DIURNAL VARIATIONS IN THE APHELION CLOUD BELT AS OBSERVED BY THE EMIRATES EXPLORATION IMAGER (EXI)

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Introduction: Water ice clouds are recognized to have a fundamental contribution to the Martian atmosphere both through their formation processes and their role in the atmospheric radiation budget (see references cited by Clancy et al. 2017; Wolff et al., 2019). A necessary step in delineating the nature of their interactions with the atmospheric system is the observational characterization of the spatial (vertical and horizontal) and temporal (diurnal, seasonal) domains. Significant progress has been made in recent years with respect to the spatial domain and the seasonal component of the temporal variability. However, observations of the diurnal cycle have typically been limited to a small number of points on the surface from landed assets (i.e., Mars Exploration Rovers, Phoenix, Curiosity, Insight, Perseverance), and to a combination of limited local-times from sun-synchronous orbiters (Mars Global Surveyor, e.g., Smith, 2004; Odyssey, e.g., Smith, 2019; Mars Reconnaissance Orbiter (MRO), e.g., Wolff et al., 2019) and a convolution of diurnal and seasonal timescale from orbiters with a precessing orbit (Mars Express, e.g., Giuranna et al., 2021; Trace Gas Orbiter, eg., Liuzzi et al, 2020). An exception to the latter case is the MAVEN mission (K. Connour, personal communication), which has obtained diurnal sampling of several regions on a sub-seasonal timescale. Consequently, a mission that provides global spatial coverage with diurnal sampling accumulated on a short-time scale (e.g., a week) could potentially constrain the physical processes connecting clouds and atmospheric dynamics in ways that were not possible previously.

The Emirates Mars Mission (EMM), which arrived in orbit on February 9, 2021, has a science orbit which fills the niche identified above. More specifically, its near-equatorial orbit provides a platform for spatial coverage of much of the planet with a diurnal sampling of at least 3-4 local times on the scale of a 7 to 10 days. There are two instruments on-board that sound the lower atmosphere, typically through column-integrated optical depths: Emirates eXploration Imager (EXI; Jones et al, 2021) and Emirates Mars InfraRed Spectrometer (EMIRS; Edwards et al., 2021). By combining the data from EXI and EMIRS, one can capture the full diurnal cycle, and place constraints on the water ice particle sizes. In addition, EMIRS can explicitly distinguish between water ice and dust aerosols, while analysis of EXI data must generally assume the latter.

In this presentation, we focus solely on EXI observations, which are naturally limited to illuminated portions of the atmosphere. We describe the instrument and the data very briefly, along with the analysis algorithm (and refer the interested reader to Jones et al., 2021). Most of the presentation consists of highlights of the observed diurnal behavior of the aphelion cloud belt structure through late summer in the northern hemisphere.

EXI Description: EXI is a multi-band camera capable of taking 12-megapixel images. It is described in detail by Jones et al. (2021), with post-launch updates presented at this meeting in the poster by Wolff et al. (Emirates Mars Mission 2020: Emirates eXploration Imager (EXI) Status Update). We present only the basics below.

Given the science orbit of EMM, EXI provides a spatial resolution of 2-4 km per un-binned pixel. It employs a filter-wheel mechanism consisting of 6 discrete bandpass filters that sample the optical spectral region from the mid-ultraviolet through the visible. Radiometric fidelity is optimized while simplifying

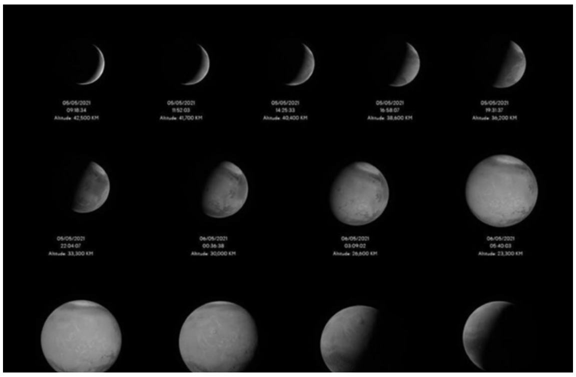


Figure 1: Illumination phases seen by EXI over an orbit. https://www.emiratesmarsmission.ae/gallery/images-of-hope-probe/1

the optical design by separating the ultraviolet (UV) and visible (VIS) optical paths. In this presentation we focus on the "f320" band. This band has solar flux weighted-mean centroid of 321 nm, with a Full-Width Half-Maximum of 24 nm. The radiometric accuracy (and precision) is better than 5%.

EXI Data: The principal observational mode of EXI is the so-called XOS-1, where XOS = eXi Observation Set. This sequence is 5 of the 6 filters, which includes the desired f320 band. Because it is direct trade-off between data volume of an observation and the data volume available, the f320 image is taken in a 2x2 binning mode, providing spatial resolution at nadir of 4-8 km (periapsis – apoapsis). Observing the full disk presents a full range of illumination conditions in each orbit, i.e., one cannot use every pixel in a visible image. This is illustrated in Figure 1.

Each image is processed to a state called Level 2A or "L2A", which includes a calibrated image (bias and flat correction) and associated metadata (a.k.a. "backplanes") such latitude and longitude, photometric angles, range from surface, etc. Keywords are also generated that allow one to transform the DN values in a pixel to radiance or the more ubiquitous I/F ("radiance factor"). The L2A file is the starting point for the cloud retrieval.

Cloud Retrieval: This retrieval is based on that developed by Wolff et al. (2019) for MRO/MARCI. Fun fact: several of the band passes for EXI were chosen to mimic those of MARCI to allow direct connection and comparison of datasets. Basically, it uses large Look Up Tables (LUTs) to replace live calls to a radiative transfer algorithm. Schematically, this requires one to specify fully the atmospheric state. One then performs a 6D interpolation followed by separate 1D interpolation. This latter step is the one that takes the I/F to a specific water ice optical depth. Of course, the trick is to specify the input parameters appropriately. The parameters that differ from MARCI are described briefly below:

Dust column: We use a contemporaneous dust climatology constructed from the EMIRS instrument (see Smith et al., this meeting). To improve the coverage statistics, we combine all local times of the EMIRS retrievals into a single bin for Local True Solar Times (LTST) 06h-18h.

Surface Model: While we adopt the basic Hapke model for MARCI band 7 and its spatial variations, we do multiply the *w* parameter by a scale factor to account for the difference in the photometric calibration of each instrument. Although the analysis is ongoing, the current scale factor is 1.07; that is to say, one makes the MARCI-derived surface brighter for EXI.

Surface Ice Filter: This is not yet implemented. However, since we are interested here in the aphelion cloud belt, it is not necessarily needed. We intend to combine the approach used by the MARCI cloud retrievals with EMIRS surface temperature maps. This will allow a much more robust "flagging" of pixels suspected to be or identified as being dominated by surface ice.

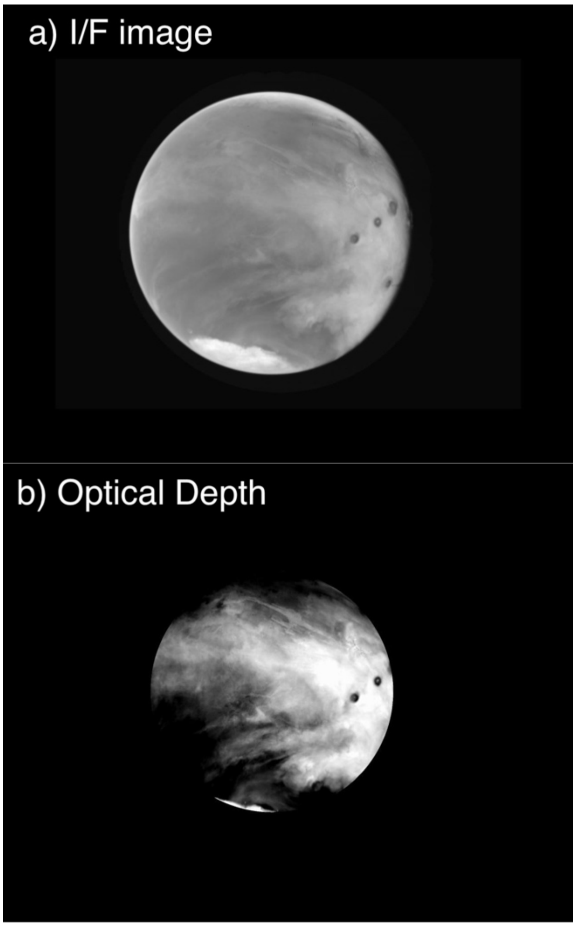


Figure 2: a) An input f320 I/F image from June 2021 (L_S=60°). b) The water ice optical depth image from the retrieval of the image in panel a. The scale in image b range from 0 to 0.65 (saturated white).

An example of the retrieval process is shown in Figure 2. It takes about a minute to perform the retrieval on fully illuminated disk at periapsis. There are nominally 60-70 EXI observations per 10-day period.

Initial Results: We construct a database on the pixel level. This allows for a flexible method to create summary products with both spatial and temporal binning. However, there is a direct tradeoff between simplicity and computation intensity/resources. With 8 months of data, this DB is about 3 GB when stored as compressed and scaled 16-bit integers.

Zonal map: One of the most basic products to create for examining diurnal variations is a zonal-mean

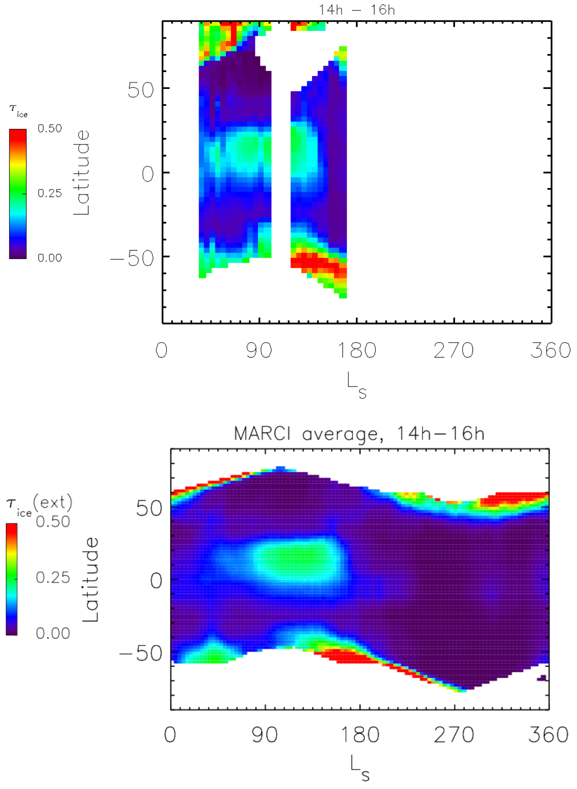
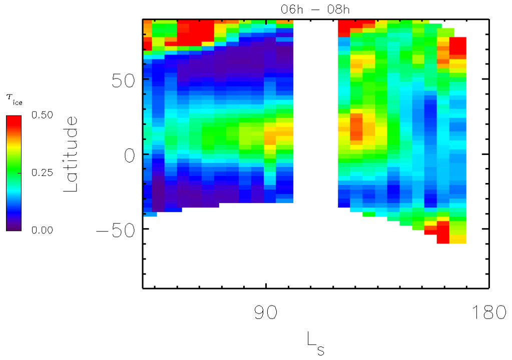


Figure 3: Zonal Mean behavior of the ACB for the mid-afternoon (14h-16h) block; TOP-EXI, BOTTOM-MARCI.

map. In Figure 3, we show the EXI water ice optical depth retrieval zonal mean as a function of season (Ls) for the typical MRO/MARCI LTST range of 14h-16h compared to that for MARCI (averaged over several Mars years). Both maps, which use the same scale bar, demonstrate the same general quantitative behavior, including the structure of the lower levels of water ice loading and clouds in the winter hemisphere. There are a few caveats/comments for Figure 3:

- the aphelion cloud belt (ACB) seems to start a little earlier in MY 36 as compared to the multi-year average of the MARCI data. This could be an artifact of the binning (EXI has relatively more data in the latter part of the block than MARCI).
- the noise due to few observations per spatial bin is quite apparent in the EXI data.
- The lack of sufficient polar ice filtering is clear in the EXI data in the North polar region.



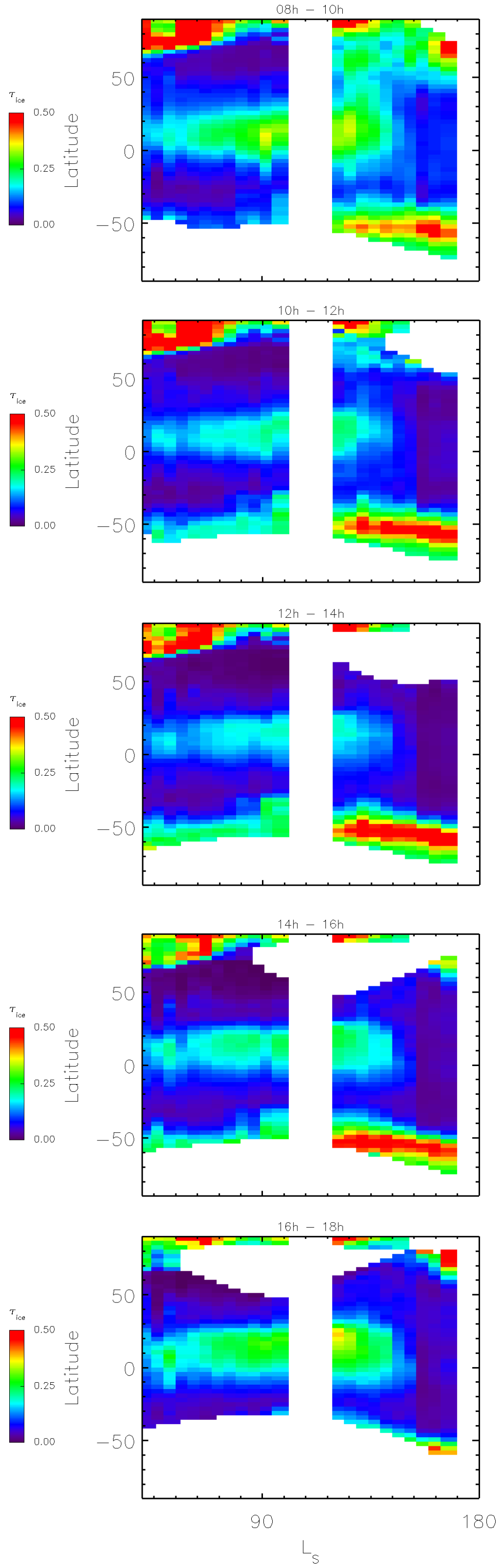


Figure 4: Series of LTST bins for the EXI zonal map product shown in Figure 3. We include the 14h-16h again for ease of comparison and truncate the L_S range in order to provide better resolution of the available data (i.e., less white space).

After having connected EXI to the MRO/MARCI observations, one can expand to other local times. Figure 4 shows a series of LTST bins of the zonal map, where each image uses the same color bar and uses an Ls range which more closely brackets the data displayed.

The local time evolution is quite striking, though perhaps not surprising given the initial indications from previous missions such as Mars Express and MAVEN. Combining the EXI observations with those from EMIRS, and in particular the nighttime observations, will provide excellent constraints and insights when compared with current Global Climate Models (GCMs).

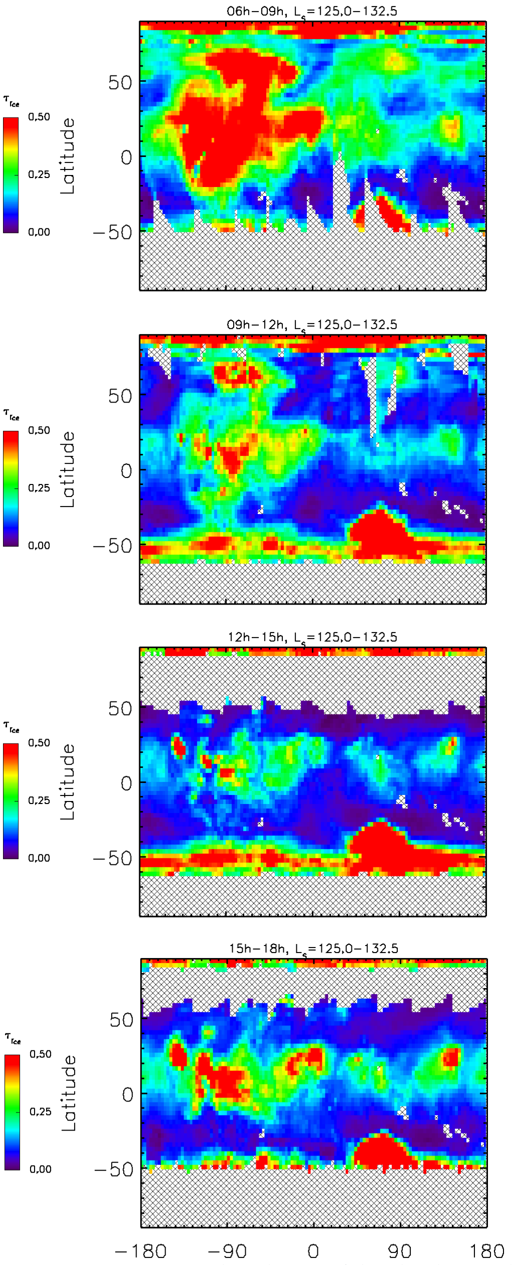


Figure 5: LTST-spatial evolution of the cloud optical depth at mid-summer in the northern hemisphere. To incase spatial resolution, 3 hour LTST bins are used.

Spatial (latitude-longitude) Maps: The spatial patterns of the diurnal evolution are more complicated to show without access to a third dimension, such as a video format. In Figure 5, we select an Ls bin for mid-summer in the northern hemisphere (i.e., Ls= 125°-132.5°). We are using the same color bar for each panel. Although the general temporal trends are naturally similar to those in the zonal mean plots, the spatial distribution of the early morning cloud versus the early evening might be considered surprising given the roughly similar structures in the zonal map. However, one should note that the 15h-18h bin may be obfuscating some the PM structure by including the late afternoon data in the average.

Next Steps: Making comparisons of the EXI local time products with the water ice columns from a GCM is a next logical step. We also plan to make direct comparisons to retrievals from other missions in addition to MRO where feasible.

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