What does Mars’ Upper Atmosphere have to do with its Climate History?

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Remember the solar system is about 4.5 Billion years old. Modern humans are about a few 100,000 years old. The space age is about 5 decades old.

Thus investigations of the early history of our own Earth and its closest neighboring planets are the stuff (like much of astrophysics) of relatively unconstrained speculations.

*MAVEN’s job is to obtain key constraints for Mars.*
Much evidence points to an earlier, more hospitable Mars climate, with significant amounts of liquid water on the surface suggesting a thicker, wetter atmosphere once existed.

Neither much atmosphere nor much water are present today. There are two possibilities:

1. The atmosphere is buried and/or frozen in the polar ice caps
2. The atmosphere was lost because it escaped to space

Which is the answer?

Isotopes—that you will hear more about later, plus measurements of the present abundance of water and ice in the polar caps and beneath the surface, plus surface composition—all point to #2—Escape to Space.

The question is HOW ??? (and of course how much?)
MAVEN is targeting this period

Lammer (2013 SSR) Mars atmosphere evolution diagram
Mars current atmosphere at the surface has only as much pressure as the Earth’s at stratospheric altitudes.

(Figures from MSL ChemCam Website and LASP website)
Upper atmospheres include gas particles at the bottom that still collide with one another, but at higher altitudes act like projectiles-either still trapped by gravity or escaping.
Concepts of “escape velocity” and of velocity distributions of atmospheric gases

The gas particles have a thermal or Maxwell-Boltzmann distribution in Velocity.

To escape planet’s gravitational field, particle must have a velocity greater than the “escape velocity”:

\[
\frac{1}{2} m v^2 > \frac{m MG}{r}
\]

or

\[
v > v_{\text{esc}} = \left(\frac{2 MG}{r}\right)^{1/2}
\]
How can it get there? By both ‘thermal’ (heating), and ‘nonthermal’ processes

Heating widens this velocity distribution so more particles make it into the $>\nu_{\text{esc}}$ area.

Other processes like chemical reactions or particle collisions can also move some above the $\nu_{\text{esc}}$ threshold by adding energy.
Impacts—mentioned earlier, were a special ‘nonthermal’ process... but not so important after the first billion years of Mars history.

(from Abe and Matsui, 1985)

(from Ahrens, 1989)
Nonthermal sources related to photochemistry (here, for Oxygen, which is particularly important for planets, including Mars)

\[
\text{CO}_2^+ + \text{O} \rightarrow \text{O}_2^+ + \text{CO}
\]

makes \( \text{O}_2^+ \) then

\[
\text{dissociative recombination}
\]

\[
\text{O}_2^+ + e \rightarrow \text{O}^+ + \text{O}^+
\]

makes superthermal \( \text{O} \)

\[
\text{photoionization (or impact ionization or charge exchange)}
\]

\[
\text{O}^+ + \text{hy} \rightarrow \text{O}^+ + e
\]

direct solar wind pickup (and loss)

pickup followed by reimpact

generation of backscattered or sputtered \( \text{O} \) with velocities sometimes above \( \text{V}_{\text{esc}} \)
The photochemistry source is related to solar activity (also solar age). The short wavelengths heat and ionize.

Images from Kitt Peak Observatory magnetograph (left) and the Yohkoh Soft X-ray Telescope, SXT (right) showing x-ray bright arcades over active regions, both evolving over the course of a solar cycle—a ‘model’ for solar evolution.
Other sources of nonthermal escape are related to the solar wind interaction.

Some typical ‘quiet time’ properties at Mars:

- Density \( \approx 1-3 \text{ cm}^{-3} \)
- Magnetic field \( \approx 1-3 \text{ nT} \)
- Speed \( \approx 300-600 \text{ km/s} \)
- Spiral Field angle \( \sim 50^\circ \)

1.5 AU

Note even quiet conditions are not uniform or constant.
Solar Wind stream interaction regions (SIRs-or CIRs if corotating) cause interplanetary field and flow deflections, and field and density enhancements.

We’ve known about the existence of the solar wind since the late 50s-early 60s—now realistic models exist.

(A model from D. Odstrcil run at GSFC)
Because Mars has no strong planetary magnetic field, this solar wind interacts directly with its upper atmosphere.
Can the much different planetary magnetic fields on Earth and Mars explain their climate differences?

Other contributing factors:
Mars is further from the Sun (~1.5 AU vs 1 AU)
Mars is smaller/less massive
In particular, do planetary magnetospheres “shield” planetary atmospheres from possibly important loss processes?

ESA web image
We know relatively much about Earth’s response to ‘space weather’

Nonthermal Escape - Earth

Earth atmosphere escape is however quite different in its details due to its strong planetary magnetic field
Earth’s Polar Atmospheric Ion Outflows

Include:
* Classic light ion ‘polar wind’ (H+ and He+)
* Cusp ‘ion fountain’
* Highly variable but most intense ‘Auroral wind’

-each outflow has a distinct physical cause.
The latter two include heavy ion species like O+.
Not all outflowing ions escape to space directly, but most are believed to eventually do so.

(from ESA Cluster News)
Mars’ More Direct Solar Wind Interaction-Related Loss Processes:

Atmospheric Ion ‘pickup’ - Observed on earlier missions but still many uncertain details on related escape
“Sputtering” - Related to ion pickup. Potentially Important but so far unobserved at Mars
Illustration of the **sputtering process** near the upper boundary of the collision-dominated atmosphere

Here- incident picked up O+ ions interact with the upper atmosphere oxygen gas and other constituents including CO$_2$. Anything present here may be ejected.
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Notice that sputtering uses pickup ions that don’t escape to make escaping neutrals
Early Mars was a complicated scene
But today it is still affected by the same escape processes—though altered by its current state.
To get rid of the atmosphere and water that is estimated to have been there, loss rates would have had to be much greater in the past.

Current (Estimated) Escape Rates

<table>
<thead>
<tr>
<th>Species</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (thermal)</td>
<td>( \sim 1.7 \times 10^{26} ) s(^{-1} )</td>
</tr>
<tr>
<td>O (nonthermal)</td>
<td>( \sim 8.6 \times 10^{25} ) s(^{-1} )*</td>
</tr>
<tr>
<td>CO(_2) (sputtering)</td>
<td>( \sim 3 \times 10^{23} ) s(^{-1} )</td>
</tr>
</tbody>
</table>

Loss over 3.5 Gyr at present rates:

<table>
<thead>
<tr>
<th>Equivalent</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)O equivalent</td>
<td>( \sim 3 ) m</td>
</tr>
<tr>
<td>CO(_2) equivalent</td>
<td>( \sim 1 ) mb</td>
</tr>
</tbody>
</table>

*includes \( \sim 6 \times 10^{24} \) ions s\(^{-1} \) picked up by solar wind.

Phobos-2 measured \( \sim 10^{24} \) - \( 10^{25} \) s\(^{-1} \)

If the current processes are the answer, could these have been high enough?
Estimated volume of an early ocean of Mars is \(~6 \times 10^7\) km\(^3\) H\(_2\)O (from surface features).

This amount contains about \(2 \times 10^{45}\) H\(_2\)O molecules.

It is relatively easy to get rid of light hydrogen by heating.

To get rid of the oxygen in this ocean over 3.5 Byr, need an average loss rate of \(1.8 \times 10^{28}\) O atoms/sec (over 100 times greater than present).
Sun-like stars tell us that in the past, the Sun may have been more magnetically active.

Images from Kitt Peak Observatory magnetograph (left) and the Yohkoh Soft X-ray Telescope, SXT (right) showing x-ray bright arcades over active regions, both evolving over the course of a solar cycle—a ‘model’ for solar evolution.
Part of the result is a trend of decreasing solar EUV emission with time.
The early Sun was also likely to have been much more active—producing more flares and Coronal Mass Ejections (CMEs).
Big CME events in particular have many parts: Including shocks

GSFC fast-turnaround ‘ENLIL/cone CME’ modeling indicated the direct STA hit for the major July 23, 2012 super-fast CME
..which are produced by magnetic ejecta that move much faster than the solar wind, plowing through and compressing the ambient flow as they travel.

CMEs produce the largest solar wind disturbances

(from Crooker, 1993)
Solar energetic particles (SEPs) with protons of up to ~100 MeV or more are also part of these events.

Here the SOHO coronagraph CCD is ‘snowed’ by SEPs in March 2012.
Typical Signatures: Earth-Directed Event Timing

- Solar X-ray Flux
- Shock is Weak e- Accelerator
- Log 100 keV Electron Flux
- "Prompt" Onset
- Occasional Flux Reduction in Cloud
- 100 keV Proton Flux
- ESP "Event"
- ~ No ESP Enhancement
- 10 MeV Proton Flux
- Flare + CME Release at Sun
- ICME Transit ~Days
- Shock Arrives
- ICME Ejecta "Cloud"

Days

|B| (nT)
A Flare occurs at the Sun. Its X-ray and EUV light bursts arrive in ~12 min at Mars. Solar energetic particles (electrons, protons) arrive ~40 min after the flare. Shock arrives - includes solar wind plasma + magnetic field enhancements and sometimes energetic particles increase.
A Flare occurs at the Sun. Its X-ray and EUV light bursts arrive in ~12 min at Mars. Solar energetic particles (electrons, protons) arrive ~40 min after the flare. Mars shock arrives - includes solar wind plasma and magnetic field enhancements and sometimes energetic particles increase. Note whole event with its different phases can last ~a week.
These disturbances energize Earth’s polar ionosphere, enhancing upper atmosphere heating, auroras, and related ion escape.

LFM MHD simulation from Goodrich et al. Inset shows the resulting enhancement of energy going into Earth’s polar region when a coronal mass ejection (CME) disturbance goes by.
Cometary tail ‘disconnection’ following a CME encounter is in some ways a counterpart to what must happen at Mars.

Question is whether this is just interruption of escape or actual enhancement?

NASA website images from comet Enke passage, and cartoon of the CME interacting with the draped cometary magnetic fields.
The responses of Mars to the large ranges of conditions is a primary theme of this new Mars mission.
Solar Cycle Settings of all observations need to be considered in drawing conclusions: EUV, solar wind structure, solar/coronal activity

In particular, many MEX observations occurred during an unusually quiet solar period. Its extended operation plus new measurements on MAVEN mission will be a big opportunity.
Where the MAVEN mission will make a huge difference:

- We will see if sputtering really occurs and its importance relative to other escape processes (some of which may be new to us)

- We will observe how Mars’ atmosphere responds to solar events—especially in ways that might enhance escape (e.g., Higher EUV—enhanced thermal and photochemical escape, and atmosphere ion production? CMEs—more sputtering and ion escape? Other processes e.g. related to crustal magnetic field interactions with solar wind, to SEPs?)

- We will use the results to constrain estimates and models of escape over time due to still-active processes. These will tell us if we can explain how Mars got where it is today—with implications for Earth and other planets as well.
Supporting information of interest to MAVEN
ESA’s Mars Express ASPERA-3 measures solar wind and atmospheric ions in a complementary orbit.

Collaborations including measurement comparisons are planned.
NASA Space weather monitoring assets include models of CME shocks out to Mars orbit, based on SOHO and STEREO mission imaging (Space Weather Center, GSFC)

2013-03-22T00:00

Earth  Mars  Mercury  Venus  Epoxi  Juno  Kepler  Spitzer
Stereo_A  Stereo_B

Ecliptic Plane

LAT = -8.8°

R² N (cm⁻³)

ENUL-2.7 lowres-2135-a3b1f WGA_2.2 GONG-2135

IMF polarity

Current sheath

3D IMF line

SWC.gsfc.nasa.gov
Since 2011 we have been able to watch solar activity anywhere.

SDO and STEREO are part of the Heliophysics Great Observatory.

Bill Thompson, GSFC
STEREO Science Ctr.
STEREO +ACE real-time multipoint measurements at 1 AU give the latest state of space weather ‘now’ (NOAA RT data plots, images from SOHO, SDO)

NOAA SWPC plots
SOHO/LASCO, SDO/AIA images
http://stereo.ssl.berkeley.edu/multistatus.php

Real-time multipoint SEP events in early April 2013