Cryogenic Nucleus Sample Return (CNSR)

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Key questions identified by the Decadal Survey and NASA Roadmap for Comets

- What is the inventory of water and organic material across the Solar System and how has this matter evolved?
- How did comets contribute to the origin and evolution of planetary bodies?
- What are the bulk physical properties of comets, and what processes led to their formation and subsequent evolution?

Why CNSR?

- The scientific importance of comets is tied directly to their role as tracers of early Solar System conditions
  - Cometary material preserves a signature of its origin in the solar nebula, and probably its ISM stage, even if comets are not completely “pristine”
- Any sample return mission that can keep its cargo below the sample’s temperature in the nucleus, and preserve its physical structure, is clearly superior to a mission that cannot
  - The colder, the better (hence “cryogenic” is preferred)
  - Maintaining sample’s physical structure (e.g., crystalline vs amorphous) may be technically impossible for return to Earth’s surface
- Depth of sample is important
  - Deeper is better, but depth “required” is uncertain scientifically, and going deeper is technically more challenging
- Get the ice (aka “volatiles)!
  - Volatiles trace the coldest, most primitive conditions

Additional Questions Addressed by CNSR

- How complex is cometary matter?
  - Do comets harbor the precursors of biological molecules?
- Did comets supply a significant fraction of the Earth’s water and organics?
- What is the detailed composition of cometary volatiles and how are they distributed vs depth in the nucleus?
- What is the nature and source of cometary activity?
  - How does the energy exchange between the incoming solar radiation and near surface materials work?

Ice vs Rock

- Ice traces the coldest, and Rock traces the hottest, conditions experienced by comets
  - Investigating both is important, but complementary in many respects
    - Crystalline grains in Stardust samples point to mixing across a large range of heliocentric distance in the solar nebula
    - Volatile inventory can be used to chart the thermal history of cometary material at temperatures ranging from ~10 K to 200 K
- Are isotopic and noble gas abundances different for Ice vs Rock?

How Cold is Cold Enough?

- Maintain T ≤263 K throughout entire mission to prevent aqueous alteration of the sample
- Maintain T ≤135 K (amorphous to cubic ice transition) throughout entire mission
  - *If* ice is amorphous, preventing this phase change will help to preserve volatiles in the sample
  - But even this might not be cold enough during *years* of cruise
- Preserving ice *phase* (e.g., crystalline vs amorphous) and *physical structure* requires mitigation of high-g environment, in addition to cryogenic temperatures
  - This requirement may be beyond even CNSR

Condensed (Ice) vs Gas Phase Volatiles

- If you can't maintain cold enough temperatures to preserve the ice sample during return, then at least collect the evolved gases
  - Must also store them in a way that prevents chemical changes (e.g., using special getters, different chambers filled at different temperatures)

How Deep is Deep Enough?

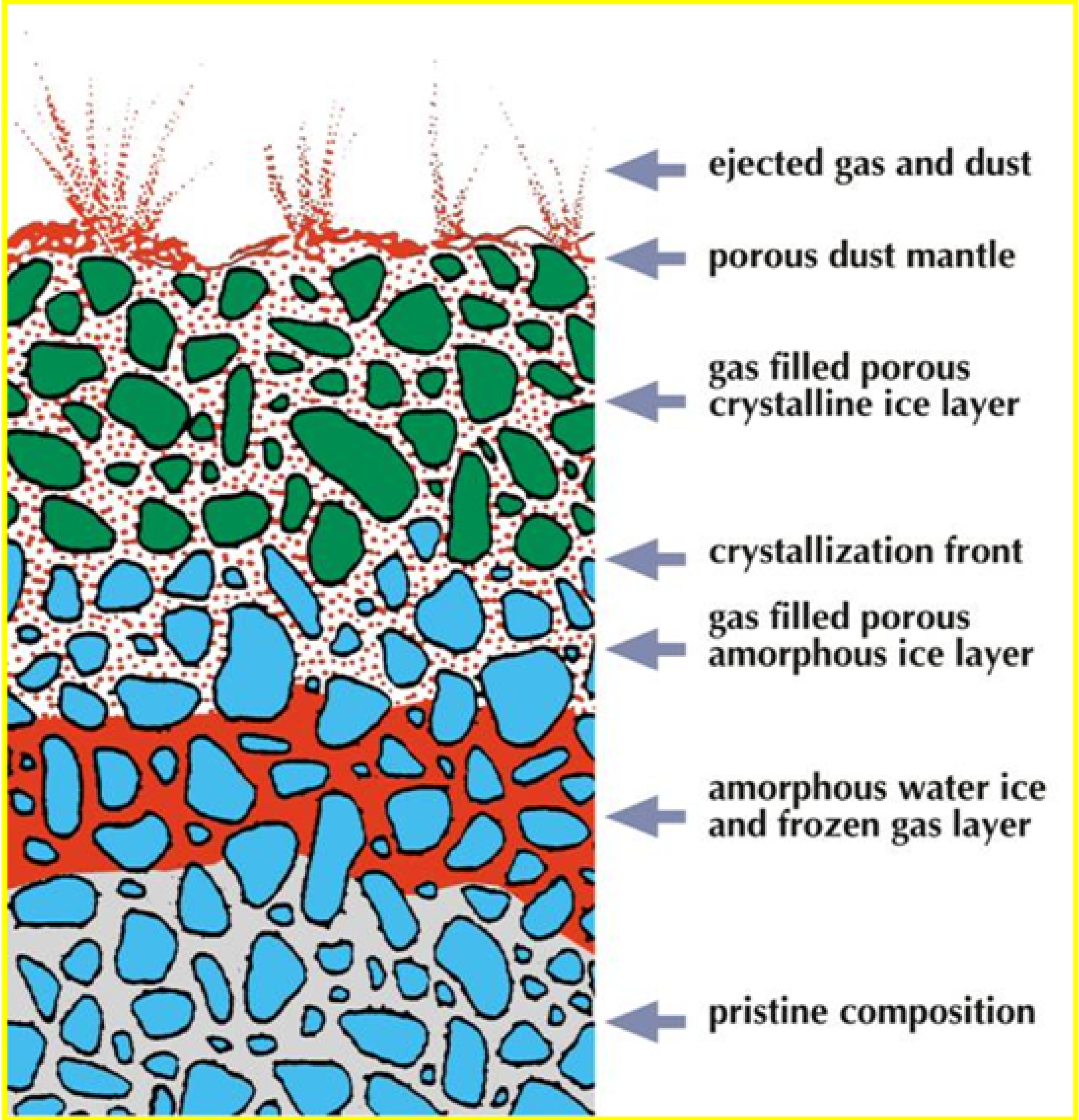
Little is known about the vertical structure of the nucleus, but here's one possible model

Surface layer has diurnal thermal skin depth of a few cm

Mass loss during typical perihelion passage corresponds to loss of ~1m averaged over nucleus

Is the nucleus onion-structured with several different layers, with several different types of ice, and different compositions?

CNSR should go *meters*, not centimeters, below the surface

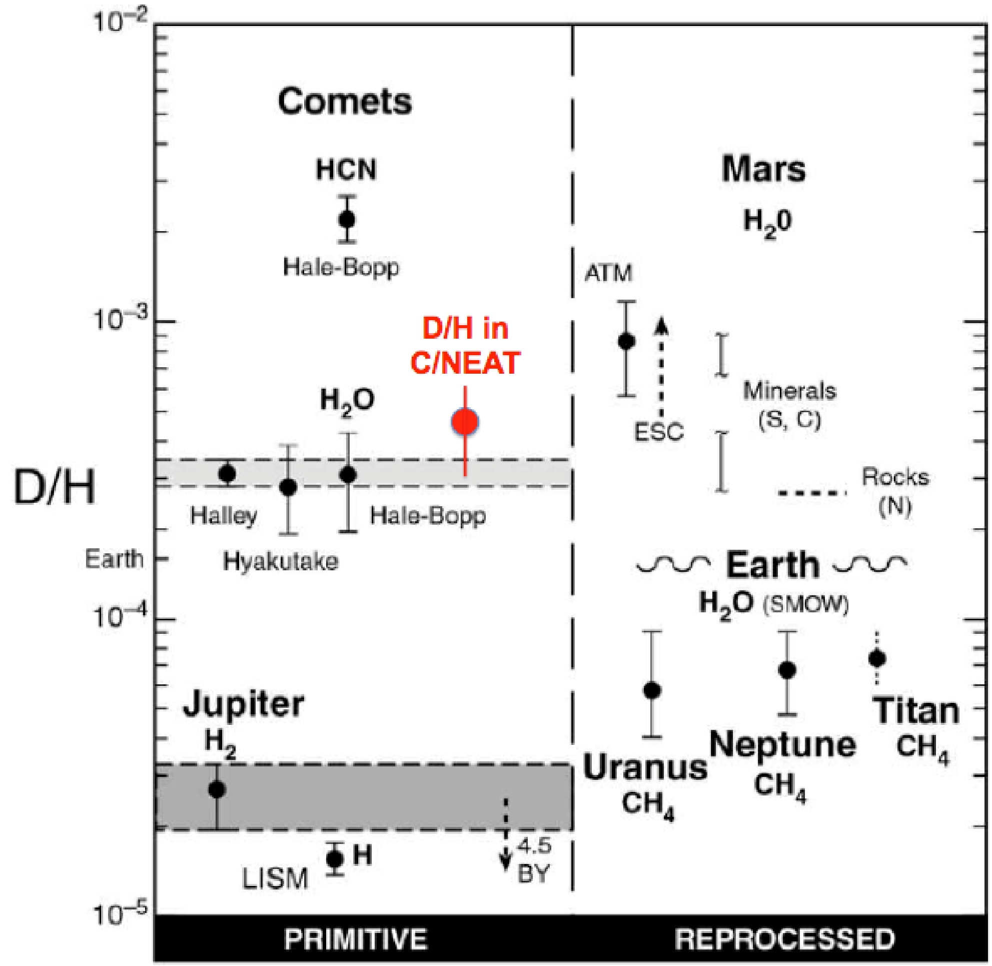


Prialnik 2004

D/H in the Solar System

Multiple different values in multiple reservoirs

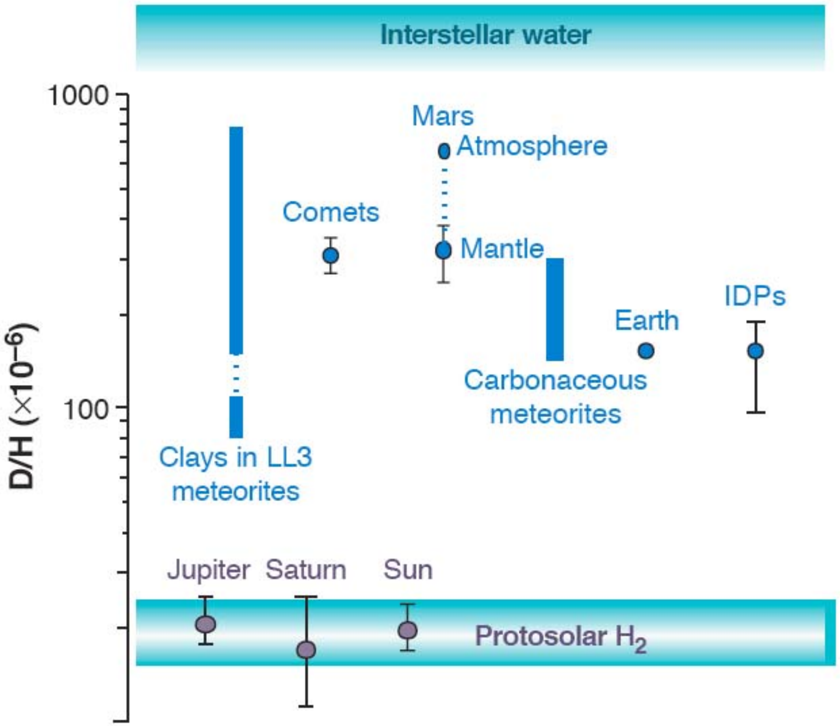
What is this telling us?

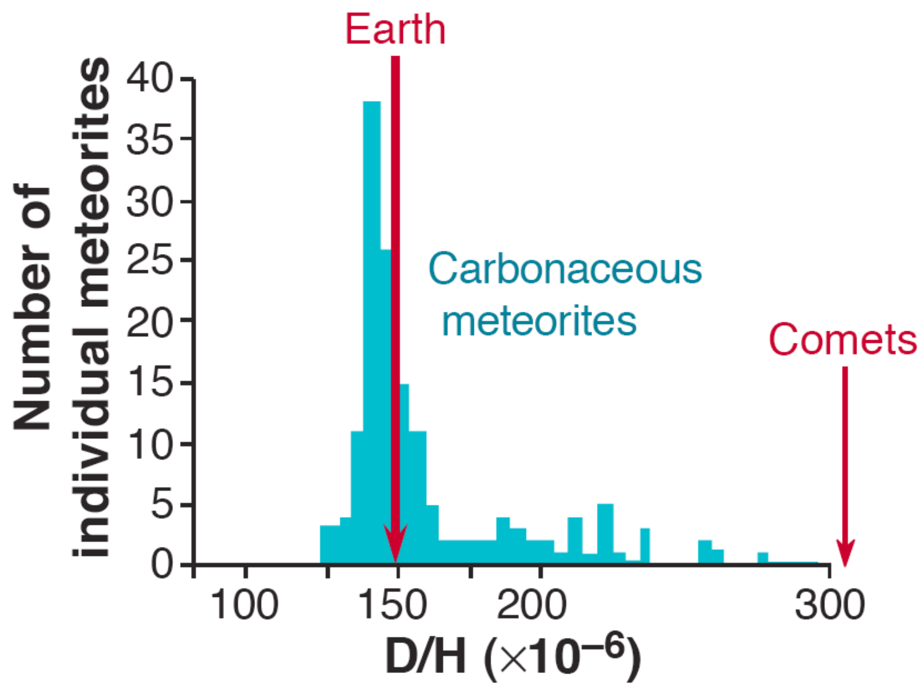


Deuterium in the Solar System

Fig 1: D in the solar system is divided into primitive (left) and reprocessed (right) reservoirs. The current value of D/H in the Local Interstellar Medium (LISM) reflects the continual decrease in D during the past 4.6 Gyr owing to nucleosynthesis by stars in our galaxy. The Jupiter D/H presumably reflects the value in the solar nebula gas where Jupiter formed. The D/H values for Earth SMOW, the Mars rocks and atmosphere, and the atmospheres of Uranus, Neptune, and Titan are enhanced relative to Jupiter, at least partly due to impacts from primitive bodies, including comets. The D/H value derived from our Hubble observations of C/NEAT is preliminary but appears to be consistent with the values derived from observations of deuterated water in three other comets. (Fig adapted from Owen & Bar-Nun [1])

Did Cometary Bombardment Deliver Earth's Water?





Robert (2001)

- Noble gases in the Solar System tell an interesting story
  - Venus has more Ar than Earth which has more Ar than Mars – What is the source of the Ar? Could it be comets?
  - Xe/Kr is *very* different for chondrites than for Earth, Mars or Sun – what are cometary values?

- Measuring the noble gases *might* require extremely high sensitivity if values in comets similar to chondrites
  - ^{36}Ar/[N] = 3x10^{-2} in Sun
  - Might be 3-5 <u>orders of magnitude</u> lower in comets!

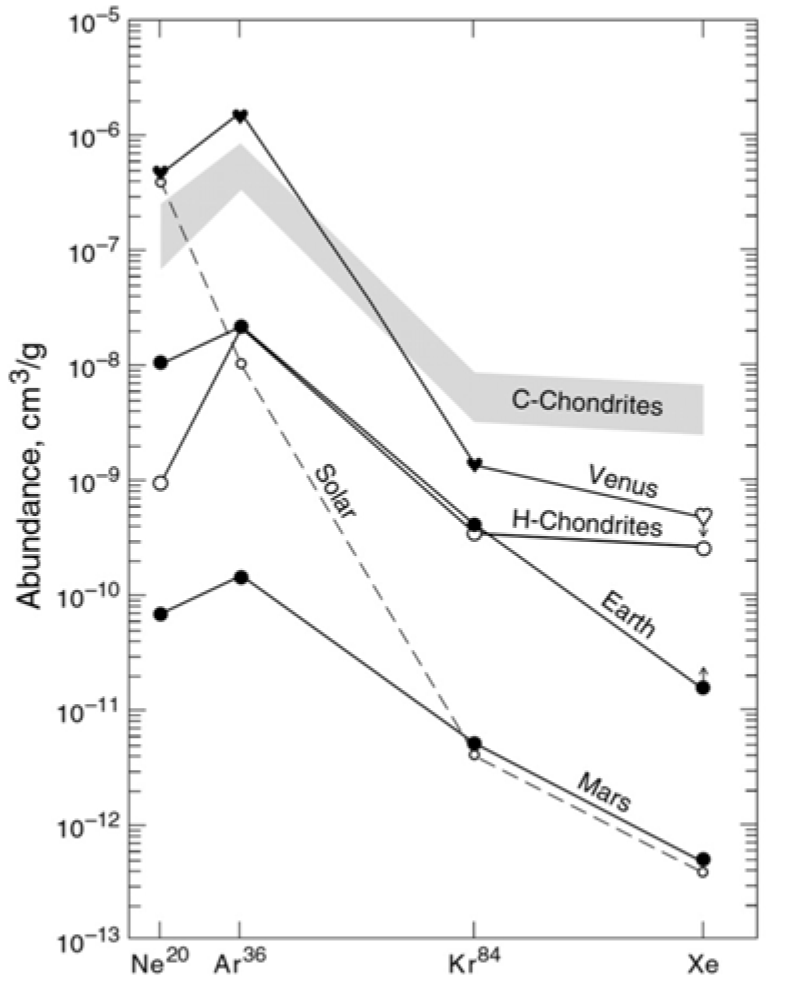


Figure 1. Chondritic meteorites contain about as much xenon as krypton. The meteoritic noble gas abundances therefore do not match the abundance patterns found in inner planet atmospheres, despite the apparent agreement for Ne, Ar, and Kr. (Solar values are normalized for ^{84}Kr on Mars). Note the high abundances of Ne and Ar per gram of rock and the solar type ^{36}Ar/^{84}Kr on Venus (Owen and Bar-Nun, 1995a).

Perhaps exogenous delivery by comets that formed, and were maintained, at cold temperatures can explain the noble gas pattern observed for the terrestrial planets.

If that's the case, comets supplied other volatiles as well.

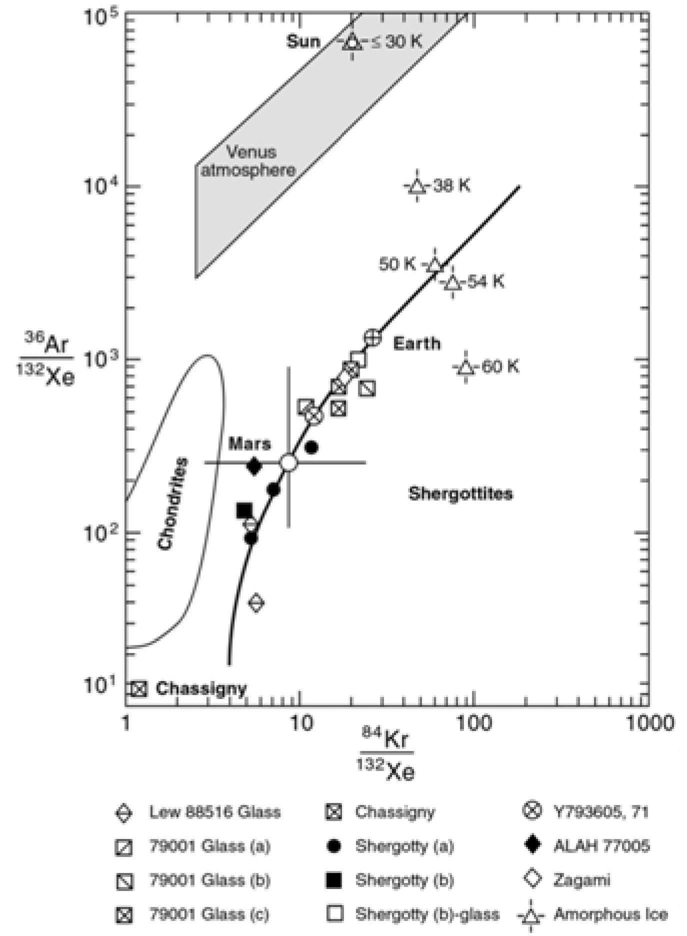


Figure 3. In a three element plot, noble gas abundances in the atmospheres of Mars (Viking) and Earth can be used to define a mixing line between internal and external volatile reservoirs. The internal reservoir lies below Mars on this plot, and consists of the rocks that formed the planet. We suggest icy planetesimals as the external reservoir, lying above the Earth mixture at the opposite end of the line. The external reservoir is represented here by the noble gases trapped in amorphous ice in laboratory experiments (the open triangles). These points correspond to solar elemental ratios multiplied by the factionation factors found experimentally (Owen *et al.*, 1991). Noble gas abundances in Shergottites (meteorites from Mars) fall along this line. The gases on Venus could have been delivered by comets from Kuiper Belt that formed at tempertures less than 30-35 K. The abundance of Xe on Venus is not yet known, hence the stippled trapezoid. References: Shergotty (a), Chassigny: Ott, 1988; Lew 885516 glass: Beck and Pepin, 1993; ALAH 77005 79001 Glass (a): Swindle *et al.*, 1986; 79001 Glass (b): Becker and Pepin (1984); Zagami: Ott *et al.* (1988); Shergotty (b), Y 793605, 71, 79001 glass (c): Bogard and Garrison, 1998.

Diversity of Comet Nuclei

- So far, no two look exactly alike
- Hills, plains, spires, mesas, craters, sublimation pits, talps, …
- Large variation in "active area"

- *Is there a preferred type of comet to sample?*