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Crismani, MMJ, Tyo, RM, Schneider, NM et al. (2023) Martian Meteoric Mg<sup>+</sup>: Atmospheric Distribution and Variability From MAVEN/IUVS. *Journal of Geophysical Research*, 128 (1). e2022JE007315. ISSN: 2169-9097

<https://doi.org/10.1029/2022je007315>

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## RESEARCH ARTICLE

10.1029/2022JE007315

### Key Points:

- Eight Earth years of Mars Atmosphere and Volatile Evolution/Imaging Ultraviolet Spectrograph observations show that Mars' persistent meteoric metal ion layer is more dynamic than initially assumed
- $Mg^+$  layer peak altitude, abundance, and top and bottom side slopes vary significantly over the observed time period
- The relative absence of northern hemispheric  $Mg^+$  during southern summer is surprising and may be related to lower atmospheric dust loading

### Supporting Information:

Supporting Information may be found in the online version of this article.

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**Citation:**

Crismani, M. M. J., Tyo, R. M., Schneider, N. M., Plane, J. M. C., Feng, W., Carrillo-Sánchez, J. D., et al. (2023). Martian meteoric  $Mg^{+}$ : Atmospheric distribution and variability from MAVEN/IUVS. *Journal of Geophysical Research: Planets*, 128, e2022JE007315. <https://doi.org/10.1029/2022JE007315>

Received 20 APR 2022

Accepted 23 DEC 2022

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# Martian Meteoric Mg<sup>+</sup>: Atmospheric Distribution and Variability From MAVEN/IUVS

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**Abstract** Since the discovery of atmospheric  $\text{Mg}^+$  on Mars in 2015 by the Mars Atmosphere and Volatile Evolution mission, there have been almost continuous observations of this meteoric ion layer in a variety of seasons, local times, and latitudes. Here, we present the most comprehensive set of observations of the subsistent metal ion layer at Mars, constructing the first grand composite maps from pooled medians of subsamples of a metallic ion species. These maps demonstrate that  $\text{Mg}^+$  appears in almost all conditions when illuminated, with peak density values varying between 100 and 500  $\text{cm}^{-3}$ , dependent on season and local time. There exists significant latitudinal variation within a given season, indicating that  $\text{Mg}^+$  is not simply an inert tracer, but may instead be influenced by the meteoric input distribution and/or atmospheric dynamics and chemistry. Geographic maps of  $\text{Mg}^+$  density as a function of latitude and longitude indicate the influence of atmospheric tides, and there is no apparent correlation with remnant crustal magnetic fields. This work also presents counter-intuitive results, such as a reduction of  $\text{Mg}^+$  ions in the northern hemisphere during Northern Winter in an apparent correlation with dust aerosols.

### Plain Language Summary

Metallic atoms in a planet's atmosphere are present when interplanetary dust particles burn up, releasing atomic species not typically found in the lower atmosphere. The discovery of a high altitude metallic layer on Mars in 2015 has led to continued monitoring in a variety of seasons across the entire planet. These results demonstrate that this magnesium ion ( $\text{Mg}^+$ ) layer appears throughout the year, with variations in peak abundances and layer heights, due to interactions with the background atmosphere. These variations track the dynamics of the middle atmosphere, providing insight into global climate patterns and may inform our understanding of seasonal deposition of interplanetary dust particles and their sources. This first-order analysis supports future modeling efforts and provides model challenges to be understood, both of which can be explored in detail with time varying full planet climate modeling.

## 1. Introduction

The NASA Mars Atmosphere and Volatile Evolution's (MAVEN) Imaging Ultraviolet Spectrograph (IUVS) (McClintock et al., 2015) observes Martian atmospheric molecules, atoms, and ions since its orbital insertion in 2014. This instrument observes in the far and middle UV range (110–190 and 190–340 nm), measuring atmospheric emissions from H, the dissociation and ionization products of CO<sub>2</sub>, atomic, and molecular species such as O and N<sub>2</sub>, as well as meteoric ions and neutrals. While MAVEN's primary mission was intended to study the upper atmosphere and atmospheric escape to space (Jakosky et al., 2015, 2018), it has been able to study a variety of additional important phenomena, from the development of twilight cloud bands and high altitude aerosol layers (Connour et al., 2020; Jiang et al., 2019; Stevens et al., 2017), mapping three different varieties of aurora (Deighan et al., 2018; Schneider, Deighan, Jain, et al., 2015; Schneider et al., 2018) and helping to characterize the role of tides in the Martian atmosphere (Lo et al., 2015; Schneider et al., 2020). However, the unexpected discovery of meteoric ions, both from Comet Siding Spring (M. M. J. Crismani et al., 2018; Schneider, Deighan, Stewart, et al., 2015) and interplanetary dust particles as a persistent background (M. M. J. Crismani et al., 2017) has led to novel chemical schemes in the mesosphere and posed new challenges for models.

Ablation, the thermal release of ions and atoms from their original minerals, occurs in planetary atmospheres when interplanetary dust particles at orbital velocities hypersonically collide with atmospheric gases. This causes

melting, vaporization, and the subsequent release of ingrain metallic atoms (e.g., Mg, Fe, and Na) into the upper atmosphere (Plane, 1991). Ablation of the primarily metallic species typically occurs at an altitude where the pressure is  $\sim 1$   $\mu$ bar, between 60 and 100 km (Plane et al., 2017), where entry speeds for particles in prograde and retrograde orbits range between 5.5 and 59.5 km s<sup>-1</sup> at Mars for Jupiter Family Comet and Asteroidal sources as slow particles whose average velocities are closer to the escape velocity of the planet and long-period comet particles are mainly populated by particles in retrograde orbits (Carrillo-Sánchez et al., 2020). Terrestrial metallic species have been previously studied, both to understand the ablation chemistry and as a way to investigate mesospheric dynamics (see (Plane et al., 2015) for a detailed summary). Metallic ions and neutrals (Mg, Fe, and Na) have been observed both during comet Siding Spring and thereafter in a persistent layer in reduced quantities (Benna et al., 2015; Grebowsky et al., 2017) as the MAVEN-Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument samples are several scale heights (140 km and higher) above the peak of the layer.

Metallic atoms charge exchange with ambient molecular ions (particularly O<sub>2</sub><sup>+</sup>) to form atomic metal ions; a fraction also ionizes through hyperthermal collisions with air molecules during ablation, recombines with free electrons, and undergoes other chemical reactions. Subsequent chemical processing of the Mg atoms and ions occurs, where charge exchange with ambient ions produces Mg<sup>+</sup> and electron recombination produces neutral Mg, with chemical loss of the metal species through the formation of meteoric smoke, potentially leading to mesospheric cloud nucleation (Plane et al., 2018). The chemical pathway that may lead to mesospheric cloud formation arose from an attempt to understand the absence of neutral Mg, observable by IUVS yet not seen in the Martian atmosphere, relying on the presence of water vapor to form large Mg-carbonates that permit cloud nucleation at higher temperatures than traditional formation schemes (Plane et al., 2018).

The density of atmospheric metallic ions is dependent on the fluence of sporadic meteors, which is modeled by a Meteoric Input Function (MIF; Carrillo-Sánchez et al., 2020; Janches et al., 2020), laboratory-measured ablation fractions as well as ionization and chemical reaction rates (Bones et al., 2016; Martín et al., 2017; Plane et al., 2015). The lifetime of Mg<sup>+</sup> with respect to neutralization is 1–2 orders of magnitude higher than other ambient molecular ions ( $\sim$ hours/days compared to minutes (Plane et al., 2018; Whalley & Plane, 2010)), which permits Mg<sup>+</sup> to trace atmospheric dynamics where observable. Transport processes such as advection, horizontal transport, etc. simultaneously serve to redistribute the metal ions as seen in the comet Siding Spring shower (Benna et al., 2015; M. M. J. Crismani et al., 2018; Schneider, Deighan, Jain, et al., 2015), and these dynamic effects are not readily separated without a Global Circulation Model (GCM) that includes meteoric ion chemistry.

## 2. Observations and Data Analysis

The MAVEN spacecraft has a uniquely elliptical orbit that benefits from atmospheric drag and subsequent fuel burns to change the location of the periapse in latitude and local time. Over the course of more than seven Earth years, MAVEN has been able to observe a variety of Martian seasons, geographic latitudes and longitudes, as well as local times. During the orbital periapse segment, the spacecraft descends through the upper atmosphere (down to 140–160 km) so that in situ measurements of atmospheric atoms and ions, as well as ambient E and B fields can be measured throughout. This spacecraft orbital geometry provides coverage of local times, solar zenith angles (SZAs), and full longitude coverage over about 4–5 orbits (each orbit is  $\sim 5$  hr). IUVS is able to create vertical profiles during its periapse orbital segment when the instrument is oriented orthogonally to the motion of the spacecraft. Using the Mid-UltraViolet (MUV) resonant fluorescent scattering of MgII at 285 nm, IUVS investigates the abundance and structure of this meteoric ion above 60 km, where scattered solar light serves to limit the lowest altitudes from observation. In this work, we present the first global results of near continuous monitoring of Mg<sup>+</sup> at Mars with implications for the formation of mesospheric cloud nuclei (Hartwick et al., 2019; Plane et al., 2018) and to provide the first constraints on a seasonally varying meteor input function MIF (Carrillo-Sánchez et al., 2020; Janches et al., 2020). As has been successfully accomplished at Earth (Feng et al., 2013; Langowski et al., 2015), this global view on meteoric ions also permits a direct investigation of the upper atmosphere, where the dynamics and chemistry can be constrained with a novel set of observations.

### 2.1. Observing Geometry

IUVS has varying observation modes for each orbit segment of the MAVEN; however, to retrieve meteoric ion abundances, only the limb-sounding segments are utilized as nadir measurements lack the necessary limb

enhancement factor for this trace species (Chamberlain & Hunten, 1990). For this work, the periapse and in/outbound segments on the orbit were utilized, when the spacecraft is between 140 and 1,000 km from the planet's surface. The former refers to measurements made near the periapse with scans oriented perpendicular to the spacecraft motion. The latter refers to the two orbit segments when the spacecraft is well outside the atmosphere, just before and just after the periapse segment, to ensure at least one daylight segment with a similar scanning motion. In the limb scanning mode, the relative size of a pixel on the tangent point is larger than at the periapse, due to the increased distance from Mars; nevertheless, reliable retrievals are readily extracted from these data.

When MAVEN is moving through its periapse orbital segment, IUVS uses a scan mirror to scan across the limb and create vertical profiles of emitted atmospheric radiation over the altitude range of 60–250 km. IUVS takes up to 12 periapse limb scans of each orbit in a ~22 min observation time period spanning ~45° across Mars and 6 in/outbound limb scans between 25° and 100° around the planet depending on the tangent point's orientation to the surface. To facilitate MAVEN's extended mission, in April 2019, the spacecraft periapse was raised between 180 and 230 km and the orbit shortened to ~4 hr, where we now take 14 scans rather than 12. Together, these data sets constitute almost continuous monitoring of the Martian atmosphere from 2015 to 2022, although only dayside data are utilized as solar fluorescent scattering is necessary to observe Mg<sup>+</sup> with IUVS (Schneider, Deighan, Stewart, et al., 2015).

## 2.2. Data Processing

The MgII doublet emission observed herein is caused by resonant fluorescent solar scattering of UV photons at 280 nm as opposed to direct excitation emission during ablation. To model the spectrum of these metallic species, its line positions, the atomic constants for resonant scattering, and the solar Mid-UV spectrum (Dymond et al., 2003; Kelleher & Podobedova, 2008; Smith et al., 1995) were utilized. Multiple linear regression fits of independent spectral components are able to extract the MgII doublet brightness from a composite spectrum fit of emission of ambient atmospheric gases (CO, CO<sub>2</sub><sup>+</sup>, N<sub>2</sub>, etc.) and were subsequently co-added (M. M. J. Crismani et al., 2018; Stevens et al., 2015). Data processing techniques for these UV spectra have been previously outlined in greater detail in other MAVEN/IUVS papers (Evans et al., 2015; M. M. J. Crismani et al., 2017, 2018; Jain et al., 2015; Schneider, Deighan, Jain, et al., 2015; Stevens et al., 2015).

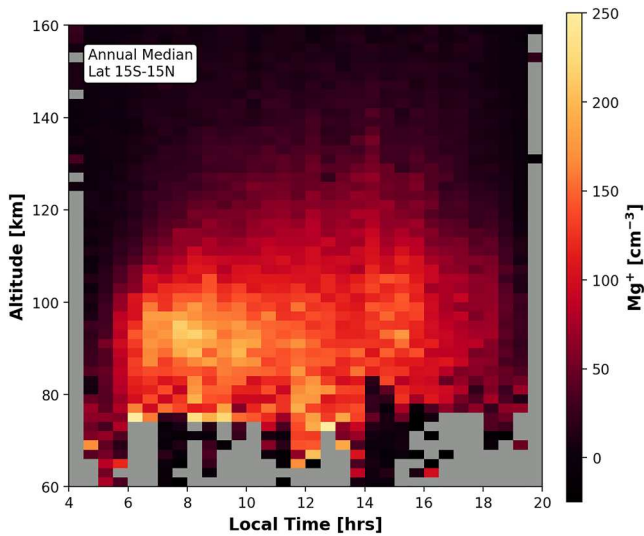
When Mg<sup>+</sup> densities are small enough (<2,500 cm<sup>-3</sup>) such that they can be considered optically thin at the line center rather than using a forward model retrieval (M. M. J. Crismani et al., 2018); the Mg<sup>+</sup> concentration can be retrieved using a simple Abel transform (Chamberlain & Hunten, 1990), which requires single scattering with no absorption. Reported retrieved density uncertainties are calculated through traditional error propagation of the IUVS instrument random and estimated uncertainties. Systematic retrieved density uncertainties are a combination of uncertainties in the parameters (scale height and atomic g-factors) as well as the IUVS MUV calibration uncertainties, estimated to be ±30%. All of the data described herein are considered optically thin as the peak densities observed do not greatly exceed 500 cm<sup>-3</sup>. This discussion has been previously covered in greater detail in (M. M. J. Crismani et al., 2017, 2018).

This work benefits from many years of observation of Mg<sup>+</sup> abundance, and two new post-retrieval data analysis filters were implemented to create statistically useful averages and medians. First, as MgII emission is due to resonant scattering of solar photons, this necessarily requires that the location of the tangent point of any observation considered in an average or median should be in “daylight.” At the surface this concept is simple, where the solar photons are extinguished at SZAs larger than 90°. However, at any altitude above the surface solar photons may illuminate tangent points past 90° SZA. The formula for the maximum illuminated SZA ( $\theta_{\max}$ ) for given tangent point at an altitude ( $A$ ) is:

$$\theta_{\max} = 90^\circ + \arccos\left(\frac{R_{\text{Mars}}}{R_{\text{Mars}} + A}\right)$$

where  $R_{\text{Mars}}$  is the mean radius of Mars, 3,390 km. Moreover, this filter serves to caution the reader that observations of nightside Mg<sup>+</sup> with IUVS are impossible and would require a separate study from the MAVEN/NGIMS instrument (Mahaffy et al., 2015); however, these data only sample the topside of the meteoric metal profiles (above 140 km) and are not representative of the peak abundances or meteoric influxes.

The second important caveat to note when interpreting Mg<sup>+</sup> retrievals is that at altitudes below 60 km, the scattered solar continuum dominates the IUVS detector signal. While the source of this scattered continuum is likely



**Figure 1.** The median  $\text{Mg}^+$  concentration (atoms per cubic centimeter) at equatorial latitudes, over the mission to date (MY 32–36), plotted against altitude vertically and local time horizontally. A notable enhancement in  $\text{Mg}^+$  concentration appears in the dawn hours. This enhancement disappears at higher latitudes (see Figure S1 in Supporting Information S1), where the diurnal forcing is weaker. The dark gray color represents locations where insufficient data exist, here and in all subsequent figures.

to be aerosols in the lower atmosphere, the precise modeling of this feature is hampered by an apparent change in the spectral shape from high altitudes (above 150 km) to the lowest altitudes (60 km). Significant testing of appropriate continuum shapes has been undertaken; however, for the purposes of this work, it is important to note that when the strength of the scattered continuum is too great, any difference between the spectral fit and data will inevitably lead to erroneous retrievals. Characterization of the reliability of this difference was undertaken for this work and a practical limit was set when the solar signal exceeded brightnesses of 500 kR for periape data and 100 kR for limb data.

Extremely large and/or negative values exist after the retrieval process, which are not due to reliable fits, as seen in residual fit shapes, but instead may be caused by non-atmospheric instrumental effects. These include, but are not limited to, cosmic ray impacts on the detector, background stars falling in the optical path, improper temperature-dependent wavelength alignment, or any other combination of other random errors. To restrict the small fraction (<2%) of these outlying values from disproportionately affecting any results presented herein, binned medians are presented here rather than averages, where bin sizes were constructed to never permit a median of less than 10 observations in any subdivided geophysical grouping. While individual observation uncertainties are of the order 30%, the binned observations have a minimum number of observations of 10, which reduces this random uncertainty by the square root of 10 at the least. Therefore, the variations we see here, which are larger than 10%, are not expected to be due to orbit to orbit variation or instrument performance.

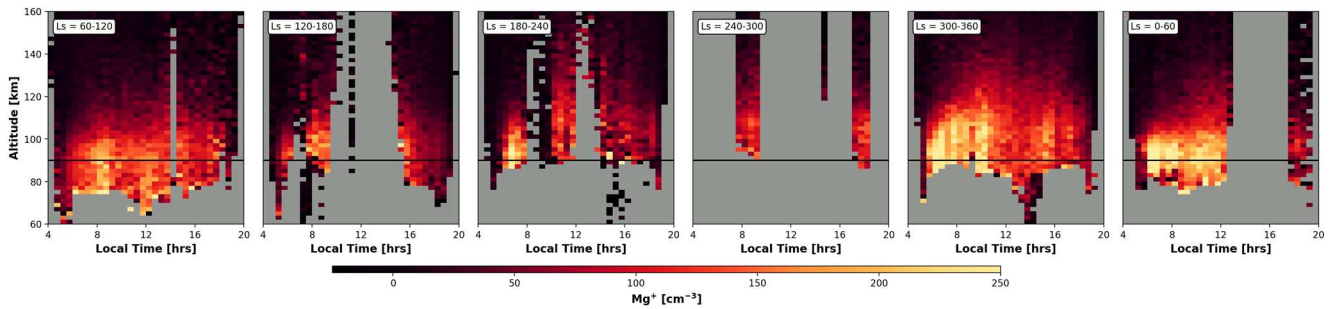
### 3. Results

With these constraints implemented in the data processing pipeline, this work draws on seven Earth years of data, from Martian Year (MY) 32–36, spanning all Solar Longitudes ( $L_S$ ), latitudes, and geographic longitudes. The results presented herein constitute the most comprehensive view of  $\text{Mg}^+$  at Mars, binned in several ways, comparing altitude, local times,  $L_S$ , latitude, and longitude. Note that the present paper does not investigate any interannual variability at the cost of completeness in these primary binning variables. Moreover, this work necessarily ignores the orbit to orbit variability and the drivers of that variability (meteor showers, ionospheric interactions with B-fields, etc.). Initial analysis searching for meteor shower correlations found these to be below the first-order effects described herein; therefore, these results are presented to permit any secondary effects, if observable, to be investigated in a subsequent manuscript.

#### 3.1. Equatorial Dawnside Enhancement

Figure 1 presents the grand composite view of equatorial ( $15^\circ\text{S} < \text{lat} < 15^\circ\text{N}$ )  $\text{Mg}^+$  as a function of local time over the eight Earth years (2014–2022) observation period. There exists a strong apparent dayside variation where peak values at 0800 hr exceed  $200 \text{ cm}^{-3}$  compared to those at 1,600 hr that are closer to  $100 \text{ cm}^{-3}$ . The dawn-side maximum in  $\text{Mg}^+$  concentration cannot be due to photo-ionization as this would cause a peak around midday or later. A potential explanation is the vertical transport of  $\text{Mg}^+$ ; the mixing ratio of  $\text{Mg}^+$  increases by a factor of  $\sim 5$  between 95 and 105 km (J. M. C. Plane et al., 2018), so downward transport of air from above 95 km during the night would explain the 2–3 fold increase in  $\text{Mg}^+$  number density at 95 km (Withers et al., 2011).

The previously published 1D model (Plane et al., 2018) showed that the  $\text{Mg}^+$  ion mixing ratio increases above 90 km, in agreement with IUVS measurements at low- and mid-latitudes. Therefore, downward transport of air from aloft will increase the  $\text{Mg}^+$  concentration around 90 km, as observed. The evidence for tidal descent comes from the temperature, which shows a marked increase between 0400 and 0800 hrs in this region, consistent with adiabatic heating of the descending air. Since ion-molecule chemistry is not strongly temperature-dependent, the change in reaction rates is a secondary effect: at higher temperatures, the rate at which  $\text{Mg}^+$  forms clusters with  $\text{CO}_2$  is reduced, which then reduces the rate of conversion to Mg via dissociative recombination with electrons. Therefore, the main tidal effect is to bring air with a higher  $\text{Mg}^+$  mixing ratio downwards. Dayside heating in the



**Figure 2.** The median dayside atmospheric Martian  $\text{Mg}^+$  (ions per cubic centimeter) for eight Earth years (2014–2022) is presented for six segmented “seasons” of the Martian Year (see text) beginning at  $L_s = 60^\circ$ – $120^\circ$  (near aphelion) with an altitude (km) shown vertically and local time (hr) horizontally, with an altitude reference at 90 km (black line). These data include all local times where  $\text{Mg}^+$  is illuminated by the Sun.

mesosphere and thermosphere has been observed over the MY, with heating in the afternoon and cooling toward the dawn and dusk terminator (Jain et al., 2021). Future 3D-GCM efforts will focus on comparing the  $\text{Mg}^+$  concentrations with the observed temperatures and model results.

### 3.2. Seasonal Shifts in Peak Ablation Altitude

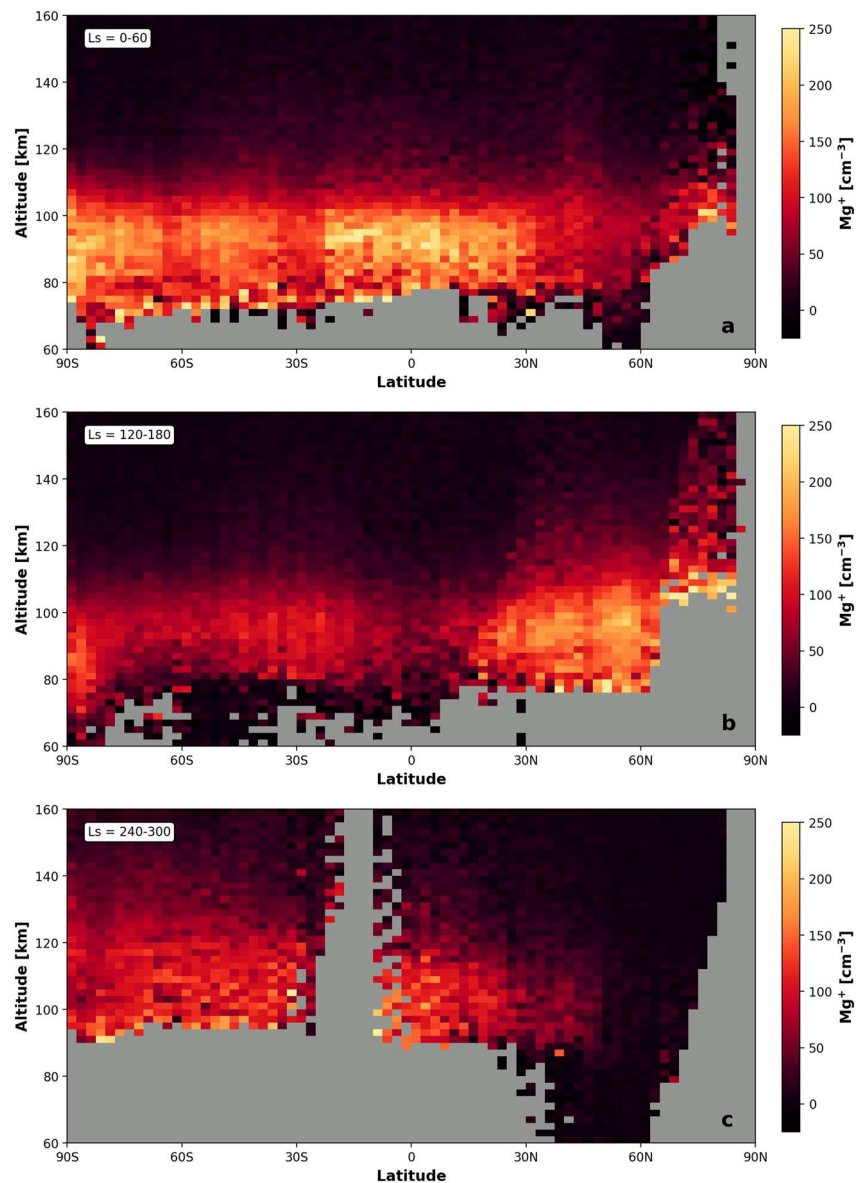
Figure 2 presents the median dayside equatorial ( $15^\circ\text{S} < \text{lat} < 15^\circ\text{N}$ ) atmospheric Martian  $\text{Mg}^+$  ( $\text{cm}^{-3}$ ) for all observations, where six “seasons” of the MY were delineated. Each of these “seasons” has a length of  $60^\circ L_s$ , where summer and winter solstices are centered around their own seasons, but the two equinoxes occur in the middle of the four pseudo-seasons, such as the end of Southern Early Spring ( $L_s = 120^\circ$ – $180^\circ$ ) and Southern Late Spring ( $L_s = 180^\circ$ – $240^\circ$ ). The framing of the seasons around the dynamical state of the atmosphere is utilized herein to link  $\text{Mg}^+$  abundances and peak altitudes with the larger atmospheric circulation patterns.

The leftmost panel of Figure 2 begins at  $L_s = 60^\circ$  (Southern Winter). The peak concentration of  $\text{Mg}^+$  appears at altitudes of 80–90 km when Laboratoire de Météorologie Dynamique-GCM (Millour et al., 2015) global mean temperatures demonstrate lower average atmospheric temperatures during aphelion. Moving left to right until panel d (Southern Summer), peak  $\text{Mg}^+$  appears at altitudes of 95–105 km, when modeled average temperatures increase to their highest during perihelion due to increased insolation. IUVS observations are obtained with respect to altitude; however, mesospheric pressures have been observed to vary with season (Jain et al., 2015; Jakosky et al., 2017; Slipski et al., 2018). Ablation of interplanetary dust particles is dependent on ambient pressure and temperature, with atmospheric chemistry controlling the top and bottom scale heights of the layer as well as the peak altitude as observed by IUVS. For example, cooling of the temperature vertical structure shifts the minimum atmospheric density (or pressure) level necessary to start thermal ablation to lower altitudes (Carrillo-Sánchez et al., 2015, 2020). However, the pressure level at which each meteoric metal is released is constant, where alkali elements—such as Na and K—are always released at 0.01 Pa, in contrast to the main metals—Mg, Si, and Fe—which are ablated when pressures exceed 0.1 Pa (Bones et al., 2016). The magnitude of the observed peak concentration of  $\text{Mg}^+$  is consistent throughout the year even with the diurnal enhancement on the dawn side as discussed in Section 3.1.

### 3.3. Latitudinal Distribution of $\text{Mg}^+$

A hemispheric view of dayside  $\text{Mg}^+$  with season (Figure 3), where altitudes (vertically) and latitude (horizontally) are presented for median solar illuminated (5–20 hr)  $\text{Mg}^+$  concentrations to highlight the use of meteoric ions as a tracer of mesospheric dynamics. This subset of seasons (for the remainder see Figure S1 in Supporting Information S1) show three unique sets of behaviors, potentially corresponding to global motions of the atmosphere.

During the southern late autumn (Figure 3a), the peak altitude of  $\text{Mg}^+$  concentration appears to slightly rise from the southern pole to the equator to northern latitudes, with the topside of the layer extending higher at equatorial latitudes than either the midlatitude or polar region. At equatorial latitudes, the scale heights of  $\text{Mg}^+$  are much shallower ( $\text{Mg}^+$  is more vertically extended) than near mid-northern or mid-southern latitudes, which may indicate that vertical mixing through eddy diffusion is rapid. This result is not surprising as these  $\text{Mg}^+$  ions are long lived (timescale of hours to days) and in contrast to ambient ions (e.g.,  $\text{O}_2^+$ , timescales of minutes) are not



**Figure 3.** Median  $\text{Mg}^+$  concentration (ions  $\text{cm}^{-3}$ ) as a function of altitude (vertically) and latitude (horizontally), where data collected over Mars Atmosphere and Volatile Evolution's mission is sorted by season. (a)  $L_s = 0^\circ\text{--}60^\circ$ : notable features include a rising peak altitude and an extended topside layer toward equatorial latitudes. (b)  $L_s = 120^\circ\text{--}180^\circ$ : a decrease in  $\text{Mg}^+$  near equatorial latitudes and a dichotomy between the hemispheres, with larger peak values of  $\text{Mg}^+$  at midlatitudes appearing in the North. (c)  $L_s = 240^\circ\text{--}300^\circ$ : a much higher abundance of  $\text{Mg}^+$  in the southern than the northern hemisphere.

produced in situ (Plane et al., 2018); therefore, the former traces the dynamics of the atmosphere and the latter shows the sources of ionization and resultant chemistry.

During the southern late spring (Figure 3b), the peak altitude of  $\text{Mg}^+$  at the south pole sinks to as low as 80 km, with a topside that extends to 100 km. While midlatitude abundances of  $\text{Mg}^+$  peak near 95–100 km, there is a noticeable decrease in  $\text{Mg}^+$  near equatorial latitudes. There is a marked dichotomy in the overall peak  $\text{Mg}^+$  abundance where there is more  $\text{Mg}^+$  in northern than southern hemispheres, seen also in Figure S1 in Supporting Information S1. Whether this is due to the meteor input distribution, dynamics, or meteoric chemistry should be investigated with subsequent modeling efforts that include each of these relevant drivers.

The most unexpected observation contained herein is the relative disappearance of  $\text{Mg}^+$  during southern summer (Figure 3c) despite good observational coverage in this period. During this period  $\text{Mg}^+$  at all latitudes becomes

reduced compared to any other season of the MY (see Figure S2 in Supporting Information S1).  $\text{Mg}^+$  is more vertically extended at southern latitudes with larger values at each altitude ( $\sim 120 \text{ cm}^{-3}$  at 120 km) compared to other seasons; however, these values are lower than typical peak values ( $\sim 250 \text{ cm}^{-3}$  at 100 km), with little to no  $\text{Mg}^+$  present in northern latitudes (above  $40^\circ\text{N}$ ). While the total number of observations during this season is not as well spread in local time as other seasons, comparisons within a single bracket of local times serve to confirm this result as we see consistent values (high or low) across latitudes in other seasons. Whereas during this season, the  $\text{Mg}^+$  appears to disappear at all local times and most altitudes moving toward high northern latitudes. Since this is southern summer, it should be noted that this is also potentially the dustiest time period of the MY (Montabone et al., 2020). While dust in the lower atmosphere has been linked to the propagation of water vapor in the mesosphere and as the lower atmosphere heats dramatically compared to non-dust storm years (A. A. Fedorova et al., 2020; A. Fedorova et al., 2018; Aoki et al., 2019; Chaffin et al., 2017, 2021; Chaufray et al., 2019; Guzewich et al., 2019; Kass et al., 2016; Neary et al., 2019; Streeter et al., 2020; Villanueva et al., 2021), there is no obvious explanation for what process dust in the lower atmosphere could remove  $\text{Mg}^+$  in the upper atmosphere.

### 3.4. Geographic Variations in $\text{Mg}^+$ and Absence of B-Field Influence

Solar thermal heating produces global atmospheric tides, longitudinal variations in temperature, density, and pressure whose periodicity are fractions of the Martian day (England et al., 2016; Forbes et al., 2020; Hanel et al., 1972; Lo et al., 2015; Schneider et al., 2020). These tides serve to redistribute energy throughout the atmosphere, both horizontally and through the vertical propagation of these tides. Tidal waves can be either migrating or non-migrating, where the former refers to sun-synchronous waves and the latter refers to waves that move either east or west relative to the apparent motion of the sun (including stationary relative to the surface). These tidal waves are denoted by their temporal harmonic, propagation direction, and wave number; for example, a diurnally propagating westward wave with wave number 3 would be called DW3.

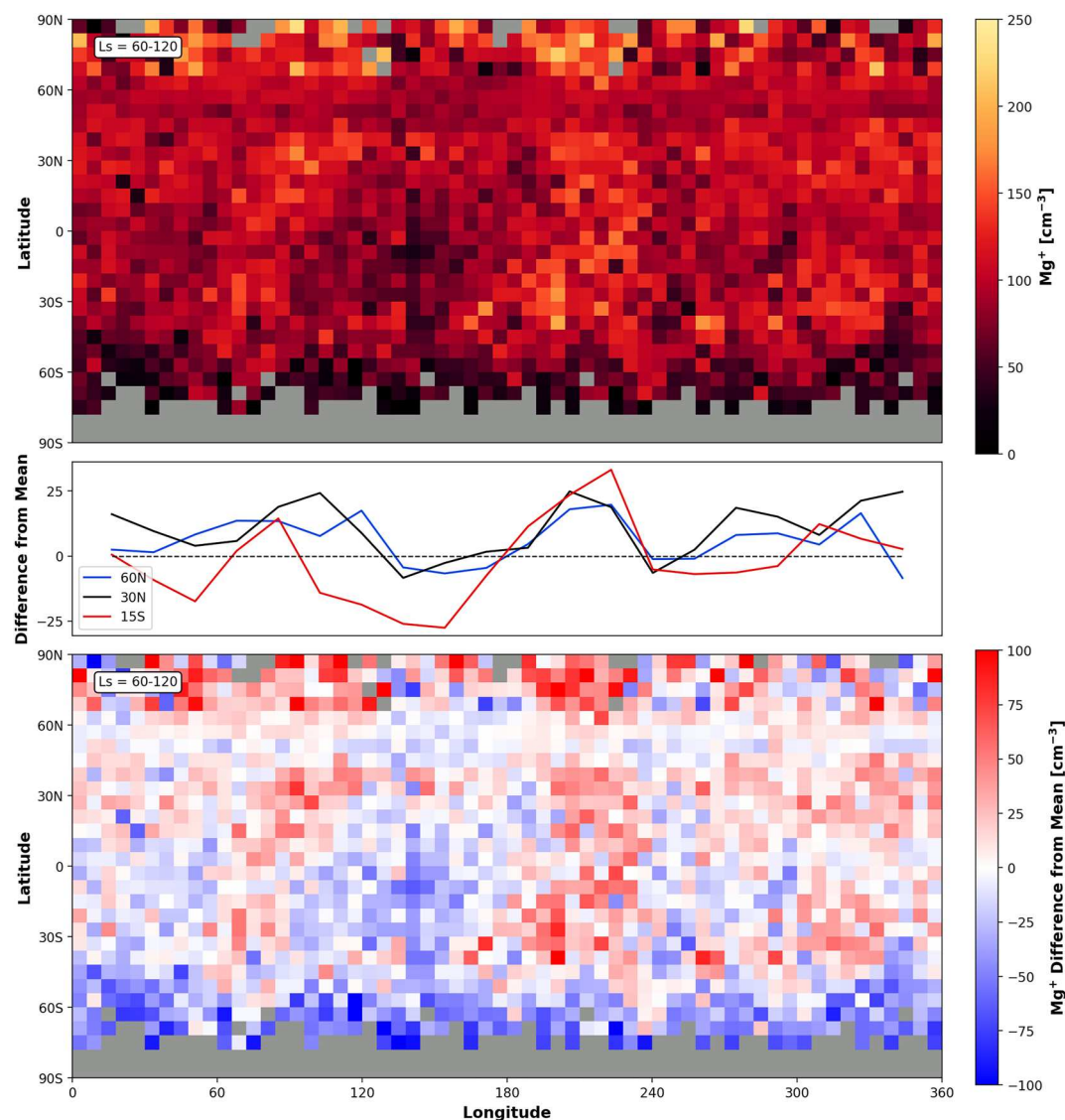
Figure 4 presents geographic variations in  $\text{Mg}^+$  during  $L_s = 60^\circ\text{--}120^\circ$ , where dayside medians and their differences show enhancements and reductions of  $\text{Mg}^+$ , whose origin is likely tidal. Averaging all of the dayside hours will tend to eliminate semi-diurnal variations and enhance either stationary or diurnal variations, so the tidal variation seen in Figure 4 is likely DE2 (diurnal, eastward); however, further investigation will be necessary to determine the motion in longitude with local time. These variations are also seen in a previous season ( $L_s = 0^\circ\text{--}60^\circ$ ) although they were there confined to equatorial latitudes (Figure S3 in Supporting Information S1). Previous observations with the Mars Climate Sounder and GCM modeling showed similar DE2 wave patterns between 76 and 108 km present between  $L_s = 0^\circ\text{--}120^\circ$  (Forbes et al., 2020), consistent with the observations presented here, and weakened throughout the remainder of the MY. Tidal variations were observed in a similar season with MAVEN/IUVS using observations of Nitric Oxide nightglow; however, these emissions occur at much lower altitudes, and it is perhaps not unexpected that the locations of these enhancements do not line up at the same longitudinal regions (Schneider et al., 2020).

The variations here do not indicate novel meteoric chemistry nor do we anticipate that depletions are the result of an enhanced chemical sink process. Instead, the total number of meteoric species is roughly constant, which can appear enhanced by compressing the entire layer in altitude or reducing the rate at which  $\text{Mg}^+$  is converted into other species by affecting chemistry in the bottom side of the  $\text{Mg}^+$  layer. However, these statements will require further validation in cross comparisons with a fully 3D-GCM that includes meteoric metal chemistry.

Latitude and longitude maps of  $\text{Mg}^+$  abundance at a given altitude (Figure 4, Figure S3 in Supporting Information S1) can be compared to maps of global remnant crustal magnetization (Connerney et al., 2001), which are oriented strongly E-W between  $30^\circ$  to  $90^\circ\text{S}$  latitude and  $150^\circ\text{--}240^\circ$  longitude, and there does not appear to be any correlation (positive or negative). If the dynamics or chemistry of  $\text{Mg}^+$  were strongly influenced by crustal magnetization direction or magnitude, one would expect horizontal layers of enhanced and depleted  $\text{Mg}^+$  emission near these field regions, and yet there is no preference in comparison to similar latitudes in the northern hemisphere, even within the same “season.” This is in contrast to discrete auroral emissions that are directly influenced by remnant crustal magnetization (Bertaux et al., 2005; Schneider et al., 2018).

## 4. Conclusions

Prior to the Martian insertion of the MAVEN spacecraft in 2014, ionospheric observations of a transient  $M_3$  or  $M_m$  layer of electrons near 90 km, coincident with modeled ablation heights (Pätzold et al., 2005; Withers



**Figure 4.** The top panel presents the median  $\text{Mg}^+$  between 80 and 110 km against latitude and longitude for the season  $L_s = 60^\circ\text{--}120^\circ$  (Southern Winter). The bottom panel shows the difference of each point from the mean value of the entire map, and the middle panel is a cross section of this map at the latitudes highlighted in the legend.

et al., 2008), were presented as evidence of intermittent meteoric ablation. However, after the meteor shower of comet Siding Spring (M. M. J. Crismani et al., 2018; Schneider, Deighan, Stewart, et al., 2015) and discovery of a persistent layer of meteoric ions (M. M. J. Crismani et al., 2017) provided the first observations of atomic and ionic metal species it was possible to determine that the origin of these features in the radio occultation observations was not meteoric (M. M. J. Crismani et al., 2019). Initial monitoring of the  $\text{Mg}^+$  layer due to sporadic meteoroids indicated that it was a persistent layer with a fixed altitude and abundance (M. M. J. Crismani et al., 2017). However, such an early and simplified view has been supplanted by the wealth of data accumulated since 2015.

The  $\text{Mg}^+$  layer seems to be dynamic, with peak ablation altitudes shifting, abundances fluctuating, and variations in the slope of the top and bottom-sides of the  $\text{Mg}^+$  layer, all likely directly related to the underlying atmospheric structure and meteoric chemistry. At the equator, a multi-year analysis shows an enhancement of  $\text{Mg}^+$  at morning local times whose layer topside increases throughout the day. Separating these observations by season, the peak altitude  $\text{Mg}^+$  appears to respond to the background atmosphere as the former shifts up and down in altitude. Using zonal medians to compare across latitudes, the  $\text{Mg}^+$  layer peak altitude can dip as low as 80 km near the south pole and as high as 105 km at equatorial/mid-latitudes. Overall abundances also vary dramatically, in excess

of the average 250 ions  $\text{cm}^{-3}$  reported in (M. M. J. Crismani et al., 2017) to averages of 300–500 ions  $\text{cm}^{-3}$  in some cases, but the reduction of  $\text{Mg}^+$  in specific seasons warrants further investigation. Finally, in two seasons ( $L_s = 0^\circ$ – $120^\circ$ ), the geographic distribution may be linked to tidal variations in the background atmosphere.

This data set represents nearly continuous monitoring of the  $\text{Mg}^+$  layer in a variety of geophysical conditions, and the results found herein will provide important constraints for the next generation of meteoric ion chemistry and atmospheric circulation modeling at Mars. Model-observation comparisons should provide insights into mesospheric transport, chemistry and interplanetary dust particle sources. Previous discrepancies between model predictions and metal ion observations led to the development of a novel nucleation scheme for mesospheric clouds (Plane et al., 2018), and we expect this data set to provide the impetus to future advances in atmospheric chemistry. Overall, this represents the broadest investigation of meteoric metal ions, summarizes their first-order behavior, and outlines new model challenges for the future.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

The level 1B data used herein are calibrated level data (Deighan, 2018), publicly available on the Atmospheres node of the NASA Planetary Data System tagged “periapse” ([https://pds-atmospheres.nmsu.edu/data\\_and\\_services/atmospheres\\_data/MAVEN/limb.html](https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/MAVEN/limb.html)). The filtered data set is hosted on Zenodo and is publicly available (M. Crismani, 2022).

## Acknowledgments

The authors would like to thank Scott England and Aishwarya Kumar for fruitful discussions on waves and tides. MC was supported in part by the NASA Award 80NSSC21M0110 through the NASA Goddard Space Flight Center. NASA supports the MAVEN mission through the Mars Scout program. DJ and JDCS were supported through the NASA ISFM Program. JMCP and WF were supported by the European Research Council (Project 291332-CODITA) and UK Science and Technology Facilities Council (Project ST/T000279/1).

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