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 $t \sim 1$ million years

Mechanism stalls when $\sim 10\%$ 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?*
Rosetta: Key discoveries I

Rosetta says no!

- 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 \( \sim 30 \text{ m/s} \)

10-1000 meter *porous* units form at \( \sim 1 \text{ m/s} \).

Small sizes: \(^{26}\text{Al}\) 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.
Comet growth in the primordial disk

The solar nebula gas disappear at $t \sim 3$ million years

Trans-neptunians growing to the size of Pluto stir the disk. Accretion velocities increase to a few $\sim 10$ 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 the situation.

Bi-lobed nuclei form in ~25 million years.

Comets avoid destructive collisions and survive undamaged.
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 $t \sim 400$ 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.
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