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Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099885

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

Key Points:

- First continuous observations of extreme ultraviolet (EUV) and far ultraviolet (FUV) dayglow on Mars
- Most of the EUV and FUV emissions observations show variations related to season and solar forcing
- Emirates Mars ultraviolet spectrograph observations are in agreement with the Hopkins ultraviolet telescope observations during solar minimum

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Citation:

Jain, S. K., Deighan, J., Chaffin, M., Holsclaw, G., Lillis, R., Fillingim, M., et al. (2022). Morphology of extreme and far ultraviolet Martian airglow emissions observed by the EMUS instrument on board the Emirates Mars Mission. *Geophysical Research Letters*, *49*, e2022GL099885. https://doi.org/10.1029/2022GL099885

Received 2 JUN 2022
Accepted 19 SEP 2022

Morphology of Extreme and Far Ultraviolet Martian Airglow Emissions Observed by the EMUS Instrument on Board the Emirates Mars Mission

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Abstract We present the first continuous observations of the extreme and far ultraviolet (EUV and FUV) dayglow emissions measured by Emirates Mars Ultraviolet Spectrometer (EMUS) onboard the Emirates Mars Mission. We found excellent agreement between the previous observations from the Hopkins Ultraviolet Telescope and recent observations by EMUS both in shape and magnitude. We presented the average disk brightness of major EUV and FUV emissions for about 10 months of data from April 2021 to February 2022. The solar activity was mild/minimum during the first half of the period presented in this study, but we noticed significant day-to-day variations in the major dayglow emissions independent of solar activity, indicating possible coupling from the lower atmosphere via waves/tides. The solar activity increased significantly during the second half of the study period. Our analysis showed that all major EUV and FUV emissions are highly correlated with solar forcing as well as seasonal changes.

Plain Language Summary Emirates Mars Ultraviolet Spectrograph on the Emirates Mars Mission is capable of observing emissions emanating from Mars' upper atmosphere in Extreme and Far Ultraviolet wavelengths. This is the first orbital mission to Mars that can observe Mars in extreme ultraviolet (EUV) wavelengths that provide important information about minor atmospheric species on Mars. Our analysis in this study shows that both EUV and far ultraviolet disk emissions on Mars show large day-to-day variability in short term. These emissions show long-term variability that depends on the season and solar forcing.

1. Introduction

Spectroscopy in the extreme and Far ultraviolet wavelengths has been extensively used to study planetary atmospheres. The FUV and EUV emissions provide information about the atmospheric composition (both neutral and ionized) and structure and can be used to study energy deposition, dynamics, and chemistry. There have been several studies of Mars in Far and mid ultraviolet (FUV and MUV) wavelengths starting from Mariner spacecraft (Barth et al., 1969, 1971; Stewart, 1972) more than four decades ago to very recently by SPICAM/MEx (Leblanc et al., 2006) and the IUVS/MAVEN (Jain et al., 2015; McClintock et al., 2015). These observations have provided a wealth of information regarding the composition and structure of the Martian upper atmosphere (Barth et al., 1969, 1971; Jain et al., 2015, 2020, 2021; Leblanc et al., 2006). With ongoing missions such as MAVEN, we have been getting continuous observations of the Martian thermosphere in FUV and MUV wavelengths. However, there has been a dearth of airglow measurements in EUV. Prior to 2021, there have been few observations in EUV-FUV wavelengths from earth-based spacecraft/telescopes, namely, the Far Ultraviolet Spectroscopic Explorer (Krasnopolsky & Feldman, 2002), the Hopkins Ultraviolet Telescope (HUT) (Feldman et al., 2000), and the Hisaki Spacecraft (Masunaga et al., 2020). There have been EUV and FUV disk and exosphere observations of Mars from the Rosetta-Alice fly by (Feldman et al., 2011). These observations provided importantly constraints on minor species such as Ar, N_2, CO, O, and H (Feldman et al., 2000; Krasnopolsky & Feldman, 2002) and made a strong case for continuous measurement in EUV/FUV wavelengths to characterize the seasonal behavior of both major and minor species in the Martian upper atmosphere.

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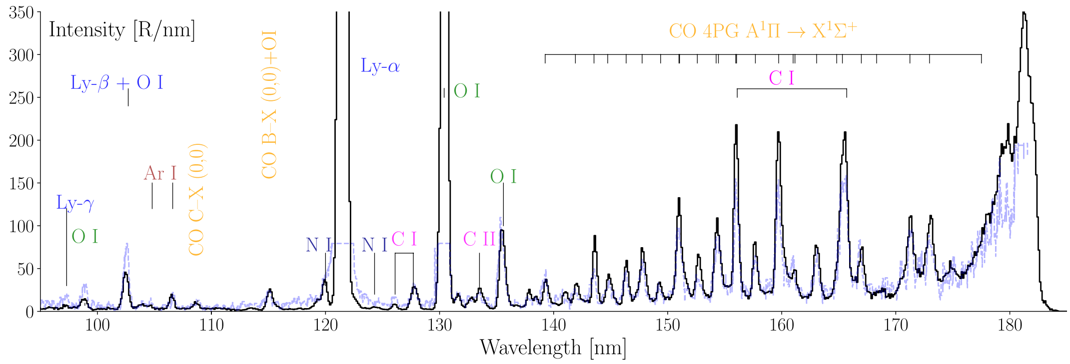

Figure 1. The figure shows the average Emirates Mars ultraviolet spectrometer (EMUS) extreme and far ultraviolet spectrum from EMUS SYS15 observations taken on 2 March 2021, with a very high-resolution slit (0.4 nm spectral resolution). The blue curve shows the disk observations taken from the Hopkins Ultraviolet Telescope (Feldman et al., 2000). The Lyman alpha and OI 130.4 nm were out of scale in the data provided in Feldman et al. (2000).

The Emirates Mars Mission Ultraviolet Spectrometer (EMM/EMUS) is the first instrument capable of simultaneously observing the EUV and FUV emissions emanating from the Martian upper atmosphere (Holsclaw et al., 2021). Due to the large and unique orbit (43,000 km × 20,000 km; 55 hr elliptical orbit) of the EMM spacecraft around Mars, the EMUS disk observations cover the majority of temporal (local hours) and spatial (latitudes and longitude) conditions in a relatively small-time scale (within a few weeks of observations) (Almatroushi et al., 2021; Holsclaw et al., 2021). These disk observations of Mars in the EUV and FUV wavelength regions are enabling us to understand the global scale variations in the upper atmosphere. In this study, we use ~10 months of EMUS data to understand and characterize the variability in the EUV/FUV airglow emission with the Martian seasons and solar forcing.

2. Observation and Data

The EUV and FUV spectrum on Mars is rich in atomic and molecular emissions as shown by earlier observations (Feldman et al., 2000; Jain et al., 2015; Krasnopolsky & Feldman, 2002; Leblanc et al., 2006). Figure 1 shows the average disk spectrum of Mars taken in a special observation campaign during EMM insertion orbit. In this campaign, very high spectral resolution disk and limb (0.4 nm) observations were made (Chaffin et al., 2022; Evans, Correira et al., 2022; Evans, Deighan et al., 2022). The FUV spectrum is dominated by the CO fourth positive group band system along with the brightest atomic emissions of H Ly-α and OI130.4 nm. The EUV wavelength region of the spectrum is mostly dominated by atomic emissions from atomic H, Ar, N, and O along with the Hopfield-Birge band system of CO. This high-resolution spectrum is very similar in shape and magnitude to the one reported by Feldman et al. (2000) observed using the HUT (see Figure 1).

In this analysis, we have used disk observations from EMUS's observations modes U-OS1 and U-OS2 (Holsclaw et al., 2021). Both types of observations provide coverage across latitude, longitude, and local time. The U-OS1 observations use a higher spectral resolution of 1.3 nm compared to 1.8 nm used in U-OS2. Both U-OS1 and U-OS2 observations produce raster scanned images of the disk of Mars with U-OS2 observations going up to 1.6 R_M to monitor the inner exosphere of Mars (Holsclaw et al., 2021). The U-OS1 observation cadence is roughly twice per orbit, mapping the morning and afternoon hemispheres. EMUS takes up to six U-OS2 observations per EMM orbit, spanning a range of Martian local times and longitudes. We used data from 21 April 2021 to 26 February 2022 spanning solar longitude (Ls) from 35.5° to 179°. There is a data gap from mid-September to mid-November 2021 due to solar conjunction. We used Level 2b, version 2 data in this analysis which contains brightness for various EUV and FUV features that are used in this analysis. We use the Poisson multiple linear regression (MLR) technique that uses the model templates for each emission presented in the EMUS data to retrieve the best-fit radiance for various EUV and FUV emissions (Evans, Correira et al., 2022; Evans, Deighan et al., 2022) that are provided in publicly available L2b data. This approach is similar to that used by Jain et al. (2015) on MAVEN IUVS data. The data used in this study is limited to the Martian disk with solar zenith and emission angle constraint of angles lower than 70°.

Figure 2 shows an example of one observation set of U-OS2 taken on 24 April 2021. The top left panel shows the position of the EMM spacecraft in orbit around Mars in MSO coordinates. It also depicts slit projections

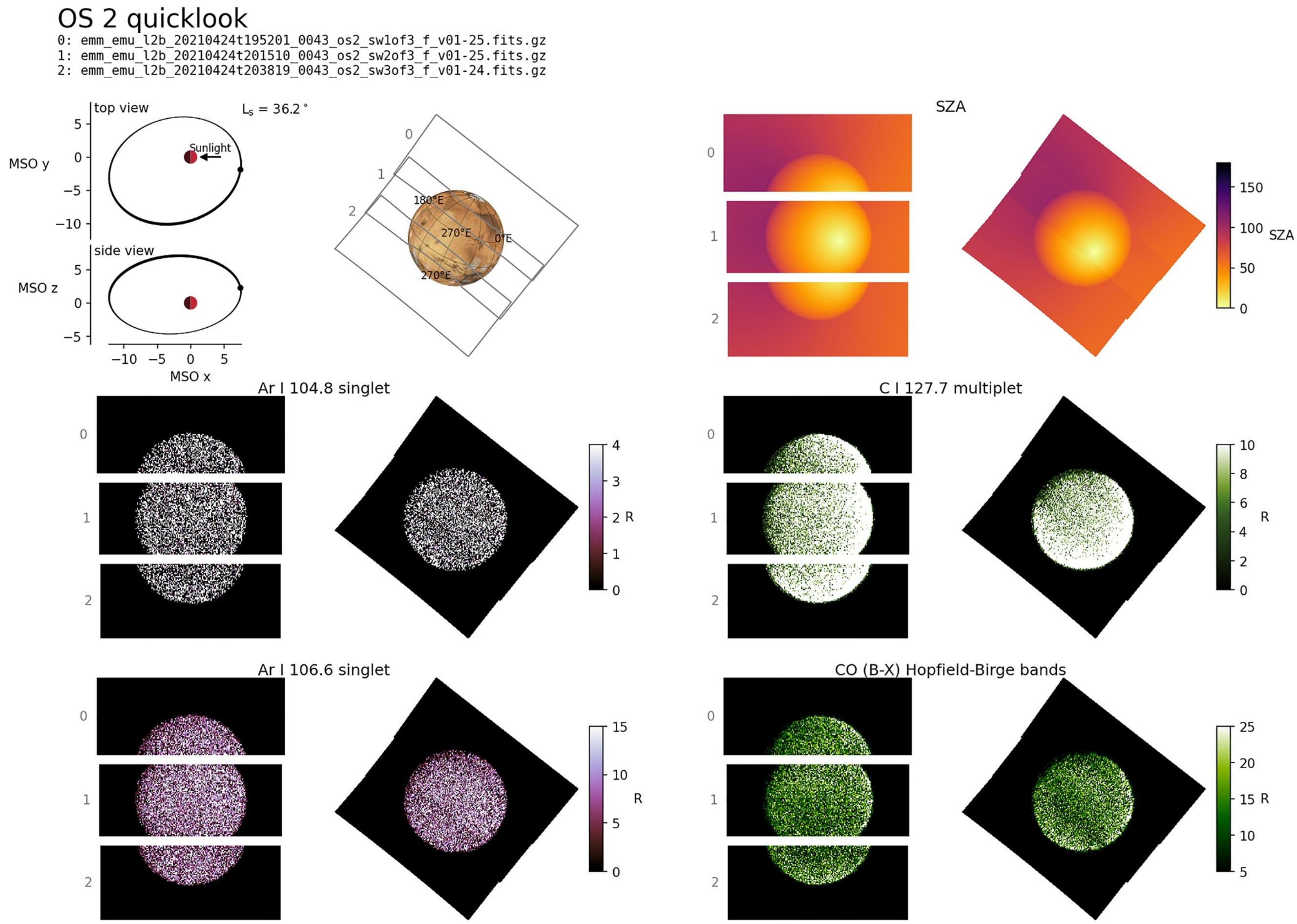

Figure 2. Figure shows an example of Emirates Mars ultraviolet spectrometer U-OS2 observation. The top left panel shows the location of Emirates Mars Mission (EMM) orbit around Mars in MSO Y and Z coordinates and three raster images overlapping as viewed from EMM. The top right panels show solar zenith angle (SZA) coverage for the individual three scans and also combined overlapping images as the view from the EMM. The middle panels show the disk images of Ar I 104.8 nm and CI 127.7 nm emissions in a similar way as the SZA. The bottom panels show the disk images of Ar I 106.6 nm and CO (B–X) Hopfield-Birge bands.

during the three raster scans of the Martian disk and inner exosphere. The top right panel shows the solar zenith angle image of the observations. The middle and bottom rows in Figure 2 show raster images of a few selected emissions from EUV (Ar I 104.8 and 106.6 nm and CO (B-X)) and FUV (CI 127.7) wavelength region. Figure 2 also shows the observations as viewed from EMM as the EMUS takes the observation across the Martian disk.

3. Results

Figure 3 shows the average disk brightness of various EUV and FUV emissions observed by the EMUS instrument between April and September of 2021 along with the disk average brightness observed by HUT observations (Feldman et al., 2000). The disk brightness of EUV emissions observed by EMUS is in good agreement with the earlier observations by HUT except for the disk brightnesses of H I 102/OI 102 nm, NI 120 nm, CI 156.1 and 165.7 nm, and OI 135.6 nm emissions. The latter three emissions are blended with a strong CO Fourth positive band system (Evans, Correira et al., 2022; Evans, Deighan et al., 2022), and the emission at 102.6 nm is a blended feature of HI 102.6 nm and OI 102.57 nm emissions. The Poisson MLR algorithm used in this analysis is better suited for blended emissions if the knowledge of model templates is known precisely, that is why the brightness values presented in this analysis are a preliminary estimate based on the MLR technique. The NI 120 feature sits right on the shoulder of the Lyman alpha, which makes it difficult to reduce the brightness of this feature (Evans, Correira et al., 2022; Evans, Deighan et al., 2022).

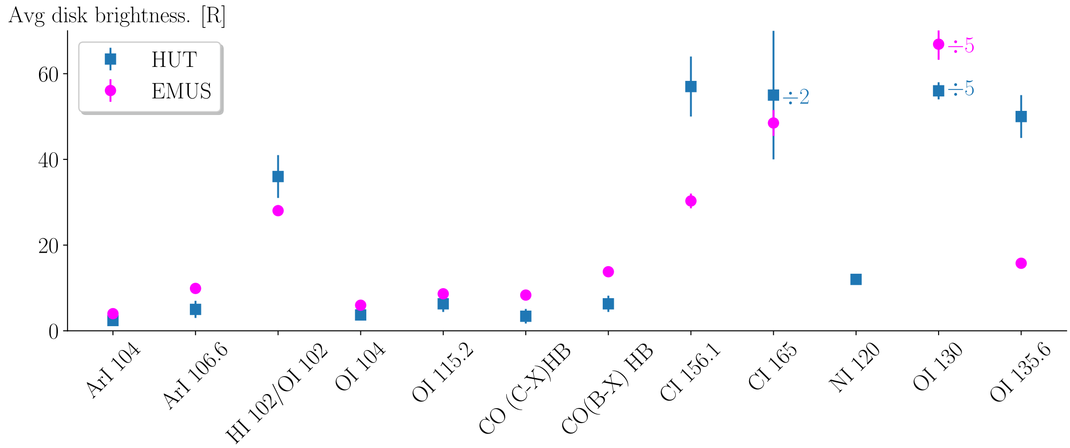

Figure 3. The figure shows the average disk emissions from Argon, Oxygen, Hydrogen, Carbon, and nitrogen atoms along with band emissions from CO Hopfield-Birge bands between April and September 2021. The average disk emission from the Hopkins ultraviolet telescope (HUT) observations is also in the figure (Feldman et al., 2000). The OI 130.4 nm disk brightness of both the HUT and Emirates Mars ultraviolet spectrometer are divided by a factor of 5. The CI 165.7 nm observations made by the HUT are divided by a factor of 2.

Figure 4 shows the average daily disk brightness of major FUV (C I 156.1 nm, OI135.6 nm, OI 130.4 nm, and H I 121.6 nm) and EUV (Ar 106.6 nm, CO HB: C-X; B-X bands,HI 102.6/OI 102.7 nm) emissions from April 2021 to February 2022. The daily average solar Lyman alpha irradiance measured by MAVEN EUVM monitor (Eparvier et al., 2015) is also shown in panel (f). The solar Lyman alpha irradiance is normalized and scaled to the

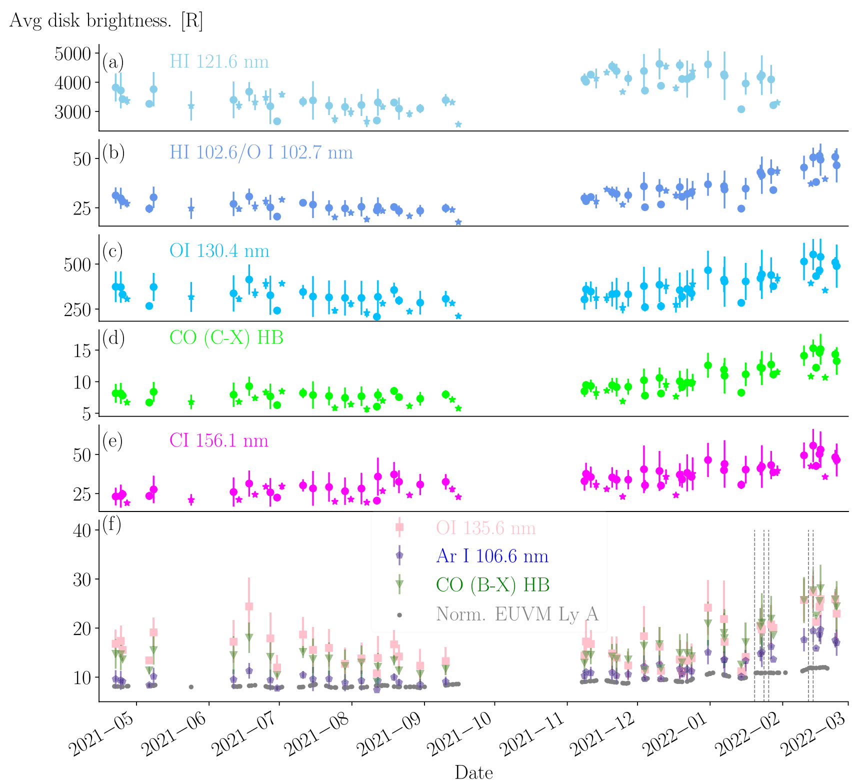

Figure 4. The daily average disk brightness for various emissions observed by Emirates Mars ultraviolet spectrometer (EMUS) instrument on board Emirates Mars Mission from the end of April 2021 end to 26 February 2022. Solid star and circle symbols show average brightness from EMUS USO-1 and USO-2 observing mode. The geophysical variations are 1-σ standard deviation in the plots. The bottom panel shows normalized Lyman alpha irradiance measured by the EUVM monitor on board the MAVEN spacecraft (Eparvier et al., 2015). The dashed vertical lines in the panel (f) indicate the location of C-class flares observed by EUVM/MAVEN.

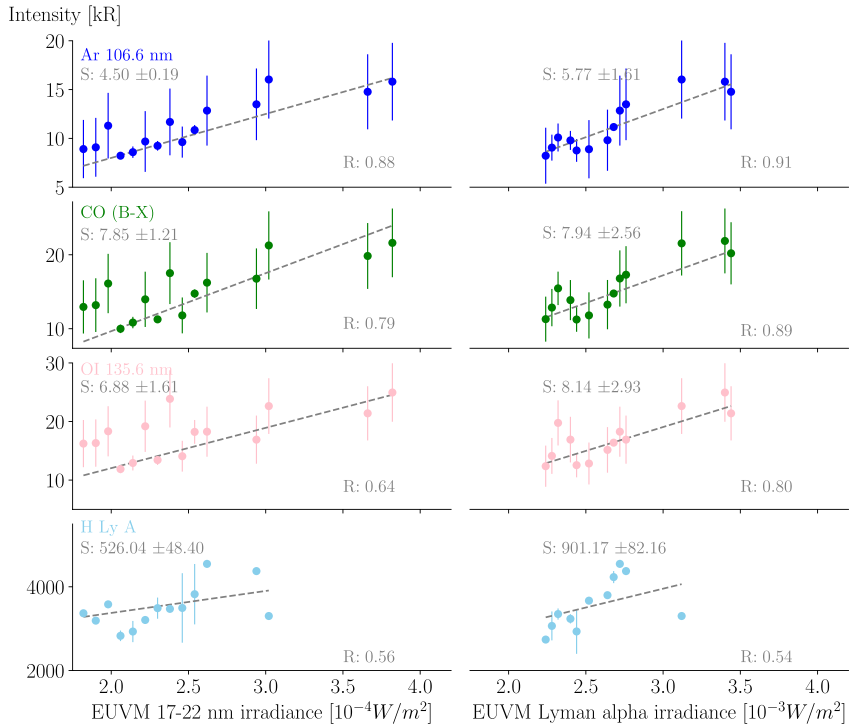

Figure 5. (Left panels) show the correlation between EUVM monitor 17–22 nm irradiance and average daily brightness of Ar 106.6 nm, CO (B–X), OI 135.6 nm, and HI 121.6 nm emissions. The symbol *S* is the slope of the fit with a unit of $R/10^{-4}$ W/m^2. The correlation coefficient *R* is also shown in the panels (right panels) same as the left panel except that the emissions are plotted against EUVM Ly-α irradiance (slope is in the unit of $R/10^{-3}$ W/m^2).

disk brightness values for better comparison against the airglow emissions. The intensity of Lyman alpha is only considered up to the end of January 2022 due to some issue in reducing its brightness. From the start of nominal science observations until 15 September 2021 (hereafter, the first time period), the average disk brightness didn't show significant long-term variations due to the low solar activity during this time period. Between December 2021 and February 2022 (hereafter, the second time period), all the major EUV and FUV emissions start to show upward trends. During this time we also notice ramp up in the Lyman alpha irradiance measured by the MAVEN-EUVM instrument.

The solar forcing effect on HI 121.6 Lyman alpha emission is not evidently clear in the figure due to its large optical depth (Chaffin et al., 2015). However, HI 102.6 Lyman beta emission clearly shows dependence on the solar EUV forcing (Chaffin et al., 2022). The Lyman beta emission is not as optically thick as HI 121.6 nm emission and is also blended with optically thin OI 102.7 nm emission in EMUS data. This may explain the increasing trend with the Mars season as it orbits around the sun. The OI 130.4 nm and Ar 106.6 nm emissions are also optically thick but have contribution from electron impact also (Evans, Correira et al., 2022; Evans, Deighan et al., 2022; Ritter et al., 2019), and both emissions show strong seasonal variation.

Figure 5 shows the major EUV/FUV emissions plotted against the solar EUV 17–22 nm (left panels) and the solar Lyman alpha (right panels) irradiance. Except for H Lyman alpha, other emissions show a strong dependence on both solar Lyman alpha and 17–22 nm irradiance. The solar Lyman alpha is an indicator of the heliocentric distance of Mars. The strong correlation (as shown by *R* values in Figure 5) between EUV/FUV airglow emissions and solar Lyman alpha and EUV provides a clear indication of a ramp-up in solar activity as well as the transition of Mars toward perihelion (southern summer). Overall, the correlation between airglow emissions and solar Lyman alpha is marginally higher than that of dayglow and solar ionizing irradiance (17–22 nm irradiance), indicating that the seasonal (i.e., heliocentric distance) response dominates over any potential solar UV spectral hardening that may occur as solar activity increases.

4. Discussion

The solar radio flux at 10.7 cm (referred to as the F10.7 index) is an excellent proxy for solar activity. The F10.7 index was ∼75 when the HUT measurements were obtained; which is very close to the average F10.7 index value of ∼80 between April-September 2021 when the first period of EMUS observations was taken. This might explain the good agreement between the HUT and EMUS disk observations as shown in Figures 1 and 3. Assuming the fluorescent scattering as the dominant source of CO HB band system, Feldman et al. (2000) reported a total CO column density of 3.4×10^{16} cm^{-2} using the atmosphere model from Fox and Dalgarno (1979). Using the opportunistic limb measurements from the EMM insertion orbit (the solar activity was similar to the HUT observation) and Mars Climate Data 5.3 model atmosphere (Forget et al., 1999; Millour et al., 2019) we calculate a mean value of 1.9×10^{17} cm^{-2} for CO column (Evans, Correira et al., 2022; Evans, Deighan et al., 2022), that seems to be consistent with the values derived by Feldman et al. (2000). Despite a very good agreement between the two observations for the EUV emissions, there are differences in the FUV emissions that are blended with a strong CO 4PG band system. The use of the MLR technique is the best way to retrieve the brightnesses of the blended emissions if the correct model templates are known. Based on the recent lab data for electron impact on CO (Evans, Correira et al., 2022; Evans, Deighan et al., 2022; Lee et al., 2021), we are able to retrieve the brightness of various emissions that are blended by CO 4PG and that may explain the discrepancies between the few blended emissions between the HUT and our observations.

As mentioned in the previous paragraph, the solar activity was quiet during the first time period (April–September 2021) and Mars was also close to aphelion (F10.7 ∼80). The effect of lower solar activity is clearly visible in the EMUS disk observations during the first time period as shown in Figure 4, where the intensities of all major EUV/FUV emissions were mostly declining. However, we also observed large day-to-day variations in the emissions coming from minor species such OI 135.6 nm, CO HB band and Ar 106.6 nm. These large variations seem to be independent of solar activity, and rather seem related to the coupling from the lower atmosphere via waves and tides. During the low solar activity, Jain et al. (2021) noticed strong wave activity in the thermosphere.

In the second time period, we notice a ramp-up in the EUV forcing due to both increase in solar activity and decreasing Sun-Mars distance. The EUVM monitor started observing more flare activity during January–February 2022 (F10.7 ∼104) as shown in Figure 4f. This increase in solar EUV forcing due to both the seasonal change (as Mars approaches perihelion) and the higher solar activity resulted in an increase in brightness for various EUV/FUV airglow disk emissions (see Figure 4). The relation between solar EUV forcing and disk brightness becomes very clear in Figure 5 where we found a strong correlation between EUVM Lyman α and ionizing (17–22 nm) irradiance and major EUV and FUV disk dayglow emissions except HI 121.6 nm emission (due to its high optical depth). The strong correlation of disk emissions with both the solar Lyman alpha and ionizing flux indicates that the Martian EUV and FUV airglow emission observations made by the EMUS are responding to both seasonal (change in heliocentric distance) and solar forcing.

5. Summary

The EMUS instrument onboard Emirates Mars Mission is providing unique observations of the Martian disk in both EUV and FUV wavelengths. The EMUS observations cover wide spatial and temporal regions within weeks, providing continuous probing of the state of the thermosphere of Mars at all local times and latitudes. There were no orbital measurements of EUV emissions on Mars before the EMM spacecraft. We present the first continuous measurements of EUV/FUV dayglow emissions made by the EMUS instrument onboard the EMM mission. We find that the previous observations from the HUT and recent observations by EMUS are in excellent agreement except for a few emissions that are blended by other emissions. We present the average disk brightness of major EUV and FUV emissions observed by the EMUS instrument and show time series of about 10 months of data from April 2021 to February 2022. The solar activity was mild/minimum during the first half of the mission, but we notice significant day-to-day variations in the major dayglow emissions independent of solar activity, indicating possible coupling from the lower atmosphere via waves/tides. The solar activity increased significantly during the second half of the mission. Our analysis shows that all major EUV and FUV emissions are highly correlated with solar forcing as well as the Mars-Sun distance (seasonal). We will be further studying the local and spatial variability in airglow emission to understand and characterize the state of the Martian upper atmosphere.

Acknowledgments
Funding for the development of the Emirates Mars Mission mission was provided by the UAE government, and to co-authors outside of the UAE by MBRSC. Ed Thiemann, Phil Chamberlin, and Frank Eparvier are supported by NASA through the MAVEN project.

Data Availability Statement

The Emirates Mars Ultraviolet Spectrograph Level 2B V02 data used in this study are available at the Emirate Mars Mission Science Data Center (Amiri et al., 2021; Holsclaw et al., 2021) at https://sdc.emiratesmarsmission.ae/data/emus. The MAVEN EUVM Level 2 data are available at the LASP MAVEN Science Data Center server (Eparvier et al., 2015), https://lasp.colorado.edu/maven/sdc/public/pages/search/search.html.

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