PHOTOCHEMICAL ESCAPE OF CARBON FROM MARS: GREATER THAN PREVIOUSLY THOUGHT? R. J. Lillis[1], D. Y. Lo[2], J. I. Deighan[3], J. L. Fox[4], R. Yelle[2], M. K. Elrod[5], Y. Lee[5], M. Benna[5], B. M. Jakosky[5]

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Introduction: The story of the near-disappearance of Mars' early thick (>500 mbar) CO_2 atmosphere contains an interesting conundrum: the fate of atmospheric carbon. Carbon sequestration in the form of polar ice, clathrates, adsorbed CO_2, and carbon-bearing minerals, seems to be able to account for < 100 mbar [1]. The MAVEN mission has recently shown the plausibility of several hundred millibars worth of oxygen having been lost to space [2] but carbon escape rates have been estimated to be 1-2 orders of magnitude lower [3, 4]. There is currently no adequate explanation of the fate of this "missing" carbon. One of the major escape processes for both carbon and oxygen is known as photochemical escape, which is broadly defined as a process by which a) an exothermic reaction in the atmosphere results in an upward-traveling neutral particle whose velocity exceeds planetary escape velocity and b) the particle is not prevented from escaping through any subsequent collisions [5]. Here we re-examine the photochemical escape of carbon using both MAVEN data and updated model inputs.

Dataset: we use near-periapsis (<400 km altitude) data from two MAVEN instruments: the Extreme Ultraviolet Monitor (EUVM) measures solar ultraviolet radiation in 3 bands, from which full spectra from 0-200 nm can be estimated [6, 7] and the Neutral Gas and Ion Mass Spectrometer (NGIMS) measures neutral and ion densities [8]. We use MAVEN data from February 1, 2015 to November, 2018.

Calculating instantaneous escape fluxes. The primary source of hot carbon in the Martian atmosphere is the photodissociation of carbon monoxide (CO) [3, 4]. Figure 1 shows how we will calculate hot carbon escape fluxes for each MAVEN periapsis pass, using a combination of measured quantities, experimental laboratory data and models. For each profile of in situ measurements, we make several calculations, each as a function of altitude. The first uses EUV spectral irradiance and CO densities to calculate rates of CO photodissociation, and hence production of hot carbon atoms. The second uses irradiance and known thresholds for the CO photodissociation, plus conservation of energy and momentum, to calculate the probability distribution for the initial energies of the resulting hot carbon atoms (Figure 2). Last is a Monte Carlo

hot atom transport model that takes that distribution of initial C energies and the measured neutral density profiles and calculates the probability that a hot atom born at that altitude will escape. We then multiply together the profiles of hot atom production and escape probability to get profiles of the production rate of escaping atoms. This is integrated with respect to altitude to give us the escape flux of hot carbon atoms for that periapsis pass.
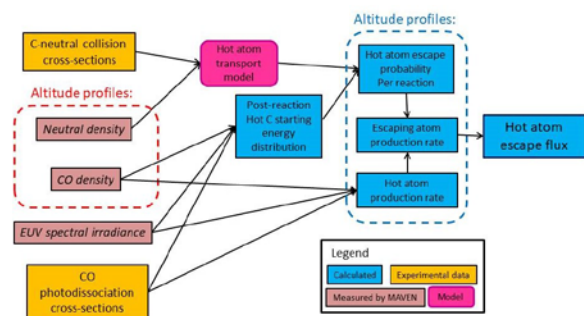

Figure 1: Flowchart of the calculation of hot carbon escape from measured altitude profiles of neutral densities.
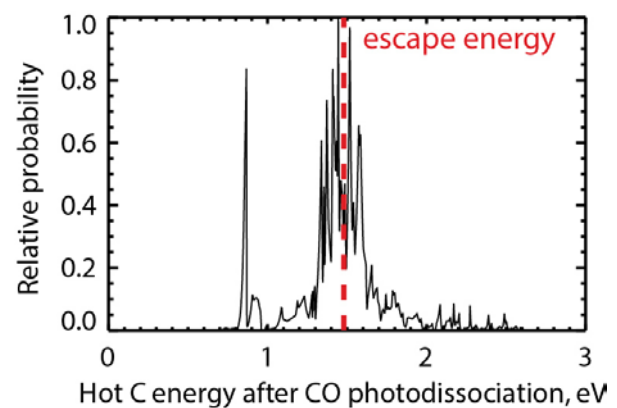

Figure 2: Sample calculation of initial energy distribution of carbon atoms following CO photodissociation.

The importance of hyperfine resolution. The production rate of hot carbon atoms is calculated by multiplying, as a function of wavelength, the CO photodissociation cross-section and the solar EUV spectral irradiance, then integrating over wavelength. However, work on this topic up to the present has not taken into account the hyperfine structure of both the CO photo-

dissociation cross-sections and solar EUV spectra. In this work we use the high resolution "Leiden" cross-section database [9] at 0.00001 nm resolution and the SUMER "solar quiet" solar ultraviolet spectrum at 0.004 nm 10]. Figure 3 shows an example calculation of the altitude profile of the rate of CO photodissociation, i.e. the production rate of hot carbon atoms, using low-and high-resolution cross-sections and solar spectra. *The bottom panel of figure 3 clearly shows that the high resolution products result in ~20 times larger hot C production rates.*
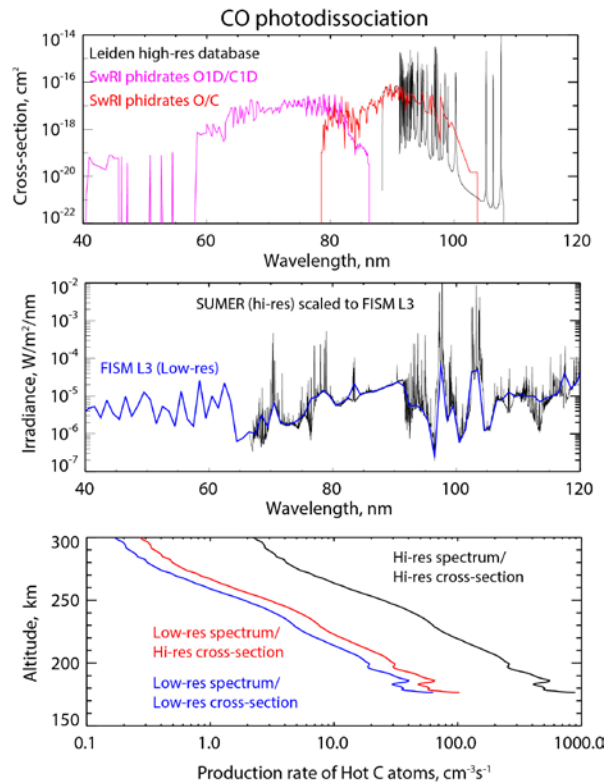

Figure 3: Demonstration of the importance of hyperfine resolution in calculating CO photodissociation rates. Thin black lines show high resolution cross-section (top panel) and solar EUV spectrum (middle panel), in comparison to commonly-used cross-sections (pink and red, top panel) and 1 nm resolution solar spectra (blue, middle panel). The bottom panel shows a much larger calculated production rate when both high-resolution products are used.

Conclusions and next steps: At LPSC we will show full escape rate calculations based on MAVEN in situ data, according to the scheme shown in figure 1. By then we may have revised neutral CO densities from the NGIMS instrument on MAVEN. In addition to these in situ-based estimates of C photochemical escape, an accurate picture of carbon escape will need to

be consistent with remote-sensing measurements from the Imaging Ultraviolet Spectrograph (IUVS) of fluorescent carbon emissions from the corona and detection of C^+ pickup ions by the Suprathermal and Thermal Ion Composition (STATIC) analyzer. These analyses are ongoing, and will hopefully lead to a detailed understanding of the role that carbon escape versus sequestration has played in Mars' climate evolution.

References: [1] Jakosky and Edwards, Nature Astronomy, 2018, [2] Jakosky et al., Icarus, 2018, [3] Groller et al, PSS, 2014 [4] Cui et al., A&A, 2018, [5] Lillis et al., JGR, 2017, [6] Eparvier et al., SSR, 2015, [7] Thiemann et al., JGR, 2017, [8] Mahaffy et al., SSR, 2015, [9] Heays et al., A&A, 2017, [10] Curdt et al., A&A, 2001.