Astrobiology 740
Follow the Ice
January 13, 2006

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Moon-Mars Initiative

- Implement sustained human / robotic exploration of the solar system and beyond;
- Extend human presence across the solar system,
  - Human return to the Moon by 2020,
  - Preparation for human exploration of Mars & beyond
  - Search for evidence of life
- Develop the necessary innovative technologies, knowledge, and infrastructures
  - Conduct advanced telescopic searches for Earth-like planets and habitable environments around other stars
- Promote international and commercial participation in exploration
We are Aqueous Beings....

- Water is the medium for life’s chemistry
- Our cells are mostly water
- Water is a liquid for large $\Delta T$
- Water ice floats
- Water affects Earth’s energy budget
- Water involved in geochemical reactions $\rightarrow$ atm chemical balance
- Water in Earth’s mantle affects internal melting behavior
Habitable Zones

Depends on

- Planet properties: albedo, atmospheric density & composition, rotation
- Age of star – luminosity increases with time
- Planetary orbit
- Internal heat sources

Distance from the central star where the equilibrium T allows for the existence of liquid water
Our Solar System

\[
\frac{F_{\odot}(1 - A)}{r^2} = \beta \sigma T^4
\]

<table>
<thead>
<tr>
<th>Planet</th>
<th>Albedo</th>
<th>Radius</th>
<th>Distance</th>
<th>Eccen</th>
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<td>(Ceres)</td>
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<td>39.529</td>
<td>0.248</td>
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</table>
Cosmic Solar System
History: Delivery of Water

>4.6 billion yr
ISM dark cloud

Planets grow

Protoplanetary disk

Cometary Delivery
Range of Temperatures

- Psychrophiles: Cold lovers (T~0-20°C)
  - Survive freeze/thaw, Reproduce 2°C
- Habitats on Earth
  - Soils, Deep ocean water, Sea ice
### Ice / Water Inventory on Earth

- **Arctic** – 4 km deep ocean, covered by ice
- **Antarctic** – up to 4 km deep ice surrounded by oceans

<table>
<thead>
<tr>
<th>Snow &amp; Ice in N Hem</th>
<th>Area (10^6 km^2)</th>
<th>Vol (10^6 km^2)</th>
<th>Sea Equiv. (m)</th>
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</thead>
<tbody>
<tr>
<td>Greenland</td>
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<td>Other</td>
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<td>Antarctica</td>
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<td>Sea Ice (S)</td>
<td>4.2</td>
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Material from T. Thorsteinsson
Ice on Earth

- Extent of Eurasian ice sheet during glacial max 20,000 yr

Pleistocene
- Last 2-3 Myr
- 20 interglacial periods
- Each last 100-150 x $10^5$ yr

Vatnajokull Ice cap, Iceland

Material from T. Thorsteinsson
Antarctica

- **Physical characteristics**
  - $5.4 \times 10^6$ sq mi
  - 7000 ft elevation
  - 75% all fresh water
  - $T_{avg} = -70^\circ F$ (low $-128.6^\circ F$)
  - Winds up to 300 km/hr

- **Historical**
  - Coal beds $\rightarrow$ Pangea 2 Myr

- **Dry Valleys**
  - 1901 Expedition
  - Penetration 1978
  - $H_2O$ just above freezing $\rightarrow$ greenhouse effect
  - Enriched from spring runoff
Isolated Environments

- **Lake Hoare – Taylor Valley**
  - Environment much like Mars
  - Permanent ice cover
  - Life Forms
    - Microbial mats
    - Increased oxygen levels; 1% sunlight
    - Algae draw Fe, S and calcite from water

- **Lake Vostok**
  - Most isolated aquatic environment on Earth
  - Largest of 70 subglacial lakes
  - Cut off 35-40 Myr ago
  - 1500 km from coast,
  - 3500m elevation
  - $T_{\text{air}} = -89^\circ\text{F}$, $T_{\text{lake}} = -3^\circ\text{C}$
Lake Vostok

- 1998 Russian Core $\rightarrow$ 3.623 km
  - Living organisms from 1500-2750 m (2-5 x 10^5 yr old)
  - Low population diversity
  - Utilized dissolved organic C and O migrating through ice
  - 4 climate changes 20,000 to 100,000 yr periods ([CO$_2$])
Water on the Moon

- Lunar Prospector: Neutron spectrometer
- 10-300 million tons water ice in shadowed polar regions
Mars Scenarios

Current conditions
- 95% CO₂, 3% N₂
- P 0.006 bar, T_{avg} ≈ 233K
- Lack of O₃

Presently, liquid H₂O isn’t stable on Mars surf

Amount of H₂O
- Atm – 1-2 km³ (10μm layer)
- Polar caps 4x10⁶ km³ (30 m layer)

Mars Viking Results
- No organics to 1 ppb
- Mars is a cold polar desert

Life Oases?
- Hydrothermal systems
- Subsurface reservoirs
- Life in Ice
Where’s the Water on Mars?

- Mars Global Surveyor
  - Polar ice inventory, gullies
  - Mola Altimetry (N ocean?)
  - Hematite ($\text{Fe}_2\text{O}_3$)
- Mars Odyssey
  - $\gamma$-ray spectrometer: subsurface $\text{H}_2\text{O}$
- Mars Exploration Rovers
  - Launch Jun-Jul ’03,
  - Arrive Jan 04
Mars Gullies & Earth Analogs

- Seepage landforms not cratered $\rightarrow$ geologically young
- Resemble terrestrial gullies (landslide promoted by ground water flow)
Hematite $\text{Fe}_2\text{O}_3$

- **Product of aqueous mineralization**
  - Hot water moves through Fe-rich rocks $\rightarrow$ dissolve Fe
  - Water cools, Fe-minerals precipitate
- **Often associated with hydrothermal vents on Earth**
- **Implies sedimentary rocks**
- **Implies long-term H$_2$O stability**
- **Image (MGS)**
  - Meridani Planum
  - 1500x1200 km
Opportunity – Bodies of Water

- Habitability at 2 sites: geological, climate, aqueous alteration records
- Drilled rocks \(\rightarrow\) sulfates
  - Long term standing water
- “Blueberries” – Hematite rich
- Wave flow patterns
Mars Mountain Glaciers?

Western Olympus Mons, Mars

Alaskan Glacier, Earth
Europa

- **Physical Characteristics**
  - Diameter 3,138 km
  - $T_{\text{surf}} = 128$K
  - $\rho = 3 \text{ gm cm}^{-3}$, $g = -0.135 \, g_{\text{earth}}$

- **Tidal heating**
  - $F = GMm/r^2$
  - Differential tide raising force
    - $dF$ proportional to $r^{-3} \, dr$

- **Susurface Ocean**
  - Magnetic induction $\rightarrow$ liquid
  - ~100 km deep
  - Beneath > 20 km thick icy shell

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*Inside Europa*
- Icy surface
- Subsurface may be a liquid ocean or a warm, convective layer of ice.
- Rocky interior

*Source: NASA*
Evidence for Ocean

- Melt through thin shell
- Diapirism – ice convection partly melts surface ice
- Icy spreading center analog
- Warm buoyant ice from below

- Diapirism – ice convection partly melts surface ice
- Domes ~10 km in diameter
Plausible sources of free energy and biogenic elements exist
- Sub-surface ocean
- Tidal stretching – heating
- Organics (spectra)

Geological processes permit surface-ocean communication
Cassini-Huygens Titan Mission
- N₂ – CH₄ atmosphere
- UV from sun produces other organics (ethane, acetylene…)
- Organics must precipitate → need to resupply CH₄
- CH₄-ethane rain and lakes?

Material from R. Pappalardo
- Dark Surface
- Mixture of water-ice and hydrocarbon-ice
- Possible evidence of fluvial erosion at base of “rocks”
Ices & Liquids on Titan?

- Drainage channels from 20 km elevation
- Hydrocarbon Lake at S Pole
Ice Physics

Temperature Scales

- Kelvin – absolute scale – atomic motion
- \( C = \frac{5}{9} (F - 32) \)
- \( K = C + 273 \)

<table>
<thead>
<tr>
<th>Scale</th>
<th>H(_2)O Freeze</th>
<th>H(_2)O Boil</th>
<th>( \Delta T )</th>
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</thead>
<tbody>
<tr>
<td>Fahrenheit</td>
<td>32</td>
<td>212</td>
<td>180</td>
</tr>
<tr>
<td>Centigrade</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Kelvin</td>
<td>273</td>
<td>373</td>
<td>100</td>
</tr>
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Water – Features Relevant to Ice

- Bent molecule (104.52°) – H Bond
  - Dipole moment
  - Tetrahedral Crystal structure
  - Expands upon freezing (less dense)
- Negative slope on melting curve
  - Le Chatlier Principle
- Triple Point [S.M.O.W.]
  - P = 611.657 Pa (0.006 bar)
  - T = 273.16 K (0.16°C)
  - D₂O: 661 Pa, 276.82K

1 bar = 10^5 Pa = 10^5 N/m^2
1 atm = 101325 Pa
Water Ice Physics

- Exists in 13 crystalline phases (diff T & P)
  - Phase I: P < 2700 atm
    - Ih – hexagonal
    - Ic – cubic (low T, low P; metastable)
  - High P forms: II to XI
- Amorphous Ice
- Clathrates
Amorphous Ice

- Forms at low T → insufficient E for crystal structure
- Physical Properties
  - Large voids:  trapped gases
  - Gases released between 35-120K
    - Annealing
  - 38-68K – transition from $l_ah \rightarrow l_al$
  - Beginning at 90K → $l_c$ (exothermic)
- Two forms
  - High Density, $l_ah$
  - Low Density, $l_al$
Clathrate Hydrates

- Crystalline framework of H-bonded H$_2$O molecules trapping guest molecules
- Guests don’t affect the chemistry
  - Released upon sublimation of water
  - Cages unstable without guests
  - Some physical properties are altered
  - Some clathrate formation not possible at low T and P
  - Stability: low T (< 273K), moderate to high P (100 atm)

- Importance
  - May store most SS inventory: CO, CO$_2$, CH$_4$
  - Catastrophic destabilization due to T$\uparrow$, P$\downarrow$
    - Collapse & flow features
    - Outgassing
    - Greenhouse gas budgets
Clathrate Hydrates

- **Type I**
  - 46 \(\text{H}_2\text{O}\) molecules
  - 2 small cages, 6 large
  - 12- and 14- sided polygons
  - Traps in ratio 1/7
- **Type II**
  - 126 \(\text{H}_2\text{O}\) molecules
  - 16 small cages, 8 large
  - 14- and 16- sided polygons
  - Traps in ratio 1/17

Clathrates in the Solar System

- \(\text{CH}_4\) – marine sediments – by 2x exceeds other fossil fuel sources
- \(\text{CO}_2\) – sequester \(\text{CO}_2\) in ocean seafloor from atm (climate)
- Destabilization on Mars & Europa – chaotic terrain?
- \(\text{CH}_4 / \text{N}_2\) on Triton – geysers
- Air – polar ice sheets – info on atmosphere up to \(10^6\) yr ago
**Ice Regimes – Interior Pressures**

- \( P_c = 2\pi G \rho^2 (R^2 - r^2)/3 \)
- \( G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \)
- \( \rho = \text{density, kg/m}^3 \)
- \( R = \text{radius, m} \)

<table>
<thead>
<tr>
<th>Regime</th>
<th>( \rho ) ( [\text{g/cm}^3] )</th>
<th>Size ( [\text{km}] )</th>
<th>( P ) ( [\text{bar}] )</th>
<th>Dust:Ice</th>
<th>Ices</th>
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<td>ISgrains</td>
<td>0.1</td>
<td>10^{-10}</td>
<td>—</td>
<td>2:1?</td>
<td>High den. amorph</td>
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<td>0.5-1?</td>
<td>1-10</td>
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<td>( 10^2-10^3 )</td>
<td>3.5-1400</td>
<td>2:1?</td>
<td>lh, II, clath, amorph</td>
</tr>
<tr>
<td>Europa</td>
<td>2.97</td>
<td>1569</td>
<td>( 3 \times 10^4 )</td>
<td></td>
<td>lh, II, VII, VIII, clath</td>
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<tr>
<td>Triton</td>
<td>2.07</td>
<td>1350</td>
<td>( 1 \times 10^4 )</td>
<td></td>
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<td>Mars Ice</td>
<td>1-1.6</td>
<td>3</td>
<td>300</td>
<td>&lt;100 ppm</td>
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<tr>
<td>Glacier</td>
<td>0.92</td>
<td>3</td>
<td>300</td>
<td>ppm</td>
<td>lh, clathrates</td>
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</table>

- Phase changes: volume changes \( \rightarrow \) fractures
- Amorphous \( \rightarrow \) lc, exothermic \( \rightarrow \) volatile release
- Clathrate destabilization \( \rightarrow \) outgassing
Comet Expectations

- **Amorphous ice**
  - Formation T: 30-100K

- **Crystalline ices**
  - Solar heating: amorphous $\rightarrow$ crystalline transition peaking at 137K
  - Balance with cosmic ray processing

- **Lack of Clathrates**
  - Small size, low central pressures
  - Release of volatiles in excess of clathrate capacity
  - Not necessary to explain activity!
Comet Formation

- Ices in comets condensed $T < 100$K
  - Amorphous form traps other gases
  - Amounts depend on $r$
- Release of gases
  - 120-137K amorphous $\rightarrow$ crystalline phase
  - Annealing (30-120K)
  - $l_c \rightarrow l_h$ $\sim$ 150 K
  - Sublimation starts 160-180K
Sublimation of Volatiles?

- Delsemme’s original work: albedo too high
- Water: $F_\odot(1 - A) \frac{1}{r^2} = \beta \left[ \epsilon \sigma T^4 + L(T) \frac{d m_s}{d t} + \kappa(z, T) \frac{\partial T}{\partial Z} \right]$
Activity in Comets at Large $r$

- **All Comets active $r \downarrow$**
  - C/1999 J2 $r=7.11\text{AU}, r=7.81\text{AU}$
  - C/2001 G1 $r=8.32\text{AU}, r=10.26\text{AU}$
  - C/2003 A2 $r=11.5\text{AU}, r=11.43\text{AU}$

- **All are dynamically new**
  - C/1999 J2 $1/a_{\text{orig}} = 20$
  - C/2001 G1 $1/a_{\text{orig}} = 35$
  - C/2003 A2 $1/a_{\text{orig}} = 45$

Material from Meech et al, in prep.
Mechanisms of Activity

Material from Meech et al, in prep.
Complications: Heat Transport in Real Nuclei

- Solve the heat conduction equation
  \[
  \rho(z) c(z,T) \frac{dT}{dt} = \frac{d}{dz} [\kappa(z,T) \frac{dT}{dz}]
  \]
  - Boundary condition: Energy Balance Equation
  - Heat sources:
    - Solar radiation – cyclic
    - Radioactivity – declining
    - Crystallization – transient, front induced

- Approximations
  - Ice Thermal properties very different
    - \( \kappa_a < \kappa_c \) (4 orders of magnitude) \( (a=amorphous, c=crystalline) \)
    - \( \kappa_a \propto T \) and \( \kappa_c \propto \frac{1}{T} \)
    - \( \kappa = \) rate of heat transfer through medium [W m\(^{-2}\) K\(^{-1}\)]
Heat Conduction in Porous Media

- Pores reduce thermal conductivity
  - Conduction by radiation
  - Conduction by vapor sublimation → recondensation
  - Releases heat, warming colder areas
  - Reduces the thermal gradient
  - Sintering → decreases porosity

Porosity: 7.5% 13% 15% 22%

![Graph showing log correction factor vs. porosity]


**Interior Pressures**

- Interior structure $\rightarrow$ affects surface features
- Modeling the structure of a body
  - Hydrostatic equilibrium $\frac{dP}{dr} = -GM(r)\rho(r)r^{-2}$
  - Mass continuity $\frac{dM}{dr} = 4\pi r^2 \rho(r)$
  - Equation of state of material (relation between \( P, T \) and \( \rho \) for a material). Approx:
    - $P = K_0 B^{-1}[(\rho/\rho_o)^B - 1]$
    - $K_0 = 2-3 \times 10^{11} \text{ Nm}^{-2}$
    - $B = \frac{dK}{dP} \sim 2.2-4$;
    - $K$ = bulk modulus
- Heat conduction equation
Terrestrial Ice Masses

- **Types of Ice**
  - Polar Ice: $T < T_{fr}$ throughout
  - Temperate: at or below $T_{fr}$ except top 15 m
  - Polythermal: part polar, part temperate

- Temperate: winter cold wave eliminated by latent heat of re-freezing
- Polar:
  - $T$ below 15m = $T_{\text{mean}}$
  - Ice warms near bedrock from geothermal heating

Material from T. Thorsteinsson
Densification of Ice

- Physical Processes
  - Rounding & settling of crystals,
  - Increase in crystal size
  - Formation of bonds between crystals
  - Decrease of air space

- Densities [kg/m^3]
  - Snow  50-400
  - Firn  400-830
  - Glacier  830-920

- Rate of transformation
  - 0°C   15-35m \(\rightarrow\) 10-20 yr
  - -30°C  70m, 200 yr
  - -55°C  110m, 2000 yr

No air bubbles due to pressure of overlying ice
Volume expansion due to warming at bedrock

Material from T. Thorsteinsson
Ice Changes

- Air bubble size decrease, Antarctica
- Fresh snow crystal
- Single ice crystals from glacier ice (Mendelhall glacier, AK)

Material from T. Thorsteinsson
Grain Growth, Clathrates

- Pressure differences across crystal boundaries result in large grains growing, small ones shrinking.
- Growth rate very T dependent prop to $e^{-Q/RT}$
- Ice clathrates can form at high P (depth)

500 year old ice at 130 m depth.
Average diam: 2 mm

100,000 year old ice at 2850 m depth.
Average diam: > 2 cm

Material from T. Thorsteinsson
Ice Regimes – Interior Pressures

- $P_c = 2\pi G \rho^2 (R^2 - r^2)/3$
- $G = 6.67 \times 10^{-11}$ Ntm$^2$/kg$^2$
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- $\pi$

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<th>Size [km]</th>
<th>P [bar]</th>
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<td>IS grays</td>
<td>0.1</td>
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