MARS CLIMATE CONTROLS ATMOSPHERIC ESCAPE: DUST-DRIVEN ESCAPE FROM SURFACE TO SPACE WITH MRO/MCS, TGO/NOMAD, TGO/ACS, AND MAVEN/IUVS.

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Mars has lost most of its initial water to space as atomic H and O. The H portion of this loss was long thought to be controlled by the O loss via a photochemical feedback cycle that ensures planetary redox neutrality [1, 2]. Recent measurements of H loss, dust activity, and middle atmospheric water content have shown that each of these vary strongly with season, suggesting a causal connection between climate cycles that drive dust and H escape [3-10]. However, no prior study has captured the full chain of events leading to H loss. Here we present measurements from the Mars Year 34 regional C storm (Jan-Feb 2019), unambiguously establishing that even regional dust events enhance planetary H loss by a factor of several. Because this storm occurred after perihelion and southern summer solstice in the declining phase of the seasonal trend, these observations allow us to conclude that dust, not season or EUV flux, is responsible for the enhanced escape. Combining dust, ice, and temperature measurements from MRO/MCS, water vapor measurements from TGO/NOMAD and TGO/ACS, and cloud and hydrogen measurements from MAVEN/IUVS allows us to establish the timescale of dust impacts on the water and H abundances of the upper atmosphere. We find that it takes approximately one week for lower atmospheric dust to affect water abundances at 60 km, and an additional week for this water to induce a change in the upper atmospheric H inventory and escape rate. Our results suggest that in addition to escape rates controlling the climate system of Mars on long timescales, feedback of climate and dust cycles on escape is possible and strong, introducing the possibility of a planetary death spiral as atmosphere is lost.

Background: Early models for atmospheric escape at Mars [1,2] posited a strong cold trap similar to Earth's, with water confined to the troposphere by declining temperatures with altitude and efficient condensation. Under this scene, long-term evolution of the atmospheric water inventory is governed by a photochemical feedback cycle in which thermal hydrogen escape is controlled by the inventory of molecular hydrogen (H2), an abundant non-condensable species that can carry H to the upper atmosphere. H2 inventories are in turn controlled by the atmospheric O2 ratio, which responds to O escape on ~10-million year timescales. In this classical scheme, H escape responds to the solar forcing that controls O loss, with no strong response to seasonal or climate cycles.

Evidence now suggests the lower and upper atmosphere of Mars are more closely connected than previously realized. Mars Express solar occultations detected water at high altitude in excess of saturation [3], suggesting that more effective transport and/or less efficient condensation than previously expected. The hydrogen inventory of the upper atmosphere was seen by Mars Express and the Hubble Space Telescope to be strongly responsive to season [4,5,6], with the highest escape rates in Southern Summer. Photochemical modeling suggested that high-altitude water could produce a rapid change in coronal H inventory [7]. Soon afterward, MRO cloud observations were used to infer the middle atmospheric water abundance [8], showing that it responds strongly to dust events and is correlated with high H loss. Further observations with Mars Express showed that water abundance at high altitude is enhanced in every southern summer at southern latitudes, with a global response in dust storm years attributed to enhanced interhemispheric transport [9]. Recent observations during the 2018 global dust storm measured middle atmospheric water with higher precision, confirming its correlation with atmospheric dust and placing limits on the speed of the response [10].

Observations: We present observations made during the Mars Year 34 regional C storm, which occurred from Jan-Feb 2019. For clarity, we emphasize that the regional dust storm we study here is not the global dust storm that occurred earlier in the same Mars year. The reason we focus on the regional storm is twofold: First, and most importantly, the MAVEN orbit was roughly aligned with the terminator during the global event, which makes determining the H abundance of the corona and the escape rate difficult; Second, focusing on the C storm allows us to attribute the effects we observe to dust alone, without the complication of disentangling a rising seasonal trend from the observations.

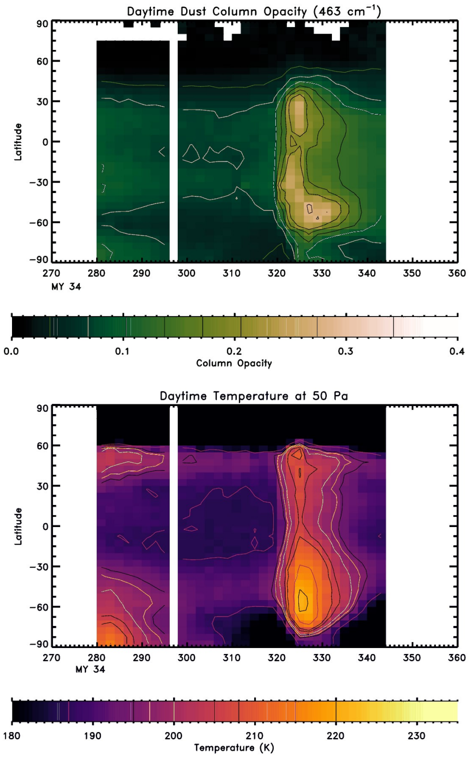

Figure 1: MRO/MCS daytime dust and temperature in the vicinity of the C event. Ls 320 corresponds roughly to 7 Jan 2019 and Ls 340 to 15 Feb.

Our observations are summarized in Figures 1 and 2. MRO/MCS measurements of vertical dust opacity show that the storm began near 7 January, peaked near 15 January, and declined into mid-February. As soon as the dust is introduced, atmospheric temperatures respond strongly, increasing by ~50 K at the 5 Pa level and showing a strong shift in circulation pattern that significantly warms the poles. Due to this warming, ice condensation is inhibited and vertical ice opacities drop.

In the middle atmosphere, TGO observes little to no water before the storm, but water line depths increase immediately after the storm begins and peak approximately one week into the event. After the peak of the event, the TGO orbit allows no occultations, introducing a gap in the water abundance timeline. After occultations resume, water abundance is seen to be elevated well into the declining phase of the storm.

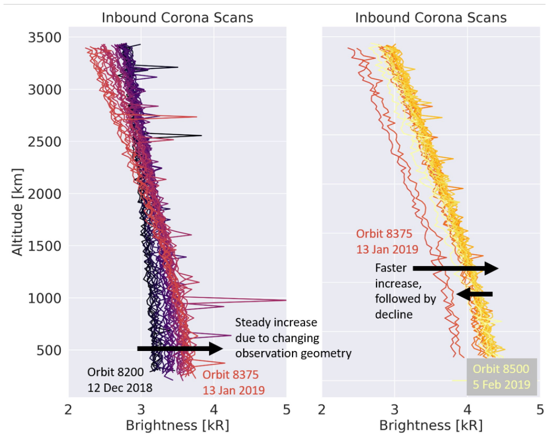

Figure 2: MAVEN IUVS Lyman alpha brightness profiles. Profiles evolve smoothly due to orbit precession until about 13 Jan, when these profiles increase uniformly in brightness at all altitudes with no corresponding change in solar brightness. Afterward, profiles return to normal on a slower timescale.

At the highest altitudes, MAVEN observes the Mars hydrogen corona in Lyman alpha. Because this emission is optically thick, the brightness observed by MAVEN is a function of the H abundance, the solar brightness, and the observation geometry. These observations occurred as MAVEN's orbit apoapsis was slowly evolving in the vicinity of the subsolar point, minimizing geometrical effects. The brightnesses we report here have been normalized using MAVEN-measured solar brightnesses from EUVM, so that what remains is due to geophysical variation in hydrogen.

We observe a strong increase in H abundance soon after the dust storm begins, with a peak response nearly one week after water appears at 60km. H brightnesses remain elevated well into February, as long as the water is present. The brightening occurs at all altitudes, providing strong evidence for an increase in H loss. As a corroborating observation, we see greatly enhanced proton aurora occurrence rates as brightening in Ly-a near 150km due to solar wind ENAs produced in the denser upstream corona at this time depositing their energy in the atmosphere.

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