[redacted]

FORMATION OF OUR SOLAR SYSTEM

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The Interstellar Medium

We are heading back 4.6 billion years in time…

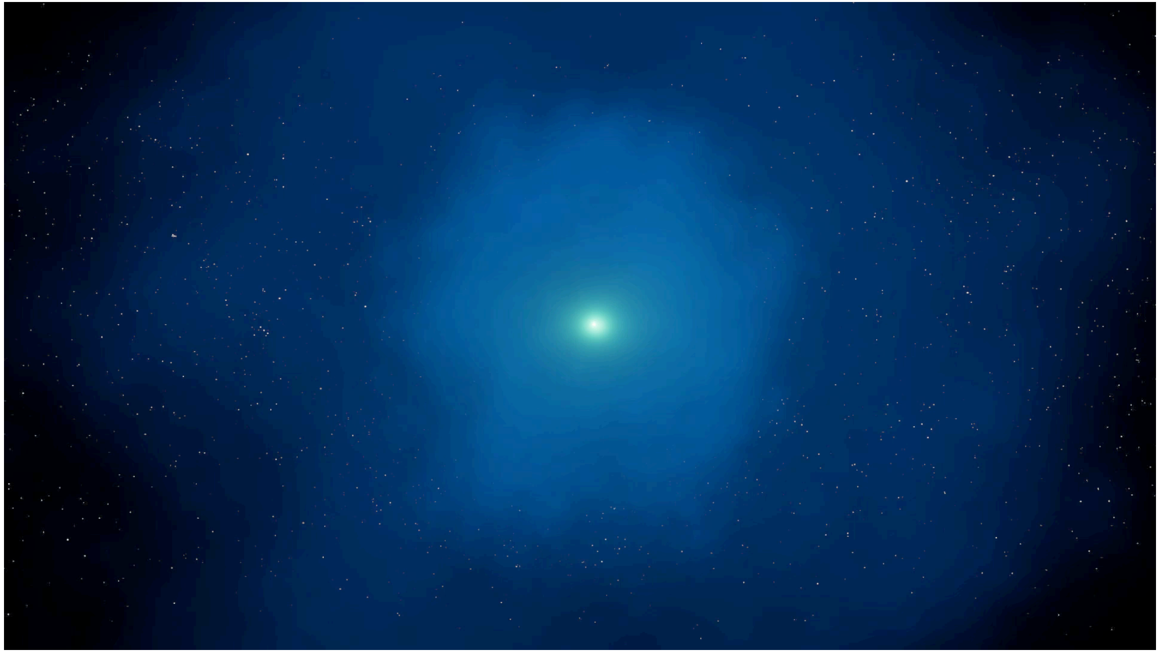
Turbulent winds in the interstellar medium form filaments that condense to *starless cores*

These ~10,000 AU★ balls of gas and dust grains live for ~ 1 million years before contracting due to gravity

★ Average distance between Sun and Earth: 1 Astronomical Unit (AU) = 150 million kilometers

Protostar formation

The starless core shrinks to ~100 AU in 10,000 years and flattens

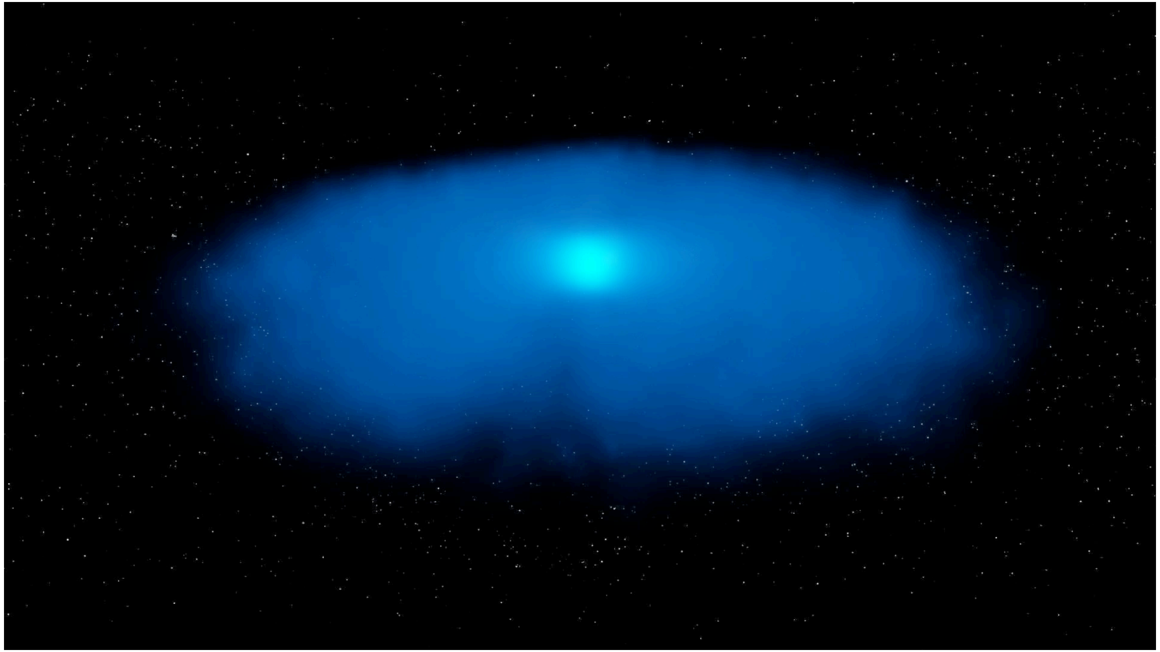


The Solar Nebula

The protosun feeds on the accretion disk

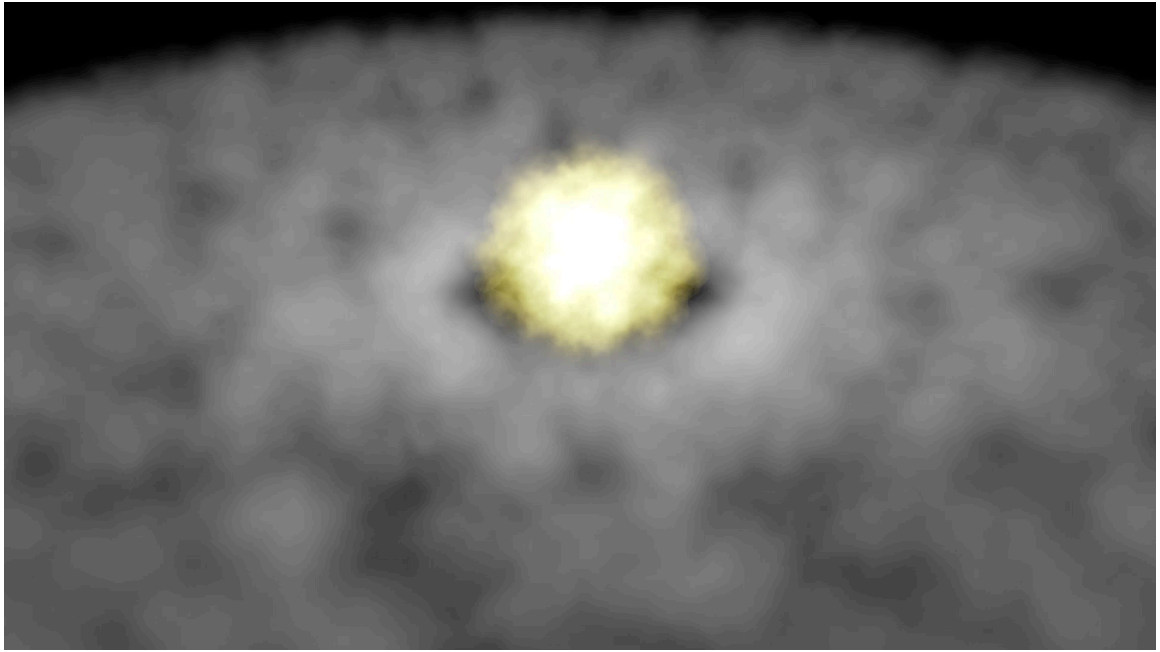
It reaches its current mass in ~ 300,000 years

A tiny disk of gas and dust remains: the *Solar Nebula*



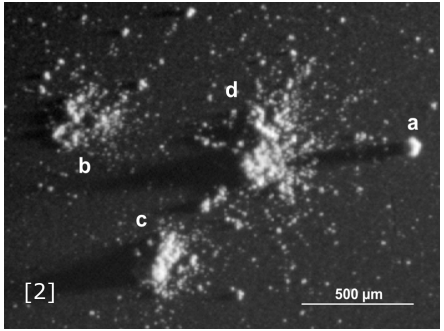
Presolar and locally produced grains

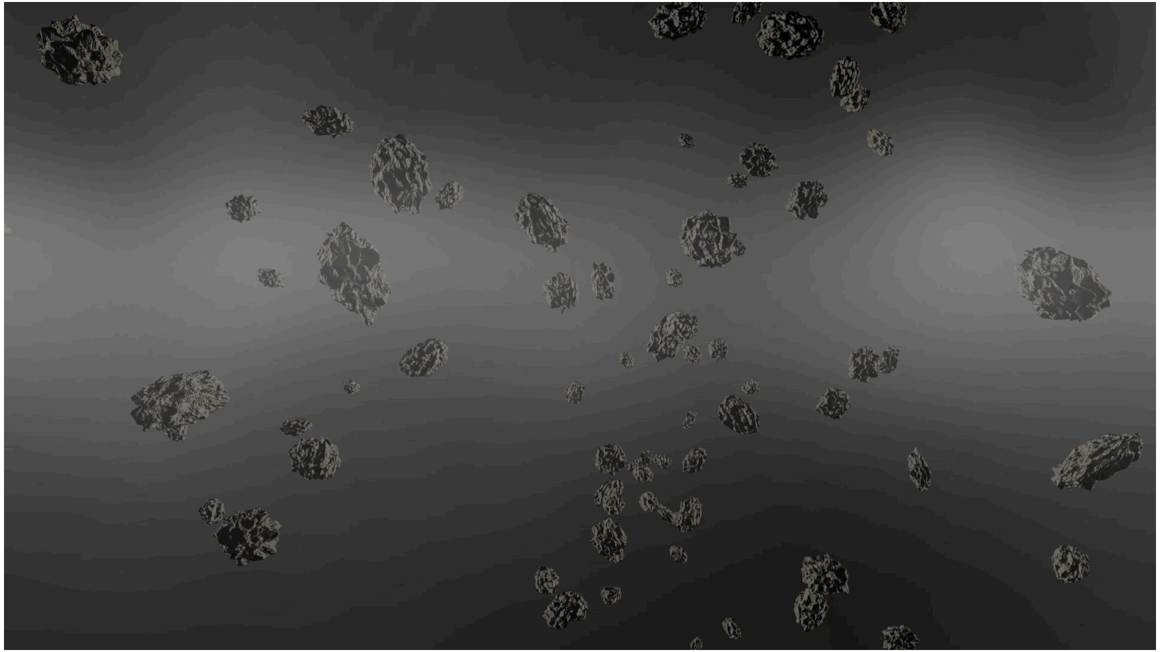
The Solar Nebula contained gas and sub-micrometer grains of silicate, sulfides, organics, and ice



Coagulation – grains stick to each other

Small fractal aggregates form, then cm-sized *pebbles*





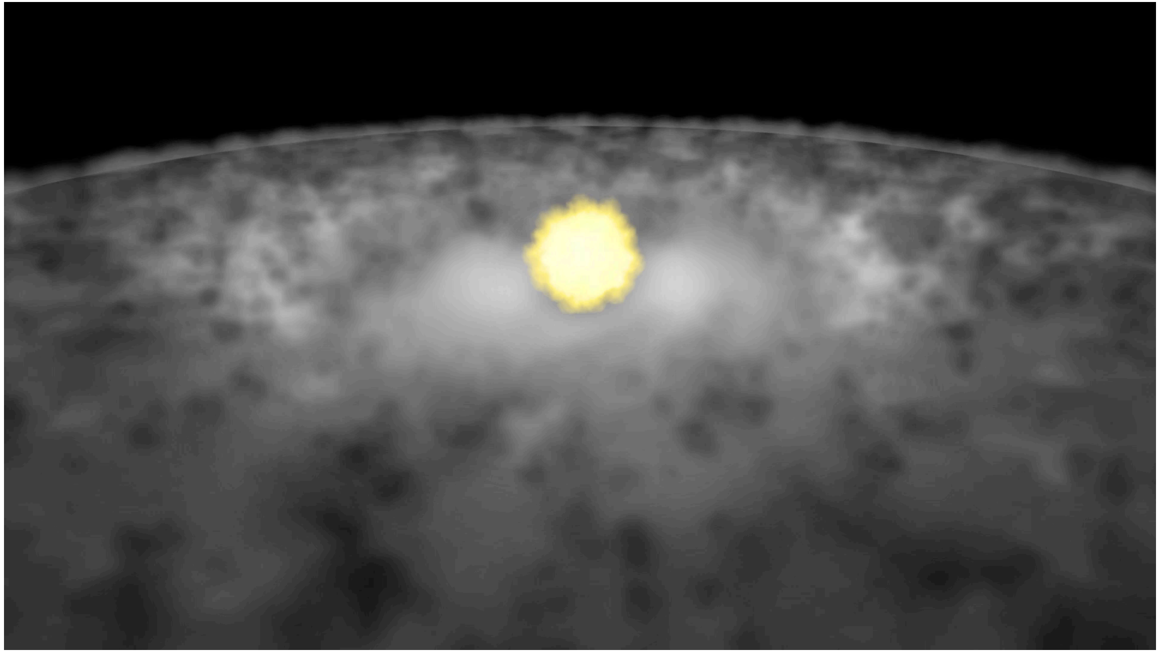
COSIMA, GIADA, MIDAS reveal aggregate size, structure, composition

Formation of large trans-Neptunians

Streaming instabilities:
Gas and pebbles interact to create *pebble swarms*

Gravitational collapse form 100km-class *porous* bodies at t ~1 million years

Mechanism stalls when ~ 10% pebbles remain



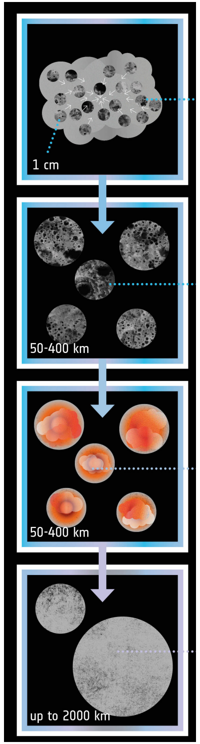
Processing of large bodies

Radioactive ^{26}Al melts ice:

- Compaction, strength enhancement
- Loss of supervolatiles
- Liquid water changes olivine and pyroxene to *phyllosilicates*

Possible example: captured Saturnian satellite *Phoebe*

Are comet nuclei collision fragments of such bodies?



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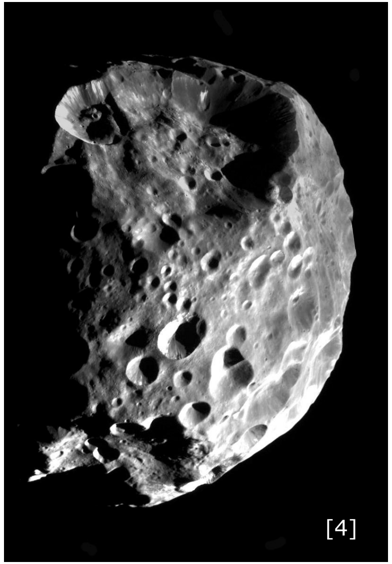

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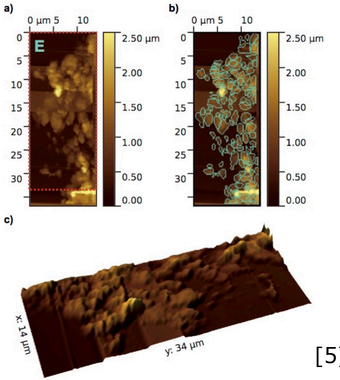
Rosetta: Key discoveries I

Rosetta says no!



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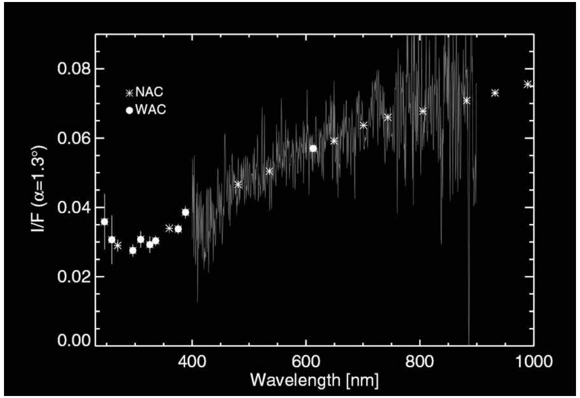

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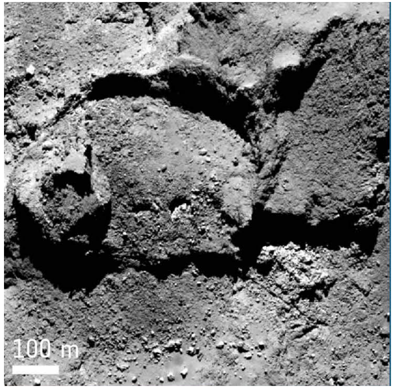

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- Very high porosity (RSI, OSIRIS, COSIMA, GIADA, MIDAS, CONSERT)
- No phyllosilicates (OSIRIS, VIRTIS)
- Weak strength (OSIRIS, Philae)
- Abundant supervolatiles (ROSINA, VIRTIS, MIRO, ALICE)

Cometesimals form out of remaining pebbles

Hierarchical agglomeration:

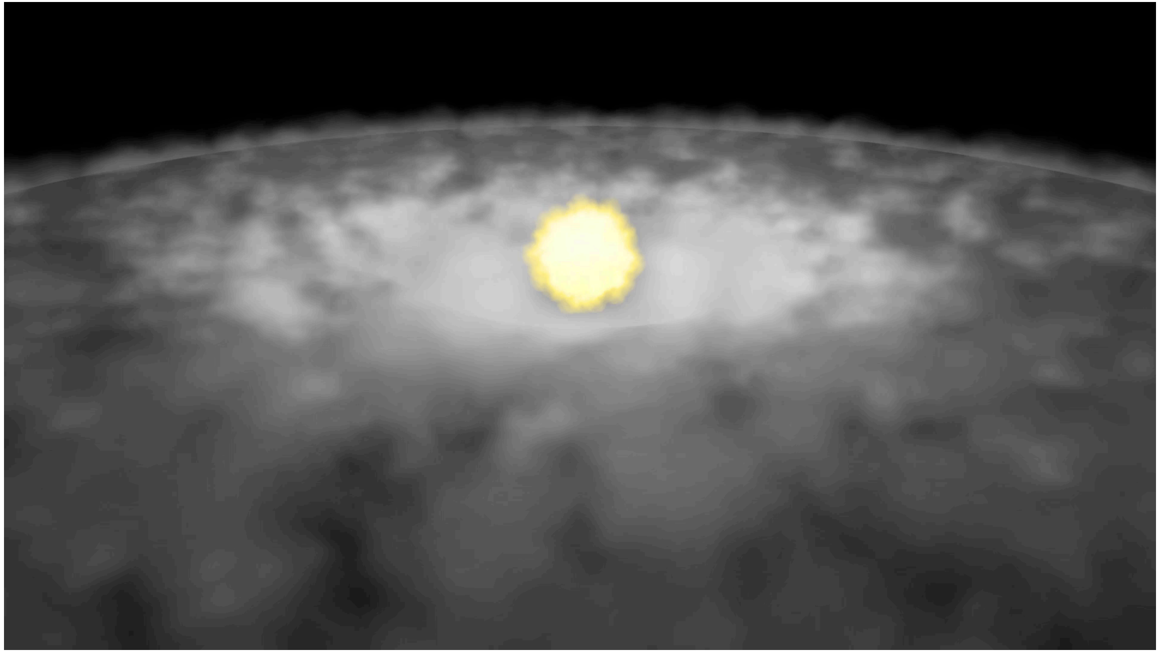
gradual growth by mergers

Meter-sized rather *dense* units form at ~30 m/s

10-1000 meter *porous* units form at ~ 1 m/s.

Small sizes: ^{26}Al heat lost!

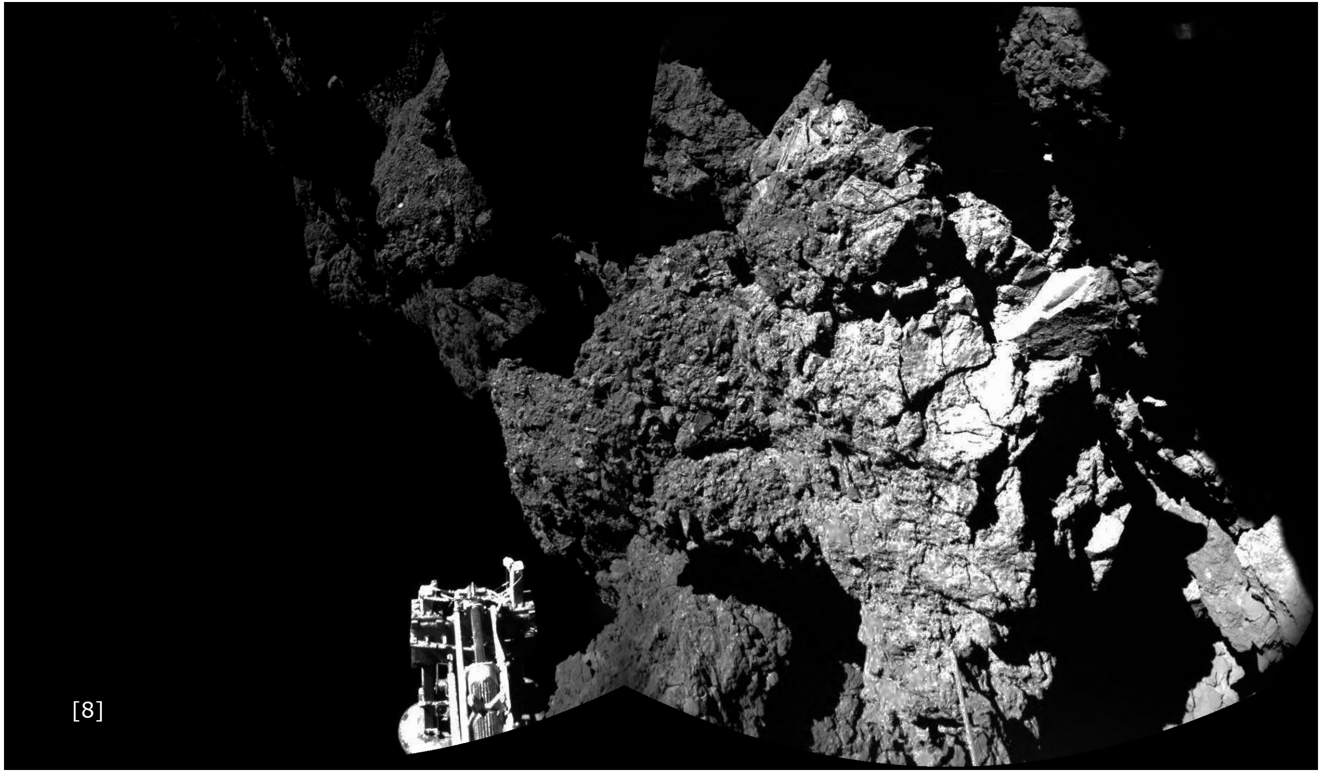
Porosity, supervolatiles survive



Rosetta: Key discoveries II

Philae (CIVA, ROLIS) reveals structures on mm, cm, dm, and m levels.

MIRO: very low heat conductivity is another manifestation of high porosity



Rosetta: Key discoveries III

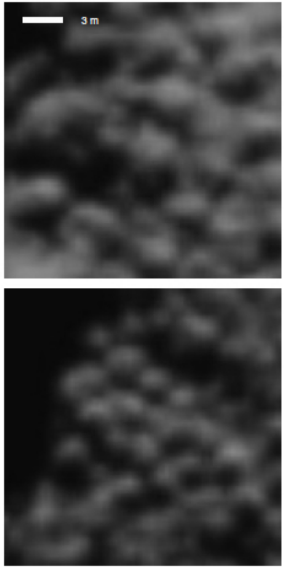
OSIRIS:

Goosebumps (~3 m) and positive relief features (~300 m) are potential evidence of hierarchical growth.

CONSERT:

Building blocks smaller than ~10m.

Porosity increases with depth over upper ~ 150 m.



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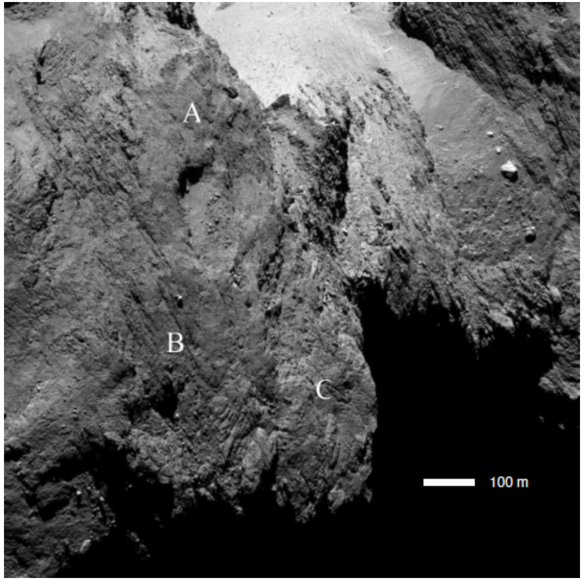

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Comet growth in the primordial disk

The solar nebula gas disappear at t ~ 3 million years

Trans-neptunians growing to the size of Pluto stir the disk. Accretion velocities increase to a few ~ 10 m/s.

Most cometesimals break up into their goosebump constituents?

Comet growth in the primordial disk

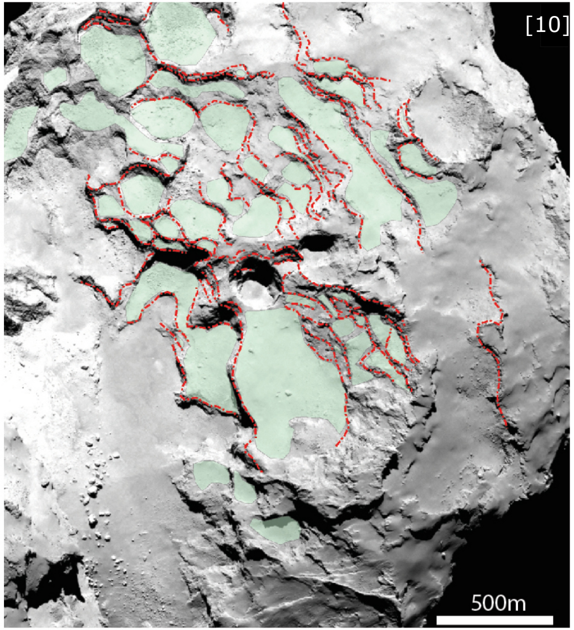
Similarly-sized objects rarely collide in the solar nebula

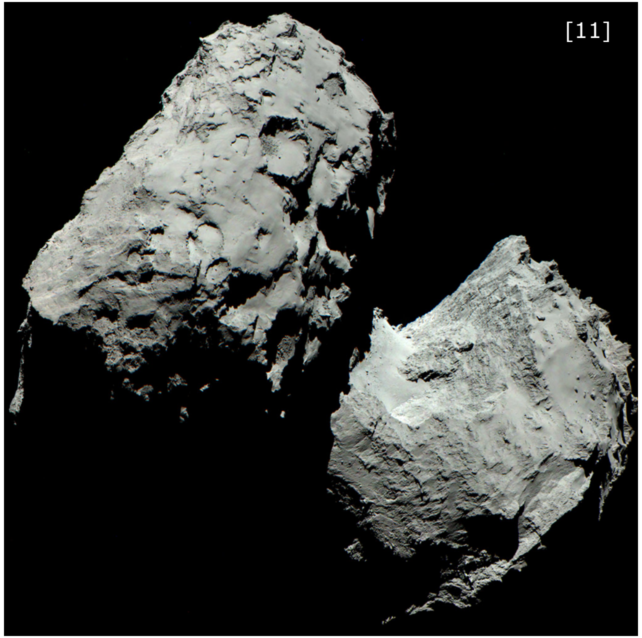
Stirring in the primordial disk changes situation

Bi-lobed nuclei form in ~ 25 million years

Comets avoid destructive collisions and survive undamaged.

Rosetta: Key discoveries IV





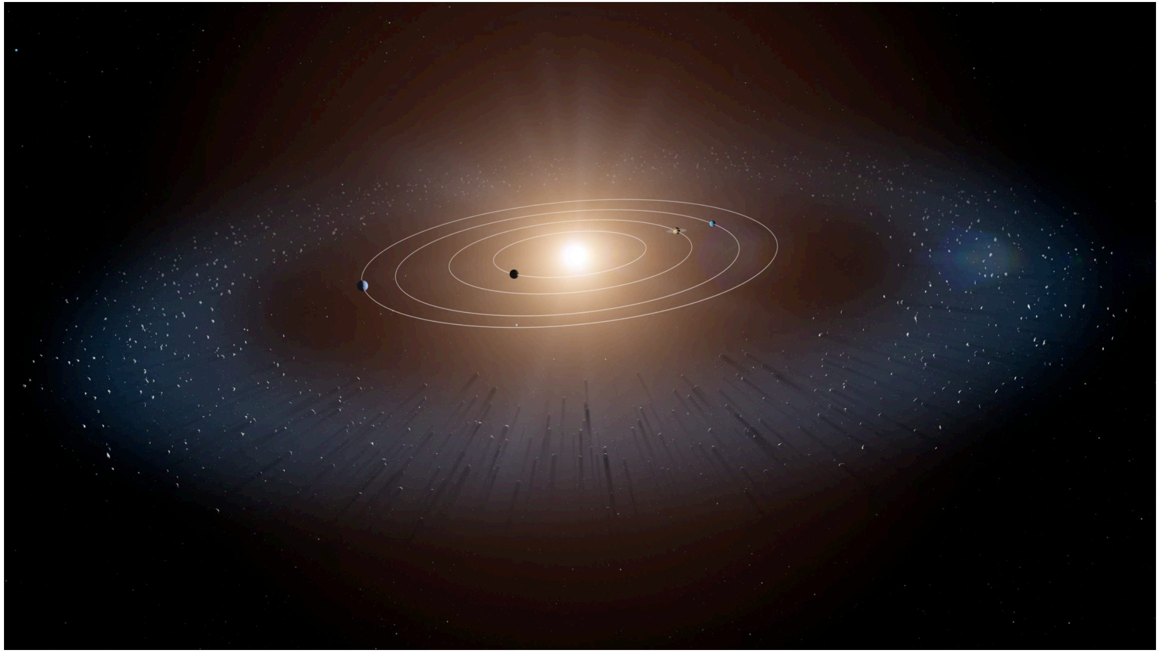
Terraces reveal deep (~600m) layering, likely formed by a sedimentation process prior to the merger of two cometesimals into 67P/C-G.

Relocation to current comet reservoirs

Primordial disk at 15-30 AU from the Sun, exterior to giant planets at 5-12 AU

Gravitational instability at t ~ 400 million years moves giant planets to 5-30 AU region

Primordial disk disrupted. Kuiper belt, Scattered disk, Oort cloud form.



Alternative scenarios

Did comet nuclei form during a late second episode of streaming instabilities?

Revealing whether small planetesimals form through hierarchical agglomeration or streaming instabilities tells how the solar nebula functioned.

Did comets collide violently with each other?

Collision rates tell us the number of comets in the early solar system.

That has direct implications for the amount of comet water and organics brought to Earth

Conclusions

Comet properties are shaped by their birth *environment*.

Understanding that *environment* is the key to understand planet formation, transport of water and organics to Earth.

Rosetta and similar spacecraft are necessary tools for advancing our knowledge about the early solar system

Image credits

All animations: Benoit Praquin (ATG Europe, Noordwijk, The Netherlands)

[1] NASA/JPL-Caltech/2MASS
[2] ESA/Rosetta/MPS for COSIMA Team MPS/CSNSM/UNIBW/TUORLA/IWF/IAS/ESA/BUW/MPE/LPC2E/LCM/FMI/UTU/LISA/UOFC/vH&S Langevin et al (2016)
[3] ESA
[4] JPL/Space Science Institute
[5] ESA/Rosetta/IWF for the MIDAS team IWF/ESA/LATMOS/Universiteit Leiden/Universität Wien
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[9] ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; Davidsson et al. (2016)

[10] ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; M. Massironi et al (2015)

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