CSSR Mission Study - Science

Mike A'Hearn & Hal Weaver

Big Questions

"Are we alone? Where did we come from? What is our destiny?"

New Frontiers in the Solar System, NRC decadal survey
Executive Summary, page 1

This was the overriding theme of the NRC's first decadal survey of planetary science (©2003) and it certainly remains today as the overarching goal of planetary science.

Recent cometary missions have made fundamental contributions to answering these questions and are expected to continue to do so.

Why We Study Comets

Why Study Comets?

Medieval copy of Josephus

Giotto di Buondoni - Scrovegni Chapel

Bayeux Tapestry

Despite these words, Ossama Bin Laden was unwilling to have me taken back to Jalalabad through the Taliban checkpoints at midnight. So I spent the night under the stars at his guerrilla camp, close to the massive rock-hewn air-raid shelter that he built during the Russian war. When the Arabs drove me back before dawn next day, they paused by the roadside to pray, kneeling on rugs with their rifles beside them, crying "Allahu Akbar" over the bleak landscape of rivers and snow-capped mountains. And amid the pageant of stars above us, a great comet trailed down the sky with a fiery tail, unseen since the time of the Pharaohs. It was, I learned later, the Hale-Bopp comet. "They say that after a comet, there will be a great war," one of the Arabs said to me.

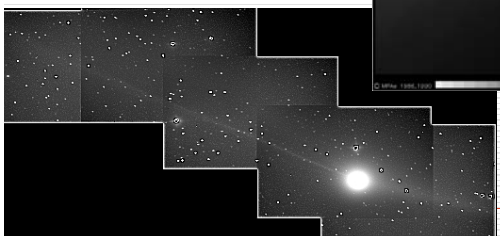
The Independent - 1997 Mar 22

More Reasons Why

C/Bennett 1970 II

C/Ikeya-Seki

C/Lee 1999 H1 - L. Sanino



C/Hale-Bopp

Why Comets: Science

- Comets play a critical role in helping us to understand the formation and evolution of the solar system
  - Composition reveals signature of ISM link
  - Composition and physical structure is sensitive to P,T conditions in the solar nebula
  - Formed the cores of the Giant Planets
  - Impacting comets shape planetary atmospheres
  - Impacting comets deliver water and organics, the seeds of life, to the terrestrial planets
  - Provide a technique for sampling the outer solar system from an inner solar system platform (very convenient!)

Why Comets? Science

- Many, if not all, formed as cold, small bodies so internal processes probably did not change the structure or the chemistry
  - All Halley-type comets (via the Oort cloud) must have originally formed as small bodies - up to the size of Hale-Bopp (r_N~40 km)
  - Some Jupiter-family comets may be fragments of large TNOs, but recent simulations suggest that the dominant source of short-period comets is the scattered disk rather than the classical Kuiper Belt and collisions are less important in the scattered disk than in the KB
  - How cold? <190K in order to preserve H_2O ice
  - How small? <100 km (all observed nuclei r_N<40 km) is probably small enough to prevent internal heating by accretion or by ^{26}Al (it is mostly ^{26}Mg by the time of accretion; but see Merk & Prialnik, 2006)

Why Comets? Science

- Formation is entirely by accretion/aggregation of solids - gravitational accretion negligible
  - Thus composition is sensitive to the T-P conditions, since composition of solids is controlled by condensation and sublimation
- Gentle accretion of cometesimals ***may*** preserve primordial cometesimal structures
  - Can test mixing of 100m-sized bodies in the protoplanetary disk

Why Comets? Science

- Comets impact Earth
  - Late heavy bombardment
    - Brought a much-argued fraction of the water and organics to Earth,
    - Other arguable sources - "wet" asteroids during the LHB and primordial accretion
    - The combination enabled us - what was brought
  - Impacts today
    - Can cause mass extinctions and other events of global scale
    - Gene Shoemaker always argued that Chixculub was a comet because of size and that highly processed core samples could be consistent with this (as well as with chondrites)
    - Short-period cometary impacts will be predictable through the NEO surveys but long-period and new comets will not be known in this way

Why Go There?

- Uncounted measurements via remote sensing have given us a wealth of data on composition, nuclear sizes, and so on
- Indirect (model-dependent) analyses have given us the density (confirmed *in situ* by Deep Impact)
- Why isn't this enough?

Processing of Cometary Matter

- ISM phase
  - Molecule formation: grain chemistry vs condensation
  - UV & CR irradiation of ice-coated grains --> organics
- Solar Nebula phase
  - Heating, sublimation, re-condensation of material during infall
  - Volatile composition affected by P,T of formation region
  - Possibly massive irradiation from X-rays, UV, particles during T-Tauri stage
- Comet phase
  - Thermal processing by near-Sun passages (volatile depletion accompanied by material stripping of the surface)
  - Processing of surface layers by particle & UV irradiation

All of the above presumably play roles, but it's unclear which are most important (and may vary among comets)

Surface Changes

- Surface layers of Jupiter Family comets are certainly processed
  - Volatiles certainly depleted but it's not clear to what extent the heavier organics are modified
- Dynamically new comets are processed by galactic cosmic rays
  - Depth 10m - all chemical bonds broken
  - Is the processed material all blown off on first approach to the planetary realm?
- Periodic comets are processed by solar heating at every perihelion passage
  - How deep does this evolution proceed?
  - Does this material get blown off at every perihelion passage so that primordial material remains "near" the surface?
- How does this affect what we see in the coma?
  - What molecules? What isotopic ratios?

Heterogeneity

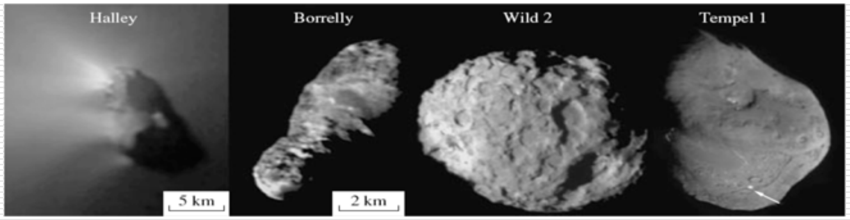
- Nuclear structure not observable
- Remote sensing has suggested that the outgassing from the nucleus is heterogeneous in some comets
  - Variation in relative abundances with rotational phase
  - No association with nuclear structure possible
  - Scale of heterogeneity not measurable
    - Is it microscopic? Macroscopic? Cometesimal scale?
- Refractory components cannot be analyzed except very superficially

What Have We Learned *in Situ*?

Physics of Comets

Conditions in Early Solar System

Nuclei Compared

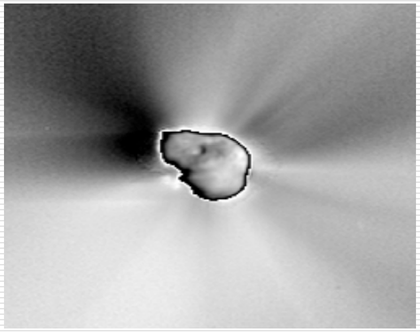


Basilevsky & Keller 2007 *Sol.Sys.Res.* **41**, 119

- Nuclei are all very different! But why?
  - Need to understand structures by detailed analysis
- What causes jets? Where on the surface do they come from? And how does this affect what we see in the coma?

Jets

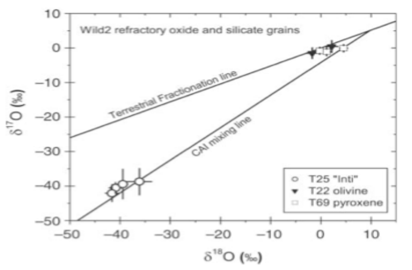
- From remote sensing we all ‘know’ that comets have active areas
  - These can create jets where excess H_2O drags more dust
- Jets on Tempel 1 are not associated with ice on surface with rare exceptions
  - Jets (dust) are better correlated with CO_2 than with H_2O
  - Water is controlled diurnally



Farnham *et al.* 2007 Icarus **187**, 26.

Mixing in Protoplanetary Disk

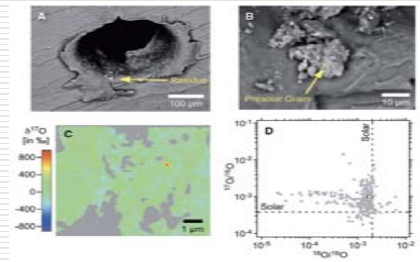
- Stardust samples show:
- Primarily crystalline silicates
  - Suggests high-T formation
  - Annealing possible but not likely
- O isotopes of one crystalline grain are clearly solar
  - Very similar to CAIs in meteorites
  - Other grains have progression of isotopes consistent with inner solar system formation
- Strong evidence for Frank Shu's X-wind mixing from 0.1 AU to 10s of AU



McKeegan *et al.* 2006 *Science* **314**, 1274

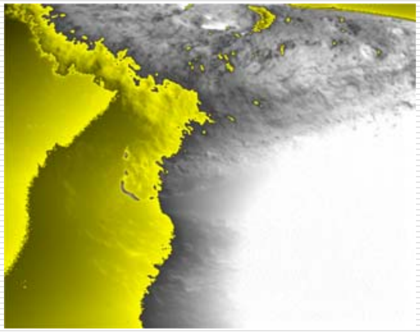
Mixing in Protoplanetary Disk

- One clearly pre-solar grain
- Implies some solids survive the accretion shock and are incorporated into comets
- All results imply a wide range of condensation conditions
- Relative amounts of material totally unknown from
  - Pre-solar solids
  - Condensation near sun
  - Condensation at 10s of AU



McKeegan *et al.* 2006 *Science* **314**, 1274

Mixing in Protoplanetary Disk

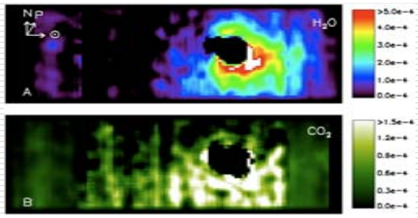


Wellnitz *et al.*, unpublished

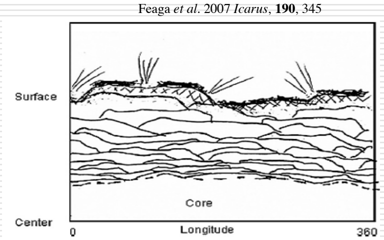
- Layers extend parallel to surface - not concentric
- Suggests layers are primordial rather than evolutionary
- Suggests preservation of cometesimal structure
- Suggests gentle accretion of cometesimals with splattering but not much interpenetration
- See Belton *et al.* 2007. *Icarus* **187**, 332

More Mixing in Protoplanetary Disk

- Large variations seen in CO_2/H_2O abundances
- Is "southern" cometesimal enriched in CO_2 relative to "northern" cometesimal? Or is it a seasonal evolutionary effect?
- Is there mixing of macroscopic bodies as well as microscopic bodies as seen from Stardust?

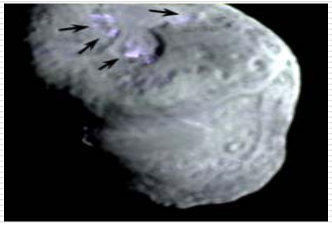


Feaga *et al.* 2007 *Icarus*, **190**, 345

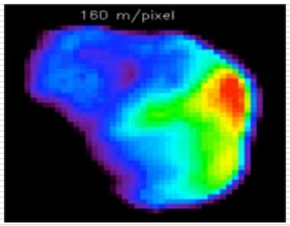


Belton *et al.* 2007 *Icarus* **187**, 332

Where Are the Volatiles?



Sunshine *et al.* 2006 *Science* **311**, 1453

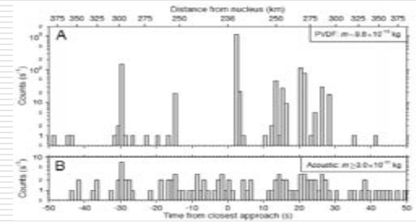


Groussin *et al.* 2007 *Icarus* **187**, 16

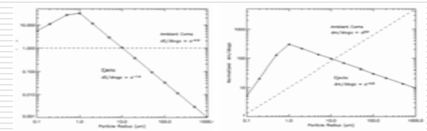
- Surface ice negligible for producing water outgassing
- Temperature of surface responds instantly to sunlight (no thermal inertia)
- Water (and other volatiles) must be near but below the surface
  - "near" = <20 cm by thermal models
  - "near" ~2 m by analogy with impacts in lab
- Need to understand this to interpret remote sensing data

Particle Structure

- Very tight clustering of small-particle hits on Stardust spacecraft
  - Fragmentation of very fragile aggregates?
  - Or icy glue evaporating?
  - Or is it mini-jets?
    - If so, why not in large particles?
- DI Ejecta had a very different size distribution than ambient coma
  - Fragmentation during excavation?
  - Loss of glue during excavation?
  - Or is it surface vs. sub-surface?
- Important to understand this for origins

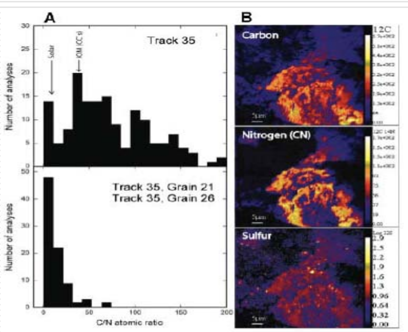


Tuzzolino *et al.* 2004 *Science* **304**, 1776



Lisse *et al.* 2006 *Science* **313**, 635, on-line suppl.

Organics for Earth



Sandford *et al.* 2006 *Science* **314**, 1720

- Stardust samples show very wide range of organics
- Team argues that volatile organics are missing
- Remote sensing can not identify all organics
  - Wide spectral range
  - Inadequate spectral resolution traded off against inadequate sensitivity

Issues for CSSR

Sample Collection

- All evidence points to very low strength at ***all*** spatial scales from μm to km
- Sample collection can be done "touch and go", without needing to anchor to the nucleus
- Collector need not drill through solid rock, nor even through a solid ice cube
- Dramatically simplifies the mission relative to what we thought a few years ago

What to Sample

- Most important objective is to bring back a macroscopic sample of the nucleus for laboratory investigation
  - "Soft" capture preserves organics (no hypervelocity impacts)
- Investigating heterogeneity implies
  - Samples from a few locations
- Degree of intimate mixing of volatiles and refractories (are Greenberg's icy mantles really on silicate/organic grains?) implies trying to return ice as a solid (<<190K)
- Key question of D/H for Earth's oceans implies returning (or analyzing *in situ*) multiple samples of solid ice
- Ice is not deep - cm to 2-3m
- Mission is not as difficult as previously thought

What Science?

- Macroscopic Sample
  - To obtain the rarer minerals
  - To allow trace-element isotopic analysis
  - Understand the intimacy of mixing at various spatial scales
  - Investigate the nature of cometary organics (how complex?)
- Collection at << hypervelocity
  - Preserve all the organics and all the relatively volatile minerals
- Shield from liquid water (or water vapor at moderate pressure for long times)
  - Eliminate any chance of aqueous alteration after leaving the nucleus
- Preserve ***all*** volatiles, even if only as captured gas
  - Complete molecular, atomic, and isotopic inventory

The Bottom Line

Comets have played key roles in our study of solar system origin & evolution

There are many unanswered questions and new implications driven by results from recent missions to comets that can only be addressed with a more ambitious mission

CSSR is still an obvious candidate for the next New Frontiers AO and is now much better defined than when it was recommended as CSSR in the decadal survey. CSSR is straightforward, and even getting to the H_2O, although more challenging, is likely within the scope of New Frontiers with reasonably inflated cost caps

CSSR is our next big step towards an understanding of cometary matter, not the final step!