Main Belt Comets and Volatiles in the Asteroid Belt

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SBAG 9 Meeting
July 11, 2013
Small Bodies & the Decadal Survey

• **Goals – Building new worlds & planetary habitats**
  – What were the initial conditions, processes & stages of Solar System formation
  – What were the primordial sources of organics and volatiles

• **Key Recent Discoveries**
  – Insights into disk structure & chemical models
  – Change our paradigm of comet formation
  – Aqueous alteration seen everywhere in primitive meteorites, Ceres outgassing
  – Moon less dry than previously thought
  – Extensive near-surface Ice on Mars
  – Explosion in the number of known exoplanets
  – New discoveries in the asteroid belt related to volatiles
  – New insights into comet chemistry from missions
Disks to Planets

- Planets form in circumstellar disks
  - Disks are flared → higher surface T (UV irradiation)
- Volatiles present as gas and ice
  - Disk chemistry affected by surface UV, X-ray, mixing of materials, disk T and density structure
  - Inside an evaporation front (snow-line) present as gas
  - Comets sample a cold reservoir in the disk
- Snowline Debates & Observation
  - Snowlines change with time
  - Models locations differ (1 AU → Ast belt)
  - Herschel/Spitzer measurement in 1 disk
    - TW Hya – gas density sharp drop
    - Snowline at few AU

Hogerheijde, Bergin et al., Science 334 (2011)
IAU Symp 280, (2011)

- **Old View**
  - Long Period Comets (LPCs)
    - Form in giant planet region
  - Scattered out to Oort cloud
  - Perturbed inward
- **JFCs form in Kuiper belt**
  - Migrate in→Centaurs→JFCs

- **A changing View**
  - *Nice model* — dynamics post-Jup form
    - Water came after Earth formed
    - Easiest to bring water from ast belt
  - *Grand Tack* — formation of giant planets
    - Explains small size of Mars
    - Delivers outer SS icy objects to Belt & Earth

- **Implications**
  - Significant mixing in nebula
Water in the Asteroid Belt

• Aqueous Alteration in Asteroids
  – Chondrites – sampled from ~15 groups
  – Aqueous alteration everywhere during first few Myr
  – Occurred at low to high T (300-1200K) - hydrothermal
  – Parent body formation location not known (ast belt)

• Ceres Outgassing
  – Water detected IUE 1991 (A’Hearn)
  – Ground searches since then, no detections
  – Herschel 11/2011 – upper limits
Water in Asteroid Belt & Comets

- Long history of asteroid phyllo-observations (Vilas et al)
- Hydrated minerals on 24 Themis
- Hydrated minerals on Vesta

D/H in Hartley 2 $\rightarrow$ JF comets don’t form where we thought


Asteroid Belt Discoveries: MBCs

- **Characterization**
  - Objects dynamically asteroidal, formed in-situ
  - Exhibit comet-like tails
  - Most must be driven by H2O sublimation
  - Surface H2O not stable – requires “activation”

- **Water not observable from Earth**
  - H2O fluxes needed to lift dust 1-2 orders of mag lower than detection capabilities w/ Keck
  - Characterization → in-situ

![Graph showing relationship between Heliocentric Distance and Log H2O fluxes](https://example.com/graph.png)

Fig. from D. Jewitt, AJ 143, 66.
**EPOXI Mission**

- **Nov 4, 2010 Encounter**
  - 12.3 km/sec; 700 km flyby
  - 2m / pix best resolution
  - 3 instruments (vis & near IR)

- **Known prior to EPOXI**
  - Comets a mix of dust & volatiles
  - Comets are physically very diverse
  - Excellent insulators
  - Mixture of high and low-T SS material

**Spacecraft**

Ball – JPL mission
Still operational
EPOXI Discoveries


- Nucleus surrounded by swarm of large chunks
  - mm to 10’s cm slow moving (ice + dust)
- Dust, CO$_2$ and water-ice grains flow together
  - New discovery: CO$_2$ drives jets & activity
  - Water vapor is everywhere – but faint
  - Minimal surface ice – associated with rough morning terminator

New view of importance of CO$_2$ as a driver of activity in comets
Ground-Based Brightness Data

- **Surface sublimation Models**
  - Energy balance at surface of nucleus
    - Incident energy
    - Thermal
    - Sublimation
    - Conduction
  - Ices sublimate
    - Drags dust from surface
    - Increased scattering from dust
  - Compute observed total brightness

**Implications:** Can get information about CO2 abundance from the ground for a large number of comets
Measurements of CO$_2$ in Comets

- Earth Atm opaque at 4.26, 15.2 microns

- **Direct Observations**
  - Giotto in situ – mass spectrometer; EPOXI in situ near IR spectra
  - ISO spectra
  - Spitzer, WISE thermal bands
  - Akari Satellite (~20 comet measurements)

- **Indirect**
  - Forbidden CO emission during photo-dissociative excitation of CO$_2$
EPOXI has shown us that we can use ground-based observations to map out chemistry of comets . . . . looking back to the early solar system chemistry
Volatile Reservoirs Explored

- Explored Small Body Volatile Reservoirs
  - Oort Cloud & Kuiper belt
    - Ground-based observations → Comets
    - New Horizons → Pluto, TNO
  - Outer solar system Satellites
    - Cassini – Enceladus
  - Jupiter family comets
    - Deep Impact, EPOXI, StardustNExT, Rosetta
    - Herschel, Spitzer, Ground based observations
  - Middle – inner asteroid belt (meteorites)

- Unexplored Volatile Reservoirs
  - Outer belt → Main Belt Comets
New Capabilities

- **Pan STARRS & LSST**
  - Survey for new active objects

- **ALMA**
  - Disk resolved chemical observations
Meeting the Decadal Goals

- **SS Dynamics Model landscape is rapidly changing**
  - Models reproduce structure, mass distribution → not chemistry

- **Many communities are interested in water in the main belt**
  - Cosmochemists – aqueous alteration everywhere in primitive meteorites (don’t know dynamical origin)
  - Planetary observations: water in outer belt: Themis family, Ceres . . . .

- **The outer asteroid belt is wet . . . .**
  - We need in-situ observations to characterize it
  - DAWN is the first step – but Ceres is evolved

- **The next decade and how to move forward**
  - Need to explore the outer belt . . .
  - If we characterize the water isotopically & combine with dynamical models and new observations (ALMA) → testable hypotheses