Geophysical observations of ice and climate on Mars

A Short Course Talk for Planetary Geodesy KISS Workshop

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In this talk:

• Primer on Mars climate history

• Gravity, topography, and radar observations of the polar deposits

• Radar observations and the debate on mid-latitude ice

• Prospects for future:
  • static gravity fields to search for ice and elucidate climate history
  • time-variable topography and gravity fields to detect active climate processes
1. Mars Climate History
Present-Day Mars Climate 101

- Mars is a cold, dusty desert
- Temperatures: -225°F to 70°F
- Atmosphere ≤ 1% of Earth’s (mostly CO₂)
- Liquid water not stable, but lots of ice!
- Ice is stable at the surface only at the poles
- Dynamic world, with dust storms, water and CO₂ clouds and snow and frost

Day = 24.6 hours
Year = 687 days

50% further away from the Sun
½ the diameter of Earth

NASA/JPL/UA/HIRISE

ESA / DLR / FU Berlin (G. Neukum) / Emily Lakdawalla
Mars has 3 main periods of geologic history.

- **Present**
  - Polar layered deposits form
  - Tharsis volcanoes still active
  - Elysium volcano still active
  - Olympus Mons volcanism

- **~ 3 Ga**
  - Tharsis volcanoes still active
  - Vastitas Borealis fill lowlands
  - Outflow channels in Xanthe
  - Volcanism at Elysium
  - Volcanism in highlands

- **~ 3.7 Ga**
  - Rifting in Valles Marineris and Noctis Labyrinthis
  - Valley networks active
  - Tharsis volcanism begins

- **~ 4 Ga**
  - Isidis basin
  - Argyre basin
  - Hellas basin
  - Utopia basin
  - Other basins
  - Northern Lowlands formed
  - Other basins?

- **~ 4.5 Ga**
  - Mars formed

*Figure Credit: Emily Lakdawalla after Tanaka & Hartmann 2012*
The Amazonian:

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>~4.5 Ga</td>
<td>Mars formed</td>
</tr>
</tbody>
</table>
| ~4 Ga | Pre-Noachian:
| | Northern Lowlands formed
| | Other basins? |
| ~3.7 Ga | Noachian:
| | Isidis basin
| | Argyre basin
| | Hellas basin
| | Utopia basin
| | Other basins |
| ~3 Ga | Hesperian:
| | Rifting in Valles Marineris and Noctis Labyrinths
| | Valley networks active
| | Tharsis volcanism begins |
| Present | Amazonian:
| | Polar layered deposits form
| | Tharsis volcanoes still active
| | Elysium volcano still active
| | Olympus Mons volcanism

Figure Credit: Emily Lakdawalla after Tanaka & Hartmann 2012
Orbital Variations Analogous to Milanković Cycles Drive Mars’ Amazonian Climate

Laskar et al. 2004 calculated solutions for ~20 Myr of Mars’ history

Beyond that solutions are chaotic, but statistically suggest:
• Max obliquity may be as high as 82°
• ~100% chance obliquity >60° in Mars’ history

Laskar et al. 2004
Obliquity is extremely important for the distribution of ice/volatiles.
Obliquity variations have primary periodicity of 120 kyr.

Obliquity:
• 120,000 years

Argument of perihelion:
• 51,000 years

Eccentricity:
• 95,000 – 99,000 years
• and 2.4 Myr

Laskar et al. 2004

Schorghofer 2008
Obliquity variations have primary periodicity of 120 kyr.

Note the amplitude of Mars’ obliquity variations compared to Earth!

Thanks, Moon.
Ice Stability Mainly Controlled by Obliquity

Low obliquity

Today’s obliquity

~25°

High obliquity

e.g. Laskar et al. 2002; Head et al. 2003
Ice Stability Mainly Controlled by Obliquity

Mars is an excellent laboratory for how orbital forcing affects planetary climates!

- Amplified forcing
- No oceans, humans, etc.

Modified from Head et al. 2003
Ice Stability Mainly Controlled by Obliquity

Mars is an excellent laboratory for how orbital forcing affects planetary climates!

Need to know where the ice is and characterize its properties.

Modified from Head et al. 2003
2. Gravity, topography, and radar observations of the polar deposits
Key instruments for Mars’ gravity, topography, and radar observations:

Radio tracking by the Deep Space Network of

- Mars Global Surveyor (MGS)  
  Smith et al. 1999
- Mars Odyssey (ODY)  
  Konopliv et al. 2006; Marty et al. 2009
- Mars Reconnaissance Orbiter (MRO)  
  Zuber et al. 2007

Goddard Mars Model-3 (GMM-3)

- static gravity field of Mars in spherical harmonics to degree and order 120  
  Genova et al. 2016

GMM-3 free-air gravity anomaly map  
Genova et al. 2016
Key instruments for Mars’ gravity, **topography**, and radar observations:

**Mars Orbiter Laser Altimeter (MOLA)**

*Smith et al. 2001*

- Onboard Mars Global Surveyor
- Collected over 600 million altimetry measurements
  - Precision of range measurements: 10s of cm (smooth, level surfaces) to meters (sloped surfaces)

Elevation map horizontal resolution: 463 m/pixel or better

*Smith et al. 2001*
Key instruments for Mars’ gravity, topography, and radar observations:

<table>
<thead>
<tr>
<th></th>
<th>SHARAD</th>
<th>MARSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft Onboard</td>
<td>Mars Reconnaissance Orbiter</td>
<td>Mars Express</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>20 MHz</td>
<td>1.8, 3.0, 4.0 and 5.0 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Vertical resolution, in free space</td>
<td>15 m moderate penetration depth</td>
<td>150 m deep penetration depth</td>
</tr>
<tr>
<td>Horizontal resolution (along track)</td>
<td>0.3–1 km</td>
<td>5–10 km</td>
</tr>
<tr>
<td>Horizontal resolution (cross track)</td>
<td>3–6 km</td>
<td>10–30 km</td>
</tr>
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</table>

Seu et al. 2007

Picardi et al. 2005

Example SHARAD radargram over North Polar cap
Mars’ poles have kilometers-thick ice caps.

- Each roughly dome-shaped, ~1000 km across, 3–4 km topographic relief compared to surroundings (from MOLA data)
- Total volume of ice similar to Greenland on Earth
- Are a record of processes on multiple spatial and temporal scales

Image Credit: NASA/GSFC Scientific Visualization Studio
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Image Credit: NASA/GSFC Scientific Visualization Studio
Mars’ poles have kilometers-thick ice caps. Are a record of processes on multiple spatial and temporal scales.

- Seasonal ice cap
- Residual ice cap
- Polar layered deposits
- Basal unit
- Underlying/Surrounding Terrain

Youngest to Oldest:

- 

Diagram credits: Milkovitch and Head 2006
Seasonal ice caps:
Up to $\frac{1}{3}$ of the atmosphere condenses out in winter.

- Seasonally deposited dusty, porous CO$_2$ ice
  - In the North, also an annulus of water frost
- Sinters into transparent solid CO$_2$ slab
- In Spring (particularly in the South):
  - Bottom of slab heats up
  - Sublimates $\rightarrow$ Pressurized CO$_2$ jets
  - Fans of dust
  - Radial channels called araneiforms ("spiders")

*e.g. Kieffer et al. 2006*
Seasonal changes in gravity combined with MOLA elevation changes constrain bulk density of seasonal CO$_2$ to $910 \pm 230$ kg/m$^3$.

Gravity detects seasonal changes

MOLA topography detects seasonal changes

Genova et al. 2016

Smith et al. 2001
Northern residual ice cap: meters-thick water ice

• Water ice of large ice grains
  • Indicate old ice is being exposed in summer, undergoing net loss
    Langevin et al. 2005

• ...But other areas retain seasonal frost and are accumulating

• Temporally and spatially variable
  e.g. Calvin & Titus 2008

• Very young surface age (kyr)
  e.g. Landis et al. 2016, Wilcoski & Hayne 2021
Southern residual ice cap: meters-thick CO$_2$ ice slab

- Layers indicate deposited in discrete events
- Pits and surface texture show active erosion
- ...But annual mass balance unknown (evidence of both accumulation and ablation)
  - Cycling of the cap proposed to occur in 10s–100s years (e.g. Thomas et al. 2016)

Layering in the residual cap

“Swiss cheese” ablation pits

Byrne 2009
Polar Layered Deposits (PLD): kilometers-thick deposit of water/dust layers

- PLD are made up of 1000s of layers, exposed at trough/scarp faces
  - Layer thicknesses: decimeter (North) to meters (South)
- Laterally continuous – indicates homogenous formation processes, but under variable ice/dust conditions
- North expected to be ~4–5 Myr old (Levrard et al. 2007)
- South older, 10s Myr (Herkenhoff & Plaut 2000, Koutnik et al. 2002)
Radar indicates bulk of PLD is nearly pure water ice.

- Contrasts in layers/layer packets cause radar reflections
- Lack of attenuation of radar signal with depth indicates nearly pure water ice
  - North: <5% dust  \((\text{Grima et al. 2009; Picardi et al. 2005})\)
  - South: <10% dust  \((\text{Plaut et al. 2007})\)
Radar data also show flat basal topography under North and South polar caps.

- No downward flexure observed (radar constrains <100 m deflection)
- Indicates thick elastic lithosphere (>300 km) (Phillips et al. 2008)

*SHARAD Radargram at North Pole

*Basal Topography at South Pole

Phillips et al. 2008

Zuber et al. 2007
Gravity, topography, and radar used in concert to constrain the density of PLD.

- Assuming surface topography from MOLA and basal topography from radar:
  - model gravity anomalies for different PLD densities
  - Find best fit to observations

SPLD Density = free parameter

CRUST (2900 kg/m³)

MANTLE (3500 kg/m³)

Lithosphere thickness ~300 km (or free parameter)

*Diagram not to scale

Zuber et al. 2007
Gravity, topography, and radar used in concert to constrain the density of PLD.

- SPLD density estimates:
  - Wieczorek 2008: $1271 \text{ kg/m}^3$
  - Zuber et al. 2007: $1220 \text{ kg/m}^3$

- NPLD density estimates:
  - Ojha et al. 2019: $1126 \text{ kg/m}^3$

- Density indicates mostly water ice (not denser CO$_2$ ice), and <15% dust

Zuber et al. 2007
Gravity, topography, and radar used in concert to constrain the composition of PLD.

- Radar and gravity are the two tools for understanding the subsurface
- Each individually provides constraints on composition
  - Dielectric properties (radar)
  - Density (gravity)
- Translation to compositions non-unique for each technique, so powerful to consider both together

Broquet et al. 2020
The Basal Unit under NPLD is composed of two units: cavi and rupes.

Provides a record of older climates

- Cavi: sandy, aeolian cross-strata weakly cemented by water ice, and interbedded with purer ice layers (middle Amazonian)
- Rupes Tenuis - lithic-rich (early Amazonian)

Bulk BU density from gravity: 2007 kg/m$^3$
  - 55 ± 25% water ice

Ojha et al. 2019
3. Radar observations and the debate on mid-latitude ice
Evidence for massive water ice in the mid-latitudes:

Phoenix excavation

Icy impact craters

Expanded craters

Scalloped Terrain

Viscous Flow Morphologies

Debris Covered Glaciers

Terraced Craters

Icy Scarps

Mellon et al. 2009

Cull et al. 2010

Byrne et al. 2009

Dundas et al. 2014

Viola et al. 2015

Dundas et al. 2015

Bramson et al. 2015

Dundas et al. 2018

Dundas et al. 2018; Dundas et al. 2021
Mid-latitude ice also records climate processes on multiple spatial and temporal scales.

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<th>Age</th>
<th>Volume Estimate</th>
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<tr>
<td>Latitude Dependent Mantle</td>
<td>kyr to Myr</td>
<td>$10^5$ km$^3$ (1 m GEL)</td>
<td>Meters</td>
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<td>Plains Ice</td>
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Regional plains ice is most relevant to geodesy, important for human exploration, and also where the most debate exists.

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Widespread radar reflections have been attributed to ice sheets across the Northern plains.

- **Utopia Planitia**
  - Stuurman et al. 2016
  - $\sim 10^4$ km$^3$
  - $\sim 80$–$170$ m thick
  - $\varepsilon_r = 2.8 \pm 0.8$

- **Arcadia Planitia**
  - Bramson et al. 2015
  - $\sim 10^4$ km$^3$
  - $\sim 25$–$80$ m thick
  - $\varepsilon_r = 2.5 \pm 0.28$

Bramson et al. 2017
But... the radar signal is being attenuated more than expected for pure ice...

- Requires higher lithic content in the subsurface
- So debate exists regarding the presence of thick, massive ice deposits at these locations

Campbell and Morgan 2018
Ultimately, we lack instruments that can resolve the debate on decameters thick mid-latitude ice.

How laterally and vertically extensive is the shallow plains ice?

***Hugely important for human exploration and formation mechanism of the ice!***
4. Prospects for future static gravity fields to search for ice and elucidate climate history
Constrain mid-latitude ice locations and purities

- Elucidate orbital forcing processes that deposit non-polar ice
- Provide critical inputs for planning for human exploration at Mars
- Current gravity field precision is weakest in northern mid-latitude plains.
Constrain lateral density variations in the polar layered deposits, including massive CO$_2$.

• Elucidate past climates that form the polar caps
  • Temporal and spatial variability in past deposition of H$_2$O, CO$_2$, and dust
• Elucidate hemispheric asymmetries in Mars’ dust and volatile cycles

CO$_2$ deposits are bounded by water ice layers
  e.g. Bierson et al. 2016; Alwarda & Smith 2021

Massive CO2 sequestered in SPLD – enough to double atmospheric pressure!
Phillips et al. 2011

No evidence for CO$_2$ in North PLD – only in South PLD
Determine the densities of the stratigraphically distinct Cavi and Rupes units in the North

- Elucidate climate conditions before the polar ice caps were emplaced
- Currently unresolvable

Ojha et al. 2019
5. Prospects for future time-variable topography and gravity fields to detect active climate processes
Determine if the mass balance of the residual cap is negative or positive.

- Current estimates from image data are consistent with annual mass balance of $-6$ to $+4$ km$^3$/Mars year (Thomas et al. 2016)
  - Is the cap net accumulating or ablating??
  - Informs how an individual layer of the PLD forms (residual cap is essentially the top-most recent layer of PLD)

- How do these exchanges contribute to secular formation and evolution of the polar cap?
  - Higher resolution time-variable gravity and topography could address
Map heterogeneities in depositional processes

- Significant variability observed seasonally and interannually in timing and placement of deposition/ablation
- Higher resolution time-variable gravity and topography could constrain:
  - Composition (dust content, porosity) of deposits as they form and evolve
  - Spatial variability in surface density, which would shed light into local and regional scale mass balance dynamics

Smith et al. 2001
Conclusions: Geodesy provides an important tool for understanding Mars’ climate and volatile cycles.

- New, higher resolution datasets would elucidate:
  - Properties of buried volatile reservoirs (including targets for human exploration)
  - Lateral and temporal variability in current mass balance across Mars
  - Keys to unlocking the climate record stored in Martian ice deposits

Distribution of seasonal CO$_2$ frost based on infrared data

Animation Credit: NASA/JPL-Caltech
https://photojournal.jpl.nasa.gov/catalog/PIA22546