Ambition film poster. Credit: ESA & Platige Image

Voyage 2050 Workshop

AMBITION

Comet Nucleus Cryogenic Sample Return

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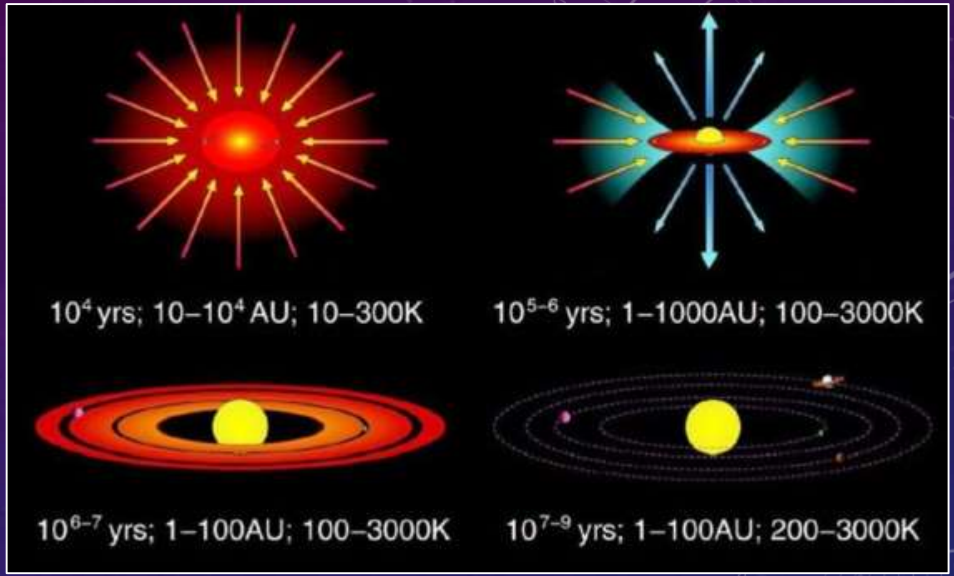
GOAL: DECIPHERING PLANETARY SYSTEMS FORMATION



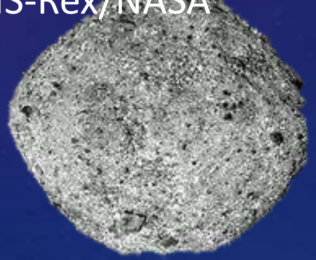
EXO-systems

- Interstellar clouds, star forming regions, protoplanetary disks
- Exo-planetary systems – exoplanets
- ➢ cannot address the wealth of processes that occured over the entire formation interval of a planetary system

Primitive Solar System bodies and architecture of the Solar System

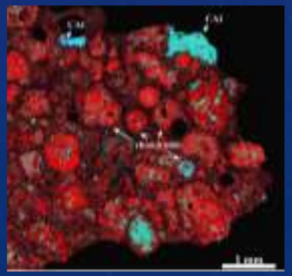
- Comets, asteroids & trans-neptunian objects
- ➢ the left-over building blocks of planet cores
- ➢ many of them retain a pristine composition
- Primitive bodies, especially extra-terrestrial samples in the laboratory
- ➢ provide detailed information on processes, conditions and timescales of Solar System history

Asteroid Bennu
OSIRIS-Rex/NASA



Comet 67P
Rosetta/ESA

Allende meteorite



Ultima Thule
New Horizons/NASA

EXPLORING COMETS AND RETURNING SAMPLES TO EARTH

Comets are the most primitive objects in the Solar System

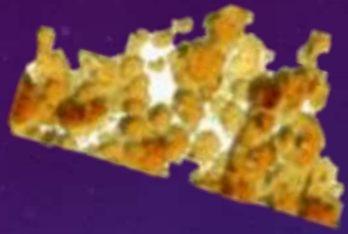
Major breakthroughs from ESA's Rosetta mission

- Low density, highly porous (70%) nucleus & homogeneous down to few meters scales
- Fluffy and fractal- like dust aggregates
- High amount of organic solid matter (50 % in mass): macro-molecular compounds
- No evidence for aqueous alteration
- Ices made of simple (H_2O, CO_2, O_2 ..) & complex molecules (including glycine) with isotopic properties consistent with low-temperature, ISM-like, chemistry
- Noble gases in Earth's atmosphere (Xe) have been delivered partly by comets

Material from outer Solar System objects is vastly undersampled in collections of extra-terrestrial samples

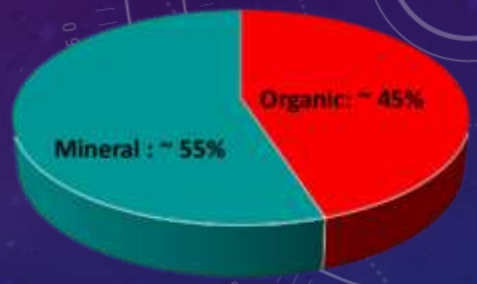
- Comet Wild 2 samples from Stardust/NASA mission were altered during collection
- Cosmic dust particles of probable cometary origin collected in the stratosphere (CP-IDPs) and polar regions (UCAMMS) may have been altered during their journey to Earth and while crossing Earth atmosphere.

67P 40-µm particles MIDAS/Rosetta



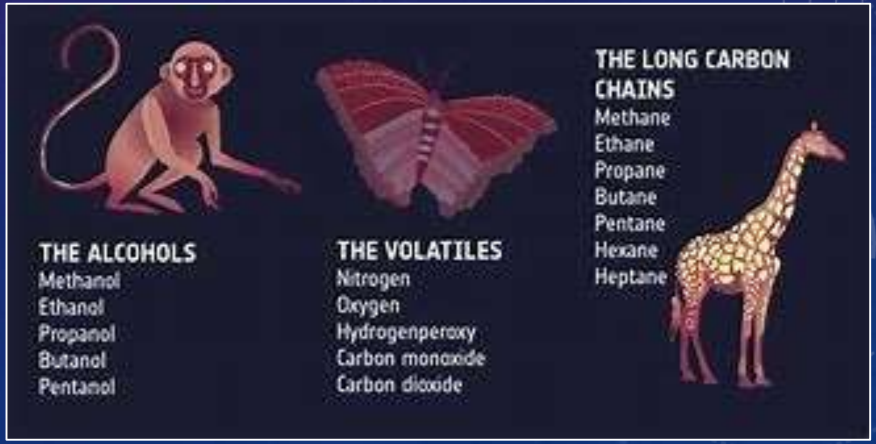
Mannel+ 2019

Dust composition COSIMA/Rosetta



Bardyn+ 2017

The Rosetta zoo (partial) – ROSINA/Rosetta



ESA Science Blog

TOP LEVEL SCIENTIFIC QUESTIONS

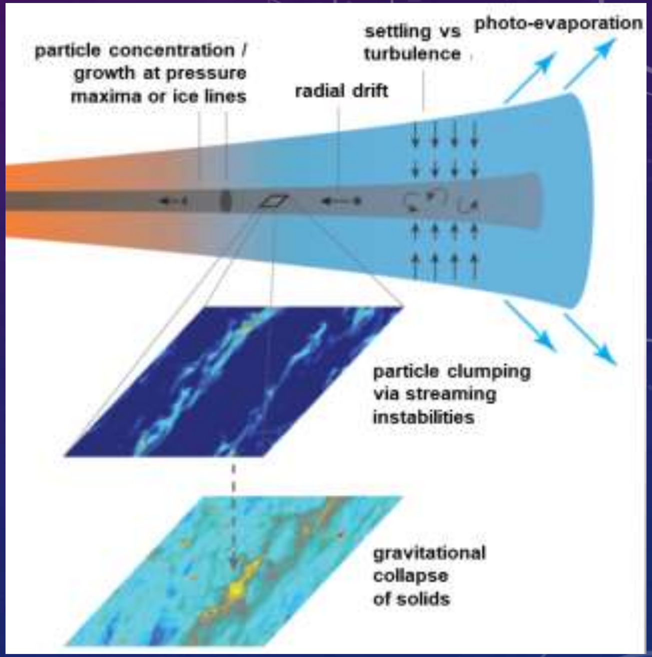
- **How and where did comets form? Which post-planetesimal evolution paths have they followed?**
- **What is the presolar heritage of cometary material, versus a Solar Nebula origin?**
- **What do comets tell us about large scale mixing and dynamical processes in the early Solar Nebula?**
- **How does comet activity work? How do surface and coma observations reconnect with the pristine deep interior?**
- **What was the role of comets in the delivery of volatiles and prebiotic compounds to Early Earth?**
- **How do the dust coma, the surrounding plasma, and the nucleus interact?**

HOW AND WHERE DID COMETS FORM?
WHICH POST-PLANETESIMAL EVOLUTION PATHS HAVE THEY FOLLOWED ?

After Rosetta, two different comet formation scenarios are debated

- Hierarchical collisional growth
- Gravitational collapse of pebble swarms formed by streaming instabilities

→ Different internal morphologies expected



Armitage 2019

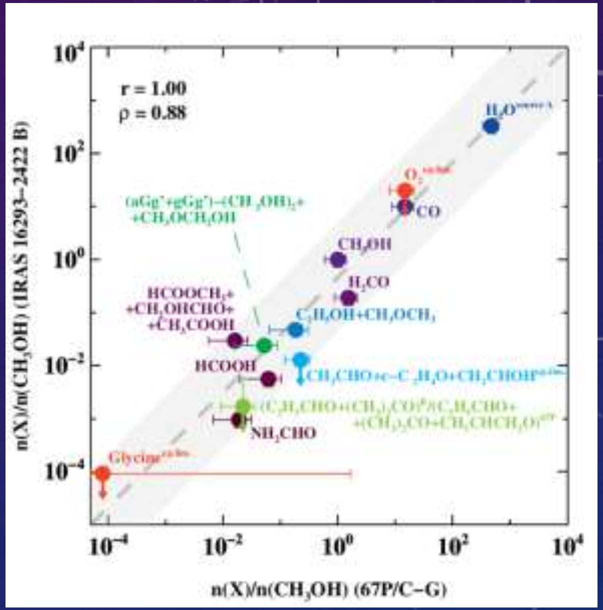
- What is the deep internal structure of cometary nuclei from grain to full size?
- What are the building blocks of cometary nuclei?
- How ices, organics and minerals are mixed together?
- Which surface features are indicative of the initial growth process?
- Are comets collisional fragments or primordial planetoids?
- When did comets form?

- **Radio science, ground-penetrating radar**
- **In situ investigations (lander/penetrator)**
- **Sample return**

WHAT IS THE PRESOLAR HERITAGE OF COMETARY MATERIALS VERSUS A SOLAR NEBULA ORIGIN ?

67P versus solar-like system
IRAS 16293-2422 B

Drozdovskaya+2019



Origin of cometary ices

- Inventory and relative abundances: ISM-like synthesis
- ➢ Chemistry in the protoplanetary disk or inheritance from prestellar ices?
- ➢ Condensation in the protoplanetary disk or prestellar condensates?

Nature and origin of solid (refractory) cometary organics

- Similarities with chondritic Insoluble Organic Matter (IOM) – origin unknown

Abundance and nature of Soluble Organic Matter (SOM) and semi-volatiles

- ➢ Is SOM found in chondrites a product of aqueous alteration?
- ➢ Are ammonium salts an important nitrogen reservoir in comets ?
  Where did they form?

Abundance and nature of presolar stardust grains in comets

- ➢ How much stardust material was incorporated into the Solar System?
- Constraints on astrophysical processes as stellar nucleosynthesis, condensation parameters, interstellar processing and galactic evolution

Sample return required for most objectives

- Isotopic ratios, composition, mineralogy
- radiometric ages

Cryogenic sample return for volatiles & semi-volatiles

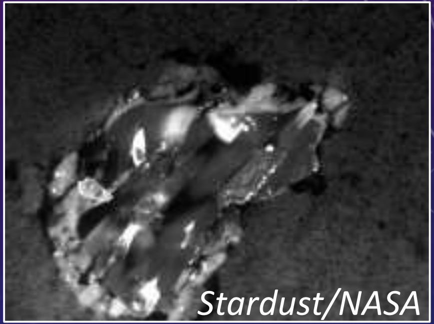
WHAT DO COMETS TELL US ABOUT LARGE SCALE MIXING AND DYNAMICAL PROCESSES IN THE EARLY SOLAR NEBULA?

The comet-asteroid continuum

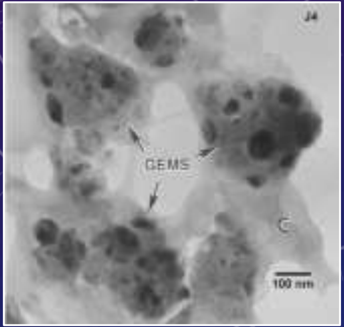
- Comets contain high-temperature material, found in meteorites

  a major insight from the Stardust/NASA sample return mission
  - crystalline silicates, chondrules, Calcium Aluminium Inclusions (CAIs) …
- Some asteroids in the Main Belt have surface ice signatures and cometary activity

Comet particle
Crystalline Olivine



CP-IDP
Amorphous Silicates



Main Belt comet 238P/Read

- ➢ How and at what scales low and high-T materials are mixed together?
- ➢ Which mechanisms transported inner Solar Nebula materials outwards?
- ➢ Where did volatile-rich asteroids form?
- ➢ Are volatile-rich asteroids and comets distinct populations?
- ➢ How were water, other volatiles, and organics distributed in the early Solar System?
- ➢ When and how large-scale planetesimal mixing related to planetary migration did occur?

Sample return required for most objectives
- Isotopic ratios & composition, mineralogy
- Radiometric ages

Cryogenic Sample: volatiles & textural relationships

Space exploration of Main-Belt comets
- Water, D/H ratio, nucleus & surface characterisation

HOW DOES COMET ACTIVITY WORK? HOW DO SURFACE AND COMA OBSERVATIONS RECONNECT WITH THE PRISTINE DEEP INTERIOR?

Understanding cometary activity is essential:

- To unveil the origin of terrain diversity on comet surfaces: primordial or activity related?
- To understand the origin of (e.g. chemical) diversity observed in the comet population: primordial or related to differentiation?
- To relate coma properties (chemical composition, dust size distribution, dust/gas ratio) to nucleus primordial properties.

Fornasier+2017

Major Rosetta breakthroughs on comet activity but little is known about:

- How ices and dust are mixed together? In which proportion?
- How minor species are mixed with water ice?
- Is water ice in amorphous form in the deep interior, or in crystalline form?
- At which depths are the sublimation fronts of the various molecules located?
- How are dust particles lifted in the coma?

Measurement requirements as a function of depth:

- Thermal, mechanical, structural, compositional properties
- In situ (lander) analysis / sample return (carrot)
- Depths > 1 m (TBD) for volatile-rich layers

Radar investigation of subsurface and deep interior

TOWARDS AN AMBITIOUS SAMPLE RETURN MISSION (L-CLASS)

Hayabusa2/JAXA

- A CRYOGENIC COMET SAMPLE RETURN will provide major breakthroughs in the understanding of Solar System and planets formation
- A CRYOGENIC sample return is motivated by numerous science questions
- A COMET SAMPLE RETURN is the MAJOR step of comet exploration after Rosetta
- Several science goals require in situ (LANDER) and remote (ORBITER) investigations

The International Context

- Two ongoing **Asteroid Sample Return missions** from NASA and JAXA
- Approved **Asteroid Sample Return mission** from Chinese Space Agency
- CAESAR/NASA **not selected** for NEW FRONTIERS 4; NASA's Dragonfly mission will explore Titan instead

➢ **For Voyage 2050, ESA should aim beyond a warm return of surface material, as considered for New Frontiers**

Mission baseline targeting a short-period comet

- Return a core of > 1m depth unaltered material: preserved stratigraphy & thermally stabilized at T < 90 K
- Deposit a surface laboratory (lander) for complementary investigations, maximizing science return
- Orbiter/lander payload for a detailed geological, chemical, comet activity context & sounding the deep interior

COMET NUCLEUS (CRYOGENIC) SAMPLE RETURN TECHNOLOGICAL CHALLENGES

Mission concept and sampling approach driven by the depth of the sample and storage temperature. The potential range of surface strengths and the low gravity environment add complexity.

Possible mission architectures

Land, anchor, drill and return to mother S/C

- Allows for deepest sampling (> 1 m)
- Multiple challenges for anchoring (harpoons), drilling and sample transfer to cryogenic chamber (e.g., heating issues)

Touch-and-Go with robotic arm

- E.g., BiBlade sampling (CONDOR/NF4, JPL, TRL6)
- Solve issues as anchoring, heating, sample transfer
- Sampling depth limited to 10s of cm
- Question whether stratigraphy can be preserved

Harpoon-based sample acquisition

- E.g. CORSAIR/NF4 APL/NASA/DLR

Grabbing a large ice-rich boulder from the surface

- Asteroid Redirect Robotic Mission (ARRM) NASA study

Keeping the cryogenic temperature chain un-interrupted

Technological study by Veverka for NASA Decadal Survey

Cryogenic chamber holding the sample

- Controled overpressure (1 bar)
- Passive thermal radiator (for cruise) & active cooling during maneuvers and Earth re-entry
- Temperature constraint: direct impact on complexity and cost

Earth re-entry

- Sample compression may be necessary to keep the stratigraphy during Earth re-entry
- Parachute-assisted re-entry would limit thermal, stratigraphy & structural alterations
- Alternative: return to international space or cislunar station

Curation: feasible, developed for superconductor industry

EURO-CARES roadmap for a curation facility in Europe (H2020)

IN SITU SCIENCE FROM A SURFACE LABORATORY

Philae/ESA experience shows that lander delivery on a comet nucleus is technically feasible though challenging

Important technological progresses in the 2035-2050 time frame

Miniaturization

- Sensors, electronics, instrumentation
- Smaller landers, CubeSats

Enhanced landing system

- Systems with 3-axis stabilization, propulsion
- Advanced Guidance, Navigation and Control
- Autonomous obstacle recognition, accurate touch-down

Mobility to explore several areas on the surface

- Feasability on low-gravity body: MASCOT/Hayabusa2

Instrumentation

- New types of instruments have space applications now
- New classes of science instruments allow better performances with lower ressources

Unique science with a lander

- Linking diffuse activity to surface and sub-surface thermal, structural and composition properties
- Sounding the deep interior

M-CLASS MISSIONS

AMBITION science goals cannot be addressed by M-class missions

Comet type	Fly-by	Rendezvous	Landing	Sample return	Cryogenic SR
Centaur	M	M/L	L+		
Jupiter Family	*DI, DS1, EPOXI* etc.	*Rosetta*	*Philae*	*Stardust*	L++ AMBITION
Extinct JFC	F/M	M/L	L	L	
Returning OCC	*Giotto* etc.	L+	L++		
Dynamically new	*Comet Interceptor*				
Main Belt Comet	M	*ZhengHe-A* M/L	L	M (*Stardust*-like) L (surface)	
Interstellar comet	M				

Centaurs : Rendezvous (M-class) & landing (L-class)

- To study the evolutionary path of short-period comets
- Remote-sensing/in situ payload for studying (sub)surface and coma properties
- Payload from e.g. Rosetta heritage
- Technical challenges: objects are distant

Main Belt Comet: Rendezvous (M) & landing (L)

- To understand how MBC activity works
- To unveil the link between MBC and comets

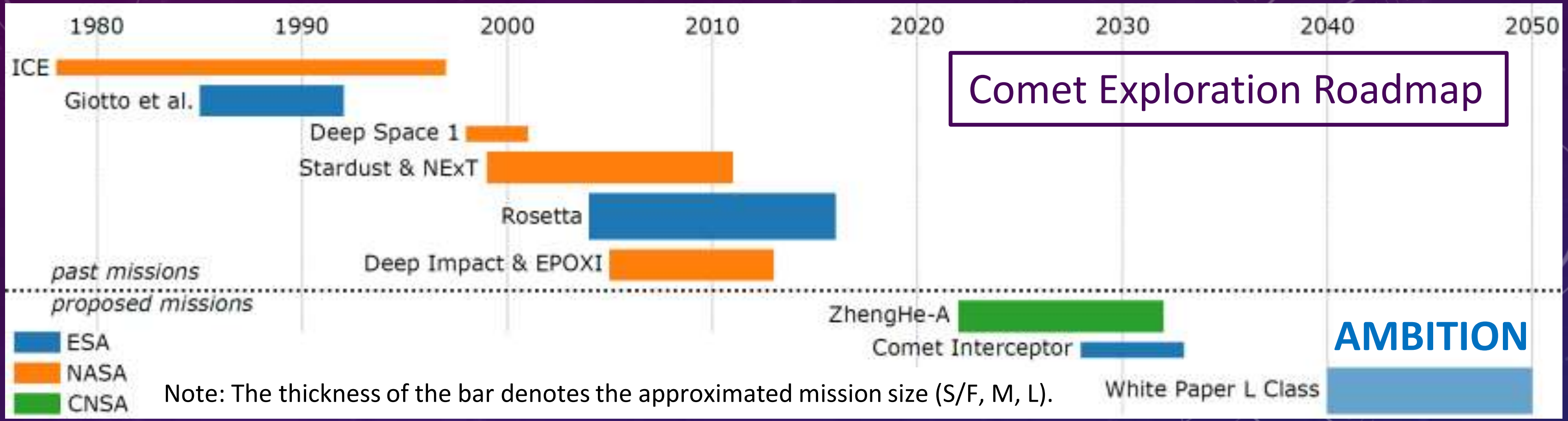
Interstellar comet: Flyby (M)

- A new window to exo-systems
- Surface, dust & gas coma characterization
- Mission concept: built upon Comet Interceptor mission
- Requires rapid-reaction operations and significant Δv

ESA F-class Comet Interceptor (CI) mission:

- ➢ a technology demonstration of multi-point measurements

CONCLUSIONS



- A cryogenic sample return from a comet nucleus is the **necessary major step for cometary science**.
- ➢ AMBITION will provide breakthrough results on Solar System formation history and on the delivery of water and prebiotic species to Earth.
- The returned sample will permit to characterize volatiles, organic matter and minerals using analytical techniques in laboratories and to reach sensitivities not achievable with remote-sensing and even spaceborne in situ instruments.
- ➢ Preservation of the samples will allow future investigations with new-developed laboratory instruments.
- ESA has a leading position in the exploration of comets (Giotto, Rosetta, CI) and should keep this leadership.
- A Comet Sample Return is supported by a strong scientific and industrial community.
- ➢ With these premises the **AMBITION** concept starts from solid bases.

WHAT WAS THE ROLE OF COMETS IN THE DELIVERY OF VOLATILES AND PREBIOTIC COMPOUNDS TO EARLY EARTH? (BACKUP SLIDE)

Comets are of prime interest for astrobiology investigations

- Have water and so-called prebiotic compounds, including amino-acids and sugars
- Are rich in organic matter (~50%)
- Are the source of a fraction of Earth atmospheric constituents (noble gases)

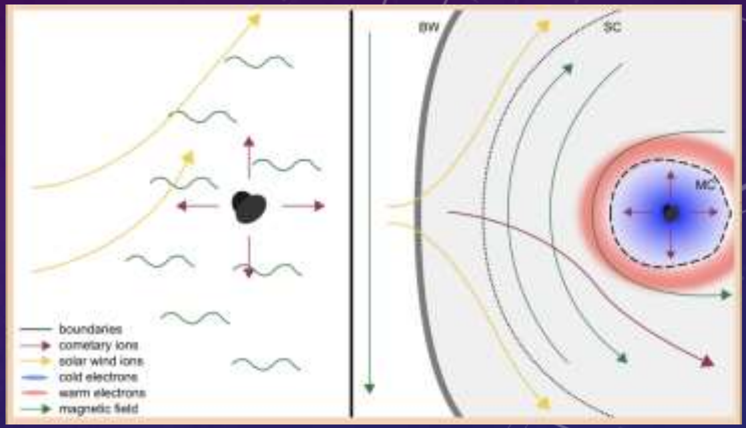
➢ To which extent did comets contribute to the Earth water budget?
➢ To which extent did comets contribute to Earth's atmosphere?
➢ What is the chemical nature of the organic matter delivered to early Earth?
➢ What is the chirality of cometary molecules?

Sample return required for:
- nature of the organics
- chirality

Cryogenic sample return for:
- Water, semi-volatiles

HOW DO THE DUST COMA, THE SURROUNDING PLASMA, AND THE NUCLEUS INTERACT? (BACKUP SLIDE)

[Goetz et al, 2019]



Comae are archetypes of *multi-phase astrophysical interaction:* **gas / plasma / dust**

Dust/plasma: *How is cometary dust dynamics and properties affected by charging processes? What is the feedback on a cometary plasma?*

➢ Dusty plasma physics (with significant expectations from laboratory plasma community to infer dusty plasma properties from *in situ* measurements) not enabled by Rosetta.

Gas/plasma: *How does partially collisional plasma behave? How does it influence the large-scale structure (e.g., diamagnetic cavity)? How is it affected by transient events?*

➢ Physics of partially collisional plasmas [see also Yanauchi et al. White Paper on "Plasma-neutral gas interactions in various space environments"]

Nucleus/plasma: *How is the nucleus affected by the plasma environment, including solar extreme events? How interactions with the solar wind influence the activity and evolution of comets?*

➢ Space weather at comets not yet understood in terms of cometary activity and evolution

See AMBITION White Paper for required Orbiter Payload

See also Goetz et al. White Paper on "Cometary plasmas"