The loss of the early Martian atmosphere and its water inventory due to the active young Sun

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The case for a wet, warm Mars: But where is all the water and the atmosphere?

- Observations of a network of valleys in crater rich areas of the southern hemisphere suggests that Mars had once a significant hydrologic activity [e.g., Carr Nature 326, 30, 1987; Baker Nature 412, 228, 2001; Carr & Head JGR 108, E5, 5042, 2003]

- Asteroids and comets from beyond 2.5 AU provide the source of Mars’ water, which totals 6 - 27% of the Earth’s present ocean equivalent to 600 - 2700 m depth on the Martian surface or in the crustal regolith [Lunine et al. Icarus 165, 1, 2003]

- Enrichment and fractionation of heavy isotopes [e.g., Pepin Icarus 111, 289, 1994]

- Estimations of volumes of potential early Martian water reservoirs from geo-morphological analysis of possible shorelines by MGS images and MOLA data $\rightarrow \ d \approx 150 \ - \ 160 \ m$ [Carr & Head JGR 108, E5, 5042, 2003]
  - Stored in present polar caps $\rightarrow \ d \approx 20 \ - \ 30 \ m$
  - Surface ground water $\rightarrow \ d \approx 80 \ m$
  - Escaped to space $\rightarrow \ d \approx 50 \ - \ 80 \ m$

- Early atmosphere $\approx 1 - 5$ bars [e.g., Pollack, Kasting et al. Icarus 71, 203, 1987]
Thermal atmospheric loss processes

- **Thermal atmospheric loss** → neutral particles
  - Jeans escape
    → light species (H, H₂) on present solar X-ray and EUV (XUV) conditions, dependent on planetary mass, thermospheric species and resulting exospheric temperature
    → heavy atoms (O, C, N) during high solar XUV flux periods of the young Sun

- **Hydrodynamic blow-off**
  → light (H, H₂) but also heavy (O, C, N, etc.) species dependent on planetary mass, thermospheric species during high XUV periods of the young Sun
Non-Thermal atmospheric loss processes

- **Non-thermal atmospheric loss** $\rightarrow$ ionized but also neutral particles
  - **Photo-chemical reactions**
    $\rightarrow$ light and heavy species (H, O, N), which are released by photo-chemical reactions
  - **Ion pick up (non-magnetized $\rightarrow$ reduced on early Mars)**
    $\rightarrow$ light and heavy ions, which can be picked up by the solar wind plasma flow
  - **Sputtering (non-magnetized $\rightarrow$ reduced on early Mars)**
    $\rightarrow$ light and heavy species of the upper atmosphere can be sputtered by solar wind plasma if the planet has no or a weak magnetic field
  - **Plasma instabilities (non-magnetized $\rightarrow$ reduced on early Mars)**
    $\rightarrow$ all ion species at the ionopause-transition layer, dependent on the solar wind and ionospheric conditions
  - **Momentum transport (non-magnetized $\rightarrow$ reduced on early Mars)**
    $\rightarrow$ light and heavy ions, which have energies larger than the escape energy
Solar irradiances and particle emission as function of time

### Main Targets of the “Sun in Time” Program

<table>
<thead>
<tr>
<th>Star</th>
<th>HD</th>
<th>Spectr.</th>
<th>$M_v$</th>
<th>$T_{\text{eff}}$</th>
<th>Mass</th>
<th>Dist.</th>
<th>$P_{\text{rot}}$</th>
<th>Age</th>
<th>Age Indicator</th>
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<tr>
<td>47 Cas</td>
<td>12230</td>
<td>G1 V</td>
<td>5.13</td>
<td>6188</td>
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<td>EK Dra</td>
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<td>G0 V</td>
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<td>5818</td>
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<td>G2 V</td>
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<td>5780</td>
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<td>20.4</td>
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<td>Isotchrones</td>
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</tbody>
</table>

- High-energy radiation observations from space
- Stellar wind observations from space (Ly-$\alpha$) and radio mm wavelengths
- Extended time series (several days) to evaluate short-term variability
X-rays

FUV

EUV

UV

High-energy irradiances


High-energy irradiances
The flux density evolution scales well with power-law relationships.

The overall XUV flux (1 - 1200 Å) decreases with a slope of \(-1.2\) higher than today 2.5 Gyr ago, \(6 \times 3.5\) Gyr ago, \(100 \times\) ZAMS!

The important Ly-\(\alpha\) line (1215 Å) decreases with a slope of \(-0.72\).
This is the last ingredient of stellar activity (stars have hot coronae and lose mass at a certain rate).

The mass loss rate also seems to correlate with $L_x$.

New observational campaigns of very young stars are going on.

Until we have no data for the first Gyr one has to be careful.
Escape rates [$s^{-1}$] of various species from present Mars to 3.5 Gyr ago

Assuming a self-regulation mechanism between the loss of O and H as postulated by McElroy and Donahue [1972], we obtain a total $H_2O$ loss over the past 3.5 Gyr of $\approx 12$ m GEL (Global Equivalent Layer)

<table>
<thead>
<tr>
<th>Species</th>
<th>Present</th>
<th>2.5 Gyr</th>
<th>3.5 Gyr</th>
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</thead>
<tbody>
<tr>
<td>$H_2O$</td>
<td>9.5E+25</td>
<td>2.0E+26</td>
<td>2.5E+27</td>
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<tr>
<td>Total: O</td>
<td>6.4E+24</td>
<td>2.0E+26</td>
<td>2.5E+27</td>
</tr>
<tr>
<td>Pick up: $O^+$</td>
<td>3.0E+24</td>
<td>4.0E+25</td>
<td>8.3E+26</td>
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<tr>
<td>Dissociative recombination: O</td>
<td>6.0E+24</td>
<td>3.0E+25</td>
<td>8.0E+25</td>
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<td>Sputtering: O</td>
<td>3.5E+23</td>
<td>1.3E+25</td>
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<td>Sputtering: $CO_2$</td>
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<td>Sputtering: CO</td>
<td>3.7E+22</td>
<td>2.0E+24</td>
<td>2.5E+25</td>
</tr>
</tbody>
</table>

[Terada et al. submitted to Icarus, 2005]

[Terada et al. submitted to Icarus, 2005]

Test particle models and complex hybrid simulations give about similar results for total loss rates
X-ray and EUV heating over Martian's history

- Thermospheric model solves the equations
  - of continuity,
  - hydrostatic and heat balance
  - equations of vibrational kinetics for radiating molecules

The applied model is self-consistent with respect to the neutral gas temperature and the vibrational temperatures of the minor species radiating (cooling) in the IR [e.g., Gordiets et al., JGR 87, 4504, 1982]

- Heating due to the N₂, O₂, and O photoionization by XUV-radiation (λ ≤ 1027 Å)
- Heating due to O₂, and O₃ photodissociation by solar UV-radiation, chemical heating in exothermic reactions with O and O₃
- Neutral gas heat conduction
- IR-cooling in the vibrational-rotational bands of CO₂, NO, O₃, OH, NO⁺, N¹⁴ N¹⁵, CO, in the 1.27 μm O₂ IR atmospheric band and in the 63 μm O line that strongly depends on the neutral atmosphere temperature
- Heating and cooling due to contraction and expansion of the thermosphere
- Turbulent energy dissipation and heat conduction

For dense CO₂ atmospheres the 15 μm CO₂ IR band is very important for cooling
**Jeans escape parameter for H and O on Mars**

**Equation:**

\[ X(r) = \frac{GM_p m_i}{r k T_{\infty}} = \frac{v_{\text{esc}}^2}{v_0^2} \]

- **Due to expansion H reaches blow-off \( \rightarrow \) dynamic escape at temperatures around 800 - 1000 K**  

*Graphs showing the escape parameter for 
\( X = 1.5 \) at various temperatures.*

Hydrodynamic escape

\( X(r) \leq 3 \) \( \rightarrow \) atmospheric expansion hydrodynamic loss
Evolution of the exospheric temperature

Model simulations high variation of exosphere Temperature [e.g., Bougher et al. JGR 99, 14609, 1994]

high O loss rates

dynamic loss of H

dynamic loss of H

≈ 300 Myr

≈ 130 Myr

Viking, NGS aerobreaking ionosphere/ EUV activity relations

XUV flux

Exosphere temperature, K

CO₂ = 1%

CO₂ = 10%

CO₂ = 96%

eff = 50%

eff = 4%

16%
Loss of O due to large Jeans escape rates

Diffusion limited escape of hydrogen can be $\geq 10^{11} - 3 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$

$\Delta t(\text{Gyr}) = 2.4 \times 10^9 \frac{\Delta p(H_2O)[\text{bar}]}{\phi_{esc}(H)[\text{cm}^{-2} \text{s}^{-1}]} \rightarrow 50 - 100 \text{ Myr (d = 150 m)}$
Effects on the Martian atmospheric and water environment

<table>
<thead>
<tr>
<th>Hydrodynamic loss [HL]</th>
<th>Ion pick up [PU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact erosion [IE]</td>
<td>Momentum transport (viscous processes) [MT]</td>
</tr>
<tr>
<td></td>
<td>Erosion due to plasma instabilities [PI]</td>
</tr>
<tr>
<td></td>
<td>Dissociative recombination [DR]</td>
</tr>
<tr>
<td></td>
<td>Sputtering [SP]</td>
</tr>
</tbody>
</table>

How much H$_2$O-ice is stored in present subsurface ice reservoirs?

→ Mars Express MARSIS

Application of a hydrodynamic loss model to hydrogen loss and impact erosion → diffusion-limited loss of hydrogen

Coupling between research on water vapour in early Mars atmosphere