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Special Section:
The First Results from the Emirates Mars Mission (EMM)

# Emirates Mars Ultraviolet Spectrometer's (EMUS) Observation of Argon in the Martian Thermosphere

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**Key Points:**

- Emirates Mars Ultraviolet Spectrometer's (EMUS) provides first disk resolved images of argon in the thermosphere of Mars
- EMUS average disk brightness of argon I 104.8 nm and argon I 106.6 nm align with previous measurements reported in literature
- Argon I 106.6 nm is found to be optically thick and stimulated by fluorescent scattering as well as electron impact

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**Abstract** The Emirates Mars Ultraviolet Spectrometer (EMUS) is a far ultraviolet spectrometer on-board the Emirates Mars Mission's (EMM) which arrived at Mars on 9 February 2021. EMUS is designed to observe key neutral species in the Martian thermosphere (100–200 km) and exosphere (≥200 km). EMUS has observed two neutral argon (Ar) emission lines, Ar I 104.8 nm and Ar I 106.6 nm, in the thermosphere. Our interest in these emissions stem from argon's non-reactiveness, making it a tracer for transport between the upper and lower atmosphere. We report average argon disk brightness measured by EMUS and compare them to measurements from Earth orbiting observatories. For the first time, this work investigates the variability of Ar I 106.6 nm brightness due to emission angles, solar zenith angles, solar longitudes, local times and latitudes. To contrast the behavior of inert argon we compare these results with the photochemically reactive oxygen 135.6 nm.

**Plain Language Summary** The Emirates Mars Ultraviolet Spectrometer (EMUS), on board of the Emirates Mars Mission, measures airglow from the upper atmosphere of Mars. Here we report on the first disk images of argon gas at Mars and compare them to past observations. We also compare the brightness of the argon to a well-studied oxygen airglow feature. The optical depth of the argon airglow and how it is excited are discussed.

## 1. Introduction

### 1.1. Emirates Mars Mission

Emirates Mars Mission (EMM), the first interplanetary mission developed by the United Arab Emirates Mission, launched to Space on 20 July 2020, achieved a successful Mars Orbit Insertion (MOI) on 9 February 2021 and commenced its science phase on 23 May 2021. EMM is designed to explore the dynamics of the Martian atmospheric layers on a global scale, simultaneously sampling diurnal, and seasonal timescales (Almatroushi et al., 2021; Amiri et al., 2022). On board the EMM's spacecraft "Hope Probe" are three scientific instruments designed to study these different layers: (a) Emirates eXploration Image (EXI) (Jones et al., 2021) (b) Emirates Infrared Spectrometer (EMIRS) (Edwards et al., 2021) and (c) Emirates Mars Ultraviolet Spectrometer (EMUS) (Holsclaw et al., 2021). EMUS is a far ultraviolet imaging spectrometer designed to investigate the abundance and spatial variability of key neutral species in the thermosphere (100–200 km) and in the exosphere (≥200 km). The EMUS wavelength range is from 100 to 170 nm, detecting key emissions in the upper atmosphere of Mars such as oxygen (135.6 nm, 130.4 nm), hydrogen (Lyman-β: 102.6 nm, Lyman-α: 121.6 nm), carbon monoxide Fourth Positive Group band system (140–170 nm) and argon (104.8 nm, 106.6 nm) (Holsclaw et al., 2021).

### 1.2. Motivation to Study Argon on Mars

Argon is a photochemically inert gas with molecular weight of 40 g/mol, close to carbon dioxide's ($CO_2$) 44 g/mol, but does not condense at the temperatures found in the Martian atmosphere. This causes an apparent accumulation of Ar at the winter poles as $CO_2$ condenses near the surface, and this compositional change propagates to the upper atmosphere, making Ar/$CO_2$ mixing ratios a useful indicator of vertical transport in the atmosphere of Mars. Understanding the distribution of Ar has been of interest to scientists for some time, as it is a good tracer of atmospheric circulation and can provide input on how to constrain transport parameters in Mars Global Climate Models (GCMs) (Sprague et al., 2012). Moreover, analyzing inert Ar with other ultraviolet emissions in the thermosphere, such as photochemically active carbon monoxide and atomic oxygen, can also provide insight on vertical transport (see Evans et al., 2022, this issue & England et al., 2022 this issue). Argon emission lines on Mars were first detected in 1995 by the Hopkins Ultraviolet Telescope (HUT) (Feldman et al., 2000), and since then measurements have also been made by the Far Ultraviolet Spectroscopic Explorer (FUSE) (Krasnopolsky & Feldman, 2002). However, these previous observations were disk integrated measurements and provided only snapshots at two seasons and solar activities. Now, with EMM's comprehensive seasonal, temporal and global coverage, EMUS can provide us with novel information about Ar that has not previously been possible. EMUS detects two atomic argon emissions, Ar I 104.8 nm and Ar I 106.6 nm, both of which are examined in this paper. We compare the disk averaged brightnesses of both Ar emission lines obtained by EMUS to the results previously reported by HUT and FUSE. We also conduct a further analysis of Ar I 106.6 nm brightness variability due to geometrical, seasonal, and temporal factors such as solar longitude ($L_s$), emission angle (EA), solar zenith angle (SZA), latitude and local time. Finally, we examine how the Ar brightness varies with solar activity by comparing with two other emissions measured by EMUS, namely oxygen (O) I 135.6 nm and hydrogen (H) I 121.6 nm.

## 2. Data Set Specifications

EMM has a unique elliptical orbit ranging from a periapse of 19,970 km to an apoapse of 42,650 km, with a 25° inclination, and a 54.5 hr orbit period (Amiri et al., 2022). The EMUS instrument performs four standard scientific observations. In this paper we conduct our analysis using the EMUS observation strategy 1 and 2 (U-OS1 and U-OS2). U-OS1 collects data from the Martian thermosphere by performing raster scanned images of the disk of Mars, see Figure 1. At a minimum of one orbit per week, U-OS1 performs two swaths twice per orbit to be able to cover both morning and afternoon hemispheres (Holsclaw et al., 2021). U-OS2 conducts raster scans of the Mars disk and inner corona by performing three swaths at least 6 times in one orbit per week (Holsclaw et al., 2021).

In this paper, we have considered data up to the end of January 2022, due to an issue of reducing the Lyman-α past that date (Jain et al., 2022, this issue). Specifically for our analysis of Ar I 106.6 nm variability due to geometrical, seasonal and temporal factors we utilize EMUS L2b data captured by U-OS1 at the following conditions:

1. Data set 1: Observed on 2021/07/02 at $L_s$ 66.4° at a phase angle of 19°, as seen in Figure 1.
2. Data set 2: Observed on 2021/12/24 at $L_s$ 146.8° at a phase angle of 40°.

It is significant to note that until recently EMUS observations have been taken at a solar minimum.

## 3. Results and Discussion

### 3.1. Ar I 106.6 nm and Ar I 104.8 nm EMUS Average Disk Brightness

In Table 1 we provide the disk average brightness from EMUS for both Ar emission lines and compare them to values previously reported by HUT and FUSE at similar $L_S$. EMUS values seem to be significantly larger than those of HUT at aphelion, even though both observations have been acquired under solar minimum conditions and similar mean phase angles. The discrepancy between the values could be due to HUT observations covering northern latitudes, where we expect less of Ar as it increases closer to the southern latitudes (see Section 3.4). In addition, EMUS data shows a geophysical variability on the order of 20%, which may contribute to the difference between EMUS and HUT values (see England et al., 2022, this issue, and Jain et al., 2022, this issue). We also note that FUSE values at a similar $L_S$ are substantially brighter than those measured by EMUS. This is consistent with the FUSE observation being acquired under solar medium conditions, with the higher EUV activity stimulating brighter airglow.

### 3.2. Ar I 106.6 nm Optical Thickness and Brightness Variability to Geometrical Factors (SZA and EA)

Forward modeling work that has been conducted in preparation for the return of EMUS data leads us to believe that in the Martian thermosphere Ar I 106.6 nm is an optically thick emission, contrary to what has been assumed in literature (Krasnopolsky & Feldman, 2002). Using an oscillator strength of 0.0616 for Ar I 106.6 nm (Ligtenberg

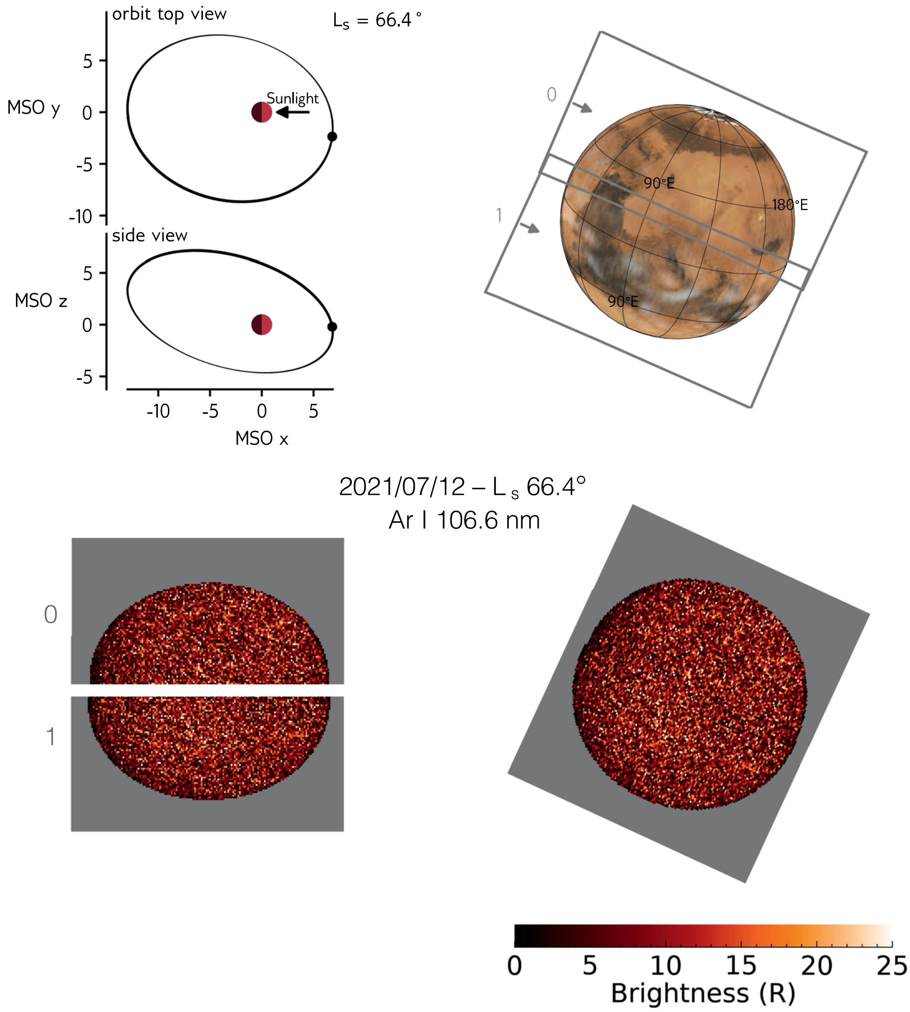


**Figure 1.** Data set 1 U-OS1 disk observations of Ar I 106.6 nm captured on 2021/07/02 near the subsolar point. Only lines of sight that intersect the planet at an altitude of 130 km or lower are shown.

et al., 1994) and a temperature of 200 K, we obtain a scattering cross section of $3.62 \times 10^{-13}$ cm$^2$. Assuming an argon column depth of $1.5 \times 10^{15}$ cm$^{-2}$ at ~130 km from Mars Climate Database version 5.3 (Forget et al., 2008) for conditions consistent with EMUS observations considered here, we obtain an optical depth of approximately 540. This estimate of optical depth indicates that the Ar I 106.6 nm emission is optically thick.

Using EMM's comprehensive data provides an opportunity to further investigate this hypothesis. Our approach here is to compare Ar I 106.6 nm behavior to the well-studied optically thin O I 135.6 nm emission and observe

**Table 1**
*Ar I 106.6 nm and Ar I 104.8 nm Mean Disk Brightness Observed by EMUS Compared to Values Measured by HUT and FUSE*

| | | Average disk brightness (R) | | | | |
|---|---|---|---|---|---|---|
| Date | Instrument | Ar I 106.6 nm | Ar I 104.8 nm | Solar activity | $L_s$ | Mean phase angle |
| 03/12/1995 | HUT[a] | 5 ± 2 | 2.4 ± 1.0 | Minimum | 70 | 21° |
| 07/02/2021 | EMUS | 10.66 ± 0.09 | 4.52 ± 0.07 | Minimum | 66.4 | 19° |
| 05/12/2001 | FUSE[b] | 21.8 ± 0.28 | 6.36 ± 0.15 | Medium | 160 | 24° |
| 12/24/2021 | EMUS | 13.02 ± 0.13 | 5.61 ± 0.08 | Minimum | 146.8 | 40° |

[a]Feldman et al., 2000. [b]Krasnopolsky & Feldman, 2002.

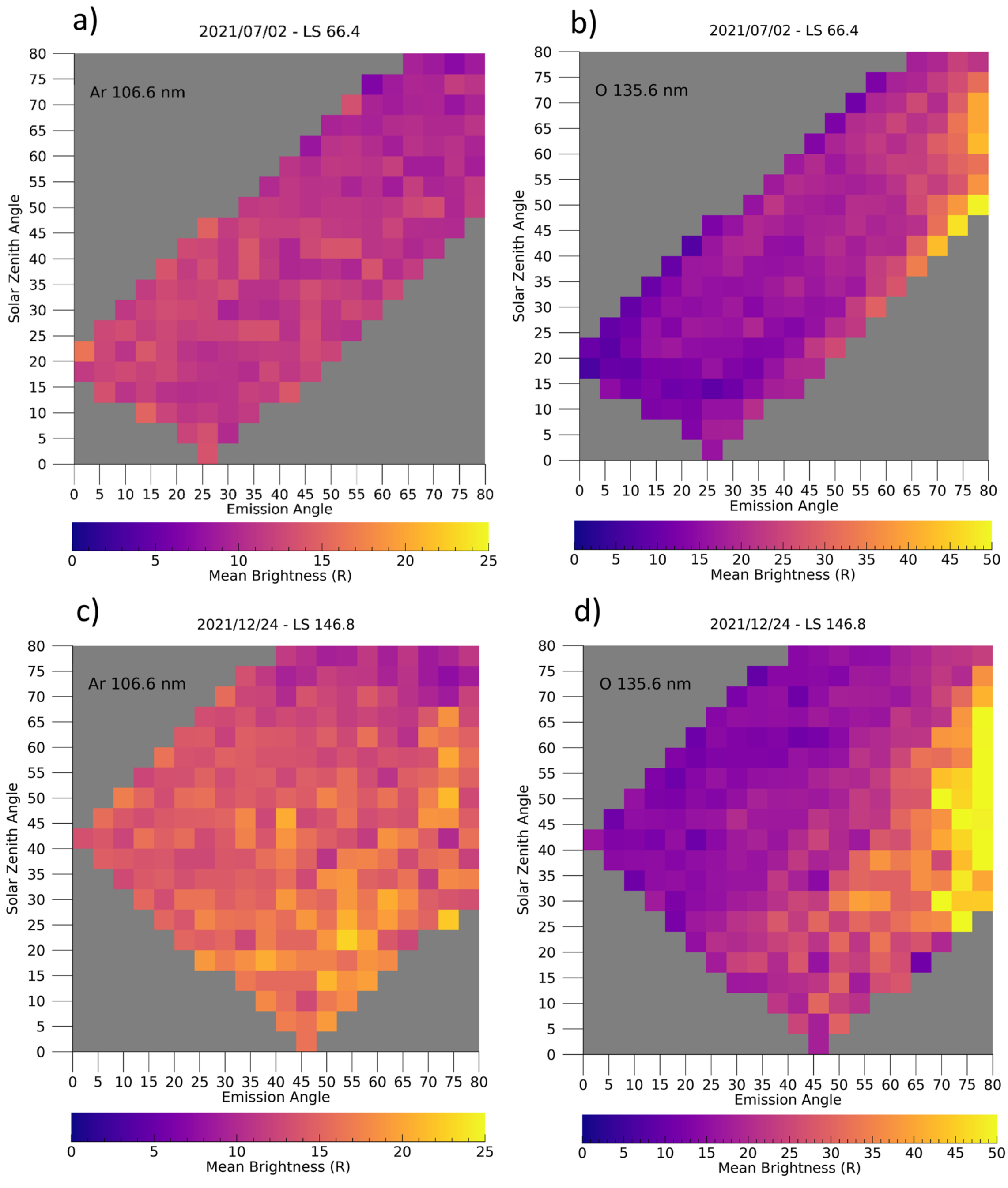


**Figure 2.** Mean emission brightness with 5° bins in SZA and EA for all of the above images. Figures 2a and 2b are of Ar I 106.6 nm and O I 135.6 nm on 2021/07/02 at a mean phase angle of 19°. Figures 2c and 2d are of Ar I 106.6 nm and O I 135.6 nm on 2021/12/24 at a mean phase angle of 40°.

the difference in behavior. Our expectation is that an optically thin emission's brightness increases as EA increases (i.e., limb brightening). Therefore, we begin by investigating how Ar I 106.6 nm brightness behaves with respect to EA and SZA.

In Figures 2b and 2d we can see that O I 135.6 nm gets brighter as EA increases and SZA decreases – a behavior expected from optically thin airglow emissions driven by solar extreme ultraviolet radiation. Meanwhile for Ar I 106.6 nm in Figures 2a and 2c, that is not the case, and instead the brightness remains almost in the same range across all EAs. This aligns with our hypothesis that it is indeed optically thick, with multiple scattering producing a flatter distribution by enhancing emission from the thermosphere at low EA and suppressing it at high EA.

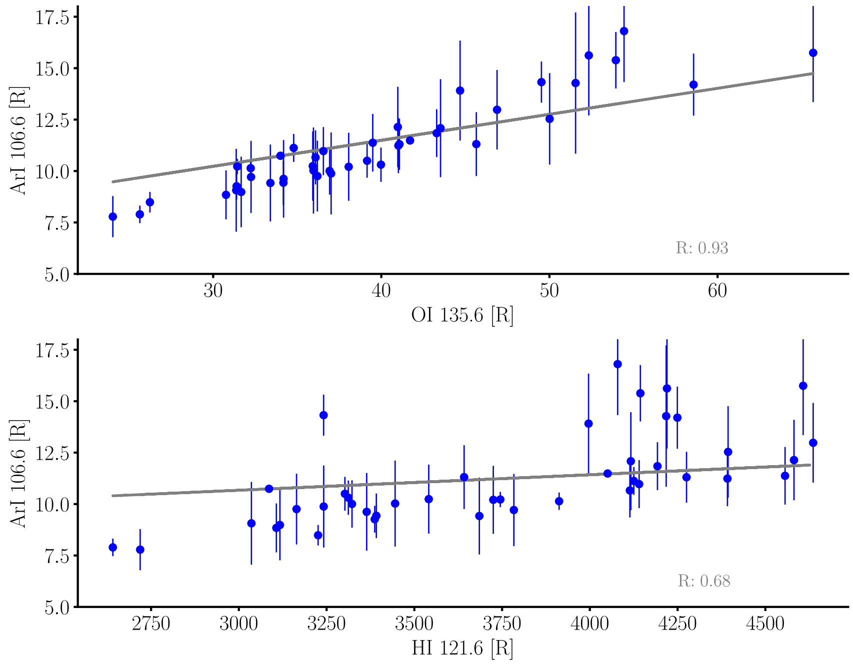


**Figure 3.** Top panel shows average disk brightness of Ar I 106.6 nm emission intensity against O I 135.6 nm and bottom panel shows H I 121.6 nm. The data is captured using the EMUS observation strategy 2 (UOS-2) up to January 2022. The disk brightness of Ar I 106.6 nm, O I 135.6 nm, and H I 121.6 nm emissions are constrained for SZA and EA less than 70°.

We also notice that there is a dimming occurring for Ar I 106.6 nm at larger SZA, which we attribute to geometric effects due to reduction in solar irradiance.

### 3.3. Ar I 106.6 nm Electron Impact Source Contribution

In addition to solar resonance fluorescence, photoelectron impact has previously been considered as a minor source for the Ar I 106.6 nm of Mars (Krasnopolsky & Feldman, 2002). In light of our finding that Ar I 106.6 nm is optically thick, the relative contribution of this source must be revaluated. Optically thin emission lines have a linear relationship between column abundance and brightness, while for optically thick emissions when column abundance increases the amount of scattered light increases sub-linearly. Taking into account Ar I 106.6 nm optically thick nature, a calculation of the solar resonance fluorescence source is unable to fully explain the observed brightnesses. Moreover, this raises the possibility that an electron impact source may be a major contributor to this emission. In Figure 3, we investigate this by comparing Ar I 106.6 nm to O I 135.6 nm, another emission line that is known to be primarily stimulated by electron impact.

As seen in Figure 3, the brightness of Ar I 106.6 nm is highly correlated with the optically thin O I 135.6 nm emission stimulated by electron impact, whereas we see relatively weak correlation between intensities of Ar I 106.6 nm and the optically thick H I 121.6 nm emission stimulated by solar resonant fluorescence. Analysis of dayside limb scans during the transition phase of the EMM mission indicate that modeling both the solar resonant fluorescence and electron impact sources are necessary to replicate the brightness profiles observed by EMUS (Evans et al., 2022; this issue). In addition, analysis of EMUS disk spectra from the nightside of the planet has found that auroral events driven solely by electron impact contain detectable emission at Ar I 106.6 nm (R. Lillis et al., 2022 this issue). These independent results are consistent with the high correlation we find between Ar I 106.6 nm and O I 135.6 nm emissions in the Martian dayglow.

### 3.4. Ar I 106.6 nm Brightness Variability Due To Latitude and Local Time

In Figures 4a and 4c of Ar I 106.6 nm we notice that there are both seasonal and latitudinal variations. We note a gradual increase of Ar I 106.6 nm brightness between $L_S$ 66.4 going to $L_S$ 146.8, consistent with Mars moving closer to the Sun along its eccentric orbit during that time, as also can be noted in Table 1. In addition, there is

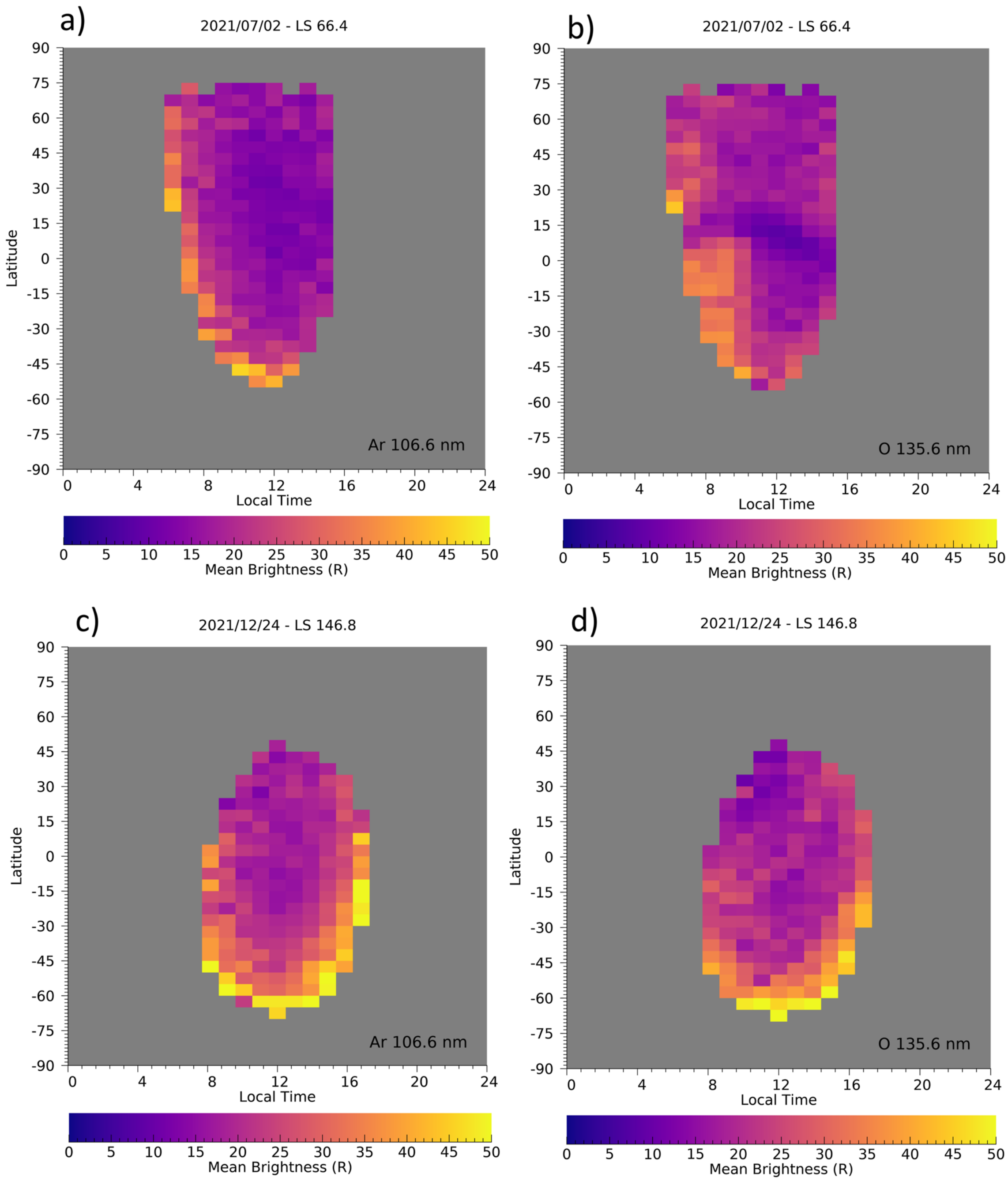


**Figure 4.** These images show the average emission brightness with 5° bins of latitude and 1 hr bin local time. To normalize geometric effects and better reflect the underlying atomic abundance, we have applied a cos (SZA) correction to both emissions, as well as a 1/cos (EA) correction to O I 1356 nm to account for limb brightening. Brightness at SZA and EA above 80 have been filtered out. Figures 4a and 4b are of Ar I 106.6 nm and O I 135.6 nm on 2021/07/02 at a mean phase angle of 19°. Figures 4c and 4d are of Ar I 106.6 nm and O I 135.6 nm respectively on 2021/12/24 at a mean phase angle of 40°.

a gradual increase of Ar I 106.6 nm moving down to the southern latitudes in both seasons. The increase of Ar I 106.6 nm when approaching southern latitudes is consistent to the analysis conducted by (Sprague et al., 2012) using Mars Odyssey's Gamma Ray Spectrometer's reported Ar mixing ratios for the lower atmosphere. It is also aligned to the Ar latitude variability predicted using Labortoire de Meteorologie Dynamique's climate model (Forget et al., 2008). We ascribe at least a portion of the brightening near the edges of the coverage to residual non-linear geometric effects due to variations with SZA and EA. The EMUS images also display no major change in the equatorial zone across the two seasons, and this is also in agreement with the conclusions made by

(Sprague et al., 2012). Comparing with O I 135.6 nm, the results generally follow a similar pattern, however, there is evidence for finer scale structures for the oxygen emission. These are thought to be linked to oxygen being a photochemically active and relatively light atomic species, unlike argon. For a detailed analysis of the variability of thermospheric atomic oxygen observed by EMUS, see (England et al., 2022, this issue).

## 4. Conclusion

EMM provides us with comprehensive coverage of neutral species in the thermosphere, including the two Ar emission lines at 104.8 and 106.6 nm. Based on a priori calculations and analysis performed using EMUS data, we present evidence that the Ar emissions are highly optical thick, contrary to what has been previously reported in the literature. In order to explain the observed brightnesses, we argue that solar resonant fluorescence alone is insufficient, and there must be a large electron impact source contribution. Independent of the source mechanisms, we find the Ar disk averaged brightnesses observed by EMUS to be consistent with previous studies from literature, giving us confidence in the quality of the data being returned. Future work will compare EMUS disk observations of Ar at different seasons to radiative transport models to further support these findings and refine our understanding of the variability of Ar in the upper Martian atmosphere.

## Data Availability Statement

Data from the Emirates Mars Mission (EMM) are freely and publicly available on the EMM Science Data Center (SDC, http://sdc.emiratesmarsmission.ae). This location is designated as the primary repository for all data products produced by the EMM team and is designated as long-term repository as required by the UAE Space Agency. The data available (http://sdc.emiratesmarsmission.ae/data) include ancillary spacecraft data, instrument telemetry, Level 1 (raw instrument data) to Level 3 (derived science products), quicklook products, and data users guides (https://sdc.emiratesmarsmission.ae/documentation) to assist in the analysis of the data. Following the creation of a free login, all EMM data are searchable via parameters such as product file name, solar longitude, acquisition time, sub-spacecraft latitude & longitude, instrument, data product level, and etc.

Data products can be browsed within the SDC via a standardized file system structure that follows the convention:

/emm/data/<Instrument>/<DataLevel>/<Mode>/<Year>/<Month>

Data product filenames follow a standard convention:

emm_<Instrument>_<DataLevel><StartTimeUTC>_<OrbitNumber>_<Mode>_<Description>_<KernelLevel>_<Version>.<FileType>

Emirates Mars Ultraviolet Spectrograph (EMUS) data and users guides are available at: https://sdc.emiratesmarsmission.ae/data/emus

The data files used for this paper are of version V01 and brightness values need to be multiplied by a factor of 1.25 to accurately reflect the current calibration of the instrument.

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