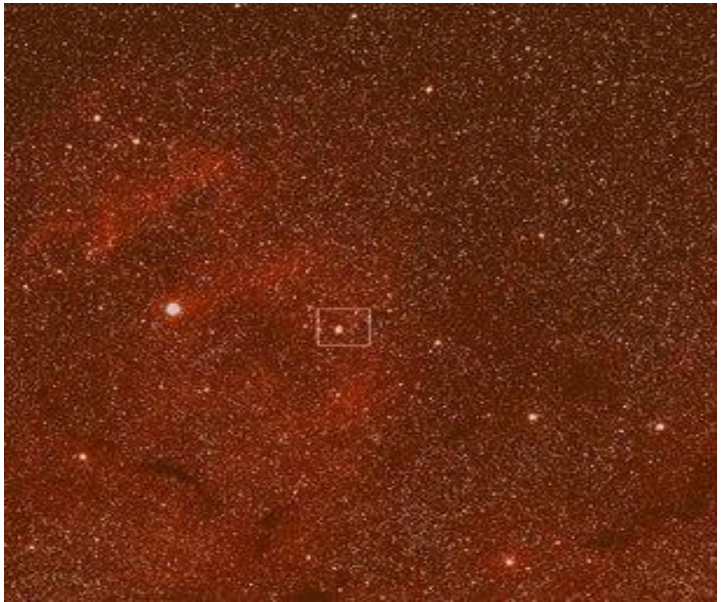
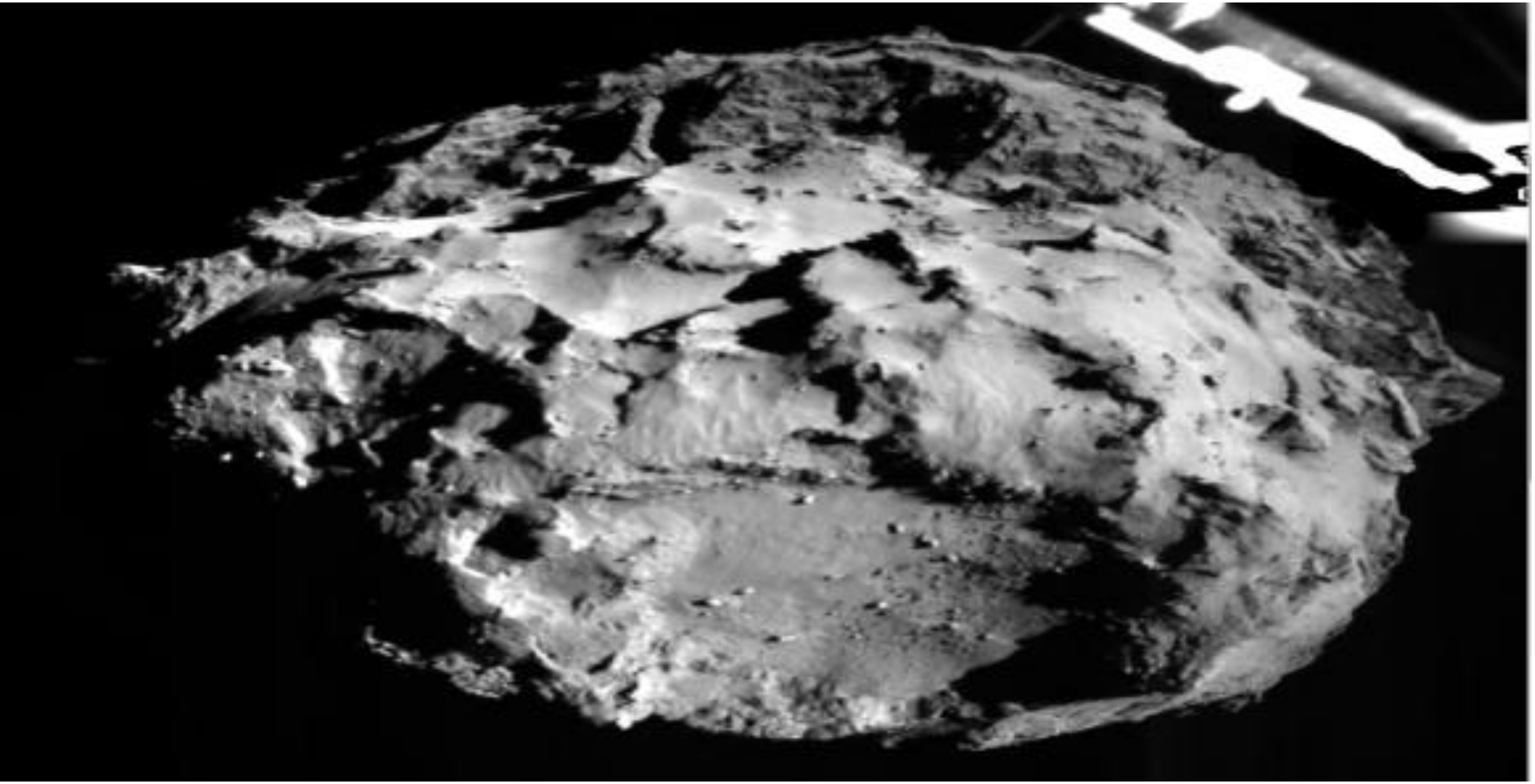


Image of comet 67P/CG acquired by the ROLIS instrument on the Philae lander during descent on 12 Nov , 2014 from a distance of approximately 3 km from the surface. The landing site is imaged with a resolution of about 3m / pixel.



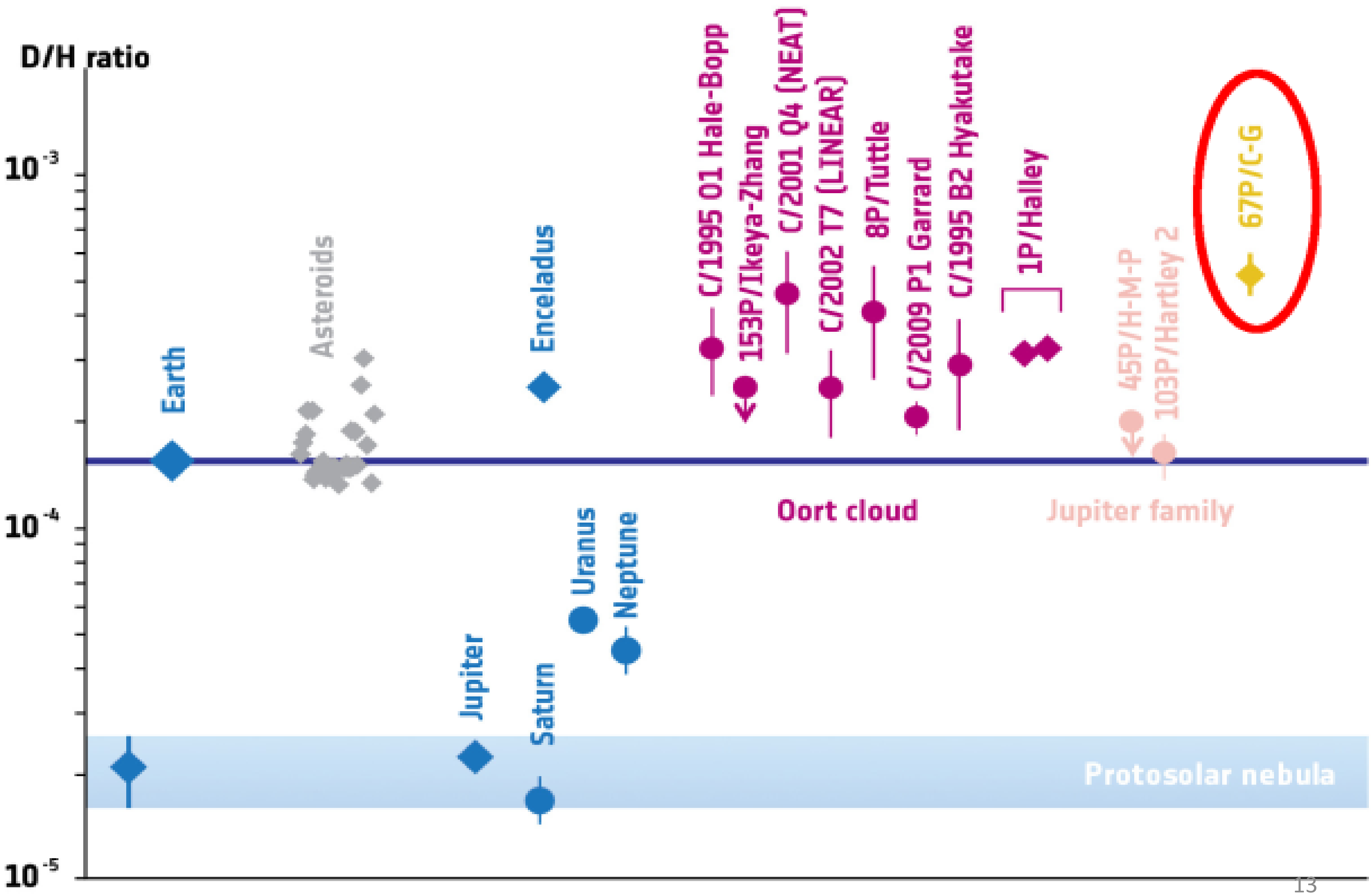
The Rosetta has detected some strange water vapor from 67P. Significantly different from what we have here on Earth. The discovery challenges the popular assumption that much of our water was delivered here by comets.

Water on earth was delivered by comets and asteroids after our planet had cooled down. Relative contribution comets /asteroids   is still debated.

(D/H) ratio measured for 11 comets (showing wide range of values), only for JFC 103P/Hartley 2 the ratio matches the terrestrial value . (ESA's Herschel mission *Hartogh et al. 2011 Nature)*

Meteorites originally hailing from asteroids match the terrestrial value. Asteroids have a much lower overall water content, impacts by a large number of them could still have resulted in Earth's oceans.
D/H ratio from Rosetta (5.3 x10^{-4}), is more than 3 times greater than for Earth's value and is even higher than measured for any Oort cloud comet as well. (Science , Altwegg et al 2014)

⇒diverse origin for the Jupiter-family comets – perhaps they formed over a wider range of distances in the young Solar System than we previously thought,"
Asteroids were the main delivery mechanism for water on Earth's oceans. ??



D/H ratio
10^-3
10^-4
10^-5
Earth
Asteroids
Enceladus
Jupiter
Saturn
Uranus
Neptune
C/1995 O1 Hale-Bopp
153P/Ikeya-Zhang
C/2001 Q4 (NEAT)
C/2002 T7 (LINEAR)
8P/Tuttle
C/2009 P1 Garrard
C/1995 B2 Hyakutake
1P/Halley
45P/H-M-P
103P/Hartley 2
67P/C-G
Oort cloud
Jupiter family
Protosolar nebula

The recent spacecraft encounters with comets gave us two important results :

1. Comets contain particles which carry signatures of both (i) the outer part of solar nebula (or interstellar medium) and (ii) the inner part of solar nebula => thorough mixing in the early part of the history of solar system formation.

2 . Water on earth may have diverse origins : asteroids and comet. => diverse origin for the Jupiter-family comets – perhaps they formed over a wider range of distances in the young Solar System than we previously thought.

- Were the Asteroids, the main delivery mechanism for water on Earth's oceans. ??

(May 2016 Scientific American, The violent Biography of Solar system)

The findings from the spacecraft encounters can not be explained by the current theories of solar system formation viz. nebular theory (Safranov 1969(Rus)/ 1972 (Eng)) and the Modern version of it.

According to the above theory

- Sun was born by gravitational collapse of a rotating nebula.
- In the accretion disk around Sun, there was almost smooth temperature gradient, so that planets with different compositions and sizes were formed.
- Comets formed initially in a region near Jupiter, by later thrown by perturbation to spherical a reservoir of 10^5 AU (Oort cloud) (Sen and Rana, AA 1993)

How do the ground based studies
on comets help us to understand
some of the key issues:

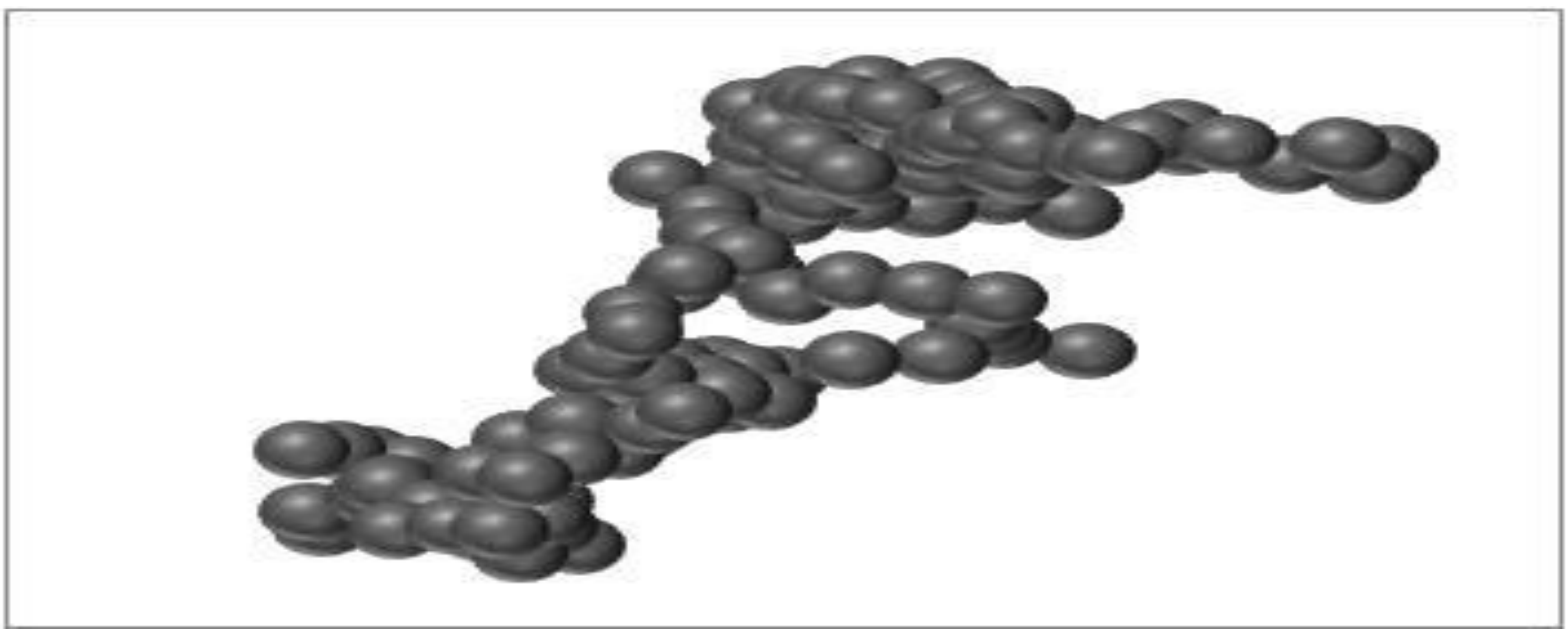
Understanding the cometary particles

through photopolarimetry

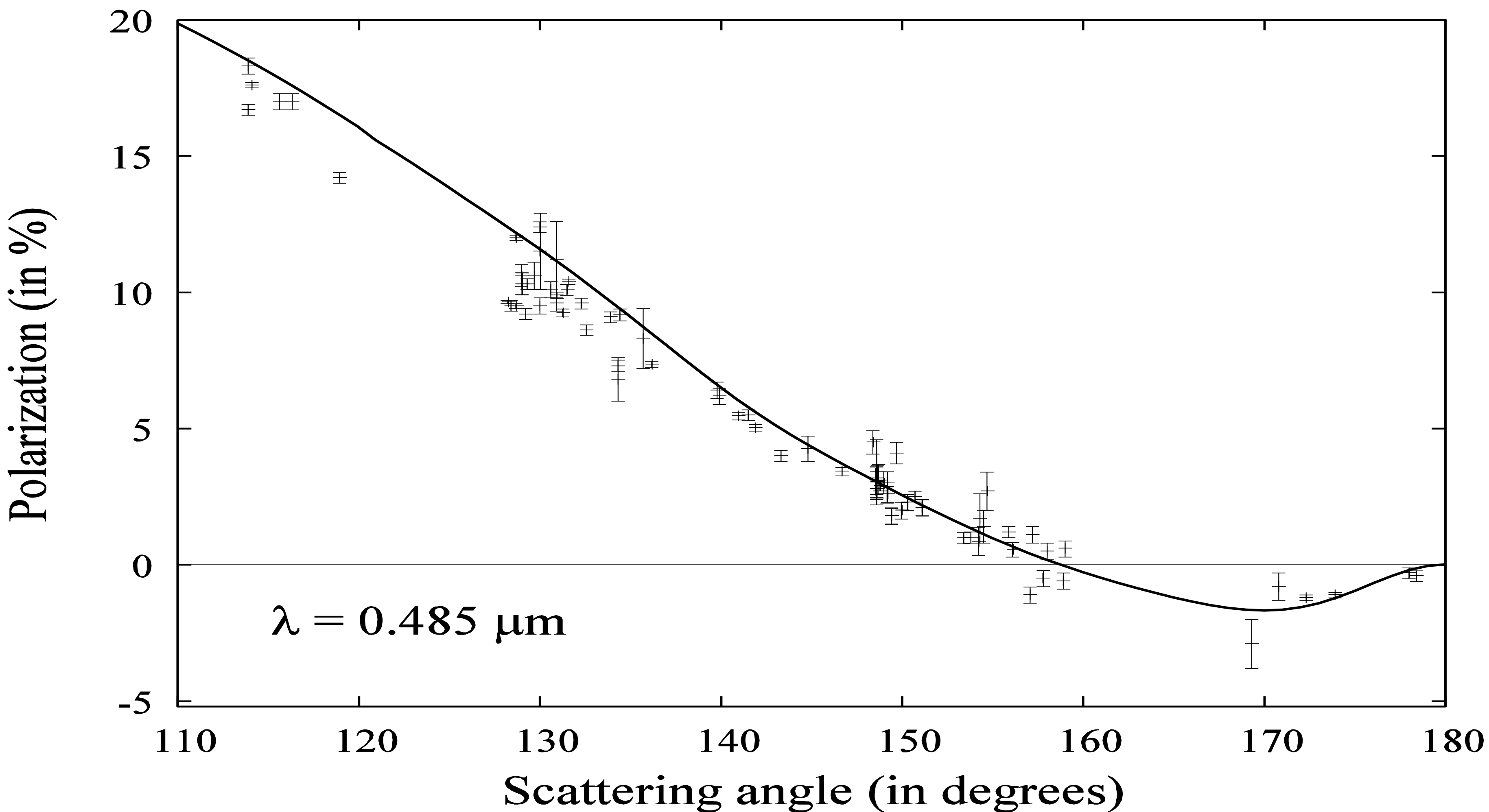
How do cometary grains look like ?

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

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

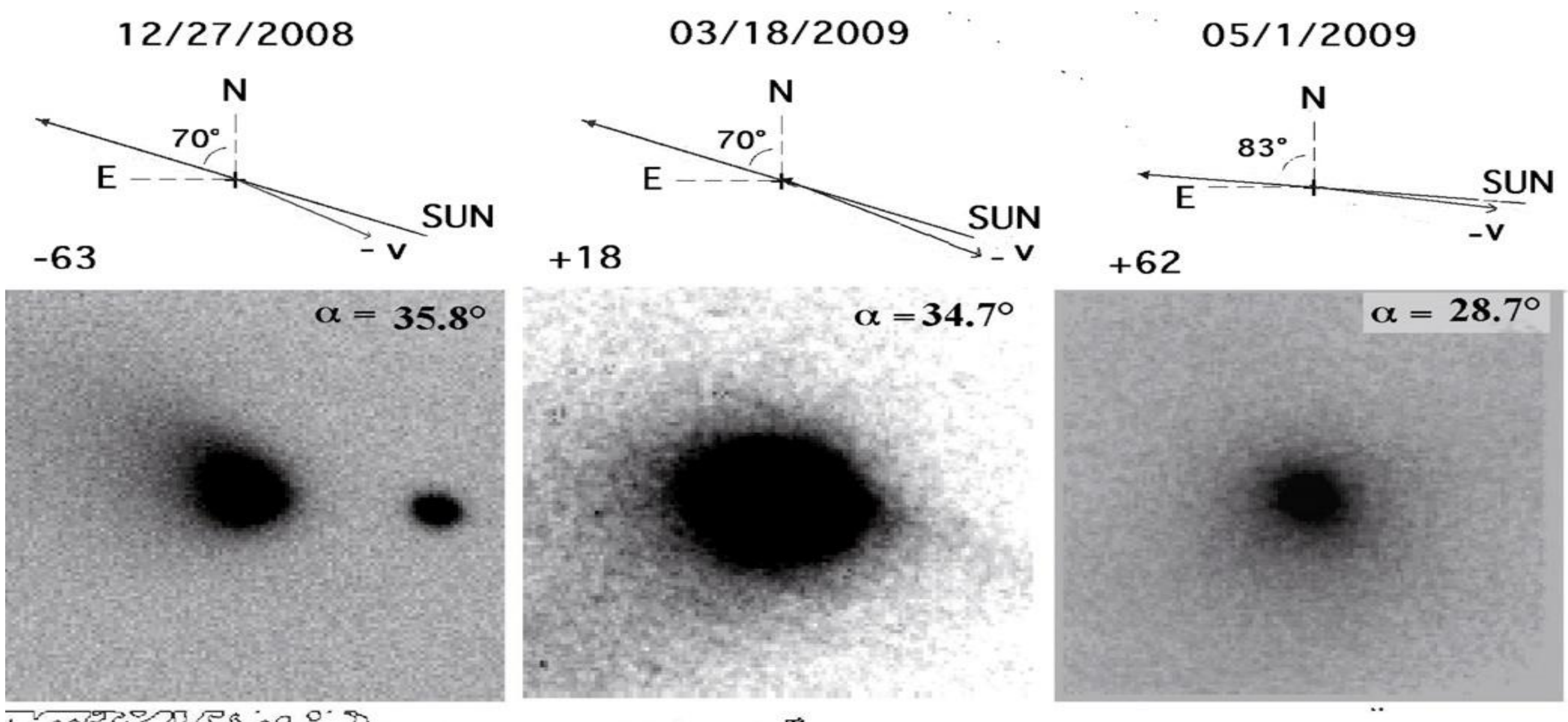


The polarization data of comet Halley at 0.485 μm fitted with a model containing Compact and Aggregate (BAM2+BCCA) in the ratio 65:35 taken from STARDUST Wild 2 mission. Compacts are spheroids. The fitted parameters are BCCA:BAM2 =1:1 and SILICATE : ORGANIC =78:22 by volume . (Das and Sen 2011 JQSRT; Das et al 2011 MNRAS)



Comet 67P/ C-G : Our analysis (Hadamcik et al. 2010, AA) indicated there was post perihelion ejection of small fluffy aggregate grains, increasing suddenly the intensity and polarization. Results also indicated different grains being ejected at different hemishperes of nucleus. There were large variations of polarization in inner coma (< 3000 km), indicative of several ejections. Whether grains have surface or sub-surface origin ?

(Below:Images from IUCAA 2 m telescope, 1 pixel was corresponding to 370 km, <-> 400 pixels. March observation are from OHP, France.).



Since cometary dust particles are expected to be porous in Nature , we need a model to describe it

- Definitions of porosity
- Different types of porous irregular structures BPCA, BCCA, RLCA etc.
- Our porous model (randomly connected dipoles).
- Its application on comet data

- Cosmic dust particles are responsible for the observed polarization, extinction (in intensity), thermal re-emission etc. Examples are comets, asteroids, interstellar medium, circumstellar matter, nova etc

- First evidence of polarization by dust scattering were reported independently by Halt (1949) and Hiltner (1949).

- First theoretical expression for the polarization and intensity of light scattered by a spherical, homogenous and compact sphere was given by Mie (1908).
- Brownlee (1985) gave the first direct evidence that cosmic particles (Interplanetary dust particles, IDP) are highly porous and irregular.

- Slowly different semi-analytical (numerical) models were available which could simulate scattered intensity and polarization for irregular and porous particles (viz. T-Matrix (Mishchenko et al 1994), DDSCAT (Draine 2000); Separation of Variables Method (Nikolai et al 1996) etc.

- Polarization $P=(I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp})$ and Intensity $I = I_{\parallel} + I_{\perp}$

Brownlee [1985] directly detected for the first time the porous/fluffy dust particles in our upper atmosphere through in situ measurements.

⇒The collected IDP densities 0.7 to 2.0 g per cc for sizes of few μm.

⇒ BCCA or BPCA structures with Silicate compositions are inconsistent with such bulk densities, though these have been frequently used to explain cometary polarization.

⇒ neither BCCA nor BPCA could solely fit the observational data on comets.

⇒The bulk density of particles in comet 81P/ Wild2 was reported by Horz et al. [2006] to range from 0.3 to 3.0 g per cc, which is too high for BCCA or BPCA dust particles.

⇒ Also in comet 67P, the morphology of the micron sized dust particles was recently reported by Bentley et al. [2016] to be very dense and that is again not consistent with BCCA or BPCA.

The above have prompted us to look for a new porous dust model for comets.

Also we note that, in comets the structure of the particle is not decided only at the time of formation , but the structure can also change later due to different disruptive forces in the solar system.

Porosity $f = V_p / (V_m - V_p)$

where V_p is the total volume of the pores or voids in a dust particle.

V_m is the total volume of the dust covered by the circumscribing surface

$= (4 \pi/3) r^3$ for a sphere

- But if the surface irregularities are of the same order as the size of the particle (or wavelenth), then

$f = 1 - c(R/a_0)^{df}$

where df < 3 is the fractal dimension of the matter distribution inside the particle, and

R is the radius corresponding to total equivalent sphere volume.

a_0 is the volume of the grain (monomer) of which the material is made up of c is a constant.

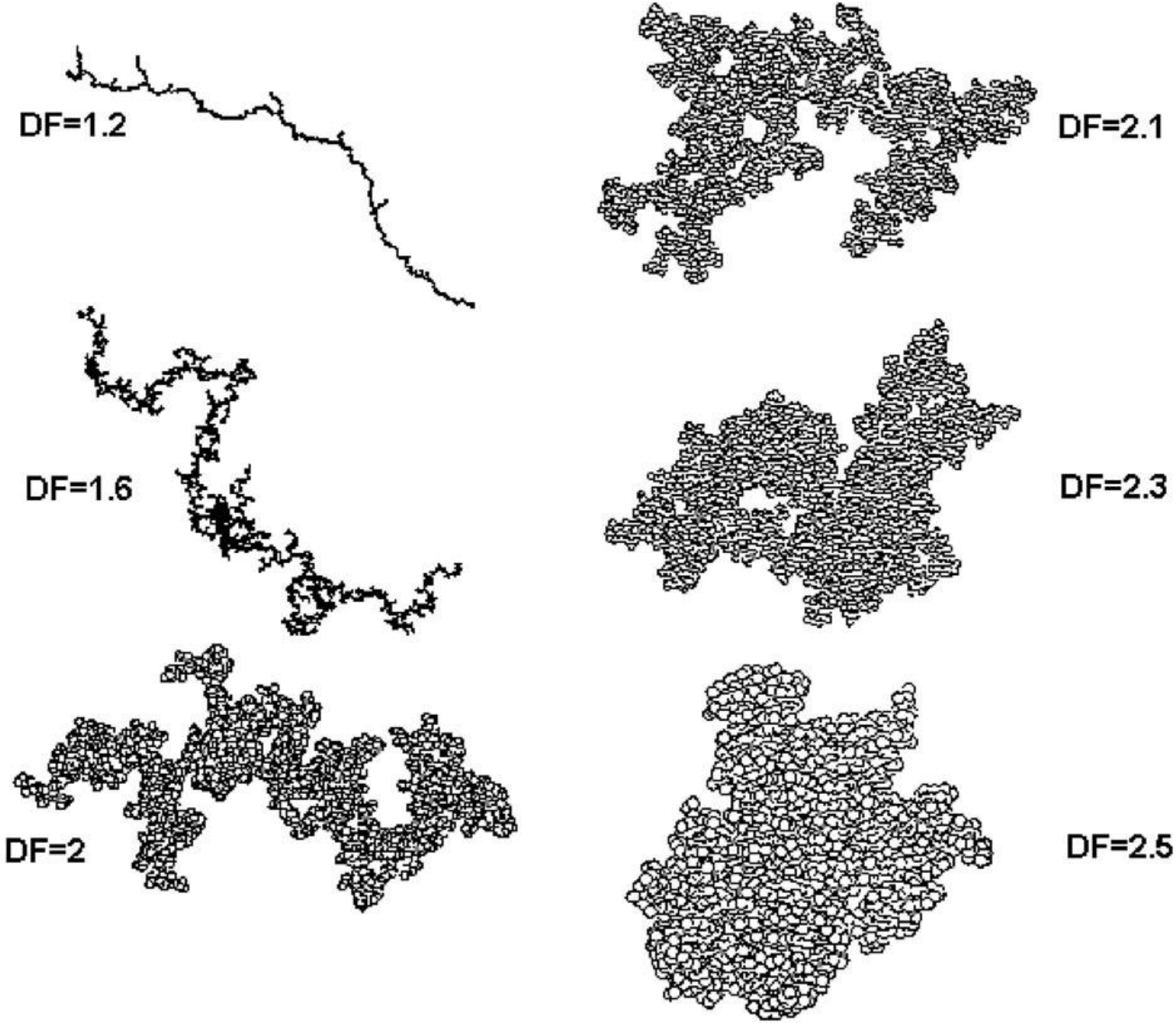
Various algorithms are used to generate aggregates of *grains (monomers)* with different shapes and porosities

1.Ballistic Particle Cluster aggregates (BPCA) *df* ≤3 Meakin 1983 : the procedure allows only single grain to join the cluster of other grains

2 Ballistic Cluster Cluster aggregates (BCCA) (*df*≈ 1.9) Wurm & Blum 1998 : Procedure allows cluster to join another cluster.

3.Reaction-Limited Cluster-Cluster Aggregation model (RCCA or RLCA). In the RCCA, sticking is hard to occur, for example because the aggregates are electrically charged. (*df*≈ 2.1) Robert and Jullien 1983

4. diffusion-limited cluster aggregation (DLCA) (*df*≈ 1.65) **Asnaghi**
1992, Meakin 1993 (both the clusters and grains are mobile)


DF=1.2
DF=2.1
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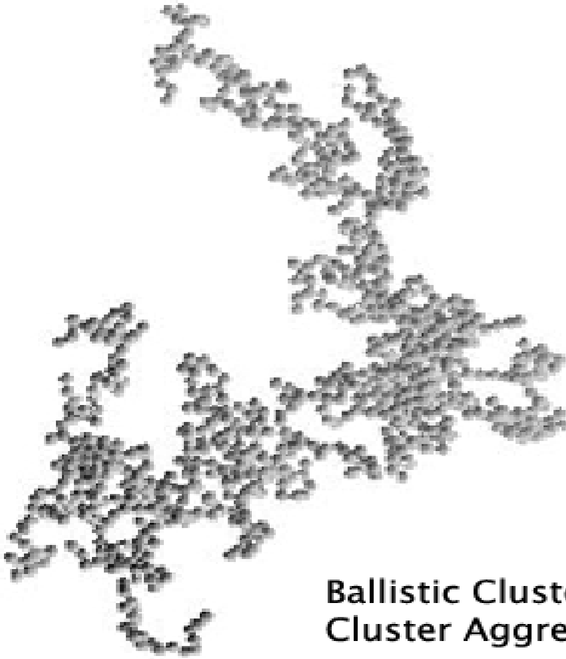
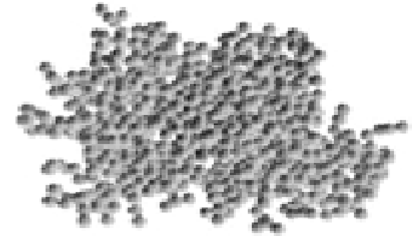
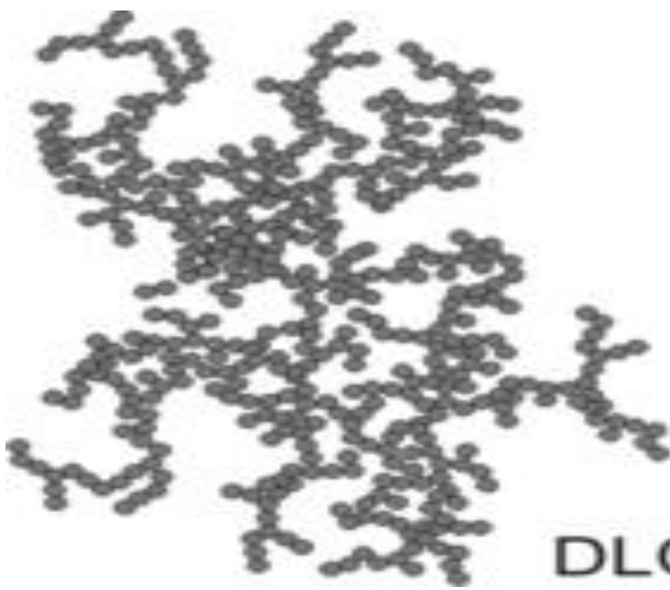
DF=2.5



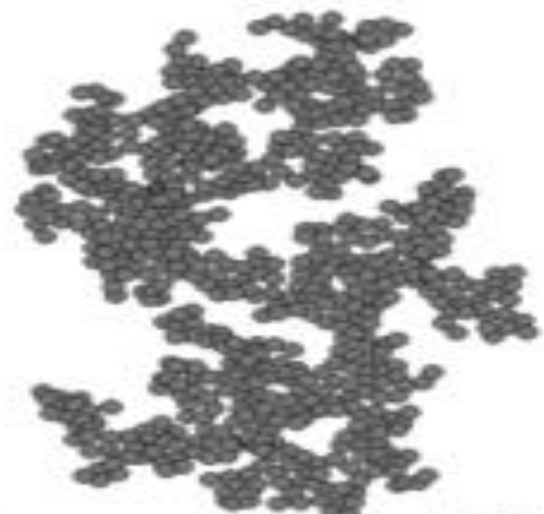
Ballistic Cluster-
Cluster Aggregate



Ballistic Particle-
Cluster Aggregate



DLCA



RLCA

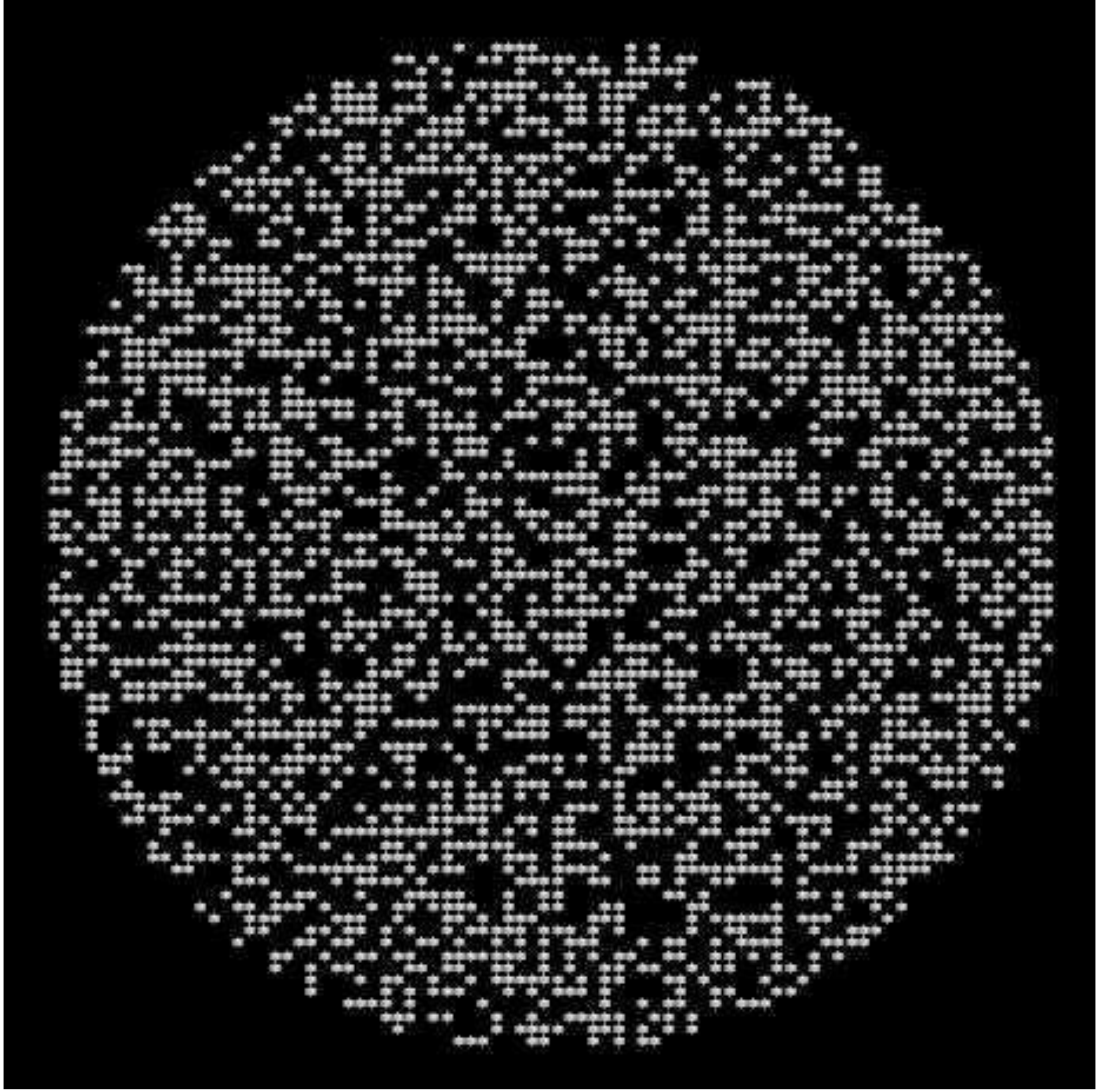
- The above models can not generate aggregate structure with an arbitrary porosity for fixed size of the aggregate (dust particle).

- Cosmic particles have wide size distribution. Halley has a size distribution function $n(a) \sim 1 / (a^{\alpha})$; α= 1.8, 2.8, 3.8

- A new model (Sen at al JQRT 2017) considers a compact sphere containing dipoles (grains). These dipoles are then removed randomly, such that finally there are no isolated (un-connected) dipoles. Therefore *porosity (f)=(number of dipoles removed) / (original total number)* .

- The DDA (Discrete Dipole Approximation) Code was used to simulate intensity and polarization values.

- Simulated values are compared with the actual observation. For comets, we have very wide scattering geometries putting more constraints on the model and large data base (viz Halley).



Slice of an aggregate structure generated for the 50% porosity value. The width of the slice is 1 grain-diameter. The slice passes through the geometric center of the particle.

- Mie particles having very uniformly mixed two compositions , can be represented by an Effective Refractive Index using Maxwell Garnett Rule. This is called Effective Medium Theory (EMT). (Voshchinnikov et al. 2007)

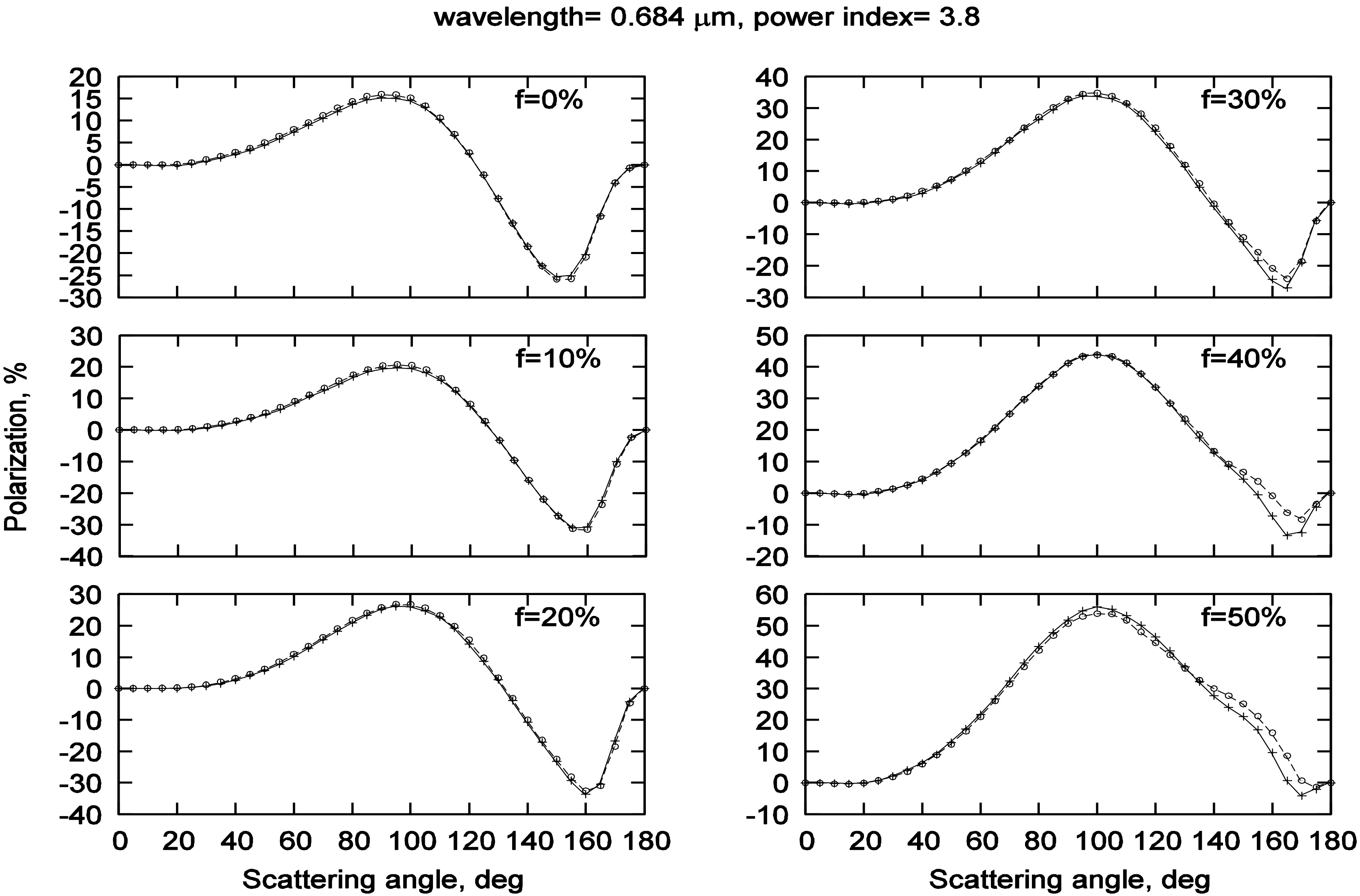
- In past, Wolff et al(1993, 1998), had worked on voids (vacuum inclusions) which are having sizes smaller than the wavelength (Rayleigh inclusions). The authors observed that the light scattering properties are similar to EMT for low porosities.

- For non-Rayleigh they extended the work and found differences.

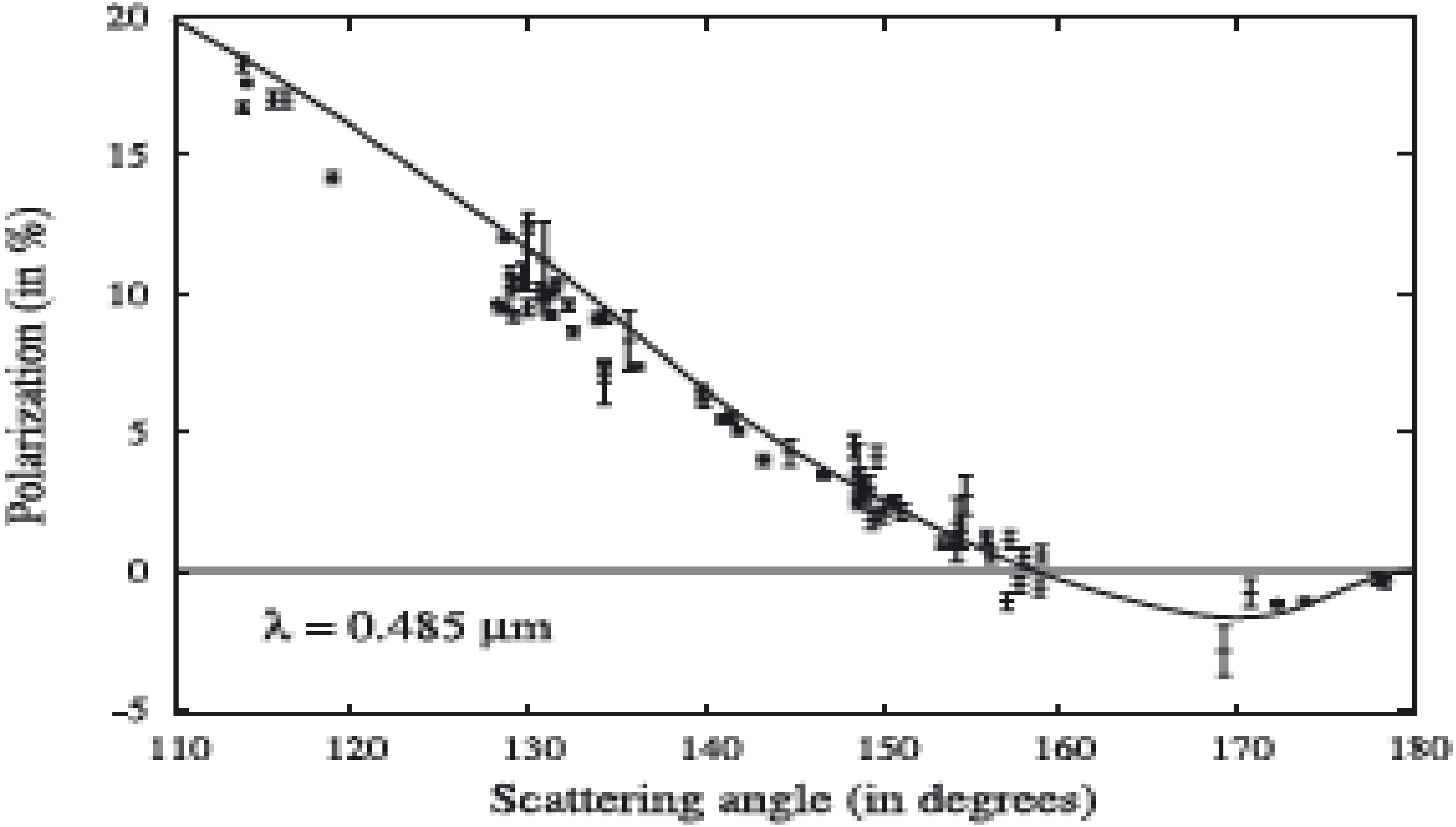
- In our work, we just randomly remove the dipoles. So we have both Rayleigh and non-Rayleigh inclusions.

- Then we systematically study the role of porosity on light scattering

- Compare the simulated polarization values with observations on comet.



Polarization v/s scattering angles , for various values of porosities. The particles having size range 0:01m - 1:0m, with a power-law size index = 3:8 and wavelength= 0.684 m. The curve (joined by 'o' symbols) is the one drawn using the DDA method, and the curve (joined by '+' symbols) is the one drawn using the Mie theory combined with Effective medium Theory (mixing rule of Bruggeman , from Voshchinnikov et al 2007)



- Shows our model curve at 0.485 micron with 40 % porosity and 3.8 power law index compared with actual observation on comet Halley.

Conclusions

- An algorithm has been developed to generate porous particles containing connected dipoles with arbitrary value of porosity and size.
- As calculated using DDA, such particles produce polarization values which are different from EMT.
- These particles are more realistic and should be considered in future to simulate observed polarization and extinction values.
- These particles also provide us a tool, to study the effect of porosity (for any particle size) on polarization, extinction etc.

Thank You……