Venus, Earth and Mars have somewhat similar orbits, and should have started with similar atmospheres, but have evolve differently. Considering their orbits, early atmospheres, and endogenic processes – Answer the following – addressing where is the water?

Why doesn't Venus have liquid Oceans?
A – Didn’t get water to begin with
B – No plate tectonics to remove CO$_2$, close to sun
C – Water chemically combined with different surface minerals on Venus
D – close to sun, ocean evaporate → runaway greenhouse, UV breaks up water

Why doesn’t Mars have liquid Oceans?
A – Didn’t get water to begin with
B – No plate tectonics to resupply CO$_2$, far from sun atm cools
C – Water chemically combined with different surface minerals on Mars
D – There are liquid oceans on Mars.

**Evolutionary Paths**

**Venus**
- Early sun less L
- Liquid H$_2$O?
- Plate tectonics?
- T incr → H$_2$O evap
- UV+H$_2$O → H$_2$+O
- H escapes
- O combines w/rock
- Volcanism → CO$_2$
- Runaway greenhouse

**Earth**
- Cooler initially
- Needed greenhouse to keep from freezing
- Plate tectonics
- CO$_2$ dissolves in rain
- CO$_2$ → carbonates
- Falls to ocean floor
- Subduction → melting
- Volcanism resupplies
- Life emerges

**Mars**
- Early sun less L
- Needed greenhouse
- 1 bar atm may have formed
- No plate tectonics
- Cooler core
- CO$_2$ dissolves in rain
- CO$_2$ → carbonates
- No CO$_2$ recycling

**Definitions**

- **Comet** – km-sized bodies with volatiles & refractories
- **Asteroid** – small planetary bodies orbiting the sun (mostly refractory)
- **Meteroid** – small (< km) extra-terrestrial body orbiting the sun
- **Meteor** – meteoroid passing through Earth atm
- **Meteorite/Fall** – meteoroid which hits the ground
- **Fireball** – very bright meteor
- **Find** – meteorite found on ground, not associated with a fall
- **Parent body** – comet or asteroid-like body in which the meteoroid formed
Comets Inspire Terror

- Sudden appearance in sky
- Only a few bright naked-eye comets / century
- Tail physically large → millions of km
- Early composition: toxic chemicals

Historical Highlights

- 1066 Halley: Wm conqueror
- 1456 Halley: Excommunicated
- 1531 Halley: Observed by Kepler
- 1744 De Cheseaux: 6 tails
- 1858 Donati: Most beautiful
- 1811 Flaugergeus: Comet wine
- 1861 Tebbutt: Naked eye, aurorae
- 1901 Great S: Daytime visibility

McNaught 2007

Recent Great Comets

- Ikeya-Seki, 1957
- Hayakutake, 1996

Historical Comet Halley

- Top:
  - Babylon 164 BC
  - 1145
  - Korea - 1222 at Chomsongdae Obsity
- Middle / Bottom:
  - Giotto Fresco 1301
  - Chinese 1378 (Halley - periodic)
  - 1531 - Peter Apian tail orientation
  - 1759 - Korean observations

Comet Halley’s Perception: Science & Fear

- 1680 Alarm
- 1910 Alarm
**Historical Understanding**

- Tycho Brahe 1577: Parallax – outside atmosphere
- Edmund Halley: 1531, 1607, 1681 → Orbit determination
- Newton – Principia
- 1950s – Models: F. L. Whipple → 'Dirty Snowball'
- R. A. Lyttleton → 'Sandbank'
- Resolution: 1986 Giotto Halley mission

**The Modern Comet**

- **Nucleus**: Solid body, few km radius
  - H₂O ice + dust + other volatiles: CO, CO₂ + organics
- **Coma**: Gas & dust
  - 10⁵ km
- **Tails**: Ion tail (blue: CO, CN)
  - Dust tail (yellow)

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**Phases of Water**

- **Nucleus**: Solid body, few km radius
  - H₂O ice + dust + other volatiles: CO, CO₂ + organics
- **Coma**: Gas & dust
  - 10⁵ km
- **Tails**: Ion tail (blue: CO, CN)
  - Dust tail (yellow)

**Physical Processes**

- **Sublimation of gases – Energy Balance**
  - Sunlight → Scattered light + Heating + Sublimation + Conduction
  - Usually very small
  - Energy needed depends on ice
  - Inverse square law: 1/r²
- **Draughts dust from nucleus**
  - Gravity low
  - Most dust escapes
  - Solar radiation pressure → coma → dust tail
  - Photodissociation → fluorescence
  - Ionization → gas tail

**Cold Storage: Oort Cloud & Kuiper Belt**
Comet Types and Source Regions

1 AU = 1.5 \times 10^8 \text{ km}

- Outer Oort Cloud: $15,000 - 10^5$ AU
- Stellar perturbations > $10^4$ AU
- Inner Oort Cloud: $2000 - 15,000$
- Galactic Tides
- Dynamically inert: $50 - 2000$ AU
- Kuiper Belt: $35 - 50$ AU
- Stable, dynamically active - chaos
- Classical, 3:2, scattered
- Dynamically new
  - $1/a_{orig} < 10^4$ AU
- Long Period: $P > 200$ yr
- Short Period: $P < 200$ yr
- Halley family - Oort cloud origin
- Jupiter family - KBO origin
- Centaurs transition objects

Comet Spectra

- Comet spectral components
  - Reflected sunlight from dust (blackbody radiation)
  - Emitted "heat" (blackbody)
  - Fluorescence (emission lines)

- Spectra shown: Kohoutek from space (above), comet Tuttle

Comet Tail Formation

- Dust Tail
  - Reflected sunlight (yellow)
  - Follows orbit
- Plasma Tail – ions
  - Caught by solar B field
  - Anti-solar
  - Fluorescing → blue (CO$^+$)

Plasma Tails

1P/Halley, 1910

Cometary Fates?

- Surface turns off (clogged)
- Rocky body with no ice
- Completely sublimates
- Breaks up
- Collision
Zodiacal Light

Physical Source
- Dust throughout solar system
- From comet outgassing
- Asteroid collisions

Visible from Earth
- In plane of solar system
- Looks like bright glow after sunset and twilight has ended

Sungrazing Comets

- Defined by q < 0.005 AU (50,000 km)
  - No special composition – hard to observe
  - Daytime obs:
    - atomic lines (Na, Ca, Cr, Co, Mn, Ni, Cu...)

- Breakup of a large comet
  - Parent – seen by Aristotle in 371 BC
  - Great comets 1843, 1882, Ikeya Seki

- Kreutz Group
  - ~85% of SOHO comets belong to Kreutz group
  - As of mid 2011 – the count was 2110

Sungrazers: Comet Lovejoy

12/15/2011 – interaction with the sun’s corona

Meteor Showers

- Earth passes thru dust along comet orbit
  - Burns in Earth atm
- Larger chunks result in meteorites from
  - Moon
  - Mars
  - Asteroids

Fireballs / Debris

Why we Study Comets

“Comets are the most pristine things in the Solar System”

“Comets tell us about the formation of the Solar System

Making NASA willing to spend $$ on missions
Space Exploration

Giotto Mission: Comet Halley
- L: July 2, 1985; E: March 14, 1986
- First in-situ comet exploration
- Science Results
  - Proved solid nucleus
  - Discovery: organic dust (CHON)
  - Gases: 80% H₂O, 10% CO₂

Deep Space 1: 19P/Borrelly
- Test 12 advanced space technologies
- Science Results
  - First hint of smooth plateaus
  - No direct evidence of water ice

Comet Nucleus Uncertainties
- Comet unknowns
  - Bulk density – only to within 10x
  - Strong disagreement of what lies beneath the surface
  - Unknown chemistry
- Primary Goal
  - Differences between interior and surface
  - Pristine Solar System material
- Secondary Goal
  - Cratering physics
  - Assess comet impact hazard
  - Calibrate crater record
  - Comet evolution

Deep Impact
- L: Jan. 12, 2005; E: Jul. 4, 2005
- 1st Active experiment
- Science Results
  - Comets are good insulators!
  - Little surface ice
  - New ideas about formation
  - Can study geology!

Mission Profile
- Launch January 12, 2005
- Encounter July 4, 2005

Approach & Encounter
- Geocentric Dist: 0.89 AU
- Heliocentric Dist: 1.49 AU (q)
- Approach phase: 63°
- Solar Elong: 104°
- 364 kg impactor
- 10.2 km/s

Simple but Challenging, 38 yrs ago

It [an asteroid] was racing past them at almost thirty miles a second. They had only a few frantic minutes in which to observe it closely. The automatic cameras took dozens of photographs, the navigation radar’s returning echoes were carefully recorded for future analysis - and there was just time for a single impact probe. The probe carried no instruments; none could survive a collision at such cosmic speeds. It was merely a small slug of metal, shot out from Discovery on a course which should intersect that of the asteroid.

...They were aiming at a hundred-foot-diameter target, from a distance of thousands of miles... Against the darkened portion of the asteroid there was a sudden, dazzling explosion of light. ...  

World Coordination

- Largest coord. Obs. program
- ~50 observatories, 130 obs
- 1997-2004: 229 nts, 14 tel
- 2005: 550 nts, 73 tel, 35 obsy
- Earth orbital satellites
- Real time communication

Deep Impact

- Comets are a mixture of dust (organics) & volatiles
- Primary volatile is H₂O – but mostly not on surface
- Comets are physically very diverse
- New ideas about formation
- Excellent insulators
- Comets are a mixture of high and low-T solar system materials.

Deep Impact

- Comets as icy primordial left-overs of planet formation – key for delivery of volatiles & organics.

Impact Site

- ITS (impactor) images – impact site indicated by arrows (ecliptic N: upper right quadrant, sun to right)
- Sense of rotation – top is approaching
- Oblique impact – 20-45° from horizontal

Re-Useable Missions

- DI → EPOXI
- Explore 85P/Boethin
- Stardust → Stardust-NExT
- Return to 9P/Tempel 1
The StardustNExT Mission

- **Encounter** 2/14/2011
  - Close approach 178 km (10.9 au)
- **Goals**
  - Look for changes since 2005 passage
  - Extend coverage of surface, image DI impact site
- **Science Experiments**
  - 72 images (+4 min of close approach; 11-12 m/pix)
  - Dust data from DFMI & CIDA

**Challenge – Arrival Time**

- Targeting specific longitude: 100's nights obs
- Analysis of TOA predicted by 2 techniques
- TCM 2/17/10 to delay arrival by 8.5 hrs
- Success! Arrived within 2-3° of desired longitude
EPOXI Mission

- Nov 4, 2010
- 12.3 km/sec
- 700 km flyby
- 2m / pix best res

- Radius ~ 0.58 km
- Density ~ 0.2-0.4 g/cm³
- Mass loss >> 1% per orbit (~1-10 m per orbit)
- Complex rotation – long axis circulation dP/dt ~1% per period

EPOXI – Close Approach

- HRI - High resolution Camera – Jets from dark side, “snow”, interesting surface features
Activity Drivers

- Dust, CO₂, and water-ice grains flow together
  - New discovery: CO₂ drives jets & activity
  - Implication: comet has not spent a lot of time in inner solar system
- Water vapor originates from “waist”
  - Water vapor is everywhere - just faint
  - This was the behavior seen by Tempel 1

What’s Next: ESA’s Rosetta Mission

Mission Timeline / Details
- Orbiter – 11 instruments
- Lander – 9 instruments

What can Rosetta Do?
- Watch a comet come to life
- Understand the process of outgassing
- Detailed chemistry
- Physical properties
- Peer inside the nucleus – how is it built?

Pluto & the Kuiper Belt

Pluto is not a planet . . . .

New Horizons
- Look at ancient relics - “big comets” in cold storage
  - Map the surface of Pluto and its moon Charon
  - Study its atmosphere
  - Search for rings
  - Search for new moons

Origin of Water – Another Place to Look?

Objects we have “sampled”
- Oort Cloud & Kuiper Belt Comets
- Small Icy Moons
- Asteroids (meteorites)
- Main Belt Comets – a New Reservoir

- Dynamically asteroidal
  - Physically cometary
  - Amount of dust is small
  - No gas detected

Summary

- Comets are left-overs of SS formation
- May preserve chemistry of early SS
- Comets may have delivered volatiles & pre-biotic molecules to early Earth
- May be important for extrasolar habitable worlds