MAVEN Update: Recent Discoveries and Results on Atmospheric Loss

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MAVEN Objectives And Status

Science Objectives:

• Understand the behavior of the upper atmosphere at the present
• Determine today’s rates of loss of atmospheric gas to space and processes controlling them
• Extrapolate to long-term behavior of loss to space

MAVEN Status:

• In orbit since September 2014
• Spacecraft and instruments all operating nominally
• New observations implemented for current Extended Mission
• Fuel to last possibly as long as a decade
• Long-term implementation for relay support under discussion
Characterization of H Corona and H Escape

- Observed by SWIA based on incoming solar-wind protons that “charge exchange” with neutral corona; determination of integrated H column in corona; also observed by IUVS
- Corona density controls escape rate
- Order-of-magnitude seasonal variation seen; likely results from dust-driven temperature changes that allow water to rise higher into atmosphere and supply H corona more easily
- Better characterization than variations seen by HST and Mars Express

(J. Halekas, M. Chaffin)
**Discovery Of Long-Lived Metal-Ion Layer In The Ionosphere**

**NGIMS:**
- Metal ions detected in ionosphere – originally discovered associated with Comet Siding Spring, but now detected continually throughout mission.
- Observed *in situ* with NGIMS, remotely via scattered sunlight by IUVS.
- Source is interplanetary dust from comets/asteroids.
- May be important in driving chemical reactions and in dust providing cloud condensation nuclei, similar to on Earth.

**IUUVS:**

(J. Grebowsky, M. Crismani, N. Schneider)
NGIMS Measurement of Neutral and Ion Winds

- NGIMS yaws left/right during periapsis pass to derive winds, implemented on all orbits one day/month
- Measure both neutrals and ions, on consecutive days
- Results show both similarities to model circulation and differences, plus significant longitudinal variability
- First synoptic measurements of upper-atmospheric winds

(M. Benna et al.)
Discovery of Proton Aurora at Mars

- Solar-wind protons can “charge exchange” with H in corona to become neutral, and penetrate at solar-wind speeds
- Collision with molecules in upper atmosphere induceauroral emission from incoming H atoms
- Scattering seen in H Lyman alpha profiles occurred simultaneously with penetrating high-energy solar wind protons.

(J. Deighan, N. Schneider)
Characterizing Low-Energy (Cold) Ion Outflow

- MHD simulation (right) shows magnetic-field lines that connect to planet at both ends (red) and that are open to space at one end (green)
- Electron measurements (center) uniquely identify open field lines connected to the day-side ionosphere
- Acceleration of ions up open field lines drives low-energy outflow loss to space
- New STATIC measurements of ion velocities in this cold-ion outflow (left) show substantial loss at velocities just above Mars escape velocity
- Previously uncharacterized, this loss could dominate \( \text{O}_2^+ \) ion loss at present epoch

(D.L. Mitchell, J. McFadden, C. Dong)
Integrated Hydrogen Loss

- H is lost by thermal (Jeans) escape from an extended corona surrounding Mars; H is derived from atmospheric H₂O
- Loss of H equivalent to atmospheric column of H₂O in 4 x 10³ – 4.1 x 10⁴ years (using the extreme seasonal values of loss rates)
- At current rate, loss over 4 b.y. of ~2 - 15 m H₂O global equivalent layer
- Extrapolation difficult due to uncertain cause of present-day variability; there are reasons that loss could be greater or less than the 2-15 m estimate
Oxygen Ion Loss

- Ions are stripped away from the upper atmosphere by the solar wind
- Loss over mission shown here in two views – mapped and projected onto plane (with Sun at the right), both sorted by solar-wind magnetic field
- Mean loss rate would remove atmospheric O (mainly from CO$_2$) in ~2 b.y.
- Modeled extrapolation into past based on greater EUV flux early in history that drives much greater loss
- Estimated loss as high as ~0.4 bar CO$_2$ equivalent
Sputtering Loss of O

- Oxygen ions get picked up and accelerated by solar wind
- Those picked up upstream of Mars get accelerated into Mars’ upper atmosphere, and can physically knock other atoms and molecules out
- Loss at present epoch ~10x less than for O ion loss; not significant today
- Loss rate early in history as much as $10^4 x$ greater
- Integrated loss of >0.6 bar CO$_2$ equivalent
Loss During Solar Storm (Space Weather) Events

- Example solar event hitting Mars, with MAVEN measuring all pertinent parameters
- Escape enhanced by ~20x for this moderate event, shown both in data and in MHD models of loss
- Solar events likely to have been stronger and more abundant early in history, and storm-induced loss could dominate total loss
Summary Of Atmospheric Loss To Space

- **Jeans escape loss of H**
  - Loss of Global Equivalent Layer (GEL) of ~ 2 - 15 m H₂O
  - Could be substantially larger

- **Solar-wind stripping of O**
  - Loss of O from multiple processes, equivalent to
    - Up to a couple of bars of CO₂, or
    - 2 - 40 m H₂O, or
    - A mix of these end-members

- **Loss from solar storms**
  - Enhanced loss observed during solar events
  - Storms early in history were stronger and much more abundant, and resulting loss could dominate total loss
$^{38}\text{Ar}/^{36}\text{Ar}$ Requires Substantial Loss

- Above homopause ($\sim 100$ km), each gas has a scale height determined by its own mass; shown in upper left as profile of two gases having different masses
- Causes $^{36}\text{Ar}/^{38}\text{Ar}$ ratio to increase with altitude; loss from top of atmosphere preferentially removes $^{36}\text{Ar}$ and leaves remaining gas enriched in $^{38}\text{Ar}$.
- We use this enrichment to quantitatively determine fraction of gas lost by sputtering alone
- Indicates directly that majority of atmosphere has been removed to space
Integrated Results on Atmospheric Loss

- Loss to space would have been able to remove the largest part of a thick, early atmosphere
- O that is lost can have come from either CO\textsubscript{2} or H\textsubscript{2}O
- Argon-isotope enrichment requires loss of the bulk of the atmosphere by sputtering but applies to all constituents; O loss has to include loss of CO\textsubscript{2}

**Bottom line:** Loss to space likely was a (if not the) major process for changing Mars from having an early warm, wet climate to the cold, dry climate we see today.
Ongoing and Upcoming Measurements

- Observations through a second Mars year (interannual variations)
- Different time in the 11-year solar cycle (effects of different solar drivers)
- Comprehensive measurements not previously made
- Coordinated observations with *Trace Gas Orbiter*