Dust Dynamics in Gale Crater Observed Using the Line-of-Sight Extinctions through 3663 sols of the Mars Science Laboratory Mission

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Introduction: Dust on Mars is a widespread aerosol in the planet’s atmosphere, with key implications for moderating the climate of Mars. Images of the northern crater rim captured with the Navigation Camera (Navcam) onboard the Curiosity Rover have been used to analytically derive the line-of-sight (LOS) dust extinction between the rover and the northern crater rim through 2500 sols [1,2,3,4, including during the Mars Year (MY) 34 global dust storm [5]. These data show a consistent trend in the dust loading in Gale Crater, where a minimum in extinction occurs around Ls = 100°, and a maximum occurs near Ls = 300°.

Recently, a diurnal trend in the column opacities observed with Curiosity’s Mast Camera was found, where in the latter half of the year, the optical depth was observed to peak in the morning and decline throughout the day [6]. At Jezero Crater, where the Mars 2020 Perseverance Rover explores, observations of the column opacity using the Thermal InfraRed Sensor showed a broad maximum in dust opacity at solar noon, with lower values in the morning, evening, and throughout the night [7]. In this work, we seek to determine if the diurnal trend in column dust opacities at Gale and Jezero Craters exists within the LOS dust extinction.

Previous studies of the LOS extinction have been temporally constrained to observations obtained between 10:00 and 14:00 local true solar time (LTST), providing only a small glimpse into the dust dynamics occurring in Gale Crater. This work uses a new method when processing the LOS images to factor in the changing illumination throughout a sol.

Applying the new technique to the images when calculating the dust extinction, we observe diurnal trends within the LOS record. Additionally, the LOS recorded is reanalyzed and updated to include over 1000 new sols through the end of MY 36 (up to sol 3663). From this, diurnal and spatial trend in the dust extinction in Gale Crater are observed.

Methods:

Navcam LOS Image. The LOS observation consists of a single-frame Navcam image, with a 45 x 23° FOV (width x height). Each image has been calibrated such that each pixel (512 x 256 pixels per image) provides a spectral radiance in units of W m⁻² sr⁻¹ nm⁻¹. The site frame azimuth of each is image is 0°, imaging the crater rim directly to the north of the rover. Additionally, the local elevation of each image is 5°, such that a portion of the ground, crater rim, and sky are present.

LOS Extinction Determination. The method to calculate the LOS extinction closely follows that described in previous LOS studies [1,2,3,4]. Namely, portions of the sky, crater rim, and ground are isolated in each image (represented by the blue, pink, and green sections in Figure 1) and the radiance values in each section are used in Equation 1 described in [1] to derive an opacity between the rover and the crater rim. Then, a digital terrain model is used to divide the opacity by the distance between the rover and the crater rim, giving an extinction in km⁻¹.

Solar Angle. An assumption used to derive the equation to calculate the LOS extinction is that the scene captured in the image is illuminated evenly, which typically holds up well between 10:00 and 14:00 LTST. To address the uneven illumination outside of these times, the angle of the sun across the image frame is calculated using the solar azimuth and zenith angles as determined from the metadata header of each image. The pixels in each image are then shifted according to the calculated solar angle, such that Equation 1 is carried out on sections of the image along the same path as the incoming sunlight. An example of the solar angle can be seen with the yellow dashed line in Figure 1.

Figure 1. An example of a LOS observation captured on sol 1930. The image was acquired at 09:56 LTST. The blue, pink, and green areas show the isolated sections of the sky, crater rim, and ground, respectively. Here, the sun is in the eastern sky, with the solar angle calculated to be 62° (yellow dashed lines), determining the pixel offset in calculating the LOS extinction. A solar angle of 90° represent a sun that is fully overhead with no pixel offset.
Results:

Seasonal Results. The LOS extinction through sols 3663 (up to the end of MY 36) are shown in Figure 2. The first 2500 sols of published data were reanalyzed, and the extinctions through an additional 1000 sols were added. The seasonal trend observed in [2,3,4] continues to hold through MYs 35 and 36 (Figure 2). The lowest extinction occurs near southern winter $L_s = \sim 100^\circ$. After the minimum in extinction, the dustiness steadily rises until a maximum occurs around $L_s = 300^\circ$. The dustiest time of year was unfortunately not observed in MY 36 due to local topography within Gale Crater blocking the view of the crater rim. While small variations occur each year, the extinctions are largely consistent on a year-to-year basis.

Figure 2. The LOS extinctions (captured between 10:00 and 14:00) through MYs 31 to 36. A repeatable, annual trend is observed each MY in the dust extinction.

Diurnal Results. The dust extinctions are divided into 30-degree bins of $L_s$ and plotted as a function of LTST. Figure 3 shows the $L_s = 90 - 120^\circ$ and $L_s = 270 - 300^\circ$ bins, representing the time of year with the minimum and maximum extinctions. The data in each bin are fit to a standard parabola, as this fit produced consistently better $R^2$ values compared to a linear fit.

Here we see a trend that persists through each season where the dust extinction is low in the morning, rises broadly throughout the day with a peak near local solar noon, and declines into the evening. This trend is seen in the average extinctions across the crater rim, as well as in individual west, north, and east pointing extinctions within the LOS frame. Though the trend in diurnal dust extinction is persistent over the entire year, the change over a sol is enhanced in the southern summer compared to the less-dusty times of year. We hypothesize that enhanced dust lifting activity near solar noon [8], which is also higher in the southern summer, as well as diurnal pressure variations within Gale Crater [6] may contribute to the diurnal effect in the dust extinction.

Figure 3. The diurnal dust extinction for (a) $L_s = 90 - 120^\circ$ and (b) $L_s = 270 - 300^\circ$. The extinction starts low in the morning and peaks in the midsol period, before declining into the afternoon.

Conclusions: The LOS dust extinction in Gale Crater was updated through sols 3663 using a new method to include observations captured throughout an entire sol. The annual dust extinction saw minimal variability compared to previous years, with the minimum and maximum in dust loading occurring in the southern winter ($L_s = \sim 100^\circ$) and southern summer ($L_s = \sim 300^\circ$), respectively. For the first time, the diurnal dust extinction is reported. The extinction is highest near solar noon, with lower values in the morning and evening. This effect is larger in the dusty season compared to the non-dusty season, potentially caused by increased dust lifting.

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