Mars’ climate and exploration

- Present Mars
- Ancient Mars
- Climate variation
- Mars exploration

NASA MAVEN's Imaging of Mars with UltraViolet Spectrograph

Mariner Mars images taken in 1960's
Dust in the atmosphere

- Micrometer-sized small mineral particles float in the atmosphere with a background optical thickness of 0.1-0.5.
- The dust loading changes with time and space.
- The dust serves as a heat source in the atmosphere by absorbing sunlight.

Dust a a heat source

- Absorption of solar radiation
  - much stronger than the greenhouse effect of CO₂, which is only several kelvins
  - much stronger than cloud albedo effect and latent heat

40 K difference between thick-dust year and thin-dust year

Smith et al. (2002)
Radiative-convective model
Gierasch & Goody (1972)

Without dust

With dust

Fig. 1. Martian temperature calculations. The stippled area represents temperatures reported by Kilcoyne et al. (1972) and Hinson et al. (1982). The lines are theoretical profiles for a pure CO$_2$ atmosphere, at 1000 and at 9000 hours (the coldest time). Both theory and observation refer to mid-latitude summer conditions. The tags indicate the ground temperatures. In the case of the 1600 theoretical profile a strong boundary layer is indicated.

Convective boundary layer

• Depth of 3-10 km
• Variable in time and space
• Deep (8–10 km) where the surface elevation is high, and shallow (4–6 km) where the surface elevation is low

Radio occultation

Hinson et al., Icarus 198 (2008) 57–66
Season of Mars

- Hemispherically asymmetric due to large eccentricity of the orbit
- Sun-Mars distance becomes minimum in southern summer

Seasonal variation of northern polar cap

Viking 1  22N, 48W (1976 ~ 1980)
Viking 2  48N, 225W (1976 ~ 1982)

Surface pressure

Fig. 1. (Bottom) Sol-averaged surface pressures recorded at Viking Lander 1 and 2. (Top) The standard deviation of surface pressure about the 50 mean at VL1. Both for 3.3 Mars years. Note the signatures (S) of the two 1977 and the 1982 great dust storms and the presence of several transient events (T) (figure from Titman 1998). See also Color Plate 16.
Meridional distribution of temperature

General tendency is similar to Earth’s stratosphere

Latitudinal-seasonal variation of insolation
Radiative relaxation time

- When temperature perturbations affect the structure of the atmosphere, the atmosphere will decay back to the radiative equilibrium state over a certain timescale, the radiative relaxation time.
- Radiative relaxation time is different among the planets:
  - Earth: 100 Earth days
  - Mars: 3 Earth days
  - Venus: 50 Earth years

- The timescale of Martian atmospheric circulation is ~100 days, which is much longer than the radiative relaxation timescale.
  - Large temperature variation
  - (The opposite is true for Venus)

Dust storms

Seasonal variation of optical thickness in infrared
(Smith et al. 2004)
Dust devils

• Source of background atmospheric dust?

Global dust storm

• Global dust storms tend to occur in southern spring-summer
• Positive feedback between dust heating and the intensification of winds is expected in the development of global dust storms.
Episodic occurrence of major dust storms → irregular nature of Martian meteorology

Fig. 7. Timeline of the detection of regional and planet-encircling obscurations, clouds and storms. These events are listed in Table III. Earth dates are indicated at the top, and perihelion (and thus Mars years) at the bottom of the dust-storm timeline. The second timeline indicates periods of photographic coverage of Mars, defined in terms of the percentage of L degrees that photographs were taken. Coverages of <1%, of 1 to 20% and >20% are indicated. The third timeline indicates the apparent size of Mars, as seen from Earth, on a scale of 0 to 30 seconds of arc (figure from Zurek and L. Martin 1999).

Dust storms in numerical models

Figure 3. Multi-year globally averaged 9 μm opacity for the infinite surface dust simulation (black solid) the finite surface dust simulations (colored solid and dashed lines).

Kahre et al. (2005)
Long-term change of surface dust?

Surface dust tendency between pre- and post-global dust storm in 2001

Surface dust tendency during one year after 2001 dust storm

(Szwast et al., 2006)
Ancient Martian climate

- Warm climate in ancient past?
- Water remains below the surface as ice

History of Mars

<table>
<thead>
<tr>
<th>Time (Gyr before present)</th>
<th>Early Noachian</th>
<th>Middle &amp; Late Noachian</th>
<th>Hesperian</th>
<th>Amazonian</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic field protection of atmosphere</td>
<td>Formation of bulk of Tharsis</td>
<td></td>
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<tr>
<td></td>
<td>High erosion rates</td>
<td>Hydrodynamic escape of earliest atmosphere</td>
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<tr>
<td></td>
<td>Impact ejection of atmosphere</td>
<td>Formation of valley networks</td>
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<tr>
<td></td>
<td>Impact ejection of atmosphere</td>
<td>Impact supply of volatiles</td>
<td></td>
<td>Catastrophic outflow channels</td>
</tr>
</tbody>
</table>

Jakosky (Nature, 2001)
Evolution of the atmosphere

Chassefiere et al. (2007)

Fig. 3. Schematic chronology of atmospheric escape on Mars. A factor of 100 loss is expected to have occurred during the heavy bombardment period, by impact loss and possibly hydrodynamic escape. In the subsequent period, by using radiogenic argon as a tracer of sputtering escape, an additional loss by a typical factor of 10 occurred.

Remnant crustal magnetic field

Connerney et al. (2005)
Can the ancient Mars be warm with CO₂ greenhouse effect?

Kasting (Icarus, 1991)

- The ancient Sun was 25% dimmer than the present.

- Warm lower atmosphere causes convection, which induces condensation of CO₂ in the upper atmosphere. The associated latent heating raises the temperature at upper levels, and at the same time cools the lower atmosphere so that the net energy balance is maintained.

Effect of CO₂ condensation

- When the solar constant is less than 86% of the present value, the surface temperature cannot exceed 0°C.

![Diagram showing temperature-altitude profile with and without CO₂ condensation.][1]

- Surface pressure of 2 bar
- Present solar constant
- No cloud albedo

**CO₂ condensation**

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Greenhouse effect due to CO₂ ice clouds

Forget & Pierrehumbert (Science, 1997)

• CO₂ ice clouds scatter infrared radiation emitted from the surface, thereby causing greenhouse effect.

• CO₂ ice clouds also have cooling effect via increase of the planetary albedo. However, thick CO₂ atmosphere itself has a high albedo even when no cloud exists, and thus the effect of cloud albedo is relatively minor.
  – For example, cloud-free 2-bar CO₂ atmosphere has an albedo of 0.38. Addition of CO₂ clouds increases the albedo to 0.65, thereby reducing the solar absorption by 40%. At the same time the clouds absorbs 60% of the infrared radiation emitted from the surface.

Atmospheric structure calculated for 2-bar CO₂ atmosphere, CO₂ ice clouds with visible optical thickness of 10, and the insolation 75 % of the present value

→ 1-2気圧のCO₂大気があれば0℃以上になりそう
Early martian climate under a denser CO₂ atmosphere (Forget et al. 2013)

- A CO₂ atmosphere could not have raised the annual mean temperature above 0°C anywhere on the planet. The collapse of the atmosphere into permanent CO₂ ice caps is predicted for pressures higher than 3 bar.
- Consistent with a cold early Mars scenario in which nonclimatic mechanisms must occur to explain the evidence for liquid water.
Polar caps

- Seasonal variation
- Residual polar caps in summer
  - $\text{H}_2\text{O}$ only on the north
  - $\text{H}_2\text{O} + \text{CO}_2$ on the south
- Southern $\text{CO}_2$ ice serves as a cold trap of $\text{H}_2\text{O}$?
Subsurface ice

Mars Odyssey
Neutron Spectrometer (NS) and
High-Energy Neutron Detector
(HEND)

Comparison with models

Near equilibrium?

Schorghofer and Aharonson (2005)
Seasonal variation of dust, clouds, and H$_2$O vapor observed by an infrared spectrometer (TES) on Mars Global Surveyor

Seasonal cycle of Martian water

- 北極冠の消長が全体を駆動
- 北半球の春～夏に北極冠が昇華して北極域の水蒸気濃度が上昇、これが（この時期の弱い）水平渦で低緯度に拡散的に運ばれる。
- 低緯度に運ばれた水蒸気の一部は赤道越えのパドレー循環で南半球へ
- 北半球の秋～冬には北極冠で凝結により水蒸気濃度が低下し、南北濃度勾配が逆転するため、傾圧不安定などに伴う水平渦で低緯度から北極域に水蒸気が拡散的に戻る。低緯度の水蒸気量はそれまでの水蒸気輸送の履歴で決まる。

Figure 3. Chart describing the principal events affecting the Martian water cycle over the course of a year. NPCS stands for North Polar Cap Sublimation; SCR stands for Seasonal Cap Recondensation.
Diverse water reservoirs on Mars

- running water in current climate?

Gullies

Seepages

White collars
Buried glaciers

Climate variation due to astronomical forcing?

Laskar et al. (2002)
• smaller obliquity → colder poles → more H$_2$O condensation on the poles → drier atmosphere → recession of ice sheets

• larger obliquity → warmer poles → less H$_2$O condensation on the poles → more humid atmosphere → growth of ice sheets

Mellon & Phillips (2001)
Layered deposits in the polar cap

Water transport by Hadley circulation

- Warmer southern summer than northern favors net northward transport of water.

Montmessin et al. (2004)
Permanent CO₂ cap at the South pole

CO₂ ice in blue areas  H₂O ice in blue areas

Erosion of residual Southern CO₂ cap

Observation by near-IR spectrometer (OMEGA) onboard Mars Express
Bibring et al. (2004)

H₂O ice protected by CO₂ ice?

• Water in the southern polar cap: remnant from the past where the southern water ice was stable?
• How stable is the current southern water ice cap?

Montmessin et al. (2007)
Figure 5. A comparison of water ice accumulation rates predicted by the model in the south polar region for the two perihelion configurations. Present-day map shows net accumulation only at the south pole itself (equivalent to 1 grid point in the model) where the prescription of a CO₂ cold trap forces a local and permanent deposition of water ice. In the reversed perihelion simulation (Figure 5, right), the CO₂ cold trap has been removed and the pattern of accumulation is only controlled by a precipitation versus sublimation positive balance on an annual average.

Figure 9. Illustration summarizing the sequence of events in the south polar region since the last reversed perihelion regime of the precession cycle. At event 1 time, water was extracted off the north polar cap and was deposited over the south PLD terrains thanks to a favorable summer insolation gradient between the poles. For event 2, passage to present-day configuration, with perihelion argument now entering a northern spring regime, reversed the orientation of the insolation gradient and forced water to progressively return back to the north pole. For event 3, in a third act, the erosion process stopped as permanent CO₂ ice slabs formed and kept water from subliming further.
Mars Moons Exploration (MMX)

- Under concept study in JAXA for launch in mid 2020’s
- Origin of Phobos and Deimos
  - Captured asteroid?
  - In situ formation after a giant impact?
- Sample return from Phobos, remote sensing of Deimos, and remote sensing of Martian atmosphere
- Improving understanding of the material distribution and transport in the early solar system

Images prepared by Prof. Miyamoto (Univ. Tokyo)

Observation of Mars in MMX mission

Controlling factors of Martian climate

- Water cycle
  - Atmosphere-surface water exchange controls the long-term evolution of water reservoirs
  - The seasonal/diurnal cycle controls the amount of water in the atmosphere, thereby influencing escape to space
- Dust lifting
  - Radiative effect of dust controls the surface/atmospheric temperature, thereby determining the stability of surface water
  - Radiative effect of dust controls the water vapor content in the upper atmosphere and the vertical transport of atmospheric constituents, thereby influencing escape to space
Water cycle on Mars

Small-scale water exchange with localized subsurface reservoir

Water exchange with polar caps

Cross-equatorial water exchange and transport to the exosphere

Buffering off-polar atmospheric water by various reservoirs

Stability of the southern polar cap

Localized water vapor transport and phase change: keys to understand water cycle and reservoir stability

Thick clouds on nightside

Cloud belt

Mars Express/PFS water vapor map

Previous observations did not obtain snapshots of high-resolution water vapor distribution and did not observe formation/evaporation of localized clouds

Fouchet et al. (2007)

Water Equivalent Hydrogen

Precipitation predicted by GCM

Feldman et al. (2005)
**Fast, localized dust storms: key to understand dust lifting and anomalous dust distribution**

- **Meridional cross section of dust mixing ratio**
  - Dust, $L_s=150$, MY 29, Nightside
  - $L_s=300$, MY 29, Nightside
  - Detached dust layers

- **“Rocket dust storm”: source of high-altitude dust?**

- Heavens et al. (2011)

- Spiga et al. (2013)

**Localized dust clouds:**
- Previous observations did not detect temporal development

**Limitation of observations from polar, low-altitude orbiters**

- MOC images taken on three successive days
  - *Too sparse in time*

- Concept of trace gas observations by Trace Gas Orbiter
  - *Too sparse in space*
High-altitude orbit of MMX: an ideal platform for continuous, high-resolution monitoring

4-5 hours of continuous mapping with <1 h interval

Imaging spectroscopy (NIR/UV)

- Water vapor
- Dust, cloud
- Surface pressure

Visible imaging

- Dust
- Cloud

Imaging spectroscopy (NIRS4)

- Mapping of H₂O and CO₂ (surface pressure) column amounts by near-IR spectroscopy of reflected sunlight
  - Multi-pixel FOV combined with the scanning by spacecraft attitude control enables acquisition of 2-D maps
Imaging clouds and dust (Cameras)

– Clouds (blue) and dust (red) are well distinguished by using multiple filters

HST Mars images

Importance of successive imaging

One global image per one day similar to mosaics by MOC or MARCI

Continuous global monitoring from the Mars orbiter

(provided by Ogohara)
Changing views of Martian atmosphere

Observed planetary-scale distributions of water vapor, clouds, dust and other species are interpreted based on numerical models.

Transport processes are directly detected and combined with meteorological data (with the help of data assimilation).