How Comets can help in studies of Planet Formation? Missions

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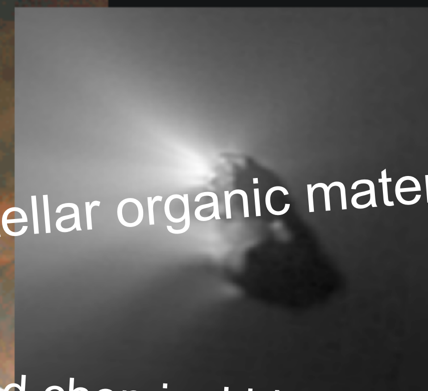
Outlook

- I.- Introduction
  - Tracers for processes that were predominant in the protosolar nebula
- II.- Missions
- - Deep Impact
- - the velocity distribution - Results
- III.- Helping us to solving problems
- IV.- Conclusion

I. Introduction

The evolution of the Solar Nebula in its phase of "planet-forming debris-disk" is not yet fully understood.

Learning about the composition of comets can help



What is the complement of pristine interstellar organic material in comets?

Is it possible to reconstruct the physical and chemical history of interstellar material in the nebula from observations of its processed end-state in comets?

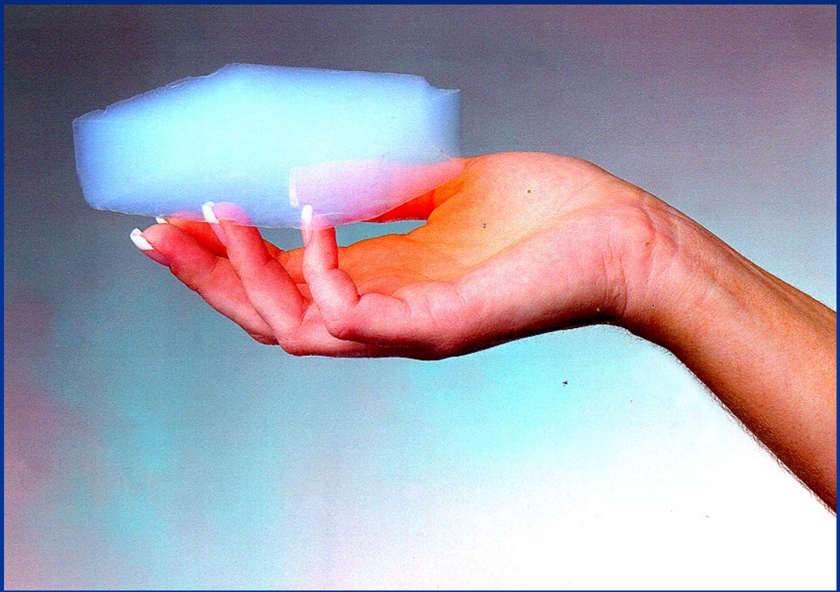
Does the chemical composition of a comet reflect its formation zone in the nebula?

Do different cometary materials originate from markedly different environments?

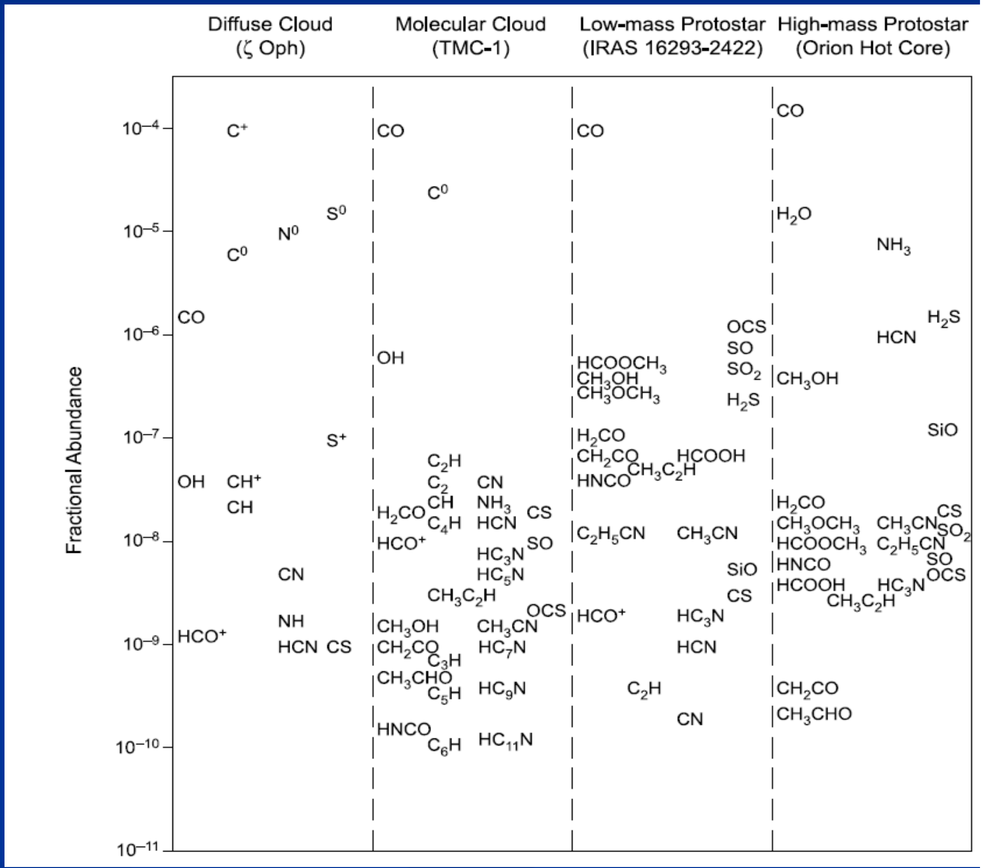
If so, what are its implications for the physical conditions of nebular evolution?

Tracers for processes that were predominant in the protosolar nebula

The different conditions prevailing during the formation of the Solar System have left traces that can be found today in **cometary material** (structure, composition of ice, dust fractions, and pre solar-grains)

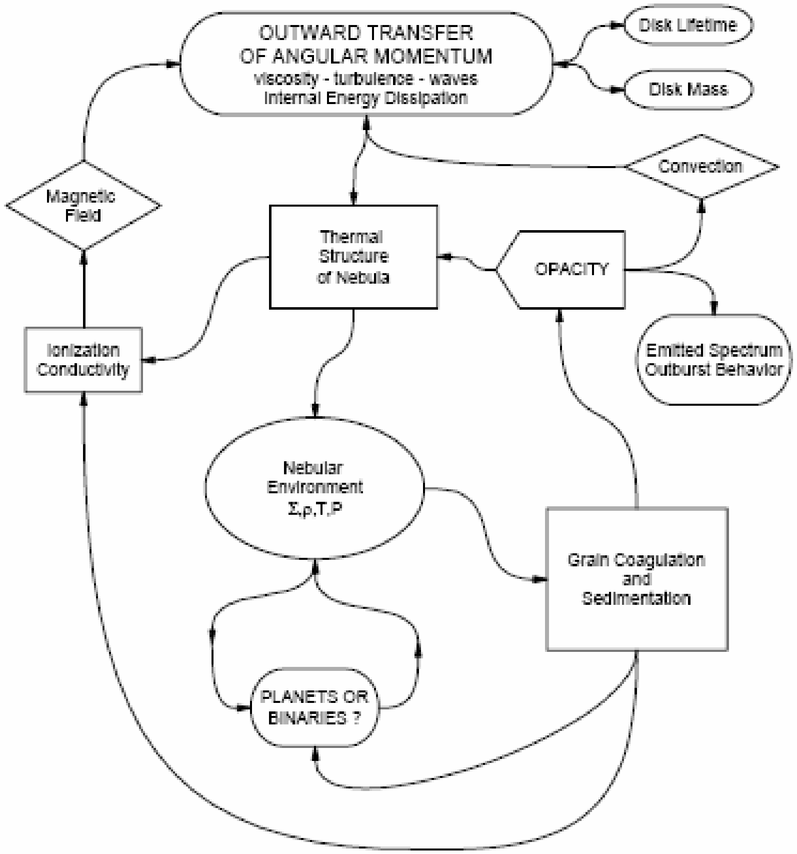


Fractional abundances of ions, atoms, and molecules in different regions of the ISM



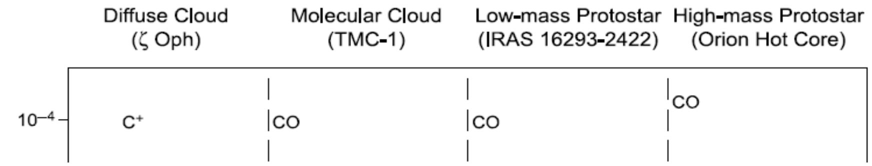
complexity of molecules increasing

- **Cometary material** (ices, organics and minerals) can provide the fundamental starting point to understand the processes during and the chronology of the formation of the planetary system

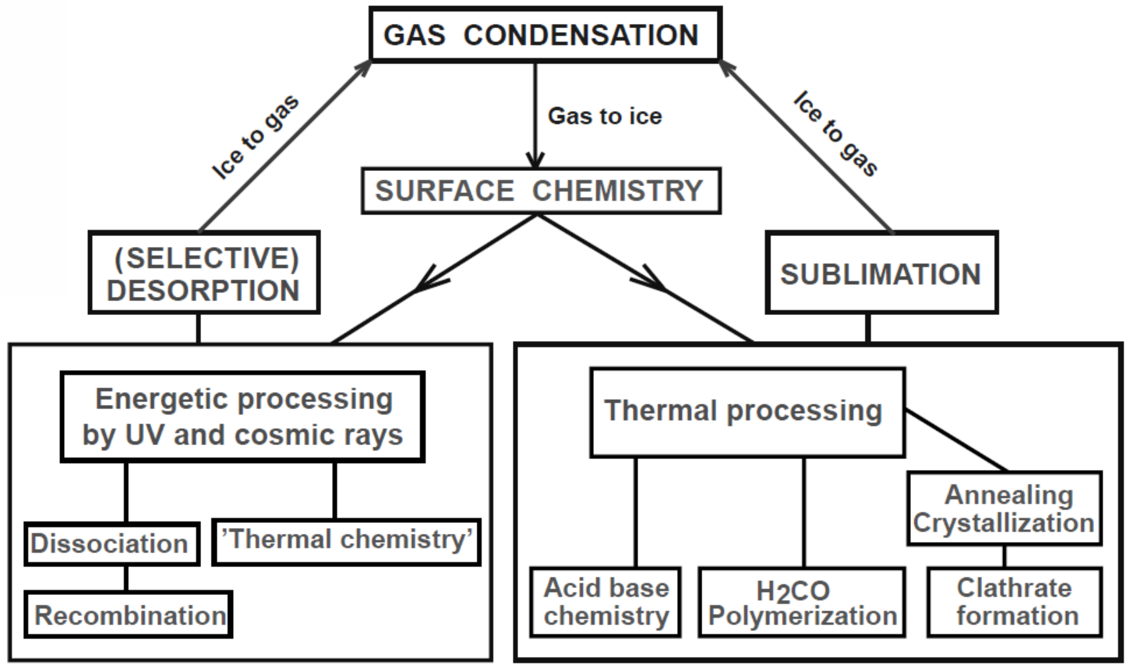


RELATIONSHIPS AND DEPENDENCIES
AMONG PROTOPLANETARY DISK PROCESSES

Credits: Ruden S.



THE CYCLE OF ICE AND GAS IN DENSE CLOUDS



Ehrenfreund & Charnley, ARA&A, 2000

Tracers for processes that were predominant in the protosolar nebula

- **PAHs** are a significant constituent of the ISM, of Circumstellar Dust Disks. and it is present in comets. Ist detection provides important clues on the processes that ocurred during the formation of our Solar System

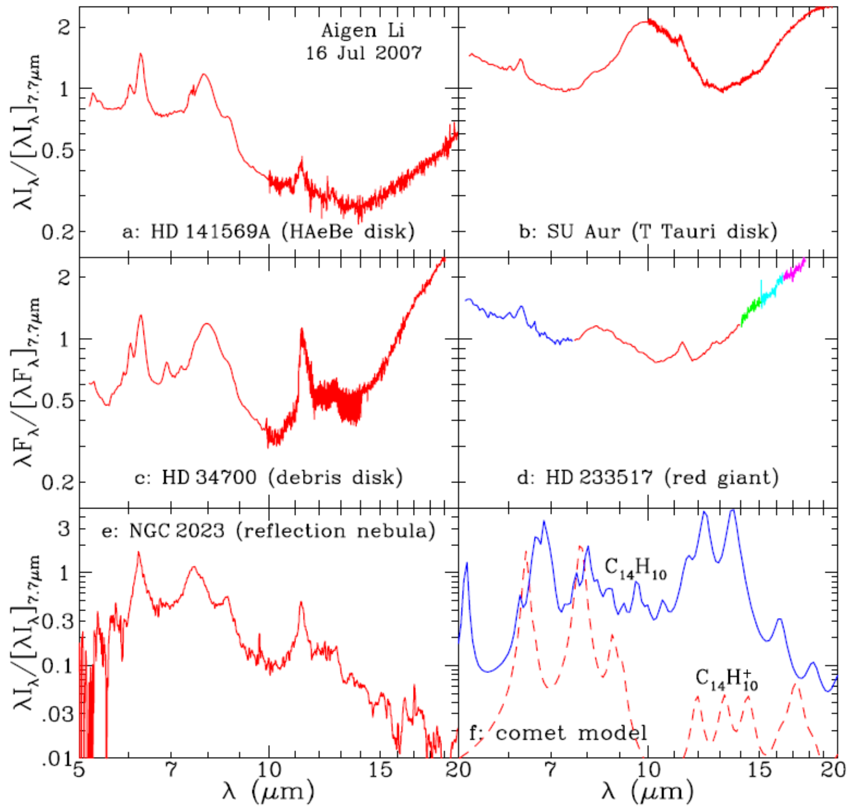


Fig. 3. Observed 5–20 μm spectra for: (a) Protoplanetary disk around HAeBe star HD 141569A (B9.5V; $T_{\rm eff} \approx 10{,}000$ K; Sloan et al. 2005); (b) Protoplanetary disk around T Tauri star SU Aur (G1III; $T_{\rm eff} \approx 5945$ K; Furlan et al. 2006); (c) Debris disk around HD 34700 (G0V; $T_{\rm eff} \approx 6000$ K; Li et al. 2008); (d) Circumstellar disk around red giant HD 233517 (K2III; $T_{\rm eff} \approx 4390$ K; Jura et al. 2006); (e) Reflection nebula NGC 2023 (illuminated by HD 37903 [B1.5V; $T_{\rm eff} \approx 22{,}000$ K]; Verstraete et al. 2001). Also shown (f) is the emission calculated for phenanthrene $C_{14}H_{10}$ and its cation $C_{14}H_{10}^{+}$ at $r_h = 1$ AU from the Sun (Li & Draine 2008).

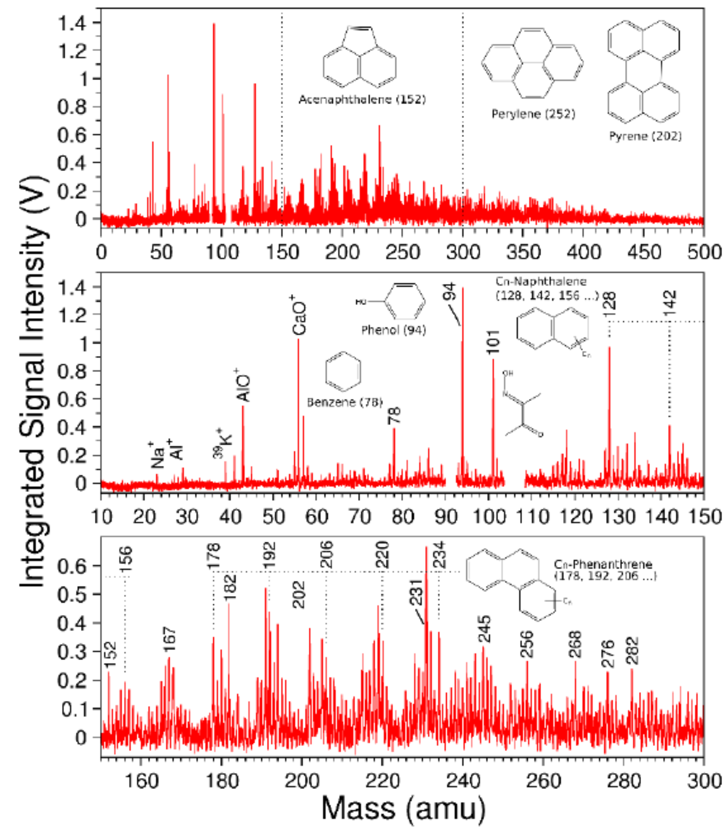


Fig. 7. PAH mass spectrum distribution for a *Stardust* sample obtained with the two-step laser mass spectrometry. The most commonly found PAH species are naphthalene ($C_{10}H_8$), phenanthrene ($C_{14}H_{10}$), pyrene ($C_{16}H_{10}$), perylene ($C_{20}H_{12}$), and their alkylated homologs. Interspersed within these species is a rich suite of auxiliary peaks which appears to represent the presence of O and N substitution, where the heterofunctionality being external to aromatic structure. Taken from Clemett et al. (2007).

Tracers for processes that were predominant in the protosolar nebula

- D/H ratio in cometary water. This will provide further constraints for **evolutionary Solar Nebula models**.

D/H ratio brings important information on the formation conditions of icy molecules, as the deuterium enrichment in ices increases at low temperatures.

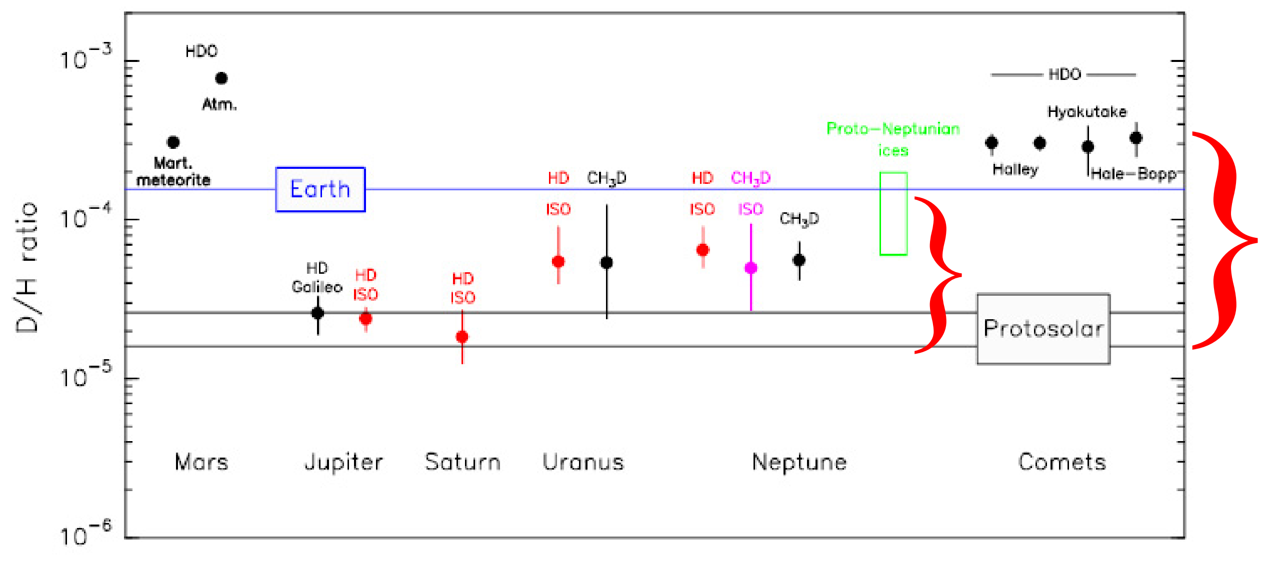


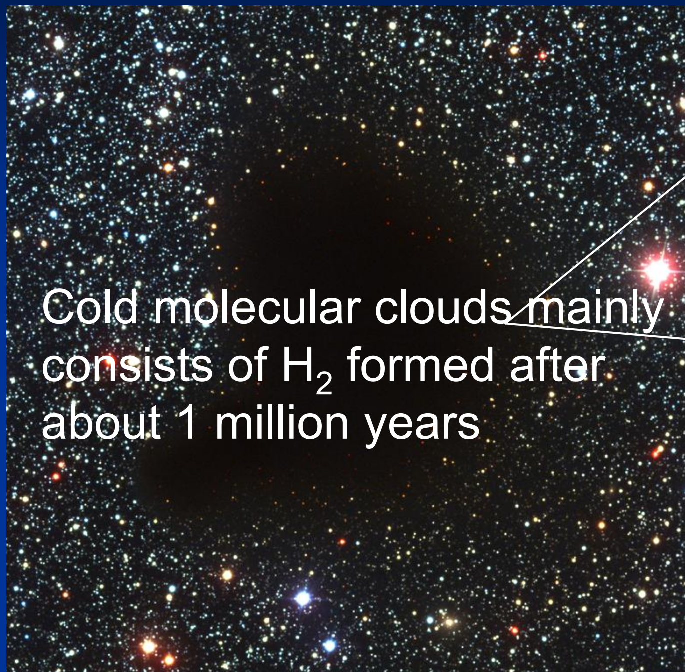
Figure 1: D/H ratios in the Solar System.

D/H ratio in comets is 15 times the prostellar value (information on the formation temp of the cometary water ice)

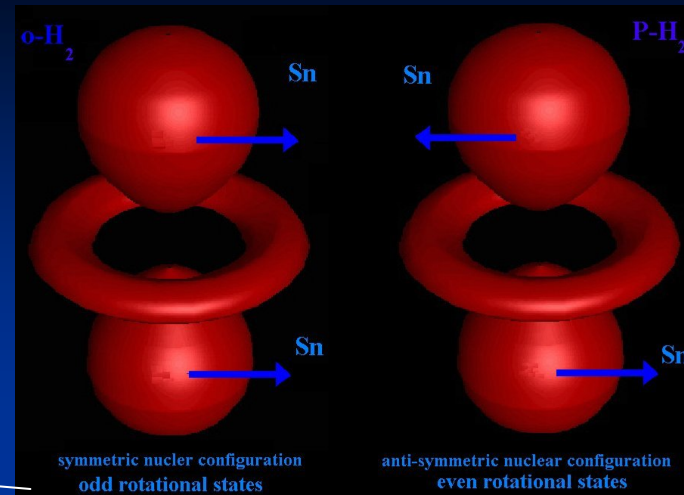
twice the terrestrial (terrestrial water could not come enterely from comets).

Tracers for processes that were predominant in the protosolar nebula

Ortho:para ratio (OPR)



Cold molecular clouds mainly consists of H_2 formed after about 1 million years



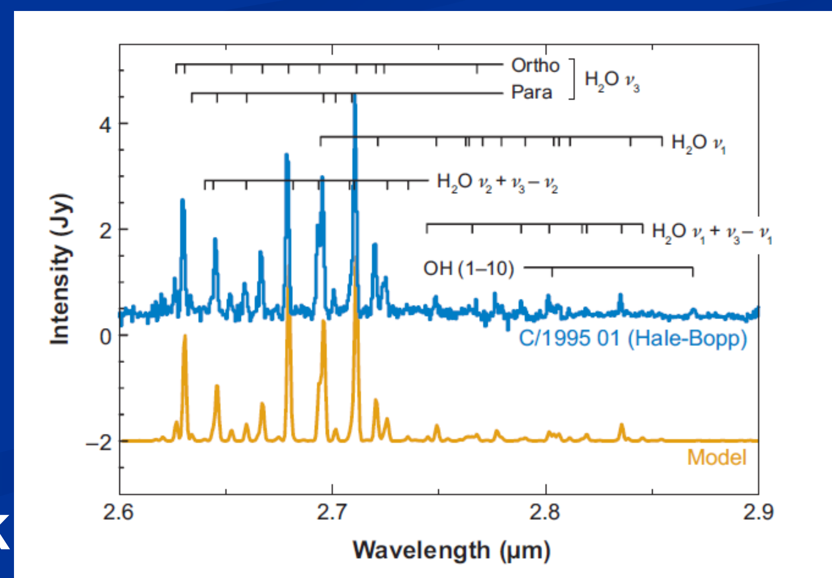
Di-hydrogen states

It is possible to measure the relative abundances of the two states

→ Information about the formation temperature of the molecule

OPR has been measured in comets:

Inferred temperatures are 25- 30 K



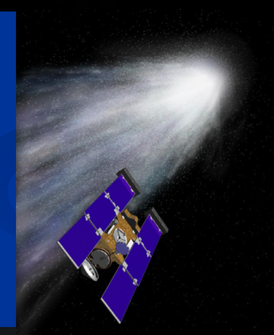
Encrenaz, Annu. Rev. Astro. Astrophysics 2008

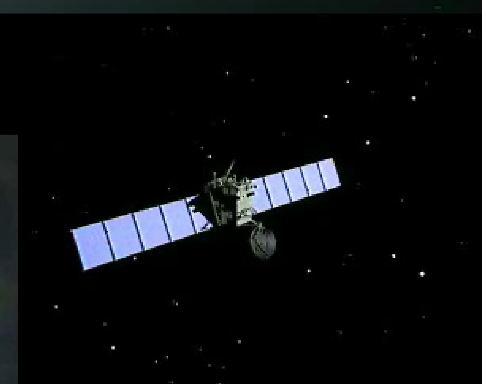
II. Missions

The driving quest of cometary research is to learn about the composition of the primordial nebula mixture and the formation of our Solar System

Archieving this goal by space programmes:

In 1986	Giotto	Fly-by a comet
In 2005	*Deep Impact*	Impact a comet
In 2007	*Stardust*	Collection of Dust
In 2014	Rosetta	Orbit and land a comet
In ?		Nucleus Sample Return





Kueppers et al., Exp. Astronomy, in press

Stardust

Wild 2 material (< 1 mg) in the Stardust sample is:

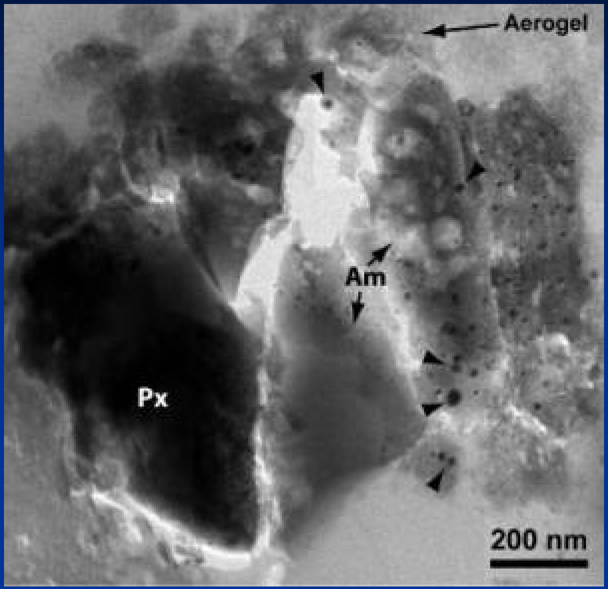
Fine dust from our Solar Nebula (*MacKeegan et al. 2006*)

mostly crystaline
not amorphous
at least 10 % of this material originated in the inner ss

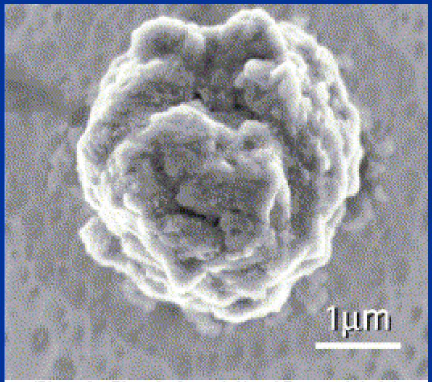
An organic component was identified, which is different than compounds in meteorites and Halley dust →
Different chemical composition → different pathways to ist formation

PAHs

One presolar grain



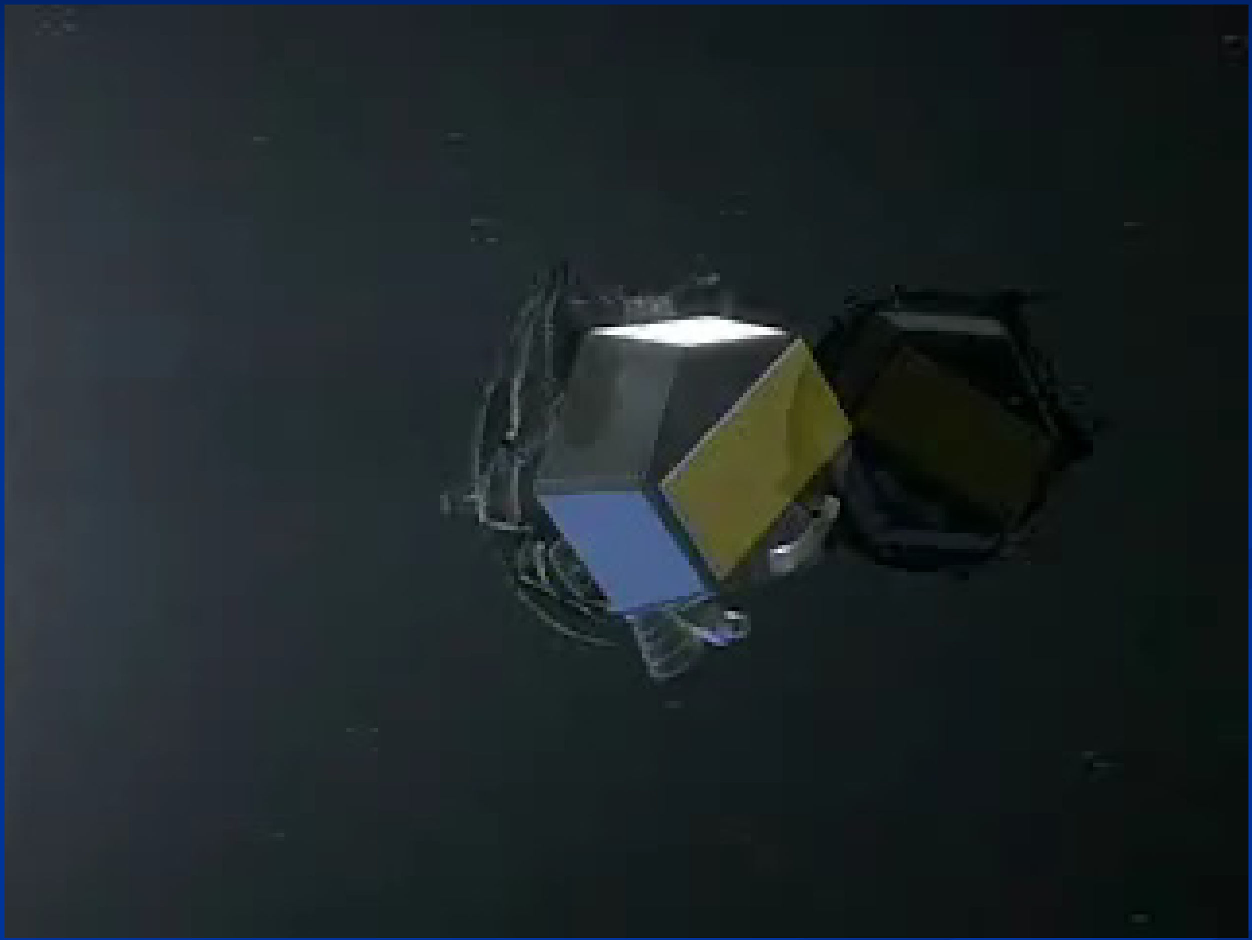
Bright-field TEM image of a mineral assemblage from Comet Wild 2. Pyroxene ($MgSiO_3$; Px), silicates (Am), Fe-Ni sulfides (black arrowheads). The aerogel capture material occurs around the assemblage. *(Credit: Naval Research Laboratory)*



(Photo by Rhonda Stroud, Naval Research Lab.)

Deep Impact

NASA **Deep Impact** space mission on 4th July 2005



Credits: Nasa

Goals of the Deep Impact mission:

Understand the difference between the surface of a cometary nucleus and its interior, and the physical properties of the outer layers of the comet

An unprecedent world-wide observation campaign:

Remote sensing from Earth

Space

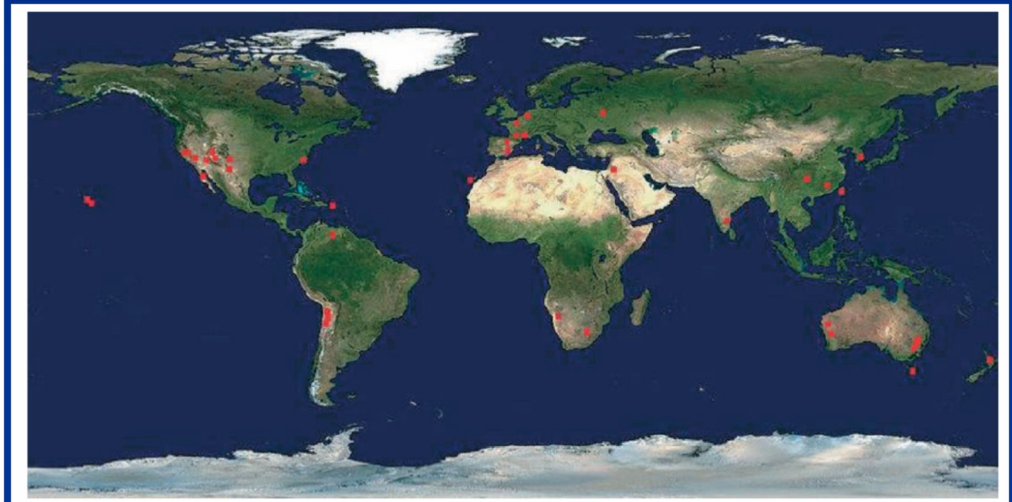


Fig. 1. Map of Earth, showing the locations of observatories collaborating in the coordinated campaign (red dots). World map credit: NASA.

Credits: NASA

Spacecrafts & Satellites

Deep Impact,
HST,
Spitzer,
XMM
SWAS

and

- Rosetta was activated for an observational campaign of Tempel 1 during 17 days

-Continuous monitoring of the comet for more than two weeks
-Offered a slightly different viewing geometry. It was closer to the comet than Earth-based observers (0.53 AU vs. 0.89 AU)

Rosetta Orbiter Instruments

OSIRIS: Scientific cameras onboard Rosetta

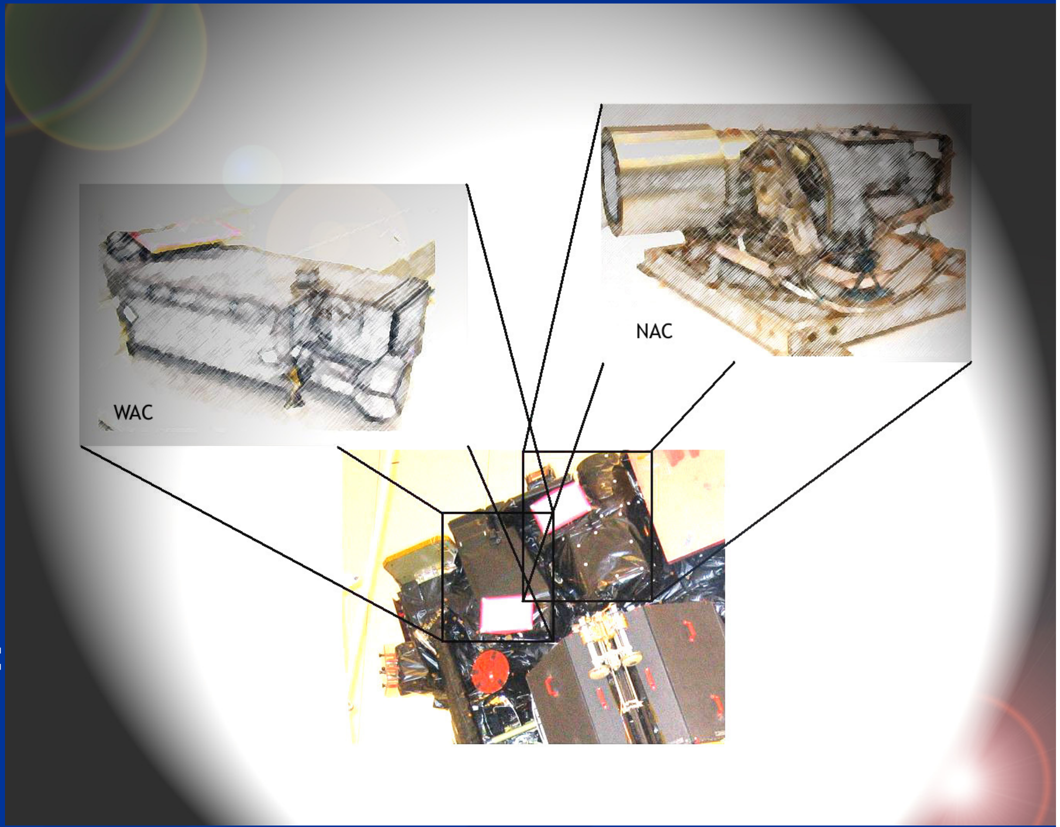
- **O**ptical, **S**pectroscopic, and **I**nfrared **R**emote **I**maging **S**ystem

P.I.: Horst Uwe Keller, MPS (Germany)

Continuous monitoring of the comet for more than two weeks

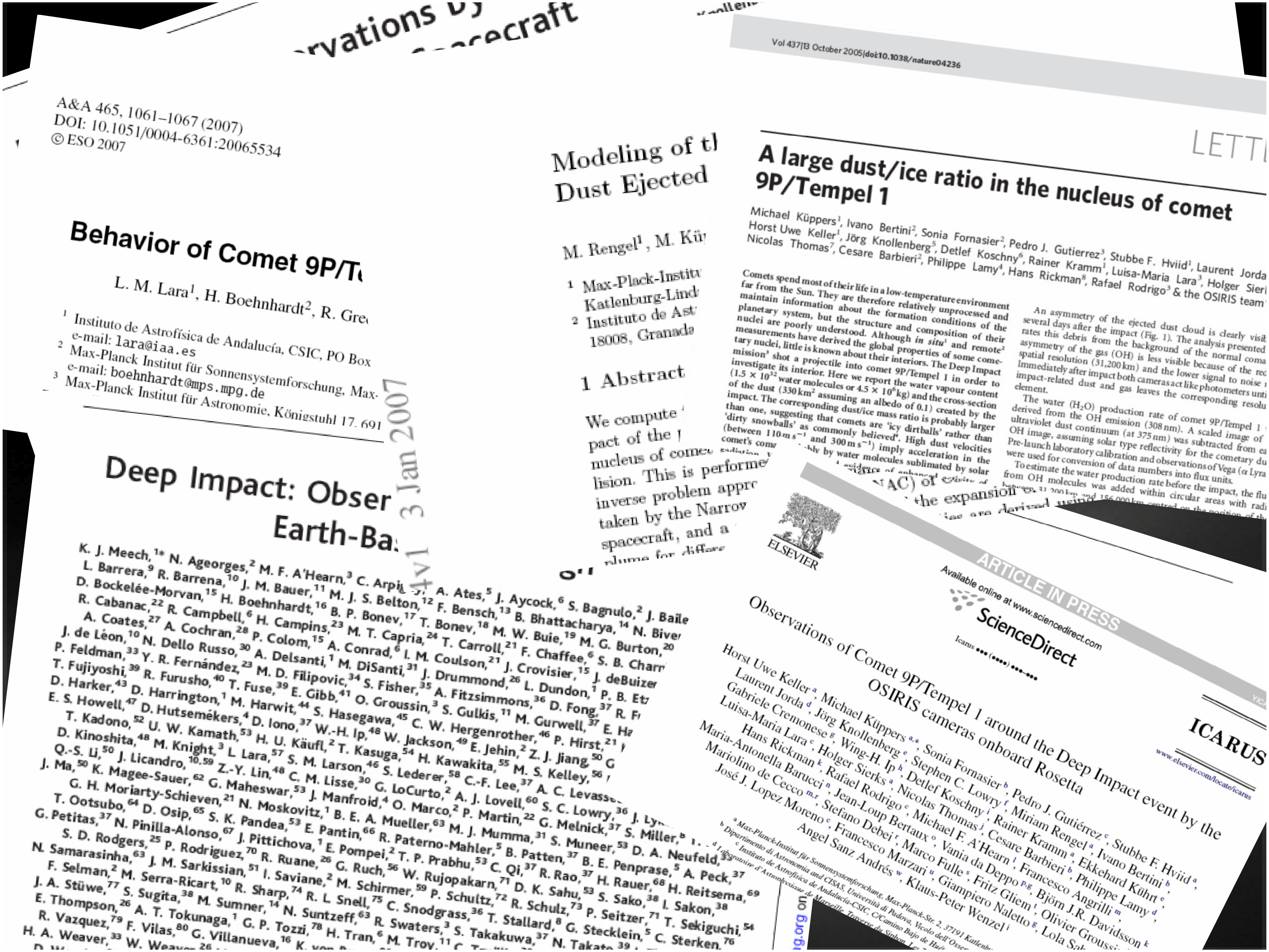
	Filters used	Pixel scale:
NAC	4 at 648-980 nm and clear filter	1:1500 km
WAC	OH,CN,Na,OI, near-UV and red continuum	7800 km

Cameras



FOV=3.88 arcsec

Keller et al, 2007, SSRv.



A&A 465, 1061–1067 (2007)
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Behavior of Comet 9P/T

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Deep Impact: Obser
Earth-Ba

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D. Bockelée-Morvan,[15] H. Boehnhardt,[16] B. P. Bonev,[17] T. Bonev,[18] M. W. Buie,[19] M. G. Burton,[20]
R. Cabanac,[22] R. Campbell,[6] H. Campins,[23] M. T. Capria,[24] T. Carroll,[21] F. Chaffee,[6] S. B. Charn
A. Coates,[27] A. Cochran,[28] P. Colom,[15] A. Conrad,[6] I. M. Coulson,[21] J. Crovisier,[15] J. deBuizer
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E. S. Howell,[47] D. Hutsemékers,[4] D. Iono,[37] W.-H. Ip,[48] W. Jackson,[49] E. Jehin,[2] Z. J. Jiang,[50] G
T. Kadono,[52] U. W. Kamath,[53] H. U. Käufl,[2] T. Kasuga,[54] H. Kawakita,[55] M. S. Kelley,[56]
D. Kinoshita,[48] M. Knight,[3] L. Lara,[57] S. M. Larson,[46] S. Lederer,[58] C.-F. Lee,[37] A. C. Levasse
Q.-S. Li,[50] J. Licandro,[10,59] Z.-Y. Lin,[48] C. M. Lisse,[30] G. LoCurto,[2] A. J. Lovell,[60] S. C. Lowry,[36] J. Ly
J. Ma,[50] K. Magee-Sauer,[62] G. Maheswar,[53] J. Manfroid,[4] O. Marco,[2] P. Martin,[22] G. Melnick,[37] S. Miller,
G. H. Moriarty-Schieven,[21] N. Moskovitz,[1] B. E. A. Mueller,[63] M. J. Mumma,[31] S. Muneer,[53] D. A. Neufeld,
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F. Selman,[2] M. Serra-Ricart,[10] R. Sharp,[74] R. L. Snell,[75] C. Snodgrass,[36] T. Stallard,[8] G. Stecklein,[5] C. Sterken,[76]
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R. Vazquez,[79] F. Vilas,[80] G. Villanueva,[16]
H. A. Weaver,[33] W. Weaver

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Modeling of t
Dust Ejected

M. Rengel[1], M. Kü

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1 Abstract

We compute
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Vol 437|13 October 2005|doi:10.1038/nature04236

LETT

A large dust/ice ratio in the nucleus of comet 9P/Tempel 1

Michael Küppers[1], Ivano Bertini[2], Sonia Fornasier[2], Pedro J. Gutierrez[3], Stubbe F. Hviid[1], Laurent Jorda
Horst Uwe Keller[1], Jörg Knollenberg[5], Detlef Koschny[6], Rainer Kramm[1], Luisa-Maria Lara[3], Holger Sierk
Nicolas Thomas[7], Cesare Barbieri[2], Philippe Lamy[4], Hans Rickman[8], Rafael Rodrigo[3] & the OSIRIS team

Comets spend most of their life in a low-temperature environment far from the Sun. They are therefore relatively unprocessed and maintain information about the formation conditions of the planetary system, but the structure and composition of their nuclei are poorly understood. Although *in situ*[1] and remote[2] measurements have derived the global properties of some cometary nuclei, little is known about their interiors. The Deep Impact mission[3] shot a projectile into comet 9P/Tempel 1 in order to investigate its interior. Here we report the water vapour content (1.5×10^{32} water molecules or 4.5×10^{6} kg) and the cross-section of the dust (330 km^2 assuming an albedo of 0.1) created by the impact. The corresponding dust/ice mass ratio is probably larger than one, suggesting that comets are 'icy dirtballs' rather than 'dirty snowballs' as commonly believed[4]. High dust velocities (between 110 m s^{-1} and 300 m s^{-1}) imply acceleration in the comet's coma

An asymmetry of the ejected dust cloud is clearly visi several days after the impact (Fig. 1). The analysis presented rates this debris from the background of the normal coma asymmetry of the gas (OH) is less visible because of the red spatial resolution (31,200 km) and the lower signal to noise Immediately after impact both cameras act like photometers unti impact-related dust and gas leaves the corresponding resolu element.

The water (H_2O) production rate of comet 9P/Tempel 1 derived from the OH emission (308 nm). A scaled image of ultraviolet dust continuum (at 375 nm) was subtracted from ea OH image, assuming solar type reflectivity for the cometary du Pre-launch laboratory calibration and observations of Vega (α Lyra were used for conversion of data numbers into flux units.

To estimate the water production rate before the impact, the flu from OH molecules was added within circular areas with radi

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Observations of Comet 9P/Tempel 1 around the Deep Impact event by the OSIRIS cameras onboard Rosetta

Horst Uwe Keller [a], Michael Küppers [a,*], Sonia Fornasier [b], Pedro J. Gutiérrez [c], Stubbe F. Hviid [a],
Laurent Jorda [d], Jörg Knollenberg [e], Stephen C. Lowry [f], Miriam Rengel [a], Ivano Bertini [b],
Gabriele Cremonese [g], Wing-H. Ip [h], Detlef Koschny [i], Rainer Kramm [a], Ekkehard Kührt [e],
Luisa-Maria Lara [c], Holger Sierks [a], Nicolas Thomas [j], Cesare Barbieri [b], Philippe Lamy [d],
Hans Rickman [k], Rafael Rodrigo [c], Michael F. A'Hearn [l], Francesco Angrilli [m],
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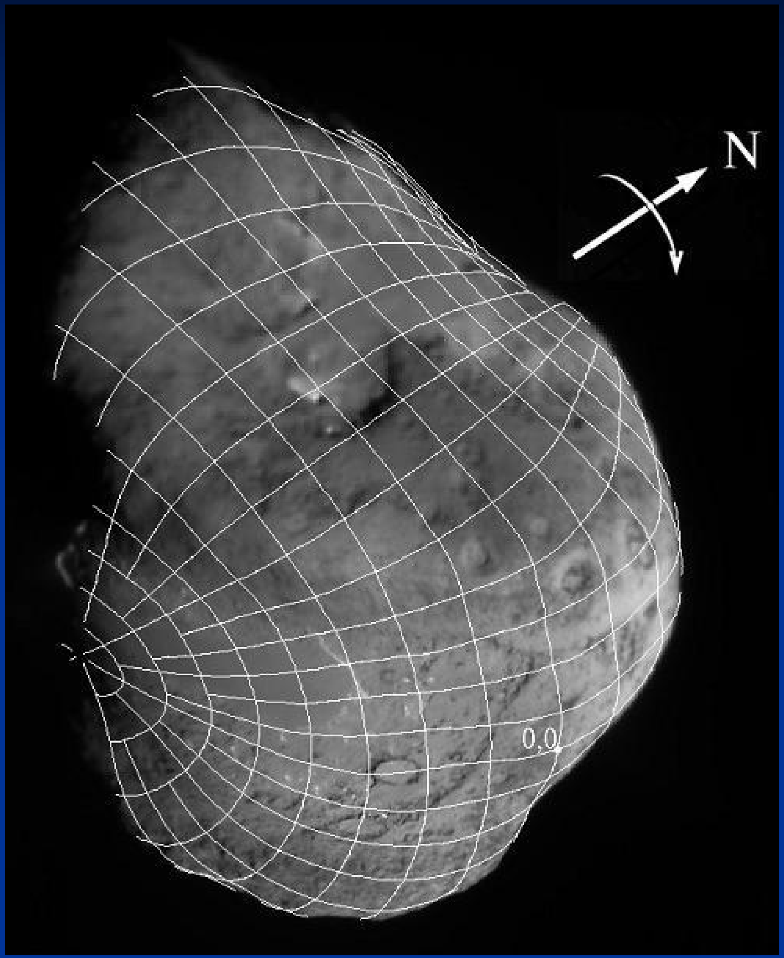
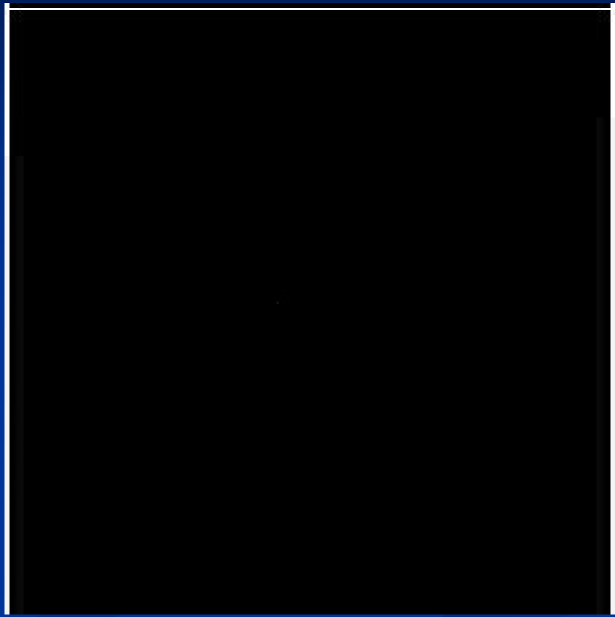
[d] Laboratoire d'Astrophysique de Marseille

Results of general interest



impact site indicated by arrows



•Oblique impact - 36° from horizontal by shape model but 20 to 35° from assuming circular craters (A' Hearn).

•Crater size: 30 m

- Impactor = Energy $2x10^{10}$ J, Weight 364 kg, v= 10.3 km/s
- Nucleus is highly porous, and material weaker than ice. Bulk density of the comet: 350 kg /m^3

Density of cometary nuclei is low (<1000 kg/ m3)

- Most of the mass of the impact is in the dust component (Küppers et al. 2005)

Results of general interest

Total dust mass = unknown

But

M_{tot} (<1.4 µm) = 1.5 x 10 ^{5} kg (Küppers et al.)

M_{tot} (<100 µm) = 1-14 x 10 ^{6} kg (Küppers et al.)

M_{water}= 4.5 – 9 x 10 ^{6} kg (Küppers et al. , Mason et al. 2006), 13 x 10 ^{6} kg (Schleicher et al. 2006), 5 x 10 ^{6} kg (Biver et al. 2006)

Composition:

Fast material in the ejecta: amorphous carbon grains

0.2 µm diverse mineralogy

Harker et al. 2007

Surface: amorphous carbon

Subsurface: amorphous pyroxene & crystaline olivine grains

Some questions:

Amount of refractory material excavated?

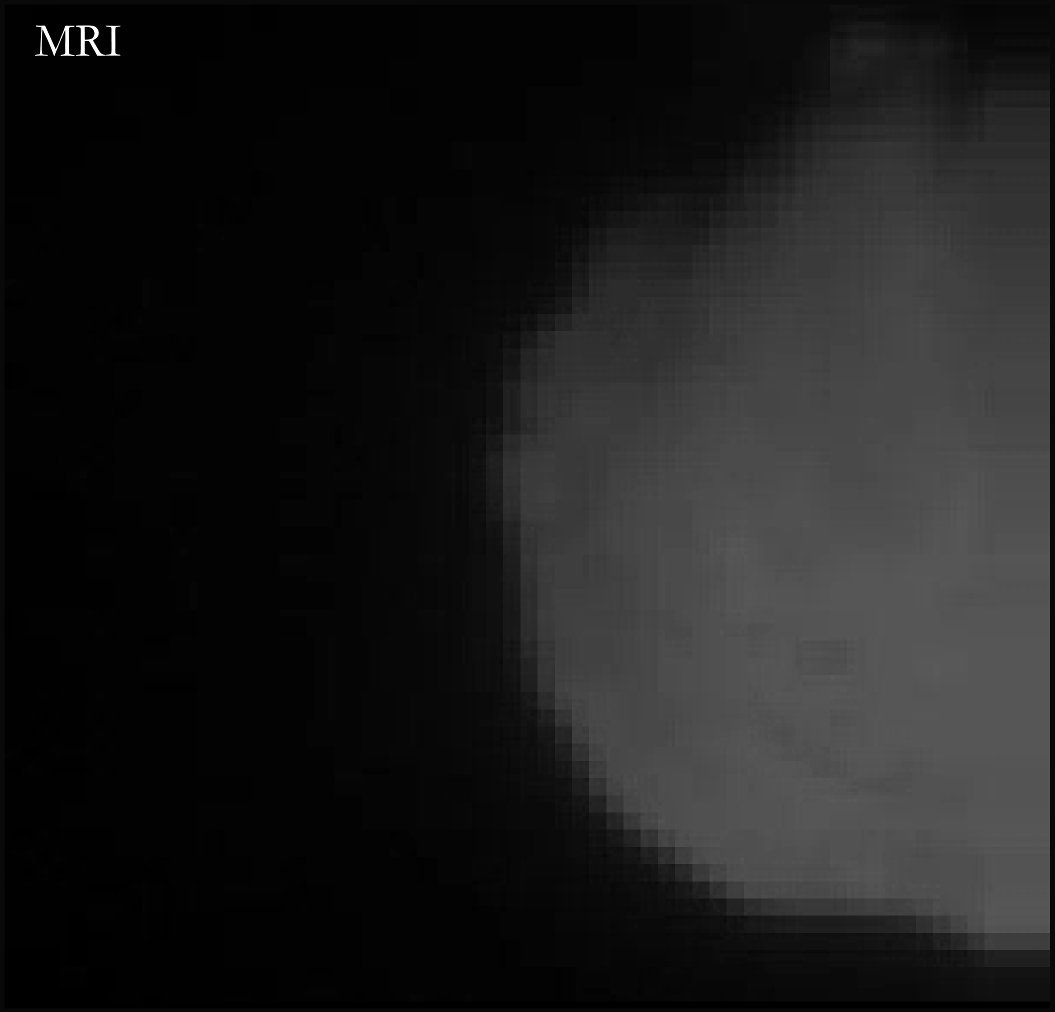
Velocity of the dust cloud?

Acceleration mechanism of particles produced by the impact?

Creation of an active area?

Strenght vs gravity regime?

Phenomenology of the event:



Credits: NASA's PDS

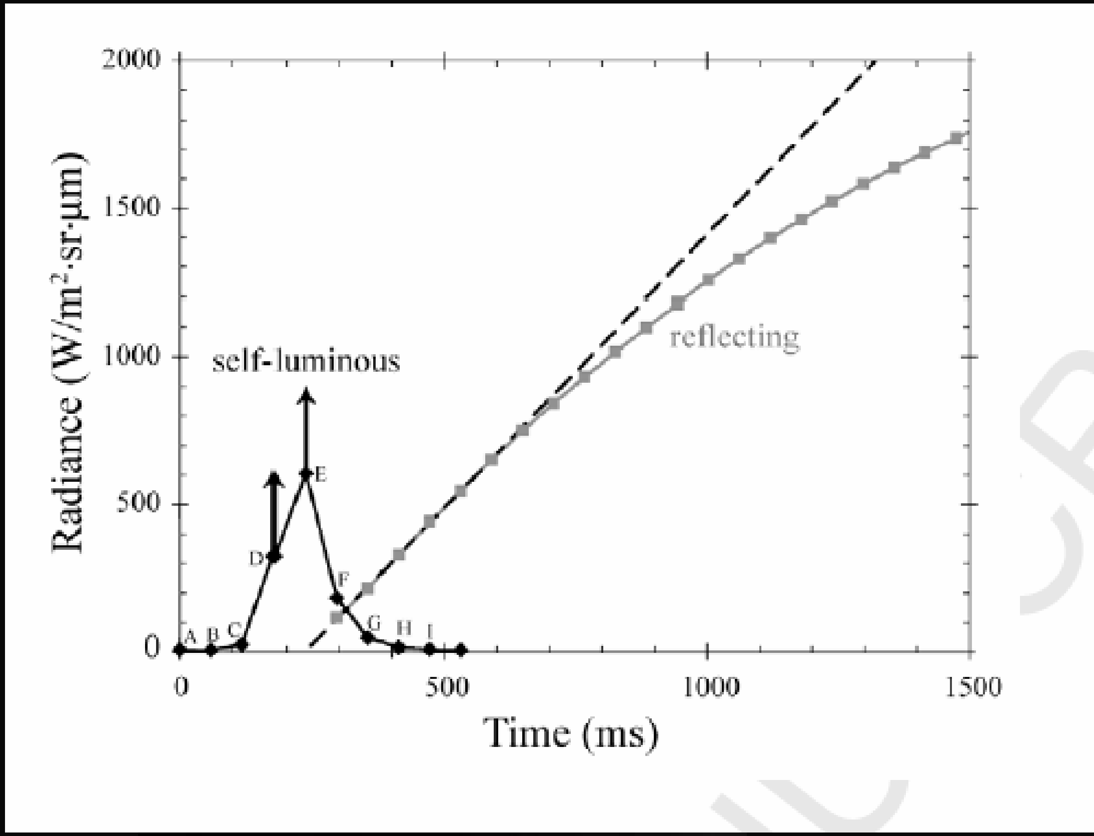
1.- Hot plume (impact flash) was generated (within 150 msec)
2.- Slow ejecta was created
3.- Material moved in a form of dust cloud
4.- Cloud dissipated during several days

What are the Velocities of the ejected Material (dust cloud) ?

Ejected particles moved with different velocities.
Therefore an important physical parameter of the dust cloud produced during the Deep Impact experiment is the velocity distribution of the ejected particles.

Phenomenology of the event:

Light-Intensity evolution of the DI collision



Ernst & Schultz, 2007

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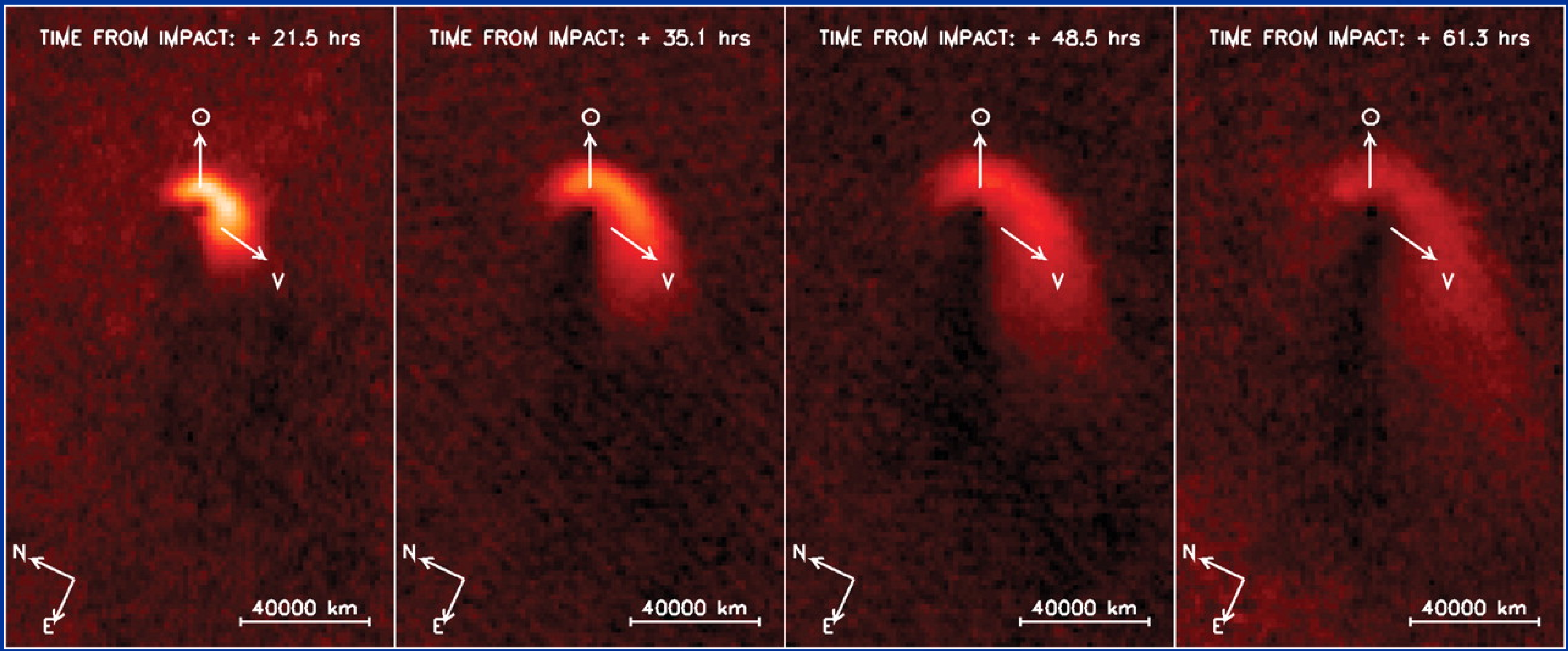
II.- Observations of DI

2277 Images required data-reduction: OSIRIS pipeline
Correction from cosmic events

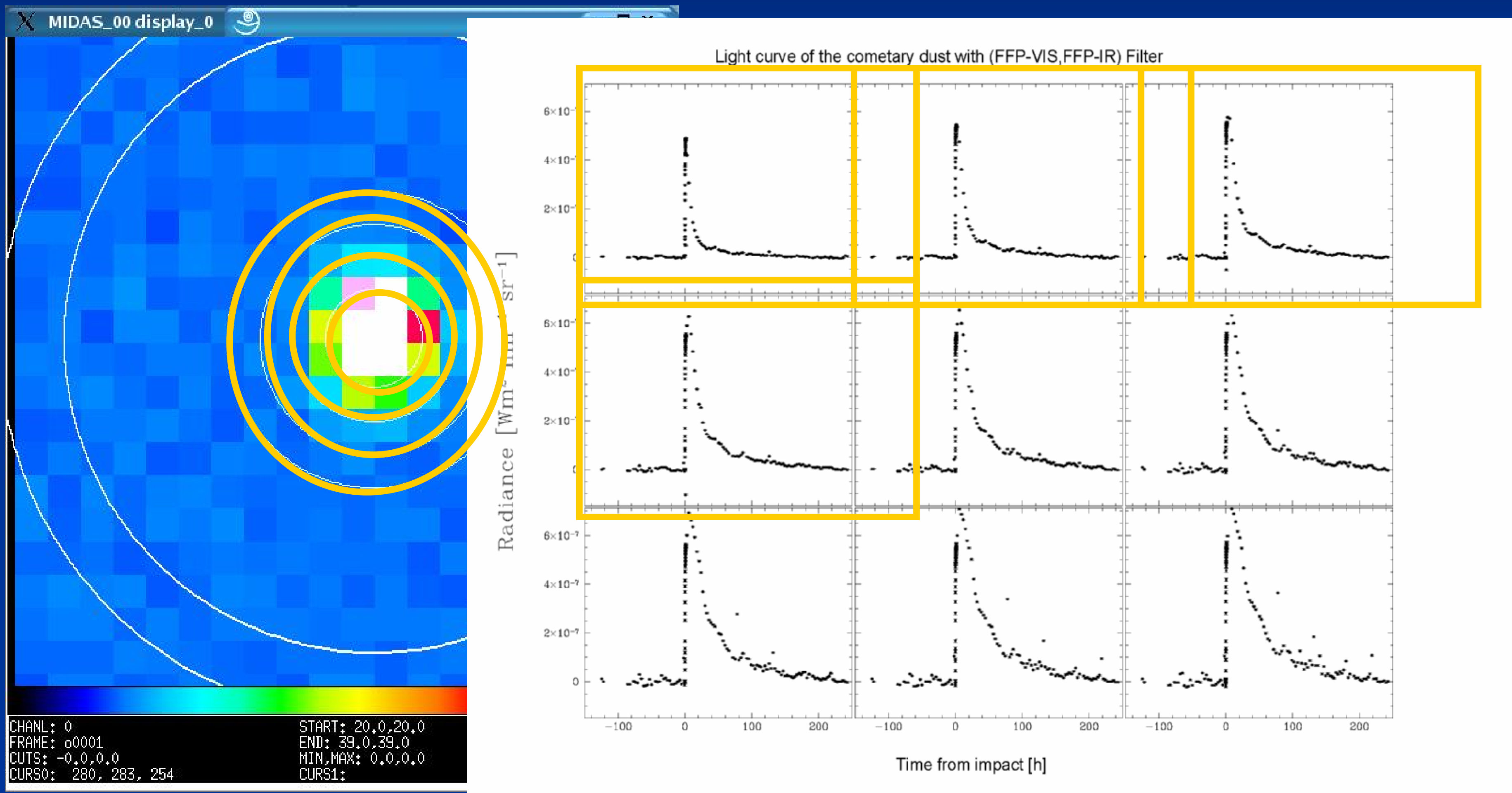
Appearance of the impact-generated dust cloud at different times after the impact.
The preimpact coma has been subtracted from the images by centering on the brightness maximum at the nucleus. The resolution is about 3000 km



Keller et al. 2005. Science, 310, 5746

Characterizing the brightness of the cometary dust

1 pixel = 1500 km



Clear Filter

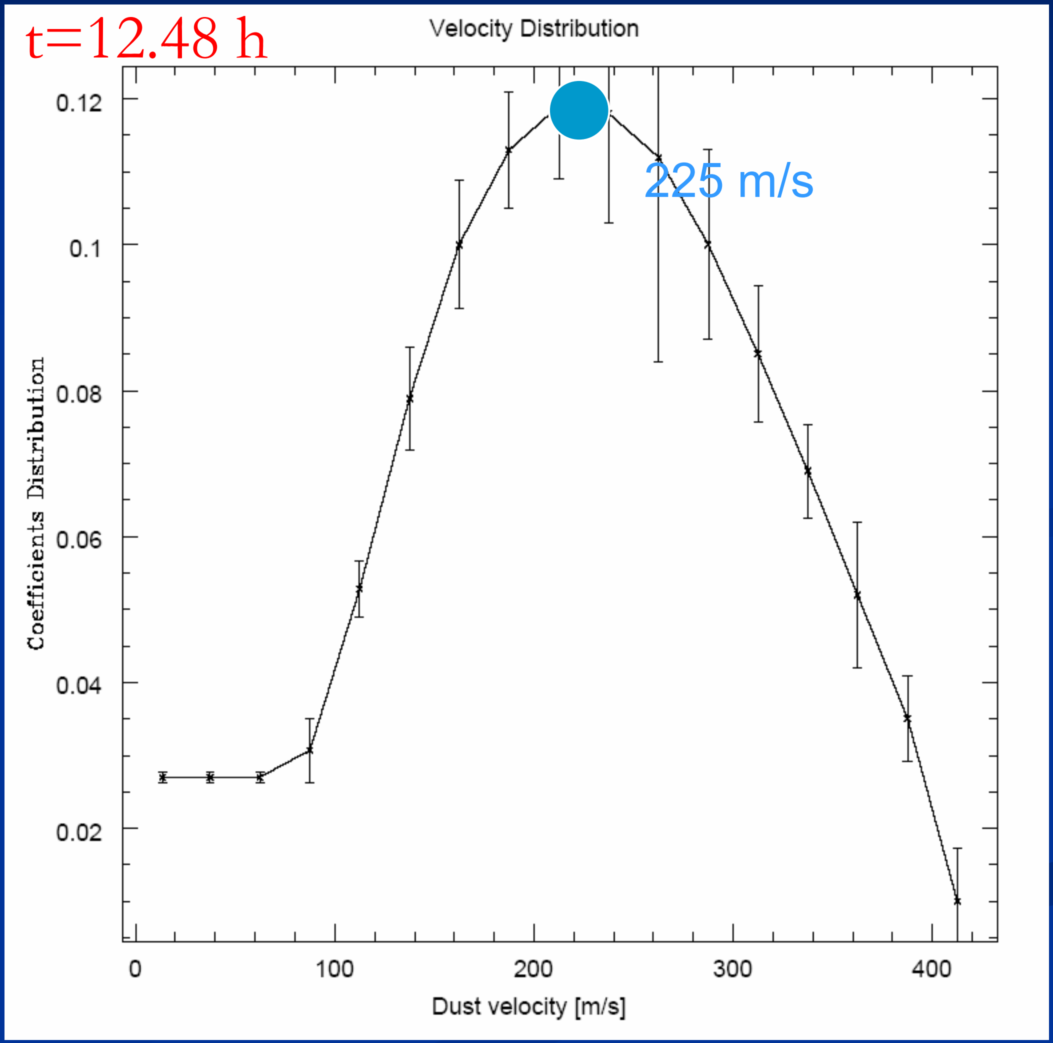
Keller et al., 2007, Icarus Volume 187, Issue 1, p. 87

Retrieval of the dust velocity Distribution

Distribution is quite close to a Gaussian

Peaks at 225 m/s

Very good temporal coverage of the OSIRIS observations and a good sampling of the parameter space

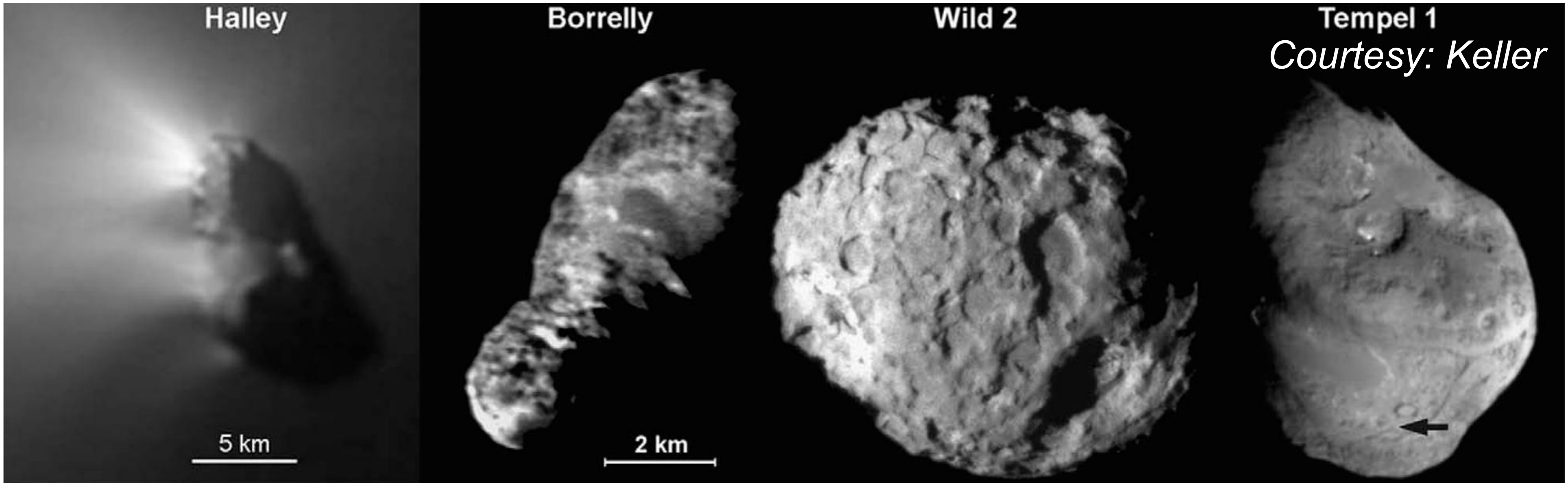


Error bars represent ±SD

Rengel et al., in press

The wide variety of phenomena that have been seen at *Tempel 1* provide a lot of information that can be used to constrain the internal structure of comets.

- Although an evolutionary explanation has not been ruled out, the **structure and the chemical heterogeneity** of *Tempel 1* as observed by *Deep Impact* suggest that large cometesimals may contain materials from different parts of the protoplanetary disk



Very active Oort cloud comet, but activity still localized Very ablated, most of the nucleus mass in meteor stream Accentuated topography Depressions, range of hills, high outcrop	Evolved (ablated) JF comet No craters anymore visible Localized activity Smooth and mottled terrains, mesas Long ridges, large terrain unities	Strongly cratered surface (saturated) Young JF comet From early history Craters eroded Material lost in the order of 100 m Suggests only short time of sublimation activity	Eroded surface but craters (still?) visible Indication of thick layers Smooth (avalanche) layers Low thermal inertia Active spots covered only by thin dust layer
Most evolved	**Strongly evolved**	**Least evolved**	**Evolved**

Appearances of the nuclei are quite different

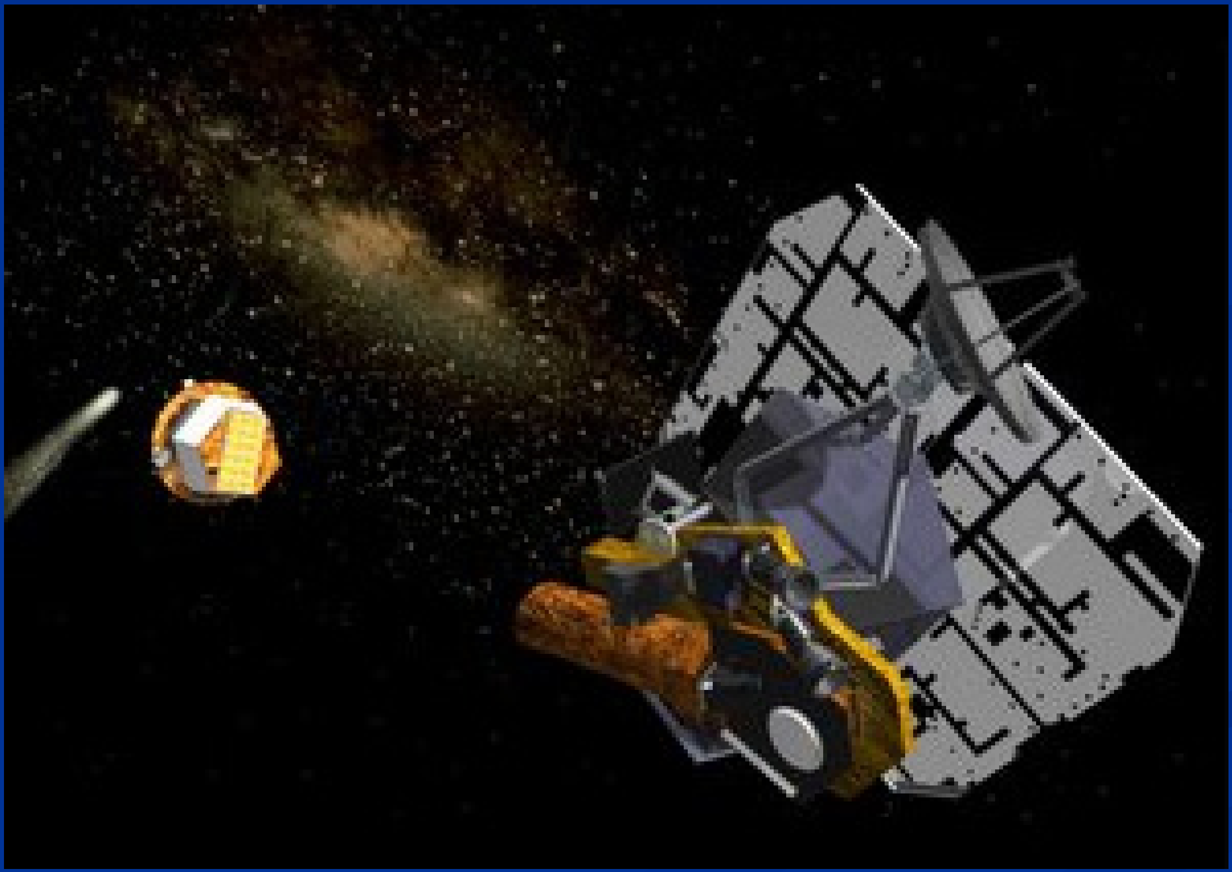
– from smooth to heavily cratered surfaces-

Does this indicate different origins and formation histories?

III.- Helping us to solve problems

Resolution of the evolutionary effects from the primordial situation requires observations of other comets, a key goal of the extended mission of the Deep Impact flyby spacecraft

NASA's **EPOXI** → DIXI Flyby Hartley 2 in 2010
→ EPOCh: extra solar planets during 2008



In order to provide a complete record of the processes in the solar nebula we would want to select comets that were formed at different stages of nebular evolution.

III.- Helping us to solve problems

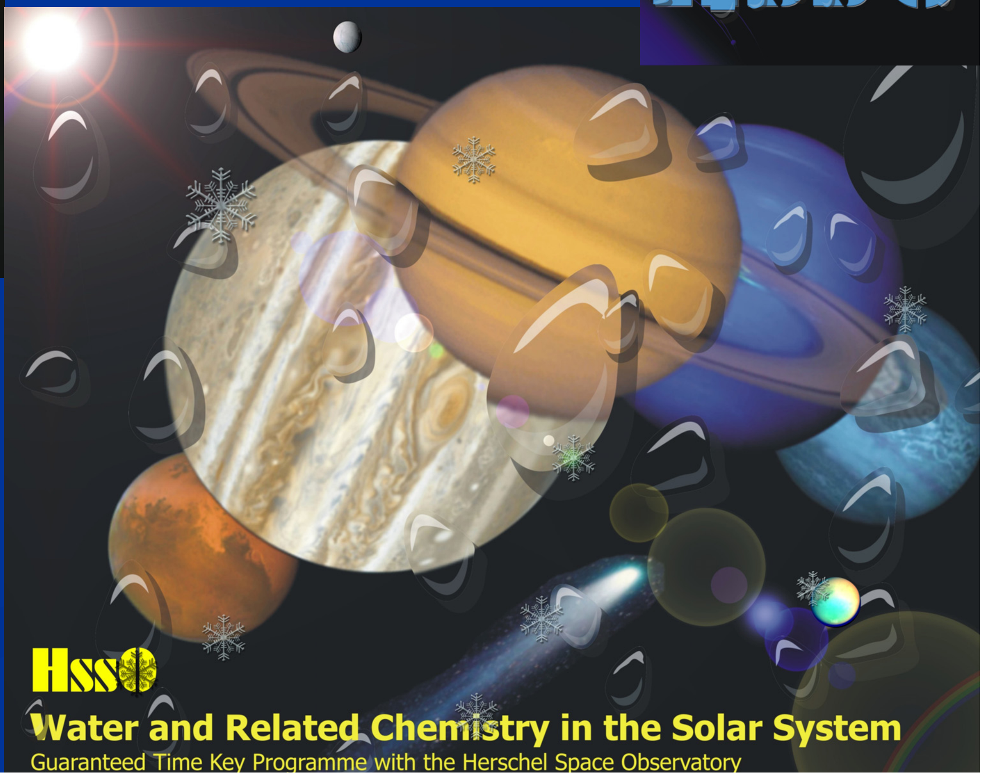
From next year, Herschel Space Observatory will observe the „cool universe“

Credits:ESA/AOES Medialab

Key Programme with guaranteed time:

"Water and Related Chemistry in the Solar System“
P.I.: Paul Hartogh (MPS Lindau)

The HssO Program will result in a comprehensive set of sensitive and well-calibrated spectra of water, its isotopologues, and chemically related species in Solar System objects: Mars, **Outer Planets, Titan and Enceladus**, comets



- Obtain full spectral scans with PACS and SPIRE.

  determination of the comet spectral energy distribution (SED)
  mineralogy
  cometary dust observation will provide important clues for **interpretation of the evolution of dusty disks** around young stars

- Observe HDO and H_2O to determine D/H in cometary water.

Conclusion

Key diagnostics- Assembling the puzzle

Cometary material (composition and structure)

- Indirecty→ in situ, remote sensing: Flybys, impacts, ground and space-based observations
- Directly – laboratory study: sample return
- PAHs

Water: the parameter D/H ratio and OPR

Appearance and structure of the nuclei ?

We derive a broad accurate velocity distribution of the smallest dust particles produced by DI. Our approach and models reproduce well the velocity distribution of the ejected particles. Evidence for the appropiateness of the models and approach.

*characterization of the comet is crutial --> size, albedo, shape, rotation period of the nucleus. velocities, gas production rates, dust and gas activity

-combined ground-based and space observations

*state-of-the art models of the gas distribution around the nucleus

*laboratory experiments

Publications & Proceedings

- Rengel, M. , Kueppers, M.; Keller, H. U.; Gutierrez, P.; Hviid, S. **"A Study of the Velocities of the Ejected Dust and of the Rotational Variability of Comet 9P/Tempel 1 around the Deep Impact Event "**. American Astronomical Society, DPS meeting 38, 17.06. California, USA, October 2006.
- H.U. Keller, M. Rengel , M. Kueppers, P. Gutierrez and S. Lowry **"Monitoring of Comet 9P/Tempel 1 around the Deep Impac event with the OSIRIS NACCamera "**. IAU XXVIth General Assembly, Prague, Chezk Republic, August 14-25,2006.
- M. Rengel , M. Kueppers, H.U. Keller, and P. Gutierrez. **"Modeling of the Terminal Velocities of the Dust Ejected Material by the Impact "**. Deep Impact as a World Observatory Event - Synergies in Space, Time, and Wavelength, Brussels, Belgium, 7-10 August 2006. Proceedings in the ESO / SPRINGER series (eds. Ulli Käufl & Chris Sterken).
- H.U. Keller, M. Kueppers, M Rengel , S. Fornasier, G. Cremonese, P. Gutierrez, W. H. Ip, J. Knollenberg, L. Jorda **"Observations of comet 9P/Tempel 1 around the Deep Impact event with the OSIRIS cameras on Rosetta"**. The 36th COSPAR Scientific Assembly, Beijing, China, 16-13 July 2006.
- Rengel M., Küppers, M.; Keller, H. U.; Gutierrez, P. **"Analysing the Post Deep Impact Brightness distribution of the Cometary Dust of the Comet 9P/Tempel 1 with OSIRIS"**. General Assembly of the European Geosciences Union, Vienna, Austria, April 2-7, 2006.

- questions
- bonus material

For extra-material (eg. Movies, papers, etc.) or any inquires, please contact Rengel by rengel@mps.mpg.de