Cometary grains : Photopolarimetric Studies of some recent Comets

Asoke K Sen*, with

Edith Hadamcik (France), Robert Botet (France) and Ranjan Gupta (India)

*Assam University, Silchar 788001, India
Email : asoke.kumar.sen@aus.ac.in
asokesen@yahoo.com
What comets are ..... 

- A small (km sized) objects orbiting the sun

- Has higher gas content compared to asteroids. So when comes closer to Sun \((1 \text{ AU} = 1.5 \times 10^8 \text{ km})\), a gaseous atmosphere is developed (COMA).

- Comes from all direction in the solar system, not contained in the ecliptic plane.

- Has a perihelion distance of \(10^5 - 10^6 \text{ AU}\) (there is a spherical reservoir called Oort cloud)
NEW ERA IN COMETARY SCIENCE BEGINS:

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); dust grains are organic compounds (C, H, O, and N); ~80% of coma is H₂O
- Dust mass distribution & elemental composition were determined by onboard instrument.
- Existence of CHON particles (30%)

Dust size distribution was established through ground-based polarimetry (Mukai et al. 1987, Le Borgne et al. 1987, Sen et al. 1990)

Ground-based Imaging Polarimetry work revealed the existence of dust jets from nucleus (Eaton et al. 1988 Icarus), 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 production rates
- rotations of nucleus
- composition, size distribution and other properties of dusts.

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

The long period comets (P > 100) are believed to come from the Oort cloud (50,000 to 100,000 AU).

The short period ones (P < 100 yrs) come from a region called Kuiper Belt (extending from the orbit of Neptune at 30 AU to 50 AU) (KB is almost 100 times more massive than the asteroid belt).

Most short-period comets (period < 20 years) called Jupiter-family comets are believed to originate in the Kuiper belt.
Apart from Halley missions (Giotto, Vega 1, Vega 2, Sakigake and Suisei) we had:

DEEP SPACE 1 – Borrelly (Oct 1998/ Sep 2001),

STAR DUST – Wild2 (Feb 1999 / Jan 2006)
→ STAR DUST NExT flew to Tempel 1 on Feb 14, 2011

DEEP IMPACT – Tempel 1 (Jan 2004 / Jul 2005, hit the comet with a 370 kg impactor).
→ EPOXI – Hartley 2 (4 Nov 2010) (an extended mission of DEEP IMPACT)

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.

In Nov 2005 it landed on the asteroid and sample was returned to earth on 13 June 2010, with capsule containing asteroid dust.
→ ROSETTA sample mission on comet 67P/C-G, Nov 2014
The Deep Space 1 mission on Comet Borrelly revealed:

- a diverse surface with smooth plains, low-lying areas filled with fine-grained materials, and multiple 100m-high structures. The nucleus is 8 kilometers long with mountains, faults, grooves, smooth rolling plains. It also demonstrated the existence of jets and geysers on the comet.

- Deep Space 1 was launched from Cape Canaveral on October 24, 1998. In an extremely successful extended mission, it encountered Comet Borrelly in Sep 2001 and returned the best images and other science data.

- During its fully successful extended mission, it conducted further technology tests. The spacecraft was retired on December 18, 2001.
• **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.

• **Stardust-NExT (Stardust-New Exploration of Tempel 1)** is an extended mission that utilizes the already "in flight" Stardust spacecraft and flew by comet temple 1 in Feb. 2011.

• 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.

• Stardust mission had also suggested that the cometary grains as mixtures of aggregates (porous particles) and solid grains.
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. It is surrounded by a thin rim of melted aerogel, the substance used to collect the comet dust samples. 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.
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)
**Deep Impact** is a NASA space probe and was launched on January 12, 2005. It was designed to study the composition of the comet interior of 9P/Tempel 1, by releasing an impactor into the comet. At 5:52 UTC on July 4, 2005, the 370 kg impactor successfully collided with the comet's nucleus.

- Upon the completion of its primary mission, proposals were made to further utilize the spacecraft. Consequently, *Deep Impact* flew by Earth on December 31, 2007 on its way to an extended mission, designated EPOXI, with a dual purpose to study extrasolar planets and comet Hartley 2.
- It first investigated extrasolar planets and on November 4, 2010, it performed a close approach to the comet 103P/Hartley (alternately named Hartley 2).
Launched: 2 Marc 2004 by an Ariane-5 G+ from Kourou, French Guiana..

- On its 10 year journey to the comet, the spacecraft had passed by two asteroids: 2867 Steins (on 5 Sep 2008) and 21 Lutetia (on 10 Jul 2010).

- Rosetta's main objective is 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 - 20 Jan 2014).

- The first picture of target on 21 Mar 2014. →
The image shows comet 67P/CG acquired by the ROLIS instrument on the Philae lander during descent on Nov 12, 2014 14:38:41 UT from a distance of approximately 3 km from the surface. The landing site is imaged with a resolution of about 3m per pixel.

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

It is believed that water on earth was delivered by comets and asteroids after our planet had cooled down. The relative contribution of comets and 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 in 2011. Hartogh et al. 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 ($5.3 \times 10^{-4}$), 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 10 Dec 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," Kathrin Altwegg, principal investigator for ROSINA Science this week.

Asteroids were the main delivery mechanism for water on Earth's oceans. ??
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** $\text{Mg}_x \text{Fe}_{(1-x)} \text{SiO}_3$  
**Olivine** $\text{Mg}_{2y} \text{Fe}_{(2-2y)} \text{SiO}_4$
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)
BPCA

BCCA 128 monomers

BAM2
Comet Halley data at 0.485 µm fitted against a model containing compact and aggregates. The contribution from individual components are shown.
Recent work on cometary dust and observations from 2m IUCAA telescope under Indo-French Collaboration (CEFIPRA)

1. Simulation of polarization and other grain properties for some previously observed comets (like Halley, Levy, HaleBopp etc)

2. Imaging polarimetry of some recently observed comets (some are targets of space missions), like 67P/Churyumov-Gerasimenko, Hartley 2, Gerrasudd along with some asteroids
Ground based work of some ROSETTA mission targets were made from IGO (India) and OHP (France).

Asteroids Stein and Lutetia (M-type, high albedo) were observed from IUCAA and OHP. (2008-10).

The spacecraft ROSETTA has passed by two asteroids: 2867 Steins (on 5 Sep 2008) and 21 Lutetia (on 10 Jul 2010). ROSETTA gave terrain map, suggested complex mineralogy and thick regolith, with rich surface features (Hadamcik .... Sen, 2011 JQSRT).

Rosetta's main objective is to rendezvous with and enter orbit around, comet 67P/Churyumov-Gerasimenko (C-G) and to perform observations and drop the lander Philae (estimated date Aug 2014, R= 3.8 AU). (perihelion= Aug 2015).

Comet C-G is a bright JFC with period 6.44 year. HST estimated rotation periodicity of nucleus ~ 12.3 hrs and Spitzer estimated diameter (~ 4 km). During 2008-09 (Dec – May), comet C-G was observed from IUCAA and OHP (Δ= 1.7 AU, R= 1.5 AU) (Hadamick, Sen, ...2010 AA).
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.)
Comet Hartley 2 (EPOXI target)
Discovered in 1986-6.47 years period-2010 last apparition – 20 Oct 2012 closest to earth at 0.12 AU (q=1.05 Q=5.88 AU). On 04Nov 2010 Deep Impact (part of extended mission EPOXI) flew close.

IGO-OHP: ground based observation (Hadamcik et al 2011, JQSRT) during the time of space encounter. Participated in an International Campaign (Meech et al. 2011ApJL). On the intensity images, the coma is asymmetric with an important tailward feature. Jets in the sunward direction are observed with an extension that depends on the nucleus phase. The decrease in linear polarization and intensity with increasing optocentric distance may be induced by large slow particles in the inner coma and possibly by their fragmentation into smaller ones.

November data are from IUCAA
Correlation between the jets in the intensity and polarization images was observed. They seem to change with the same period along with the nucleus rotation.

The intensity images and jets were used with other observations close to the DIXI encounter to study the jets and relate them to the nucleus rotation.

*Comet 103P/ Hartley 2 results (cont’d…)*

(Hadamcik , Sen ,…..,2013, Icarus)
**Comet C/2009 Garradd 9 (from OORT CLOUD)**

Comet Garradd was observed from IUCAA and OHP during Oct 2011 and March 2012, (Hadamcik et al 2014, MPS) when the phase was 28° to 35° (r=1.3 – 1.9), under Indo-French collaboration. Discovered in Aug 2009 / dynamically new comet (peri 23 Dec 2011, r=1.55). 2 or 3 months after perihelion, jets with higher polarization were observed.

Evolution of jets from Oct 2011 to March 2012
Isophotes and enhanced intensity images

Polarization maps with higher polarization in February and March (butterfly structure in March)
On the polarization maps of February and March the polarization in the jets is noticed to be higher than that in the surrounding coma. If jets were observed in the intensity images, without counterpart in the polarization maps, then the physical properties of particles inside such structures are NOT different from the surrounding dust coma. But if they are different, the fans and jets may be detected by color and/or linear polarization differences.

- This may be indicative of radial differentiation of matter in the nucleus and in turn will help us to understand the formation process of comet.
- Are the Oort cloud comets and JFCs different?
- For Garradd in some cases, we observed Jets in the intensity images, but without important counterpart in the polarization maps (Hadamcik et al 2014, MPS). No significant difference has been observed between Hartley and Garradd.

*Comet C/2009 Garradd results (cont’d…)*
The overall shape of the coma of comet Lulin is about circular without evident jet structure. The coma of comet C/2011 L4 is enlarged in the antisolar direction. Jets in a fan like structures have been noticed between position angles 225°-335° in the treated intensity images. A correlated higher polarization region is noted on the corresponding polarization map. The coma of comet Jager is also about circular in shape. Deeper negative polarization is found at the inner coma zone. The whole coma polarization values of these three comets correspond to the synthetic phase curve for comets at similar phase angles and wavelength.

Comets C/2007 N3 (Lulin), C/2011 L4 (PANSTARRS) and 290P/Jager were observed at phase angles (<40°) between 2009 and 2014; with the 0.8m Telescope at Haute-Provence Observatory (OHP) in France. The observations were mainly carried out in the red and near infra-red wavelength domain to reduce gaseous contaminations. (Roy Choudhury et al 2014, JQSRT)

Fig.: From left- Lulin, C/2011 L4, Jager at phase angles 35.7°, 38°, and 14° respectively. Upper line: Intensity Images treated by rotational gradient method. Lower line: Polarization map.
Thank You......