THE MARS SCIENCE LABORATORY OPTICAL DEPTH RECORD. M.T. Lemmon[1]. [1]Texas A&M University, College Station, TX 77843-3150, USA.

Introduction: Dust in the Martian atmosphere is important to the energy balance and the dynamics [1]. The radiative impact of the dust varies with its optical depth. Surface-based observations of optical depth are critical as ground truth for more areally extensive orbital measurements [2]. Spacecraft that land on Mars have generally used direct solar imaging to track optical depth with time [2- 6]. The Mars Science Laboratory (MSL, also known as Curiosity) Mastcam instrument includes filters capable of imaging the Sun at 440 and 880 nm [7].

Observations: Mastcam solar-imaging sequences come in 3 main varieties. (1) They image the Sun in each filter. (2) They image the Sun in each filter, and image the sky near the Sun. (3) They video the Sun in order to observe transits of the Martian moons [Lemmon abstract]. Some of the sequences used only a single solar filter (880 nm) for operational reasons. This report will discuss the measurements of atmospheric optical depth made with direct solar imaging, and the constraints on dust size from associated near-Sun sky images.

Typically, solar images are downlinked to Earth first as thumbnail images. In these, the Sun is 10 pixels in diameter at 440 nm (Mastcam 100 mm focal length camera) and 3.3 pixels in diameter at 880 nm (Mastcam 34 mm focal length camera). Subframed images at 880 nm are eventually downlinked, giving 27 pixels across the Sun. Subframed images (80 pixels across the Sun) are not always downlinked at 440 nm.

For each pixel in the raw images, the data were converted to 8 bits via look-up table on the rover. Depending on operational circumstances, the images were downlinked either with lossless compression or with JPEG quality 95 compression. The thumbnails are 8x8 downsampled images derived from a JPEG compression algorithm, and were themselves JPEG compressed at quality 95.

Once downlinked, images were converted back to 12 bits. They were corrected for electronic bias, dark current, and any scattered light background. Then they were exposure time and flat-field corrected, resulting in images with radiances expressed in effective data numbers (DN) per second.

Sky images, when available, typically include areas from 5 to 40 degrees from the Sun. Once downlinked, they were processed to radiance units in a similar fashion.

Optical depth sequences were used beginning on sol 33. They have been used, on average, every 5 to 7 sols (a sol is a Martian solar day). In some sols there is more than one measurement, to allow a calibration, as described below). Unlike Spirit and Opportunity, MSL is not a solar-powered vehicle, and daily measurements of optical depth are not required as part of routine rover monitoring.

Optical depths: During the first 450 sols of the mission, there has been no evidence in the opacity data set of dust accumulation or other degradation of the Mastcam. It is therefore expect that optical depth can be derived from the Beer-Lambert-Bouguer extinction law, $F = F_0\ e^{-\tau\ \eta}$. In this formulation F is the observed direct solar flux, F_0 is the direct solar flux at the top of the atmosphere, τ is the normal optical depth, and η is the airmass (the ratio of the optical path to the zenith optical path, which is equivalent to the secant of the solar zenith angle for plane-parallel, homogeneous atmospheres).

The pre-launch calibration was sufficient for determining exposure times, but not for an accurate knowledge of F_0. Instead, the optical depth derivation followed procedures similar to those used for the Mars Pathfinder and Mars Exploration Rover mission [2, 5]. In this case, F_0 was varied in order to determine the root means square error resulting from an assumption that optical depth was constant on any given sol (or up to 3 consecutive sols). Sols with a single measurement were therefore irrelevant. Those with one or more would have values vary about the sol-average. Certain sols at the onset of dust storms were excluded. The F_0 that provided to lowest RMS error was selected; from this, each individual optical depth was derived without the constraint that optical depth be constant within a sol. The results for 880 nm are shown in Figure 1, compared to Mars Exploration Rover Opportunity 880-nm data [2].

At the start of the mission, moderate optical depths (near 0.6) were observed. These were quite similar to the contemporaneous Opportunity observations. The Opportunity data are from a similar latitude, but from a very different longitude and altitude. The initial surprise was that the similarity did not include a correction for altitude: in the hypothetical case of strictly well mixed dust, MSL should have seen over 20% more opacity at any given time just due to the lower altitude and resulting larger atmospheric column. During the southern summer, dust storms were also observed at each site, with similar timing (to within a few sols, the MSL resolution) and magnitude. Both sites showed a decrease going in to Southern winter (and

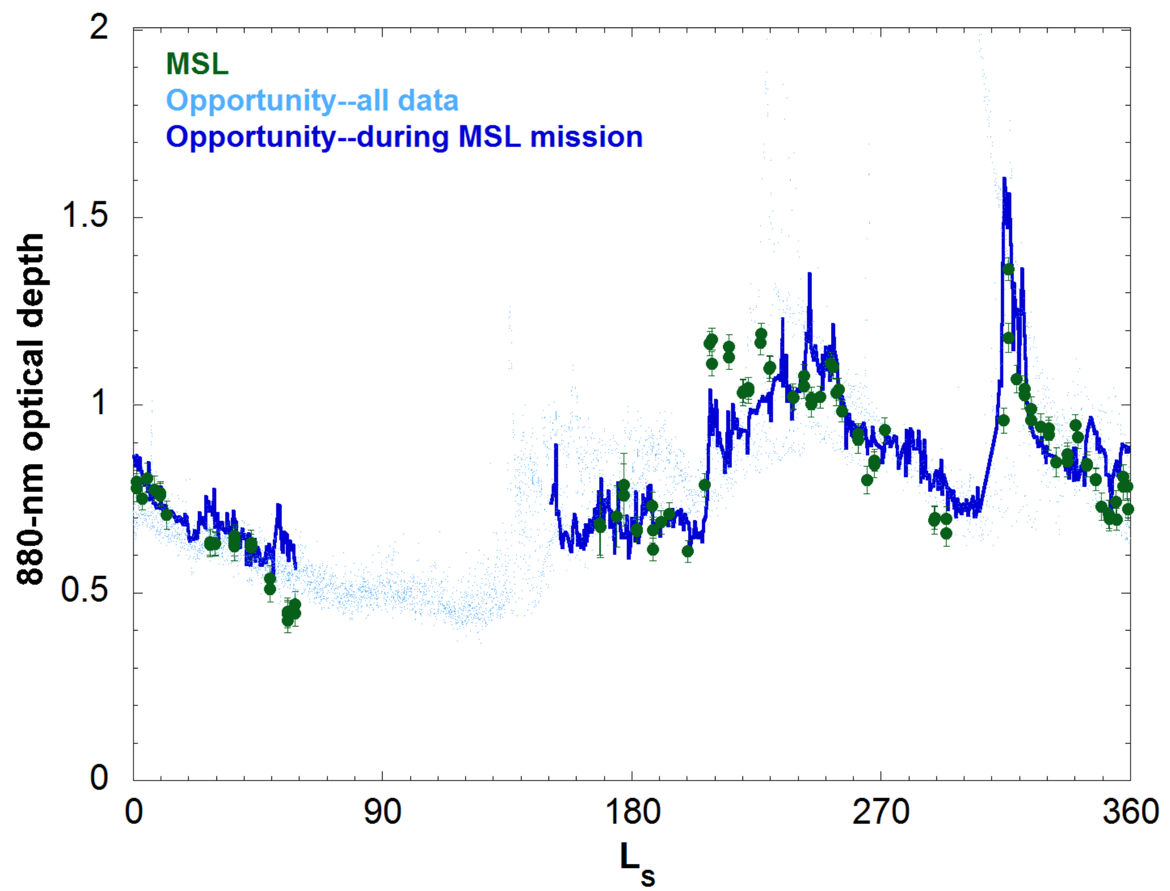

Figure 1. Measured optical depths through the MSL mission. Shown are the MSL 880-nm data (green, with error bars), Opportunity data for all years (light blue), and Opportunity data [2] during the MSL mission (dark blue). Solar longitude (L_S) is 0 at each northern Spring equinox.

the aphelion cloud belt season), with MSL's opacity declining only slightly faster.

Most of the data set has paired 440- and 880-nm values that differ in time by less than 1 minute. The 440-nm optical depth is typically about 3% smaller than that at 880 nm. This corresponds to an Angstrom exponent of about -0.05, where 4 indicates a Rayleigh-scattering regime and 0 indicates very large particles. Small negative values are consistent with dust size distributions commonly suggested for Mars, with a radius of 1-2 µm and a moderate variance (near 0.5). During the later sols, with opacity having declined under 0.5, the ratio reversed such that 440-nm opacities were higher by up tp 2%. This is consistent with smaller particle sizes. Such a reversal Is symptomatic of a change in aerosol size, but is not diagnostic: shifing the size distribution up or down by a factor of ~2 can cause such a change, as can adding a second mode of small aerosols.

Dust aerosol size: Analysis of sky images near the Sun taken as part of the opacity sequences is ongoing. Preliminary results, using triaxial ellipsoids as a representative for non-spherical dust, show only moderate changes in aerosol size, from around 1.6 to 1.4 µm effective radius, as optical depth declined after the dust storm season.

References: [1] Newman *et al.* (2002), *J. Geophys. Res.*, **107**(E12), 5124. [2] Lemmon *et al*. (2014), Icarus, in press. [3] Colburn et al. (1989), *Icarus*, **79**, 159 [4] Smith, P.H. and M.T. Lemmon (1999) *J. Geophys Res* **104**, 8975. [5] Lemmon *et al.* (2004) Science **306**, 1753. [6] Lemmon *et al.* (2009) *Proc. Lunar and Planetary Science Conf.* [7] Malin *et al.* (2010) *Proc. Lunar and Planetary Science Conf.*