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First Results from the MAVEN Mission to Mars

Key Points:
- MAVEN IUVS is making unprecedented measurements of the Martian hot oxygen corona
- The corona from 1000–3500 km has a characteristic energy of approximately 1 eV
- Correlation of coronal brightness with EUV flux is consistent with an ionospheric source

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MAVEN IUVS observation of the hot oxygen corona at Mars

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Abstract Observation of the hot oxygen corona at Mars has been an elusive measurement in planetary science. Characterizing this component of the planet's exosphere provides insight into the processes driving loss of oxygen at the current time, which informs understanding of the planet's climatic evolution. The Mars Atmosphere and Volatile EvolutioN (MAVEN) Imaging Ultraviolet Spectrograph (IUVS) instrument is now regularly collecting altitude profiles of the hot oxygen corona as part of its investigation of atmospheric escape from Mars. Observations obtained thus far have been examined and found to display the expected gross structure and variability with EUV forcing anticipated by theory. The quality and quantity of the data set provides valuable constraints for the coronal modeling community.

1. Introduction

In September 2014 the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft entered orbit around Mars and began to study the processes driving the escape of its atmosphere to space [*Jakosky et al.,* 2015]. Oxygen is the most abundant element in the Martian atmosphere, and quantifying its loss budget is crucial for understanding the evolution of the planet's CO_2 and H_2O reservoirs. The escape rate of oxygen relative to hydrogen is also important for determining the oxidation state of the atmosphere and surface. *McElroy* [1972] predicted that dissociative recombination (DR) of O_2^+ in the ionosphere should be an important loss mechanism for Mars:

$$O_2^+ + e^- \rightarrow O(^3P) + O(^3P) \qquad 7.0\ \text{eV} \tag{1a}$$
$$O(^3P) + O(^1D) \qquad 5.0\ \text{eV} \tag{1b}$$
$$O(^3P) + O(^1S) \qquad 2.8\ \text{eV} \tag{1c}$$
$$O(^1D) + O(^1D) \qquad 3.1\ \text{eV} \tag{1d}$$
$$O(^1D) + O(^1S) \qquad 0.8\ \text{eV} \tag{1e}$$

The excess energy is divided between the resulting pair of oxygen atoms, giving the two most exothermic channels ((1a)) and ((1b)) sufficient energy (>2 eV) to escape the planet's gravity. The yield of channel ((1c)) has been found to be insignificant, while the others are dependent on the vibrational state of the O_2^+ [*Petrignani et al*., 2005]. *Wallis* [1978] pointed out that oxygen atoms incapable of escaping, either generated from the less energetic DR channels or having undergone collisions in the atmosphere, would form an extended halo, also called a corona, of hot oxygen atoms surrounding Mars out to several planetary radii. Dissociative recombination of CO_2^+, a less abundant species in the Martian ionosphere, may also contribute significantly [*Gröller et al*., 2014]. Yet another source for this coronal population is expected to be atmospheric sputtering by O^+ ions [*Johnson*, 1994; *Johnson and Luhmann,* 1998]. While thought to provide an insignificant contribution to escape today, sputtering may have been an important loss mechanism earlier in Martian history [*Luhmann et al*., 1992].

The literature is replete with detailed models of the production and transport of nonthermal oxygen into the Martian exosphere and widely varying predictions for the escape rate (for a thorough review of the modeling state-of-the-art in preparation for interpreting MAVEN data, see *Lillis et al.* [2015]). However, it has been

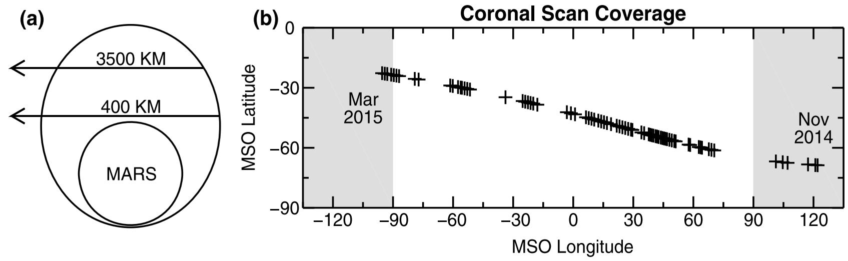

Figure 1. (a) Observational geometry of MAVEN IUVS coronal scans during the outbound segment of the orbit. The instrument line of sight is inertially aligned with the semiminor axis and typically spans tangent altitudes of 400–3500 km. (b) Planetary coverage of the coronal scan tangent point in Mars Solar Orbital (MSO) coordinates from November 2014 to March 2015 (orbits 236–812). Shaded regions indicate the night hemisphere, and each symbol represents a nominally executed coronal scan.

difficult to obtain the conclusive observations of the tenuous corona needed to validate these models. Remote sensing measurements focus on resonant scattering of sunlight by the relatively strong O I 130.4 nm triplet, but even so, the expected brightness at altitudes >700 km where the hot population dominates is on the order of 1–10 Rayleighs. The most successful previous efforts include a single profile obtained by the Rosetta-Alice UV Imaging Spectrograph during a Mars flyby maneuver [*Feldman et al.*, 2011] and a pair of spectra taken using the Hubble Space Telescope Imaging Spectrograph [*Carveth et al.*, 2012]. These measurements suggested a transition in scale height from a cold thermal oxygen population to a more energetic component at altitudes >500 km. However, they struggled with issues of altitude sampling and signal to noise in isolating the characteristics of this hot population.

In this letter we report on observations of the hot oxygen corona at Mars as measured by the Imaging Ultraviolet Spectrograph (IUVS) [*McClintock et al.,* 2014] aboard the MAVEN spacecraft. IUVS is a highly capable remote sensing instrument, with a separate image-intensified FUV channel to maximize signal and reduce stray light for faint features at short wavelengths, like the O I 130.4 nm triplet. The initial data reveal an unambiguous transition from the thermal to nonthermal oxygen population with high altitude resolution and signal to noise. Details on the lower altitude thermal oxygen component observed by IUVS may be found in *Chaufray et al.* [2015]. By coadding data from December 2014 to January 2015, an extended coronal brightness profile exceeding the altitude of 1 Mars radius is obtained. Preliminary analysis shows the anticipated gross structure of the oxygen corona, as well as an apparent response to solar EUV input consistent with an ionospheric source. The IUVS observations of the oxygen corona provide a groundbreaking data set for constraining and informing models of atmospheric escape at Mars.

2. Observations

During nominal science operations IUVS acquires an individual oxygen coronal scan once every two or four orbits, depending on the spacecraft observing scenario. For these observations the boresight of the instrument is aligned with the semiminor axis of the MAVEN orbit as the spacecraft travels toward apoapse (Figure 1a). This draws the IUVS line of sight across tangent altitudes of approximately 400 to 3500 km over 26 min, during which time it acquires over 100 integrations.

For an ionospheric photochemical source, the hot oxygen corona is expected to be densest in the dayside hemisphere. The evolution of the MAVEN orbit allowed for coronal scans with solar zenith angles (SZA) close to or less than 90° from November 2014 until March 2015 (Martian $L_S = 230$–300). During this time the line of sight tangent point attained a minimum SZA of 38.6°, and explored local times from dusk to dawn in the southern hemisphere (Figure 1b). Nominal data were acquired over a substantial portion of this period, with occasional gaps due to sharing pointing control with other instruments, communication passes, solar Keep-Out Zone constraints, calibration activities, and other irregularities. The IUVS FUV channel data set used here is available as FITS files under the label “outbound” in the v02_r01 release to the Planetary Data System.

Coronal scans of hot oxygen are among the most sensitive measurements made by IUVS. To minimize random noise introduced by dark current subtraction, a reference superdark detector image was created by coadding 417 dark images acquired on the side segments of orbit 628, when IUVS was subject to a

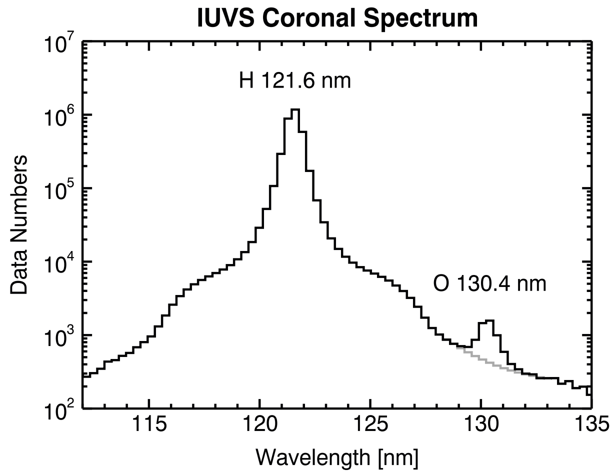

Figure 2. An averaged IUVS spectrum of the Martian corona showing the hydrogen 121.6 nm and oxygen 130.4 nm resonance lines. The spectrum was obtained by coadding 1925 spectra taken with tangent altitudes > 1000 km and SZA < 90° when the FUV detector temperature was stable at <−17°C, representing approximately 8 h of integration time. The same data were used to create the LSF template described in section 2. The gray line underlying the 130.4 nm feature indicates the exponential wing interpolation used for the LSF.

high-voltage constraint. This superdark was then scaled by a multiplier + constant to match the dark current level for each orbit of observations.

Measurement of the 130.4 nm triplet oxygen feature is complicated by its proximity and faintness relative to the Ly α line at 121.6 nm produced by the Martian hydrogen corona. There is a ratio of 1000 between the brightness of the two features, and the wing of the instrument line spread function (LSF) emanating from Ly α conspicuously underlies the 130.4 nm triplet (Figure 2). To subtract this background an empirical 2-D LSF for the spectral and spatial dimensions of the spectrograph was constructed. The LSF was composed by coadding coronal spectra obtained with tangent altitude > 1000 km, ensuring a consistent brightness along the entrance slit and minimized the oxygen signal. This approach allowed us to intrinsically account for variations in performance across the detector, such as flat field, slit tilt, change in focus, and spectral-spatial point spread function anisotropy. Spectra within this data set were filtered for cosmic ray detector events by calculating the median absolute deviation of the raw data numbers (DN) for each detector pixel for a robust estimator of typical variability and then removing samples that fell outside of 3σ. The Ly α wing was spectrally interpolated across the region containing the O 130.4 nm feature using an exponential + constant function. The resulting LSF was used as a template in a multiple linear regression (MLR) fit applied to the hydrogen and oxygen features in DN after dark subtraction. This produced an integrated DN for both emission features along with a propagated uncertainty. A similar method is used for fitting emissions in thermospheric limb scans obtained by IUVS at periapse [*Stevens et al.*, 2015]. The integrated DN was then converted to physical brightness in Rayleighs using sensitivities derived from stellar observations obtained during MAVEN's cruise phase. The current calibration for the FUV channel carries a systematic uncertainty of 25%.

3. Results

3.1. Altitude Profiles

A useful oxygen brightness profile can be derived from an individual IUVS coronal scan. The transition in slope from the cold thermal oxygen population at low altitudes to the hot population at higher altitudes is readily discerned (Figure 3a). However, signal to noise degrades substantially at tangent altitudes > 1500 km, and the MLR produces unreliable error bars for spectra containing cosmic ray detector events. We obtained dramatic improvement by coadding several orbits and binning the sampled altitudes on a regular grid (Figure 3b). Cosmic ray detector events were filtered out by applying the same method used to coadd the LSF template described in section 2. The resulting profiles allow for a more robust analysis of the hot population where sufficient scans with similar conditions are available. Perhaps the ultimate example of this is the coaddition of 48 profiles from orbits 335–624, which had good spatial continuity in MSO coordinates and sampled tangent point SZA spanning 39–81° (Figure 3c). The result is an altitude profile that is representative of the global average dayside corona. For reference, a g factor of $5.76 \times 10^{-6}\ s^{-1}$ is appropriate for O I 130.4 nm at time these data were collected.

The gravitationally bound component of the hot oxygen population dominates coronal densities at the altitudes measured here. Escaping oxygen atoms rapidly pass through this region on hyperbolic trajectories, going on to become the dominant component at altitudes > 4 Mars radii where reaction channel

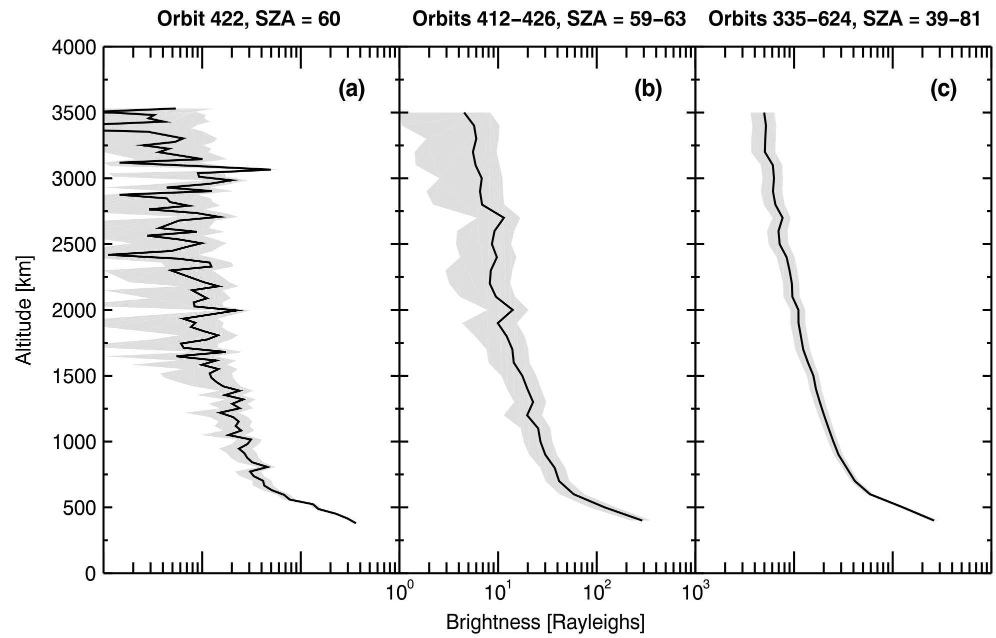

Figure 3. Altitude brightness profiles of coronal oxygen, with 3σ uncertainties in gray. This does not include the 25% systematic IUVS calibration uncertainty. (a) A single profile from orbit 422 with native altitude sampling; (b) an averaged profile using orbits 412, 414, 416, 422, and 426 binned at 100 km resolution; (c) an averaged profile using orbits 335–624 binned at 100 km resolution, approximating a global average. Each altitude bin represents 30–40 min of integration time.

((1d)) has insufficient energy to reach. Though it is somewhat dubious to ascribe a temperature to the non-Maxwellian bound hot oxygen population, assigning a characteristic energy is not inappropriate. The simplest model is that of a monoenergetic bound population with local spherical symmetry, which is then integrated through for a range of line of sight tangent altitudes to obtain a column density profile. Because the 130.4 nm line is optically thin in the corona, the slope of this column density profile can be directly related to the brightness profiles obtained from IUVS. We neglect here the illumination contributed by 130.4 nm light reflected back upward from the optically thick cold oxygen. Using this simple model and performing a least mean squares fit to the global average profile from 1000–3500 km, we find that the observations are best reproduced by a population originating in the ionosphere with a characteristic kinetic energy of 1.1 eV. This value is consistent with non-thermal oxygen atoms being produced by dissociative recombination of O_2^+ (equation (1a)–(1e)) and undergoing a small number of collisions before reaching the exosphere. Agreement in slope between predicted and IUVS observed brightness profiles has also been found in a preliminary comparison using the detailed M-AMPS model [*Lee et al.*, 2015].

3.2. Coronal Correlation With Solar EUV Input

Since dissociative recombination of ions on the topside of the ionosphere is thought to be the primary source of hot oxygen at Mars, it is reasonable to expect that the coronal density would respond to variations in the solar input of ionizing radiation. Fortunately, as part of its payload the MAVEN mission carries the EUVM instrument [*Eparvier et al.*, 2015], which is designed to monitor solar output with three photodiode channels at selected wavelengths. Of these, channel A, which covers 17–22 nm, is the most direct proxy for the incident photoionizing solar flux at Mars.

The time period from orbits 335–438 (2014 day of year 335–355) was found to have good data coverage by both EUVM and IUVS, as well as containing the majority of a solar rotation period. This made it attractive for investigating correlations between coronal oxygen and solar input. The average brightness of the 130.4 nm triplet from 700–1500 km was taken as an indicator of the hot coronal density for individual orbits. Our results are not very sensitive to the exact altitude range used, as long as it is from the region where hot oxygen dominates and there is sufficient signal. We then compared the IUVS data with daily averages for the calibrated EUVM 17–22 nm flux and the solar 130.4 nm emission derived from the FISM model

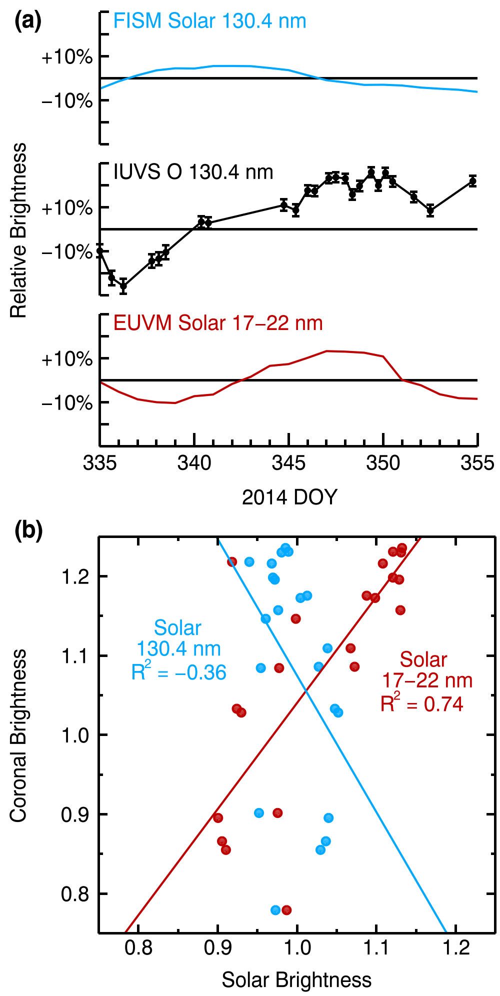

Figure 4. Comparison of the FISM model solar 130.4 nm brightness, the EUVM measured 17–22 nm solar flux, and IUVS observations of the 130.4 nm resonance line scattered from the Martian hot oxygen corona. (a) A time series of the three variables over the majority of a solar rotation period, demonstrating that the coronal brightness tends to track the solar flux at 17–22 nm. IUVS observations are shown with 1σ uncertainties. (b) Linear regression of the two solar inputs with the coronal brightness.

[*Chamberlin et al.*, 2007; *Thiemann et al.*, 2014]. Coronal oxygen brightness is expected to vary positively with both of these solar inputs: the first because it produces the ions necessary for dissociative recombination and the second because it is the source of illumination for the oxygen resonance line scattering that IUVS observes.

The details of our comparison are shown in Figure 4. Incidentally, the solar 130.4 nm line and EUV emissions were anticorrelated during the selected period. There is also a clear upward trend in the IUVS brightness, some part of which is likely due to the monotonic decrease in SZA from 80.8° to 56.8° over this time. Detailed modeling is required to accurately quantify this systematic. The current data set suggests that variations in the brightness of the hot coronal oxygen population at Mars are more closely associated with changes in ionizing solar EUV flux rather than the illuminating solar 130.4 nm line. This is not particularly surprising, as the EUV flux naturally exhibits a significantly greater variability than the 130.4 nm solar line. What is important is that these variations derive from fluctuations in the ionospheric generation of hot oxygen. By extension, these observations by IUVS and EUVM provide insight into the underlying physics driving variations in the escape rate of atomic oxygen from Mars at the present day. This is valuable for modelers who seek to understand the upper atmosphere under varying external forcings in order to more reliably extrapolate loss to space through Martian history. However, it is also a cautionary result in that care must be taken to account for changes in solar input when comparing models to observations made at different times in the MAVEN mission.

4. Conclusion

We have presented the first observations of the hot oxygen corona by MAVEN IUVS. These measurements confirm the presence of this long anticipated feature of the Martian exosphere and offer an invaluable way of probing the mechanisms driving escape of atomic oxygen at the present day. Correlation with EUVM measurements suggests a relationship between coronal density and solar photoionizing flux, supporting the expectation that dissociative recombination in the ionosphere is the primary source of hot oxygen at Mars. A variety of future studies are possible with the extensive coronal oxygen data set that IUVS has begun to acquire. These include validation of decades of theoretical modeling effort, a search for the signature of atmospheric sputtering, and ascertaining the effect of loss to space on the atmospheric evolution of Martian CO_2 and H_2O reservoirs.

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