

**DUST AND DEVILS, MICROBES AND MASS LOSS: RADIATIVE
TRANSFER IN THE ATMOSPHERES OF MARS AND ROCKY
EXOPLANETS**

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A DISSERTATION SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN PHYSICS AND ASTRONOMY
YORK UNIVERSITY
TORONTO, ONTARIO

MAY 2026

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Abstract

Planetary atmospheres are fundamentally shaped by their interaction with stellar radiation, governing climate, atmospheric dynamics, and planetary habitability. This dissertation examines the role of radiative transfer in shaping the atmospheres of Mars and rocky exoplanets through four complementary projects: dynamics in the dust loading and lifting in Gale Crater, the survivability of Earth-based microorganisms on the Martian surface, and the escape of hydrogen from rocky exoplanets observable in the Lyman- α line.

Airborne dust strongly modulates the Martian energy balance by altering the radiation budget at the surface. To reduce temporal constraints on previous observations of dust dynamics, a correction to the radiative transfer equation used in line-of-sight extinction measurements was applied. This modification revealed a diurnal cycle in dust opacity, with a peak in dust extinction near solar noon that is larger in amplitude during southern summer. Linking these results with an analysis of dust devil optical depth in Gale Crater suggests that dust devils produced under strong solar forcing contributes to the midday peak observed in dust loading, providing new insights into the dust cycle in Gale Crater.

To estimate the potential forward contamination of Mars, the survivability of Earth-based microorganisms on the Martian surface was investigated. By combining laboratory results of *Bacillus subtilis* with forward models, it was shown that UVC radiation sterilizes exposed spacecraft surfaces within 24 hours on Mars, reducing bioburden by up to 15 orders of magnitude. However, regolith and dust strongly dampen UVC radiation, meaning buried microbes or those embedded within a spacecraft may persist for up to 25 Mars Years before succumbing to low-pressure effects.

Finally, hydrogen escape from rocky exoplanets was modelled under Jeans and hydrodynamic regimes to quantify Lyman- α transit depths as a function of key planetary and atmospheric parameters. Results demonstrate that the hydrogen mixing ratio at the homopause is the main contributor to large transit depths, with temperature, planet mass, and photoionization introducing secondary variations. These results establish detectability thresholds for current and future UV telescopes. Ultimately, we find that Lyman- α transits can meaningfully constrain the atmospheric composition of rocky exoplanets, particularly when combined with multi-wavelength observations.

Acknowledgements

My first and deepest thanks go to my supervisor, Dr. John Moores. The time and care he dedicates to guiding his students, combined with his passion for science, are extremely admirable. I would not have developed into the same scientist I am today without his support and his openness in providing his students with so many opportunities for growth, for which I am sincerely grateful. I will carry the lessons I learned under his mentorship over the past six years with me throughout my career and life.

I would also like to thank Dr. Michael Mischna, Dr. Leslie Tamppari, and Dr. Robin Wordsworth, who all generously dedicated time from their busy schedules to supervise projects while I conducted research at their institutions. Some of my fondest memories made during my PhD are from my times at JPL and Harvard, and I am extremely grateful for the opportunity to learn and grow as a scientist in these environments.

The MSL ENV team has been incredibly supportive over the last six years and has helped shape some of the projects in this dissertation. I feel very fortunate to have worked alongside and learned from so many brilliant individuals on MSL. I will miss my time with Curiosity immensely.

To my friends and colleagues at PVL, thank you for always being there. Sharing this journey with all of you — whether that was exploring cities across the Atlantic together or chatting endlessly in CB 348 — has been a gift. I wish you all the very best in your next chapters, and I will always be cheering you on.

I would also like to thank my family and friends for their unconditional support. To my parents, thank you for always showing up for me and for instilling in me the belief that I can achieve anything I set my mind to. A special thank you to my nephews, Tate and Miles, who could always make me smile, even during the most stressful times. Finally, to my partner, Alex — thank you for being you. Your support has been unending, even when it meant months apart and you taking sole care of our perfect cat, Hank. Thank you for being on this journey with me and for encouraging me to take the first step toward the next one.

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Chapter 1

Introduction

1.1 Radiative Transfer in Planetary Atmospheres

Planetary atmospheres are fundamental for determining planetary climate, surface conditions, and long-term evolution. Through interactions with radiation from a host star, atmospheres redistribute energy, drive weather and climate, influence the survival of biological material, and determine the rate at which planets lose their atmospheres to space. Characterizing these processes is therefore essential for understanding planetary habitability both within the Solar System and among the growing population of known exoplanets.

Although these radiative transfer processes can occur across various regions of a planet's atmosphere over various timescales, they are all fundamentally linked by the exchange of energy between the planet's host star and its atmosphere. From dust suspended in the lower atmosphere of Mars, to ultraviolet (UV) radiation acting on terrestrial microorganisms at the surface, to hydrogen escaping from the upper atmospheres of rocky exoplanets, radiative transfer is essential for shaping the planetary environments. This dissertation investigates the role of radiative transfer across planetary environments through four interconnected studies.

The transport of energy as electromagnetic waves through a medium defines the concept of radiative transfer. As light propagates through matter, energy is redistributed by absorption, emission, and scattering processes as the photons, which are fundamental particles of light, interact with the constituents of the medium. The sum of these interactions determines the change in the radiation, such as its redirection and attenuation. In planetary atmospheres, interactions between atmospheric gases and aerosols with the light emitted from the planet's host star, as well as interactions with radiation emitted from the planet itself, shape the planet's climate, weather, and the composition of the atmosphere.

The amount of radiation received at the surface of a planet is a function of the original value of the incoming spectral radiance, I_λ , and the effects of scattering, absorption and emission along an optical path, s . The radiative transfer equation is represented by

$$\frac{dI_\lambda(s)}{ds} = -\kappa_\lambda(s)\rho(s)(I_\lambda(s) - J_\lambda(s)), \quad (1.1)$$

where $\kappa_\lambda(s)$ is the extinction coefficient. This term is further divided into scattering and absorption terms via

$$\kappa_\lambda(s) = a_\lambda(s) + s_\lambda(s), \quad (1.2)$$

where $a_\lambda(s)$ is the absorption coefficient and $s_\lambda(s)$ is the scattering coefficient. In general, both absorption and scattering will work to decrease the incoming radiation, however a medium is capable of scattering light both forward and backward, making the scattering contribution a complex function of the scattering properties of the particular medium.

In Eq 1.1, the remaining components are the density of the material along the path, $\rho(s)$, in kg m^{-3} , and $J_\lambda(s)$ is the source term, which accounts for emission. Through Planck's law, an atmosphere at a given temperature emits radiation, adding to the original intensity of the beam at certain wavelengths.

One solution to Equation 1.1 can be found when considering an atmosphere with no emission and no scattering, such that J_λ and $\kappa_\lambda = 0$. This is a reasonable assumption when working in optical wavelengths, for example, since atmospheric emissions peak at longer wavelengths in the thermal infrared (IR) region of the electromagnetic spectrum.

Defining the optical depth, τ , of the atmosphere as the total amount of material along the optical path multiplied by the extinction coefficient to determine how that material will interact with the light, we get

$$\tau = \int_{s_0}^s \kappa_\lambda \rho ds. \quad (1.3)$$

From these two assumptions, Eq 1.1 can be rewritten as

$$\frac{dI_\lambda}{d\tau} = -I_\lambda. \quad (1.4)$$

Rearranging and solving the integral yields the radiance given at the surface, also known as the Beer-Lambert Law,

$$I = I_0 \exp(-\tau), \quad (1.5)$$

where I_0 is the top-of-atmosphere radiance. From this equation, we consider atmospheres with $\tau > 1$ to be optically thick, with little light getting through, and $\tau < 1$ to be optically thin, where only a small amount of the light is attenuated by the atmosphere. Changes in the optical depth will ultimately affect total surface insolation and atmospheric heating rates, driving circulation patterns and determining weather.

Equation 1.5 gives one solution to the radiative transfer equation, however all radiative transfer in an

atmosphere is found through various solutions of Equation 1.1. More general solutions include scattering or emission processes, such as the greenhouse effect whereby atmospheric gases reradiate longwave radiation back toward the surface, increasing atmospheric temperatures. Consequently, processes ranging from aerosol-driven climate variability to upper atmosphere escape are ultimately governed by radiative transfer. Throughout this dissertation, we will explore various atmospheric phenomena relating to radiative transfer in atmospheres, from dust lifting and microbial survival on Mars to hydrogen escape from rocky exoplanets.

1.2 Introduction to Mars’ Atmosphere

Mars, the fourth planet from the sun, has a thin yet dynamic atmosphere composed mostly of CO_2 , with trace amounts of gases such as nitrogen, argon, and water vapour (Summers et al., 2002). At an average surface pressure around 7 millibar (mbar) (Martínez et al., 2017), the atmosphere of Mars is nearly $100\times$ thinner than Earth’s atmosphere. Studying Mars’ atmosphere gives valuable insight into the climate and long-term evolution of a terrestrial planet atmosphere, providing a comparison point to Earth’s own atmosphere. Examining the structure, composition, and variability of the Martian atmosphere contributes to a broader understanding of atmospheric evolution and habitability, both within our solar system and beyond.

Mars has an orbital obliquity of 25.2° and an eccentricity of 0.0934, both of which contribute to its seasonal climate variability. The planet’s obliquity drives changes in surface insolation with latitude over the course of a Martian year (Bougher et al., 2006). In addition, its relatively high eccentricity results in a $\sim 20\%$ variation in Mars’ distance from the Sun between perihelion and aphelion, leading to increased insolation when the planet is closer to the Sun.

A common time-keeping convention on Mars tracks the seasons using the planet’s position in its orbit, referred to as “solar longitude” (L_s). By definition, $L_s = 0^\circ$ corresponds to the Martian northern spring (or vernal) equinox, followed by northern summer solstice at $L_s = 90^\circ$, northern fall equinox at $L_s = 180^\circ$, and northern winter solstice at $L_s = 270^\circ$. The seasons are reversed in the southern hemisphere. In total, it takes 668 Martian sols to complete one orbit around the sun, where a sol refers to Mars’ spin on its axis, taking 24 hours and 39 minutes to complete one revolution. Since Mars’ eccentricity is large, the speed at which the planet travels is not equal at all points in its orbit, and therefore solar longitude and sol do not progress evenly throughout an entire Mars Year (MY). In this dissertation, the typical convention of MY 1 starting on April 1, 1955 is used (Clancy et al., 2000).

As mentioned, the axial tilt of Mars drives distinct seasonal variations, similar to that of Earth’s. For example, Figure 1.1 shows the daily mean air temperature recorded at five Martian landing sites — namely, the Viking 1, Viking 2, Mars Pathfinder, Phoenix, and Mars Science Laboratory (MSL) landing sites — as a

function of L_s . The Viking 1, Viking 2, Pathfinder, and Phoenix landers, which all operated in the northern hemisphere of Mars, experience maximum mean air temperatures between $L_s = 0$ - 180° , which spans northern spring and summer, and minimum air temperatures during fall and winter between $L_s = 180$ - 360° . At the MSL landing site, which is just a few degrees south of equator, the distance to the sun impacts seasonal climate changes more than the obliquity.

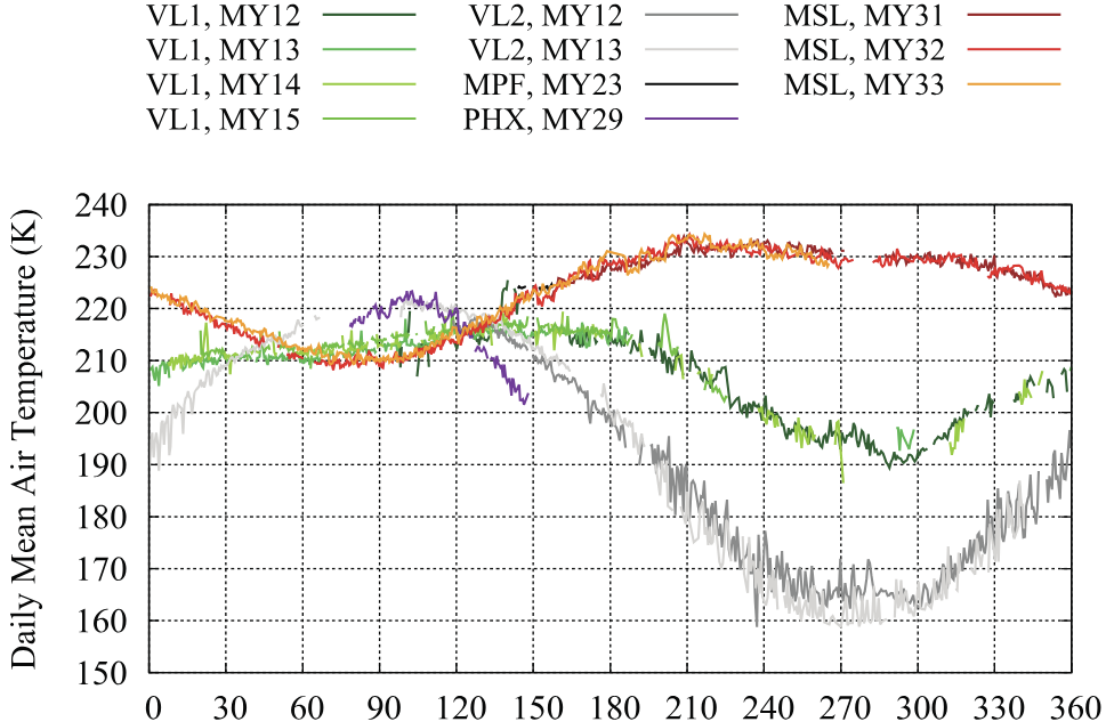


Figure 1.1: From Martínez et al. (2017), showing daily mean air temperatures measured at the Viking 1 (VL1), Viking 2 (VL2), Mars Pathfinder (MPF), Phoenix (PHX), and Mars Science Laboratory (MSL) landing sites.

Because the planet moves substantially closer to the sun during perihelion compared to aphelion, differences in global solar insolation result in changes in the global average temperatures, independent of hemispheric seasonal effects. The change in average global temperatures gives rise to two distinct “seasons” on Mars, characterized by the dominant atmospheric aerosol. During perihelion, the rise in mean atmospheric temperature contributes to an increase in atmospheric dust loading over the planet (Clancy et al., 2003; Giuranna et al., 2021; M. D. Smith et al., 2023, 2025), with the potential for planet-encircling dust storms (M. Battalio & Wang, 2021; Cantor et al., 2001; Guzewich et al., 2019; Kass et al., 2016). During the aphelion season, cooler global temperatures cause the formation of a band of water-ice clouds over the equatorial region of Mars called the Aphelion Cloud Belt (Christensen et al., 2001; Clancy et al., 1996; Glenar et al., 2003; Wolff et al., 1999). These two seasons are observed in Figure 1.2.

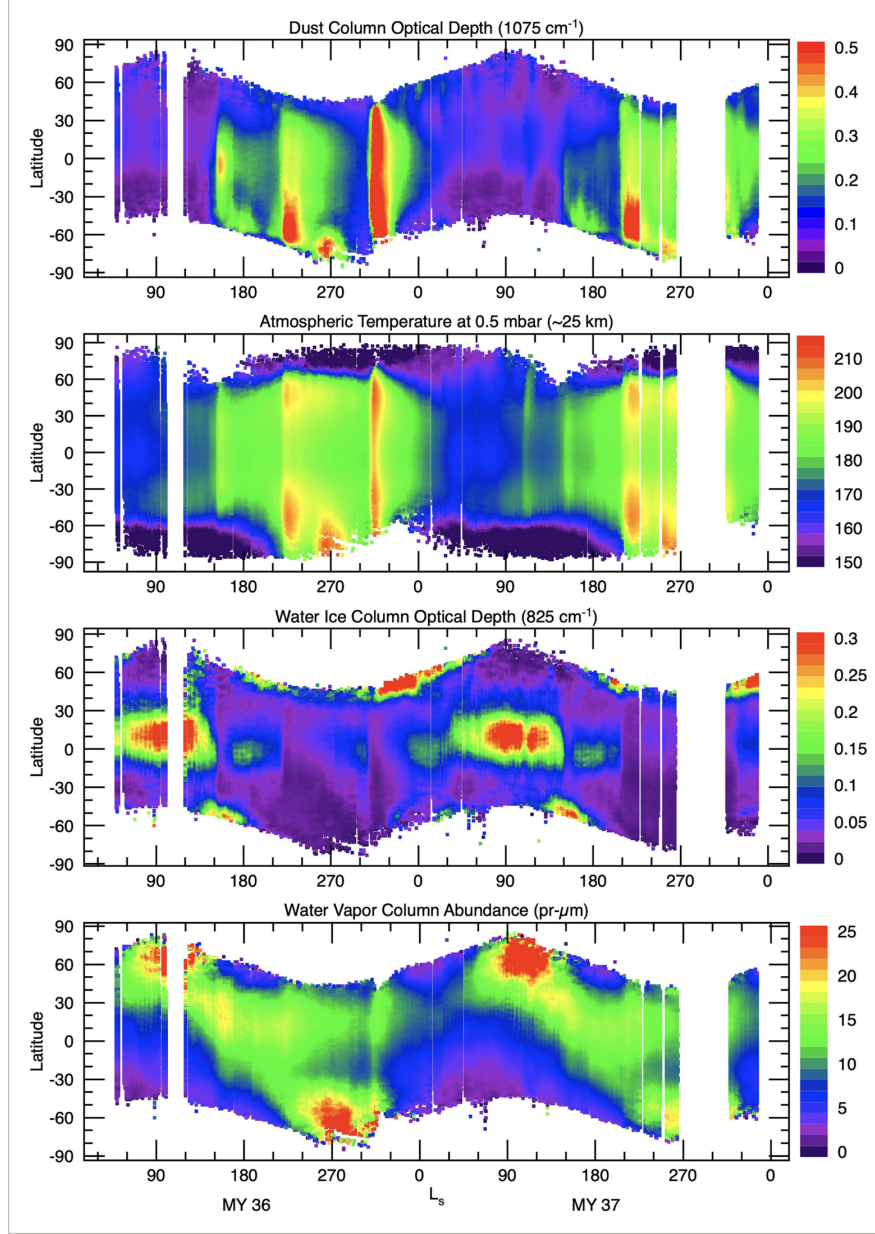


Figure 1.2: From M. D. Smith et al. (2025), demonstrating the dominant aerosol in the Martian atmosphere as a function of season. When the planet is at perihelion ($L_s = 251^\circ$), an increase in dust loading is observed in the atmosphere. At Aphelion ($L_s = 71^\circ$), water-ice becomes the dominant aerosol.

The changes in temperature and aerosol loading as the global insolation changes throughout Mars' orbit highlights the Martian atmosphere's responsiveness to radiative forcing. Variations in aerosol loading throughout the year alter the surface insolation by changing the atmospheric optical depth, as described in Equation 1.5. These seasonal variations will ultimately determine atmospheric heating rates, thereby affecting climate and weather patterns. Notably, atmospheric dust has an outsized impact on the atmospheric radiative transfer and energy balance. Therefore understanding atmospheric dust variability is crucial for

understanding the climate of Mars as a whole.

1.3 Dust in the Martian atmosphere

1.3.1 The Radiative Effects of Dust

Though an abundance of CO_2 in the atmosphere of Earth is considered a significant source of greenhouse warming, the low surface pressure of Mars' atmosphere limits the CO_2 -dominant atmosphere's effectiveness in retaining heat. Due to this, Mars has incredibly large diurnal temperature swings, which can vary up to 70 K between the minimum and maximum daily temperatures (Martínez et al., 2017). The surface energy balance is instead mostly dictated by the incoming solar radiation, which reaches the ground relatively unimpeded, and the thermal radiation emitted from the surface (Savijärvi, 2014). However, when in-situ atmospheric temperature measurements were made by the Mariner spacecraft (Kliore et al., 1972), it became clear that previous models of the Martian atmospheric thermal structure were severely underestimating the temperature when including CO_2 alone, and an additional radiative agent — confirmed to be dust — was needed to account for the observed warming (Gierasch & Goody, 1972).

Dust affects radiative transfer in multiple ways, and the total aerosol optical depth determines whether dust has a net warming or cooling effect. In general, dust will influence the atmosphere and surface through the absorption and scattering of shortwave radiation and the thermal emission of longwave radiation (Pollack et al., 1979). Studies have investigated wavelength-dependent parameters of Martian dust, such as the single scattering albedo, finding a value of approximately 0.96 across many wavelengths, except for those less than 500 nm and greater than 7000 nm, where the single scattering albedo drops below 0.8 (Wolff et al., 2009). In practice, a single scattering albedo at these values suggests that dust scatters much more light than it absorbs, however several percent of the incoming light is still absorbed by the dust. With a high single scattering albedo, surface temperatures can lower as incident sunlight is scattered away from the surface.

The absorption of light causes the dust to heat up and emit thermal IR toward the surface, acting similar to a greenhouse gas. Particularly at night, the presence of dust has a warming effect on near-surface and surface temperatures compared to a dust-free atmosphere (Cooper et al., 2021; Leino et al., 2024).

The radiative effects of dust are emphasized when considering the most intense dust-loading conditions on Mars which occur during planet-encircling dust storms. In MY 34, a dust storm began around $L_s = 185^\circ$, just after northern fall equinox. The dust storm initially started in the southern hemisphere, near the location of the Opportunity rover in Meridani Planum (Kass et al., 2020), which ultimately caused the end of the Opportunity rover's mission as the high dust loading impeded its solar panels from functioning. Growth of

the storm was detected from orbit using the Mars Reconnaissance Orbiter’s Mars Climate Sounder (MRO-MCS) instrument (Shirley et al., 2020) as the storm grew, eventually circling the entire planet over its ~ 150 sol lifetime. Global maps of the column dust optical depth are shown in Montabone et al. (2020).

Figure 1.3 shows the growth of the storm as captured during the MSL mission using the Mast Cameras on board the Curiosity Rover. Throughout the storm, meteorological conditions were monitored using the Rover Environmental Monitoring System (REMS; Gómez-Elvira et al. (2012), which contains instruments such as ground and air temperature sensors, a pressure sensor, and UV sensors. As the storm increased in optical depth, up to a peak of 8.5 (Lemmon, Guzewich, et al., 2024) with the line-of-sight to the crater rim becoming completely obscured (C. L. Smith et al., 2019), the meteorology within the crater was altered drastically. UV radiation reaching the surface was attenuated to 95% of its usual value (Viúdez-Moreiras et al., 2020), emphasizing the intense scattering and absorption properties of dust at high optical depth. Additionally, the typical 70 K difference in minimum and maximum near-surface air temperatures per sol were reduced to 30 K (Guzewich et al., 2019), with nighttime values approximately 10 K warmer than normal due to the increased downwelling longwave radiation caused by the large dust abundance.



Figure 1.3: Images captured with the Curiosity Rover’s Mast Camera during the MY 34 global dust storm. On mission sol 1997, the crater was relatively dust free and crater rim was seen in the distance. By sol 2085, increased dust loading completely obscures views to the Gale’s crater rim. Image Credit: JPL/Caltech/York University.

The convective activity of Mars’ atmosphere is also largely driven by the heating rates controlled by dust’s interaction with radiation, which in turn drives dust-lifting from the surface, causing a radiative-dynamic feedback in the atmosphere (Madeleine et al., 2011; Rafkin, 2009). The changes in pressure-gradients caused by warming or cooling by dust additionally drives winds at the surface (Kahre et al., 2017). Modelling of dust storms show that a positive radiative-dynamic feedback is needed to enhance circulation in the atmosphere to drive more dust into the atmosphere and grow the storm (Newman et al., 2002). Interestingly, this feedback at the surface becomes negative when dust loading becomes sufficiently high, suppressing convective activity,

such as dust devils, at the surface (Guzewich & Smith, 2019; Newman et al., 2002; Rennó et al., 1998).

Dust therefore plays a key role in modulating the Martian climate system through its strong coupling with atmospheric radiation and dynamics. Dust directly influences surface temperatures, boundary-layer structure, and atmospheric circulation. Understanding how dust is lifted, transported, and distributed throughout the atmosphere is therefore essential for accurately characterizing the Martian radiative balance and the broader dynamics of the planet’s climate.

1.3.2 Dust-Lifting Mechanisms

Due to dust’s significance in driving Mars’ climate processes, understanding how dust is injected into the atmosphere is critical. The two mechanisms that are attributed for supplying the majority of dust to the atmosphere are dust devils and wind-stress dust lifting (Kahre et al., 2017).

Wind-stress dust lifting occurs when particles move in one of three ways when subjected to a wind-field: 1) suspension in the air, which occurs for the finest particles and is maintained by turbulence, 2) saltation, where a particle lifts into the air, but returns to the surface due to gravity, and 3) creep, where particles move along the surface but are not entrained in the wind (Kahre et al., 2017). Though smaller particles have less mass which makes suspension easier, they also have more inter-particle cohesion which counterintuitively makes lifting these particles very difficult unless acted up by strong winds (Newman et al., 2002). Additionally, these small particles are within a laminar sub-layer of the atmosphere, which is a stable layer at the surface below the turbulent boundary layer, therefore causing the particles to be minimally affected by turbulence to set them in motion (Greeley, 2002). Studies have shown that Martian dust can be lofted into the atmosphere through the saltation of larger particles, which transfer momentum to the finer particles (Greeley & Iverson, 1985).

The second type of dust lifting is characterized by the presence of a convective vortex capable of lifting dust, also known as a dust devil. Dust devils were first hypothesized as a mechanism for lifting dust into the atmosphere (Gierasch & Goody, 1972; Neubauer, 1966), and were later confirmed from orbital imaging (Thomas & Gierasch, 1985), and have been subsequently detected by numerous landers operating on the surface of Mars (Greeley et al., 2006, 2010; Guzewich et al., 2023; Hueso et al., 2023; Lemmon, Smith, et al., 2022; Metzger et al., 1999; Newman et al., 2022; Schofield et al., 1997). Figure 1.4 shows an example of dust devils observed in Jezero Crater.

A dust devil forms when strong solar heating causes instability in the near-surface atmosphere. The instability, combined with wind shear, induces a convective vortex, characterized by a central pressure drop and tangential winds (Balme & Greeley, 2006). When dust is picked up in a dust devil, it is distinguishable



Figure 1.4: Several large dust devils captured by the Perseverance Rover in Jezero Crater. Image Credit: JPL/Caltech.

by its column-like structure due to the dust circling the vortex core (Kahre et al., 2017). In some cases, pressure drops have been measured with no associated dust devil observed, known as a “dustless” devil — this phenomenon occurred frequently at the InSight landing site (Lemmon, Campbell, et al., 2024; Lorenz et al., 2021). It is not well known why some locations are more likely to loft dust than others, which is potentially dependent on if dust is lifted due to the suction effect of the dust devil, or by the wind-stress caused by the tangential winds.

1.3.3 The Mars Science Laboratory Dust Record

1.3.3.1 Introduction to the MSL Mission

The Curiosity rover landed in Gale Crater (4.5°S, 137.4°E) in August 2012, just before southern spring in MY 31, to assess the habitability and past environment of the region as part of the MSL mission (Grotzinger et al., 2012). Gale Crater is 154-km in diameter, with the 5 km-high Aeolis Mons, also known as Mount Sharp, situated in the center of the crater. Figure 1.5 shows a topographical view of Gale Crater with the rover’s landing site indicated by a green dot. The Curiosity rover studies the geology and climate of Gale using its large suite of instruments, such as the aforementioned meteorological suite, REMS, and cameras, such as the Navigation Cameras (Navcam) and Mast Camera (Mastcam).

Though the Navcams are nominally intended for assisting in rover navigation, these cameras have been used extensively to image the environment in Gale Crater to get information on dust (Guzewich et al., 2023; C. A. Moore et al., 2016; Moores, Lemmon, Rafkin, et al., 2015; Moores et al., 2019; C. L. Smith et al., 2019; C. Smith et al., 2020) and cloud processes (Campbell & Moores, 2025; Campbell et al., 2020; Cooper et al., 2020; Hayes et al., 2024; Innanen, Cooper, et al., 2024). The Navcams are situated on the rover’s mast, enabling 360° views in azimuth and 178° views in elevation (Maki et al., 2012). The Navcams have a 45° × 45° field-of-view (FOV), which provide images composed of 1024 x 1024 pixels. Many of the images used for scientific analysis are down sampled and sub-framed vertically onboard the rover, producing images that are 1024 x 512 pixels.

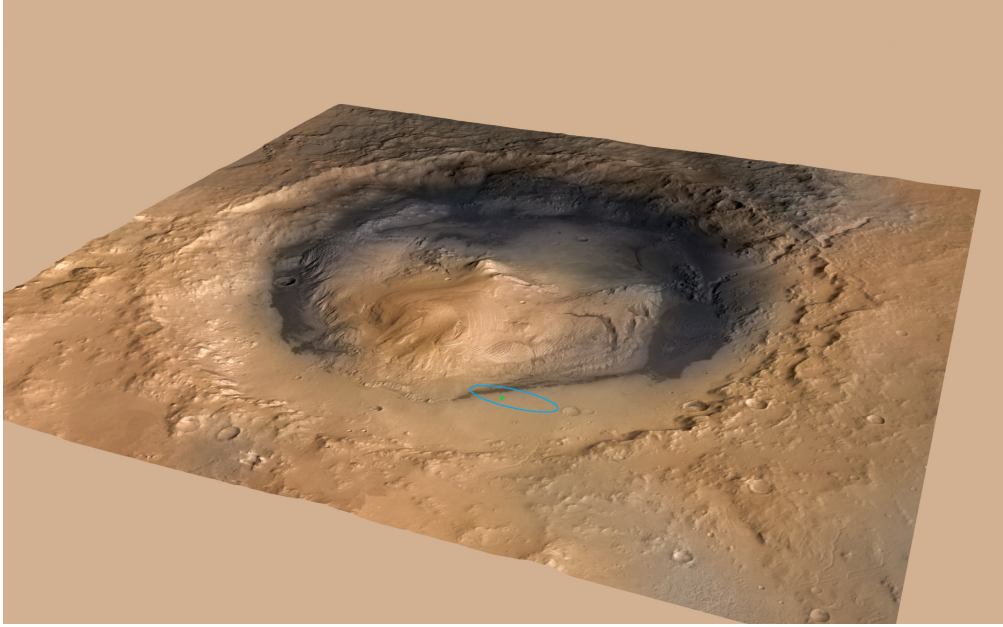


Figure 1.5: Topographical map of Gale Crater. The blue ellipse in the bottom right corner indicates the targeted region for the Curiosity rover’s landing and the green dot shows where the rover actually landed. Since landing, Curiosity has driven toward and up Mount Sharp. Image Credit: JPL-Caltech.

The radiometrically-calibrated (RAD) images produced by the Multimission Image Processing Laboratory (MIPL) are commonly used in studies of dust and clouds, where each pixel has a value of spectral radiance in units of $\text{W m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$. To calibrate these images for scientific use, flat-field, exposure time, and temperature-compensated responsivity corrections are carried out. The flat field images used for the Navcam were acquired in 2018 between sols 1171-1261, where images of the Martian sky were captured to represent the current condition of the Navcam optics. No thorough documentation for the Navcam calibration exists, however the Navcams were built-to-print copies of the MER rover Navcams and the calibration steps can be read in Bell III et al., 2006. Geometric calibration of the Navcam images, including linearization of the images, is carried out using the CAHV(ORE) camera model system described in Maki et al., 2012.

At the time of writing, the Curiosity Rover has been exploring Gale Crater for over 4800 sols, enabling studies of the near-surface climate for more than six full MYs. Studying the atmosphere from the surface of Mars offers an advantage in characterizing near-surface properties, as orbiters studying aerosols often cannot see the bottom few km of the atmosphere (Innanen, Moores, et al., 2024). In the next section, the record of dust observations and results acquired by MSL is presented.

1.3.3.2 Dust Observations and Results in Gale Crater

Using the rover’s Mastcam to image the solar disk, a record of whole-atmosphere column optical depth has been recorded by Lemmon, Guzewich, et al. (2024). In general, the optical depth in Gale Crater ranges

from 0.5 to 1.5 each year, without the inclusion of major dust storms. Lemmon et al. (2024) showed that column optical depths decreased between $L_s = 0^\circ$ - 140° , then increased generally toward the end of the year, with local maxima around $L_s = 210^\circ$ and again at $L_s = 315^\circ$, when regional storm activity increases near Gale Crater. A diurnal trend in column optical depth was noted as well, where in the second half of the year during southern spring and summer, the column optical depth is highest in the morning and decreases to a minimum in the evening.

Complementing the column optical depths is an observation known as the line-of-sight (LOS) dust extinction observation. The LOS dust extinction comprises a single-framed Navcam image pointing at the northern crater rim, from which dust extinction within Gale crater is derived. Probing the bottom 2 km of the atmosphere, the LOS dust extinction provides information on dust loading within Gale Crater itself, giving insight into the vertical stratification of dust (e.g. Guzewich, Newman, et al. (2017)), and coupling processes with other lower atmosphere phenomena, such as dust lifting from the surface (Guzewich et al., 2023).

Through sol 2500, the LOS extinctions have followed a consistent, repeating annual trend, where the minimum in dust extinction occurs around $L_s = 100^\circ$ and the maximum occurs around $L_s = 300^\circ$ (C. A. Moore et al., 2016, 2019; C. Smith et al., 2020). The timing of the maximum and minimum extinctions are in general agreement with the column optical depth, which also showed southern summer as the dustiest time of year (Lemmon, Guzewich, et al., 2024). Previous reports of the LOS extinction studied the vertical and horizontal distribution of dust within Gale Crater, showing a well-mixed atmosphere horizontally (C. Smith et al., 2020) with an increase in dust-loading near the bottom of the atmosphere during the southern summer, suggesting dust lifting from the crater floor (C. A. Moore et al., 2019). The seasonal cycle of LOS dust extinctions is shown in Figure 1.6.

Dust lifting into the atmosphere has been extensively observed in Gale Crater, using both REMS and Navcam data. The REMS pressure sensor has consistently detected pressure drops indicative of convective vortices near the rover throughout the mission (Harri et al., 2014; Kahanpää et al., 2016; Mason et al., 2025; Ordonez-Etxeberria et al., 2018; Ordóñez-Etxeberria et al., 2020). In addition, both wind-stress dust lifting and dust devils have been imaged using Navcam since sol 1545 (Guzewich et al., 2023), after a lack of dust devils were observed in the first 1500 sols of the mission (Moores, Lemmon, Kahanpää, et al., 2015). The frequency of the dust lifting events varies both seasonally and diurnally. Convective pressure vortex detections peak at solar noon, with a sharp increase in events starting after 10:00 local true solar time (LTST) and sharp decrease after 16:00 LTST (Mason et al., 2025). Seasonally, an increase in convective pressure vortex frequency occurs between $L_s = 170^\circ$ - 300° (Mason et al., 2025), consistent with the seasons when column optical depth (Lemmon, Guzewich, et al., 2024) and LOS dust extinctions (C. A. Moore et al.,

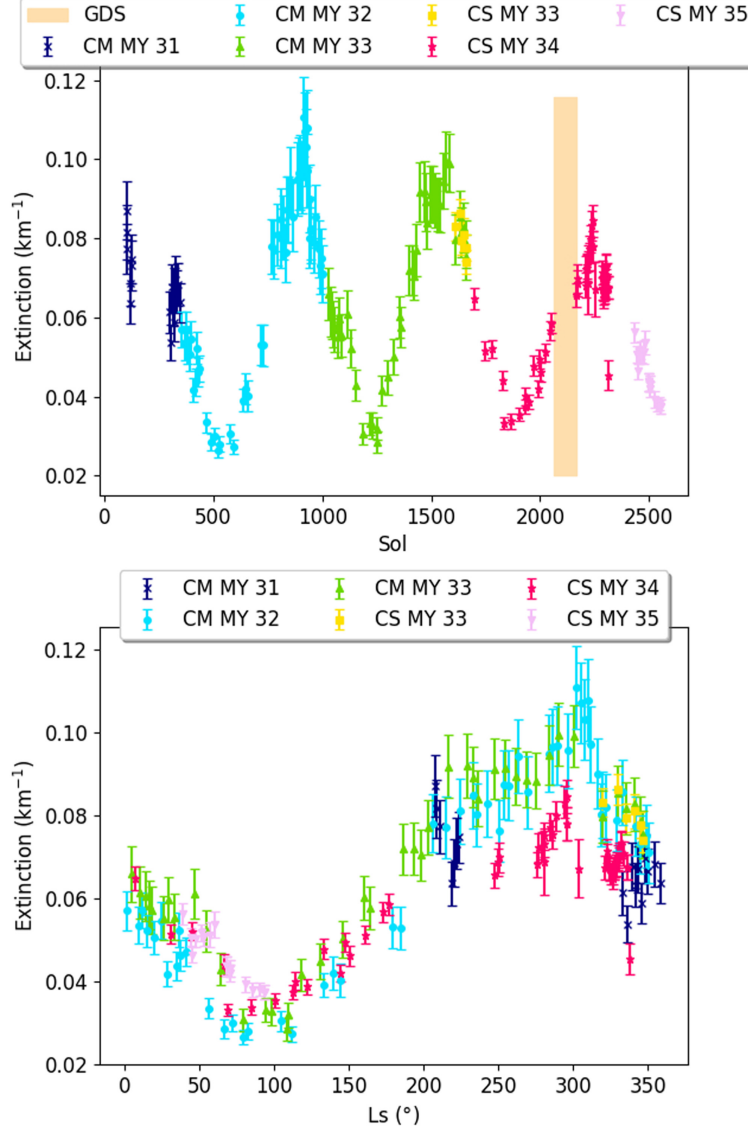


Figure 1.6: The LOS dust extinction cycle through sol 2500 of the MSL mission is presented as a function of mission sol (top) and L_s (bottom). The dust extinction shows a repeatable pattern with little interannual variability, where the peak in dust extinction occurs in southern summer and the minimum occurs in southern winter. Image from C. Smith et al., 2020.

2016; C. Smith et al., 2020) are also at their peak. Dust-entrained vortices imaged by Navcam display a similar diurnal pattern, occurring most frequently near local noon, and are largely confined to the period between 10 to 16 LTST (Guzewich et al., 2023). Analysis by Guzewich et al. (2023) found that dust devils are more commonly observed in the southern summer than winter, though substantial interannual variability between MYs was seen, largely attributed to the rover’s location in Gale Crater. Observational biases are discussed in both Mason et al. (2025) and Guzewich et al. (2023).

At Jezero Crater, where the Perseverance Rover has been exploring since 2021, a diurnal trend in aerosol optical depth was noted (M. D. Smith et al., 2023). Employing the Thermal InfraRed Sensor (TIRS) on the

Mars Environmental Dynamics (MEDA) suite, M. D. Smith et al. (2023) used a least-squares fitting routine to break up the contribution of dust and water-ice to the total column optical depth. M. D. Smith et al. (2023) found a diurnal result, where the dust optical depth was lowest overnight, increased in the morning with a broad peak at solar noon, and decreased into the evening.

Investigations from other landing sites, as well as the diurnal trends in the column optical depth (Lemmon, Guzewich, et al., 2024) and dust lifting frequency (Guzewich et al., 2023; Mason et al., 2025) in Gale, raise the question whether similar diurnal behaviour is present in the LOS extinction record. Despite the LOS extinction observation giving immense insight into seasonal variations in the dust loading in Gale Crater, short-term changes in dust loading are lacking due to a temporal constraint on the LOS record which necessitates that the LOS observation is only captured between 10:00-14:00 LTST. The equation governing the LOS extinction was validated with a radiative transfer model, showing an agreement within 4% for images taken during the 4-hour window centered on local noon (Moores, Lemmon, Kahanpää, et al., 2015). However, constraining the LOS observation to only 4 hours per sol severely limits our understanding of short-term dust evolution in Gale Crater.

In addition to the unknown in the short-term behaviour of dust-loading in Gale Crater due to the temporal constraint on the LOS observation, there are unknowns in the dust-lifting mechanisms. In particular, though previous studies have investigated when and where dust lifting most frequently occurs, the actual amount of dust lofted by these events remains poorly understood. This gap limits our understanding of how dust devils contribute to the background dust abundance, such as the LOS dust extinction in Gale Crater.

These limitations highlight two key gaps in our understanding of the dust cycle in Gale Crater: 1) the lack of information on diurnal variability in lower-atmosphere dust loading and 2) how much dust is lifted into the atmosphere by dust devils on diurnal and seasonal scales. Addressing these questions is essential for understanding how local dust lifting processes influence the vertical distribution and temporal evolution of dust in the Martian atmosphere. The work presented in Chapters 2 and 3 of this dissertation aims to address these gaps using the record of Navcam observations from the Curiosity rover.

1.4 Planetary Protection and Microbial Survival

As highlighted in Sections 1.2 and 1.3, the environment and climate of Mars are markedly different from Earth's, in part due to the presence of atmospheric dust and its influence on the radiative transfer of energy from the sun. Because of Mars' unique environment, many spacecraft have been sent over the last few decades to observe and study the planet from orbit as well as from the surface using robotic landers and rovers, giving immense insight into the Martian climate and geology.

The potential habitability of Mars is an ongoing discussion (Mellon et al., 2024), with missions such as the Mars2020 mission (Perseverance Rover) sent to Mars to search for evidence of past habitable life at the surface (Farley et al., 2020). As part of the mission, the Perseverance Rover has collected geologic samples in sealed tubes, with the intent for these tubes to be returned to Earth and analyzed, collected either by a robotic sample return mission or by a future human-led mission. Evidently, when analyzing a sample for the presence of extraterrestrial life, it is imperative that no Earth-based contamination is present in the sample, either at the time the sample is cached or later on in the process. Throughout these missions, mitigating forward contamination from Earth to Mars — or preventing back contamination from Mars to Earth — will require strong planetary protection protocols (Cataldo et al., 2024; Spry et al., 2024).

Protecting all planetary bodies from Earth-based contamination is a high priority for the planetary protection community for several reasons. By transferring Earth-based microbes to the pristine environments of other planetary bodies, we risk altering those environments through microbial processes which could affect scientific measurements. Additionally, introducing Earth biological matter to another planet could confound detections from ongoing biologic activity indigenous to that planetary body, inducing false positives when analyzing samples. For sample return missions, false positives from terrestrial contamination is a distinct possibility, which is why planetary protection protocols are necessarily put in place. On the other hand, protocols that are too strict may inhibit our scientific understanding of interesting planetary targets due to fears of contamination that may not be realistic.

For spacecraft bound for planetary exploration, bioburden limits — the number of viable microorganisms on a surface — are guided by the Committee on Space Research (COSPAR) Planetary Protection Policy. This policy defines the levels of protection needed for each mission based on a numbered classification system. Category I and II missions are deemed “low risk” missions. To be classified as a Category I mission, the planetary body of interest must be of little research interest for the origins and evolution of life, such as the Moon. For classifying Category II missions, the planetary body may be of astrobiological interest, but the mission has little chance of contaminating the body because microorganisms are unlikely to survive the environment. Missions in the categories III, IV, and V are considered “high risk”. Category III missions are those to targets of astrobiologic interest and where there is a high chance of contamination due to microbes’ ability to survive the environment. These missions are typically fly-by or orbiter missions. Category IV missions are very similar to category III, however these missions involve interactions with an environment capable of preserving terrestrial life. Lastly, Category V missions are all missions that return to Earth, which must consider significant backward planetary protection protocols (COSPAR, 2021).

The rovers and landers sent to Mars to date fall into Category IV, with various additional designations based on the purpose of the mission. Landers that do not have instruments designated for searching for life

are in Category IVa, and are restricted to bioburden limits less than 3×10^5 spores on the surface of the spacecraft. Spacecraft with the primary goal of searching for life on Mars and spacecraft landing in deemed “Special Regions” of the planet (Category IVb and IVc, respectively) are both restricted to less than 30 spores on the spacecraft surface (Olsson-Francis et al., 2023).

To achieve these bioburden levels, the interiors, exteriors, and instruments of Mars-bound spacecraft are subjected to prelaunch cleaning and sanitation protocols (Frick et al., 2014; Kempf et al., 2008; Schuerger et al., 2008; Venkateswaran et al., 2004). The Curiosity rover, for example, was launched with a bioburden under the limit for a Category IVa spacecraft, with a total spore count of 5.64×10^4 spores after undergoing sanitation processes, such as dry-heat sterilization and isopropanol wiping of surfaces (Benardini et al., 2014). The Viking 1 and 2 landers were heat-sterilized prior to launch and were considered effectively free of viable bioburden at landing due to the severe sterilization process (Puleo et al., 1977).

The cleanroom in which spacecraft are assembled determines which culturable and non-culturable species are present on the spacecraft (Chen et al., 2023; Hendrickson et al., 2021; La Duc et al., 2003). The Perseverance Rover, for example, was assembled at the Spacecraft Assembly Facility (SAF) at NASA’s Jet Propulsion Laboratory. The SAF was shown to contain a multitude of bacterial species present, with *Bacillus subtilis* being the most spatially abundant species and second most frequently recovered species (recovered in 14 samples), second only to *Virgibacillus panthothenticus* (recovered in 17 samples). In all, the microbial diversity of the SAF was shown to be 86% non-spore-formers and 14% spore formers (Hendrickson et al., 2021). The Perseverance Rover launched well below its bioburden limit at 3.86×10^4 spores (M. Cooper et al., 2023), however when non-spore forming species are also considered, this number is estimated to increase by 1-3 orders of magnitude (La Duc et al., 2004).

Based on the estimates of viable organisms (VOs) on the launched rovers, it is evident that Earth-based microorganisms are leaving our planet and touching down on the surface of Mars even with planetary protection measures in place, potentially contributing to the forward contamination of the Martian environment. Many laboratory studies have simulated the harsh conditions of the surface of Mars to determine how long terrestrial microorganisms can survive in such extreme environments. The studies have included biocidal factors such as UV exposure (Frösler et al., 2017; Newcombe et al., 2005; Osman et al., 2008; Schuerger & Nicholson, 2006; Schuerger et al., 2003; Tauscher et al., 2006; Vaishampayan et al., 2012; Wassmann et al., 2012), desiccation (Beblo-Vranesovic et al., 2018; Schuerger et al., 2012), and low atmospheric pressure (Horneck et al., 1994, 1995; Horneck et al., 2012). Chen et al. (2023) calculated the survivability of Earth microbes on the Perseverance rover during transit and after one sol on the surface of Mars. During cruise, a mortality rate of 84% was predicted, with an additional 89% mortality rate from UV exposure once on the surface. However, these were stated to be conservative estimates of the microbial mortality rates (Chen

et al., 2023).

Microbial survival models have been used to estimate the survivability of Earth-based microbes on the moon, known as the Lunar Microbial Survival (LMS) Model (Schuerger et al., 2019), and during interplanetary space travel, known as the Cruise Phase Microbial Survival (CPMS) model (Moore & Schuerger, 2020). Both models used laboratory-based data showing bioburden reductions due to the biocidal environments of the lunar surface and space, and then quantified the theoretical forward contamination by modelling the expected microbial inactivation rates over time. Both models considered both external and internal components of the spacecraft. Figure 1.7, retrieved from Schuerger et al. (2019), shows the final bioburden on each spacecraft after exposure to the deleterious environment of the moon from the time of their initial landings until January 1, 2019. All external components of the Lunar spacecraft have no remaining bioburden, while deep interior sections of spacecraft landed in the polar regions may retain some levels of bioburden (Schuerger et al., 2019).

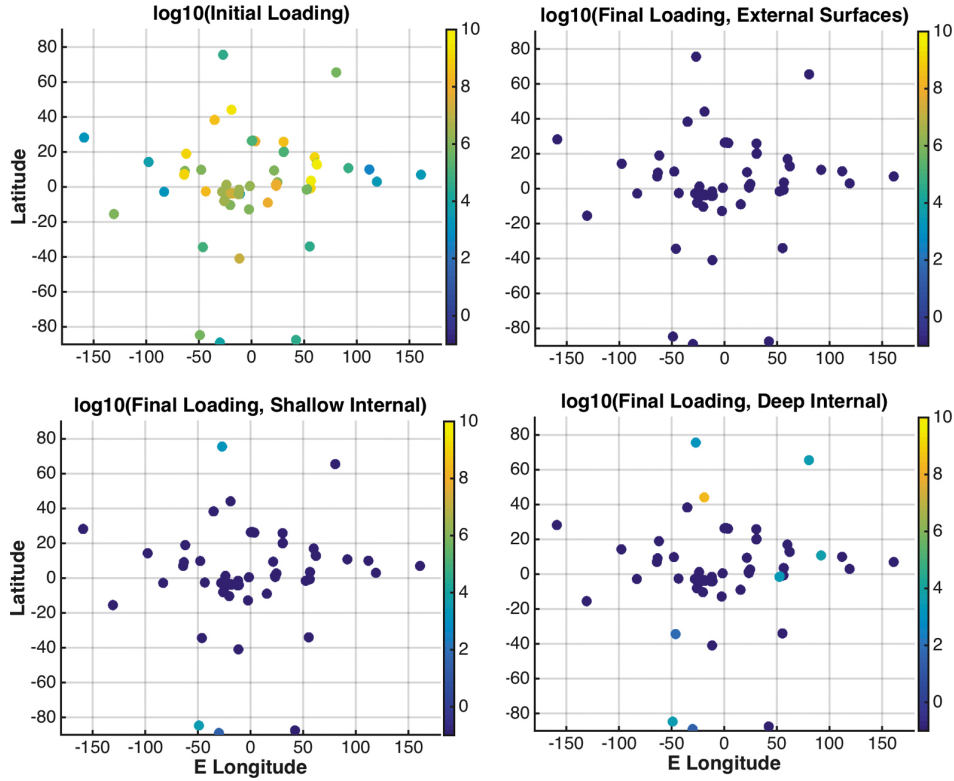


Figure 1.7: Estimates of the remaining bioburden on lunar spacecraft after exposure to the lunar environment from the time of landing to January 1, 2019 retrieved from Schuerger et al. (2019). All exterior surfaces of the spacecraft are sterilized from exposure to the biocidal environment, but some spacecraft may retain bioburden counts up to 10^8 spores in the deep interiors.

Together, laboratory and modelling studies demonstrate that terrestrial microbes are capable of surviving harsh conditions beyond Earth during cruise and on the surfaces of other planetary bodies, even with

planetary protection protocols in place to significantly reduce pre-launch bioburden. Quantifying how these microbes respond to the biocidal environment of Mars is therefore crucial for assessing the risk of forward contamination and the potential for detecting markers of past or present life at the Martian surface.

Chapter 4 of this dissertation presents the development and results of the Mars Microbial Survival (MMS) model, which estimates the survivability of terrestrial microbes on the Martian surface and evaluates the implications for past, present, and future spacecraft missions. Currently, planetary protection protocols are very stringent, which may hinder scientific exploration of interesting targets. This work will help inform planetary protection guidelines in the future.

1.5 Atmospheric Escape

1.5.1 Introduction to Atmospheric Escape

The previous sections of this dissertation have focused on radiative transfer effects in the lower atmosphere, through dust loading and lifting in the near-surface atmosphere of Gale Crater (Section 1.3) as well as the surface radiation environment that may be lethal for terrestrial microbes at the surface when considering planetary protection protocols (Section 1.4). In this section, we move up in the atmosphere and consider radiative transfer in the upper atmosphere of planets which enables atmospheric escape.

All planets undergo atmospheric escape, where gases become unbound from the planet and escape to space. Escape processes are typically divided into two categories: thermal and non-thermal escape. In the thermal escape category, atmospheric gases can escape either by Jeans escape or hydrodynamic escape, which will each be described in further detail below. In the non-thermal category, atmospheres can escape through processes such as photochemical escape — where high-energy light breaks molecules down into smaller components, giving the small components enough energy to escape the planet’s gravitational well — or other processes such as sputtering, charge exchange, or polar wind escape. The Earth, for example, experiences a combination of thermal and non-thermal escape processes, including Jeans escape, charge exchange, and polar wind escape, which causes the loss of atomic hydrogen and helium in the upper atmosphere (Gronoff et al., 2020). Figure 1.8, retrieved from Gronoff et al. (2020), shows the various escape mechanisms and the planet on which they are dominant (i.e. Earth, a generic exoplanet, Venus, and Mars).

Simply, thermal escape is designated by an atom or molecule gaining enough thermal energy to leave the atmosphere, which can occur on a molecule-by-molecule basis during Jeans escape, or as a fluid outflow during hydrodynamic escape. First, we examine Jeans escape. The molecules or atoms in an upper atmosphere are heated by the energy from the host star, causing them to move at a range of speeds described by a Maxwell-

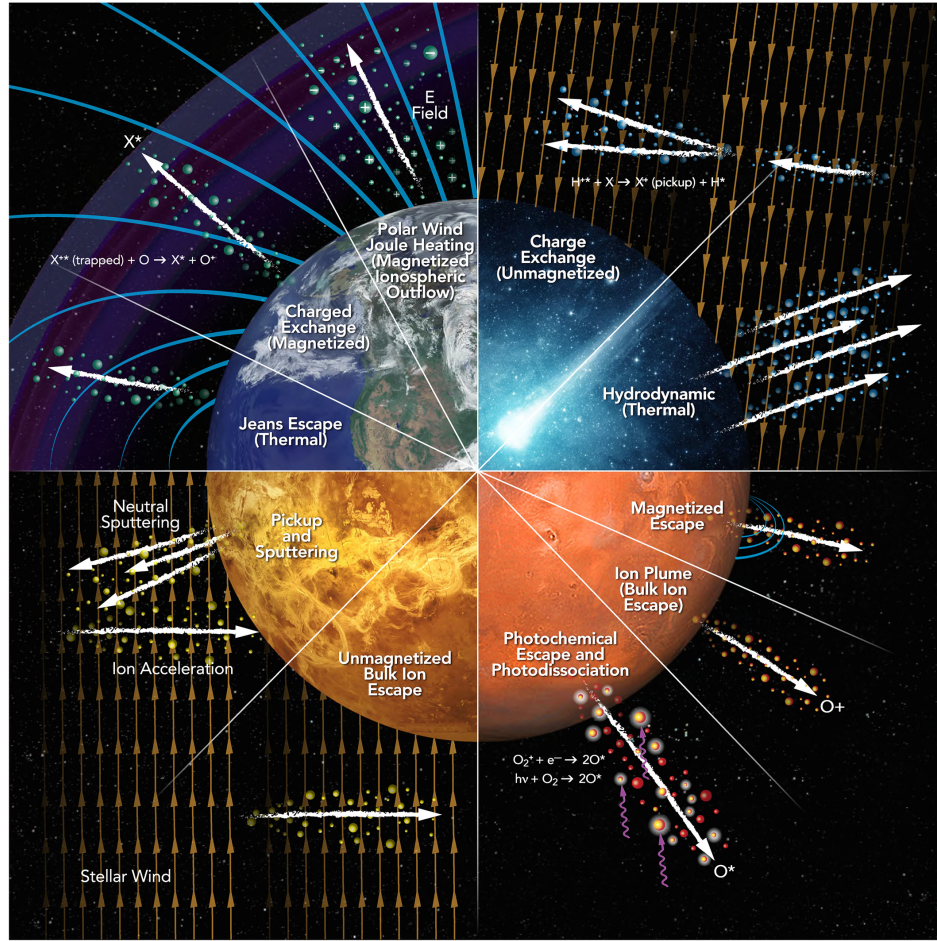


Figure 1.8: The various thermal and non thermal atmospheric escape mechanisms are shown with the planet on which they are a dominant process: top left is Earth, top right is a generic exoplanet, bottom left is Venus, and bottom right is Mars. Earth, for example, loses its atmosphere through a combination of Jeans escape, charge exchange, and polar wind escape. Image credit: Gronoff et al. (2020).

Boltzmann distribution. Particles at the tail end of the distribution will move extremely quickly. If the speed of the particle is greater than the escape velocity, the particle can overcome the gravitational pull of the planet and escape to space. As a result, Jeans escape depends strongly on particle speed and therefore on particle mass. At a given temperature, lighter particles move faster than heavier ones. For example, a hydrogen molecule will have a higher average velocity than a heavier molecule such as an oxygen molecule (O_2). Figure 1.9 shows the Maxwell-Boltzmann curves for H_2 and O_2 at 100 K and 300 K. Because O_2 is heavier, it has a larger probability density at lower speeds compared to H_2 . Additionally, when the temperature increases for each molecule, the probability density becomes higher at faster speeds.

As a consequence of the Maxwell-Boltzmann distribution, lighter species escape more readily. Jeans escape is also more efficient on lower-mass planets, where the gravitational pull and escape velocity are smaller. Under these conditions, a larger fraction of atmospheric particles can reach velocities sufficient to

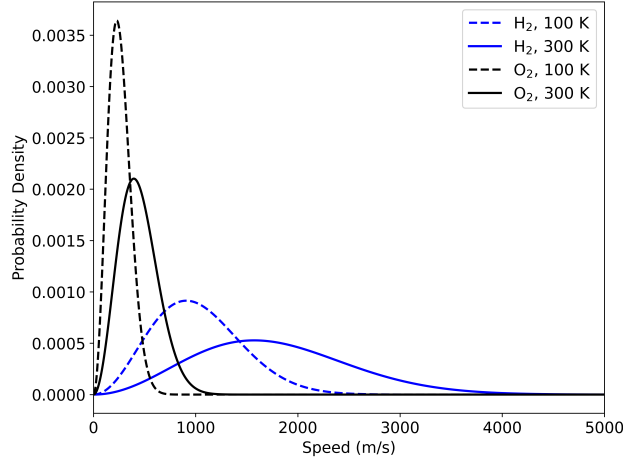


Figure 1.9: Maxwell-Boltzmann distributions for H_2 and O_2 molecules. Heavier atoms favour lower speeds, while higher temperature favour faster speeds.

escape.

Alternatively, hydrodynamic escape occurs when an upper atmosphere is sufficiently heated by high-energy stellar X-ray and UV radiation (XUV). At these high temperatures, lighter gases can escape to space as a continuous fluid driven upward by a pressure gradient. Atmospheres escaping hydrodynamically are often modelled using the concept of an isothermal Parker wind, which was first used to describe the solar wind (Parker, 1958). In this framework, the heated gas expands outward from the planet, the density decreases and the flow accelerates until it reaches a critical sonic point, where the bulk outflow velocity equals the local speed of sound. Beyond this point, the flow becomes supersonic and continues to expand outward into space.

Unlike in the Jeans escape scenario, where heavier gases in the background are considered static, the background gases in the hydrodynamic escape regime can be dynamic. If the outflow of the lighter gas, typically hydrogen, is strong enough, heavier gases can be dragged along in the outflow. Because hydrodynamic escape involves a collective outflow, rather than a collisionless escape in the Jeans regime, hydrodynamic escape can remove an atmosphere much faster.

1.5.2 Applications of Atmospheric Escape

Atmospheric escape is a key process in shaping atmospheric evolution. Within the solar system, hydrodynamic escape has played an essential role in determining the composition and structure of the atmospheres observed today. On Venus, for example, hydrodynamic escape has been proposed as the main mechanism responsible for removing surface water, leaving behind a dry, desiccated atmosphere (Kasting & Pollack, 1983). Additionally, because isotopes have different masses, hydrodynamic escape preferentially removes lighter species, leading to isotopic fractionation that increases with altitude (Hunten et al., 1987). Isotopic

fractionation in Mars’ atmosphere is indicative of previous hydrodynamic escape (Ogohara et al., 2022).

Outside of our solar system, atmospheric escape is essential for characterizing exoplanet atmospheres. Over 6000 exoplanets have been discovered, with ~ 100 exoplanet atmospheres probed to date through spectroscopic methods (Lira-Barria et al., 2022). As these planets span parameter spaces not seen in the solar system, studying atmospheric escape helps us piece together a general understanding of planetary atmospheres and evolution (R. Wordsworth & Kreidberg, 2022). When considering rocky exoplanets similar to Earth, characterizing these atmospheres offers a powerful tool for assessing planetary habitability, answering fundamental questions such as which planets are able to retain atmospheres, preserve liquid water, and ultimately create and sustain life.

The radius gap — an observed bimodal distribution of small planetary radii with few planets between 1.5 to 2 Earth-radii ($R_{\oplus}$) (Cloutier & Menou, 2020; Fulton & Petigura, 2018; Fulton et al., 2017) — highlights the significance of atmospheric escape (Lopez & Fortney, 2014; Owen & Wu, 2013, 2017; Van Eylen et al., 2021). Figure 1.10 shows the bimodal distribution designating the radius gap. Thermally-driven hydrodynamic escape efficiently strips the H_2 -He envelope from lower-mass planets, creating a population of Earth-like planets below the radius gap and gaseous sub-Neptunes above the radius gap. While atmospheric escape is initially dominated by the loss of hydrogen from these primordial envelopes, preferential hydrogen escape can continue after the atmosphere is no longer H-dominated, including during the evolution of secondary atmospheres (Tian et al., 2009). Constraining atmospheric escape from non-hydrogen dominant planets gives insight into the planet’s oxidation state (Cherubim et al., 2025; Luger & Barnes, 2015; R. D. Wordsworth et al., 2018).

1.5.3 Lyman- α Transit Detections to Constrain Atmospheric Escape

Transits have been key in the detection and characterization of exoplanets and their atmospheres. As a planet crosses in front of its star from Earth’s line-of-sight, a periodic, fractional decrease in stellar flux is observed. From the lightcurve, the planet’s radius and orbital period can be determined. By observing the transit at various wavelengths, variations in the amount of light absorbed as a function of wavelength gives insight into the composition of the planet’s atmosphere.

The Lyman- α line at 121.56 nm is strongly absorbed by atomic hydrogen (H), and has been an established tool for observing atmospheric mass loss from large, close-in exoplanets. When a planet with an abundance of hydrogen orbits close to its star, high-energy XUV heats the upper atmosphere, causing the bulk outflow of H through hydrodynamic escape. As this outflow accelerates outward, the planetary atmosphere is inflated, producing an extended neutral H exosphere.

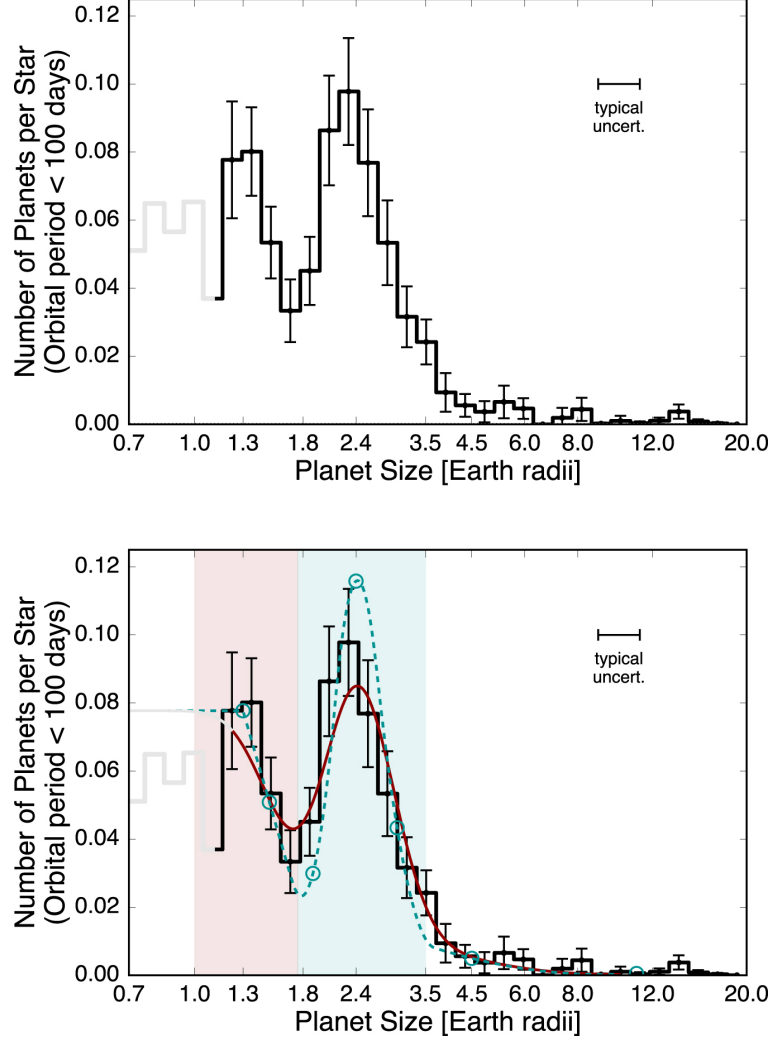


Figure 1.10: From Fulton et al. (2017), highlighting the bimodal distribution of planetary radii, where a lack of planets between 1.5 to 2 $R_{\oplus}$ are observed, shaped by atmospheric escape. The red shading in the bottom panel indicates planets considered to be super-Earths, while the blue shading encompasses sub-Neptune planets.

The H atoms in this exosphere absorb Lyman- α photons, often generating a deep transit signal compared to other wavelengths, including optical. For planets ranging in size from Jupiter to sub-Neptune, there have been many observations of a deep Lyman- α transit. These examples include HD 209458 b (Vidal-Madjar et al., 2003), HD 189733 b (Etangs et al., 2010, 2012), GJ 436 b (Bourrier et al., 2015; Ehrenreich et al., 2015; Kulow et al., 2014), GJ 3470 b (Bourrier et al., 2018), HD 63433 c (Zhang et al., 2022), TOI-776 b and c (Loyd et al., 2025), as well as a tentative detection for K2 18 b (L. A. d. Santos et al., 2020). Each of these large planets is expected to be undergoing hydrodynamic escape, due to the high hydrogen escape rates calculated based on the observed transit depths.

Although the upper side of the radius valley has been successfully probed by Lyman- α , rocky exoplanets on the lower side of the valley have yielded tentative or non-detections of extended H exospheres. This

suggests the observed rocky planets are undergoing very little mass loss or do not possess H-rich atmospheres (Owen et al., 2023). Tentative detections include the TRAPPIST-1 system, with reported transits of $40\% \pm 21\%$ and $41\% \pm 18\%$ for TRAPPIST-1 b and TRAPPIST-1 c, respectively (Bourrier, Ehrenreich, Wheatley, et al., 2017), and Kepler-444 e and Kepler 444 f, with reported transit depths of $\approx 20\%$ (Bourrier, Ehrenreich, Allart, et al., 2017). For both planetary systems, the signal-to-noise ratio of the observations was low, and the uncertain stellar variability contributed to the tentative nature of the detections. Previous observations of the TRAPPIST-1 system at $1.4 \mu\text{m}$ ruled out primordial H_2 envelopes for TRAPPIST-1 b and c (de Wit et al., 2016). Additionally, both GJ 1132 b (Waalkes et al., 2019) and GJ 9827 b were observed but no Lyman- α transit was detected (Carleo et al., 2021).

Detecting Lyman- α absorption from a rocky exoplanet would be compelling, particularly in planets that have terrestrial-type secondary atmospheres. In such cases, the presence of an extended H exosphere is a potential indicator of water in the lower atmosphere that has been photodissociated into H and OH (Jura, 2004). Earth, with abundant water in the lower atmosphere, has an H exosphere that extends out past the moon, observable out to $100 R_\oplus$ (Baliukin et al., 2019; Kameda et al., 2017). Venus (Delva et al., 2009; Gruchola et al., 2019) and Mars (Chaufray et al., 2015) both have much smaller H exospheres than Earth. The difference arises in part from differing H number densities in the upper atmosphere, as well as Earth’s hot, atomic-oxygen dominated exobase (Kameda et al., 2017), compared to the cooler, CO_2 -dominated exobases of Venus and Mars (Chaufray et al., 2012; Qin, 2020).

These solar system examples show that a planet’s hydrogen exosphere strongly depends on its atmospheric properties. Yet, no theoretical framework currently exists to interpret Lyman- α observations of rocky exoplanets in terms of their bulk atmospheric properties. Developing such a framework is essential to constrain the bulk atmospheric properties of rocky exoplanets from future Lyman- α detections. Chapter 5 of this dissertation examines the variability of Lyman- α transits based on key planetary parameters to assist in developing a framework for interpreting these observations in the future.

1.6 Motivation and Layout of the Dissertation

This dissertation examines the role of radiative transfer in governing the climate, habitability, and evolution of planetary atmospheres through four studies. We begin our exploration at the surface of Mars, where dust lifting into the atmosphere is investigated using images from the Curiosity Rover. Next at the surface, the ability for Earth-based microbes to survive is examined to understand the implications for planetary protection protocols. Lastly, in the upper atmosphere, we investigate our ability to characterize a rocky exoplanet atmosphere from observing hydrogen loss in the upper atmosphere via Lyman- α spectroscopy.

In particular, chapter 2 examines the LOS dust extinction in Gale Crater through nearly 4000 sols of the MSL mission using Navcam images taken by the Curiosity Rover. Though seasonal trends have been studied through 2500 sols of the mission (C. Smith et al., 2020), the temporal constraint on the LOS extinction observation precluding images outside 10-14 LTST severely limits our understanding of the short-term dust dynamics occurring in Gale Crater. To aid in characterizing the lower-atmosphere of Mars, a new method is presented in Chapter 2 to expand the LOS extinction observation to a wider period throughout the sol, allowing us to probe the temporal evolution of dust extinction within Gale Crater.

Complementing the investigation of lower atmosphere dust dynamics, Chapter 3 examines the optical depths of dust devils in Gale Crater. Dust devils are hypothesized to be a large contributor to the background dust observed in Mars’ atmosphere, and previous studies have examined when and where they most frequently occur (Guzewich et al., 2023; Mason et al., 2025). However, the amount of dust lofted by these events is currently unknown. In Chapter 3, the optical depths of the dust devils captured by Navcam are presented, helping constrain the role of dust lifting in the Martian dust cycle. Chapter 3 investigates whether changes in dust devil optical depth align with the known diurnal and seasonal patterns of dust loading in Gale Crater presented in Chapter 2.

In Chapter 4, the survivability of Earth-based microbes on the surface of Mars is analyzed. To ensure forward contamination of planetary bodies is minimized, planetary protections protocols are essential, especially when considering missions searching for extra-terrestrial life. The MMS model is designed to evaluate the survival of *B. Subtilis* at fourteen historical landing sites on Mars under the biocidal effects of solar UVC, low pressure, and biotoxic chemical components in the Martian regolith to estimate the forward contamination of Mars to date. We apply the MMS to potential future landing sites to inform planetary protection protocols going forward.

Lastly, moving to the upper atmosphere, Chapter 5 analyzes Lyman- α transits from rocky exoplanets. In a secondary atmosphere, a large H exosphere could be compelling evidence of water at the surface, indicating a potentially habitable environment. While the size and structure of a hydrogen exosphere are expected to depend strongly on a planet’s bulk atmospheric properties, there is currently no way to directly interpret Lyman- α observations of rocky exoplanets in terms of those underlying atmospheric characteristics. Chapter 5 models hydrogen escape from theoretical rocky exoplanets, varying parameters such as planet mass, temperature, and H mixing ratio to evaluate the resulting Lyman- α transit depth. The detectability of these transit signals with current and future telescopes is considered.

Chapter 2

Dust Dynamics in Gale Crater Using the Line-of-Sight Extinction Observation through 3663 Sols of the Mars Science Laboratory Mission

2.1 Overview and Author Contributions

The LOS dust observation monitors the dust loading in the near-surface atmosphere of Gale Crater, a region of the atmosphere not easily probed by orbiters (Innanen, Moores, et al., 2024). Trends in LOS dust extinction can be coupled to lower atmosphere phenomena, such as surface dust-lifting to better understand atmospheric dynamics on Mars. Though seasonal trends in LOS dust extinction are known (C. A. Moore et al., 2016, 2019; Smith & Moores, 2020), temporal constraints preclude acquisition of the LOS dust extinction observation outside 10-14 LTST, severely limiting our understanding of the diurnal evolution of dust loading in Gale Crater. This chapter of the dissertation details an updated method for calculating the LOS extinction, allowing images taken throughout a sol to be used. Here we observe diurnal, seasonal, and spatial trends in the LOS dust loading, highlighting the dust dynamics in Gale Crater.

The text from this chapter is adapted from the publication “Dust Dynamics in Gale Crater Using the Line-of-Sight Extinction Observation through 3663 Sols of the Mars Science Laboratory Mission” published in the *Journal of Geophysical Research: Planets* in 2024 (Bischof et al., 2024). Coauthors on this work were S. D. Guzewich, M. T. Lemmon, J. E. Moores, J. M. Battalio, D. W. Hayes, A. C. Innanen, and C. L. Smith. Using the CRediT framework, author contributions are as follows: G. Bischof (author of this dissertation): data curation, formal analysis, investigation, methodology, writing (original draft), writing (review and editing); S. D. Guzewich: conceptualization, validation, writing (review and editing), M. T. Lemmon: conceptualization, methodology, validation, writing (review and editing); J. E. Moores: conceptualization, funding acquisition, methodology, supervision, writing (review and editing); J. M. Battalio: Visualization, writing (review and editing); D. W. Hayes: Data curation, software, writing (review and editing); A. C. Innanen: visualization,

writing (review and editing); C. L. Smith: conceptualization, software, writing (review and editing).

2.2 Methods

2.2.1 LOS Observation Overview

The LOS observation consists of a single-frame image captured by the MSL Navcam. These images are composed of $1,024 \times 1,024$ pixels (width x height), which are down-sampled and sub-framed onboard to 512×216 pixels, resulting in an image with an FOV of $45^\circ \times 23^\circ$. The images are calibrated so that each pixel provides a record of spectral radiance in units of $\text{W m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$. Every image is captured with an orientation of 0° of azimuth in the site-frame, resulting in a view to the northern crater rim. The local elevation of each image is selected to be 5° above the horizon in the site-frame, ensuring that a portion of the sky, crater rim, and ground are present in the image.

LOS images have been acquired since sol 100 of the mission as part of a longer set of images in a Dust Devil Search Movie (C. A. Moore et al., 2016; Moores, Lemmon, Kahanpää, et al., 2015). On sol 1316, the LOS was given its own dedicated observation, which persisted throughout the balance of the mission shown in Figure 2.1. For the first ~ 1000 sols, the LOS was taken only in the period between 10:00-14:00 LTST — the times for which the LOS was previously validated with a radiative transfer model (Moores, Lemmon, Kahanpää, et al., 2015). Beginning around sol 1000, a suite of morning environmental science activities was executed on the rover once per weekend. After the introduction of the morning suite, an LOS image was captured before 10:00 LTST at least once a week, increasing our ability to probe the temporal variability in the LOS extinction. No dedicated effort has been put forward to capture LOS images in the afternoon; however, afternoon images are acquired past 14:00 when rover resources have allowed such imaging.

Since sol ~ 800 , the rover has been steadily climbing Mt. Sharp. As the rover has ascended in elevation, the view to the northern crater rim has become increasingly obstructed by near-field terrain. Over sols 3100–3663, we occasionally have had unobstructed views to the crater rim; however, such unobstructed views occurred much more often in the first 3000 sols of the mission. More often, the view is mostly clear, with terrain on the sides of the frame or with one central topographical feature blocking the center of the frame, with a clear view on either side. However, the view to the crater rim has also been completely blocked by terrain frequently. An example of each of these cases is shown in Figure 2.2. Since sol ~ 3200 , the azimuthal pointing of the LOS has occasionally been altered off-north in the case of terrain blocking the northern crater rim to capture different portions of the crater rim that are exposed. For this study, images pointed off-north have been neglected, and we include only those with the 0° pointing.

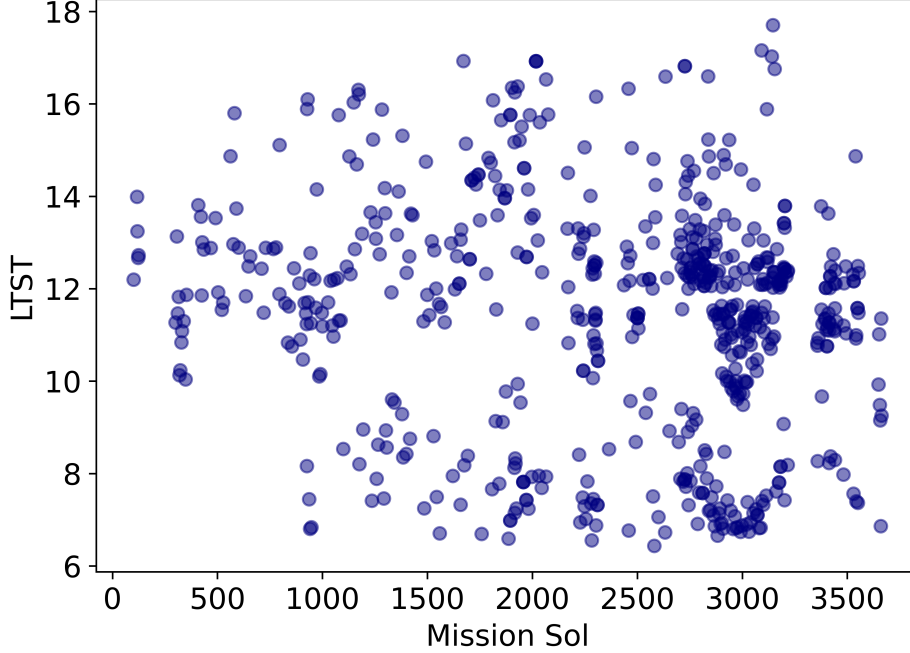


Figure 2.1: The spread of LOS observations throughout 3663 sols of the MSL mission used in this work. For the first ~ 1000 sols of the mission, images were acquired only between 10:00 and 14:00 LTST. After sol 1000, images were acquired at least once a week in the morning. The wave-like pattern in morning observations between sol 2700 and 3500 is due to the morning observations being taken at the same local mean solar time each week, which drifts relative to LTST. Notable gaps in the data around sol 3,200 are due to the terrain blocking the view to the crater rim.

2.2.2 LOS Extinction Determination

The method used in this paper to calculate the LOS extinction is similar to the method described in C. Smith et al. (2020), with key changes for addressing illumination changes in the LOS image throughout a sol. First, in agreement with previous studies, each image is isolated into three sections — the sky, the crater rim, and the ground, which are highlighted blue, cyan, and green, respectively, in Figure 2.4. Both the sky (3.5° to 5.5° in site-frame elevation) and the ground (3.5° to 10° in site-frame elevation) are averaged vertically, such that both sections are represented as a 1D array of spectral radiances, varying in azimuth (i). The crater rim section (0° to 2° in site-frame elevation) consists of a 2D array of spectral radiances that is not averaged, allowing it to vary both in azimuth and elevation (j).

In Smith and Moores (2020), the values from the sky, crater rim, and ground are used in the LOS extinction equation derived by Moores, Lemmon, Kahanpää, et al. (2015), described by

$$\tau_{[i,j]} = -\ln \left(\frac{1 - \frac{I_{S,[i]}}{I_{C,[i,j]}}}{\frac{I_{G,[i]}}{I_{C,[i,j]}} - \frac{I_{S,[i]}}{I_{C,[i,j]}}} \right) \quad (2.1)$$

where $I_{s,[i]}$ is the 1D array of sky radiances, $I_{G,[i]}$ is the 1D array of ground radiances, $I_{C,[i,j]}$ is the 2D array

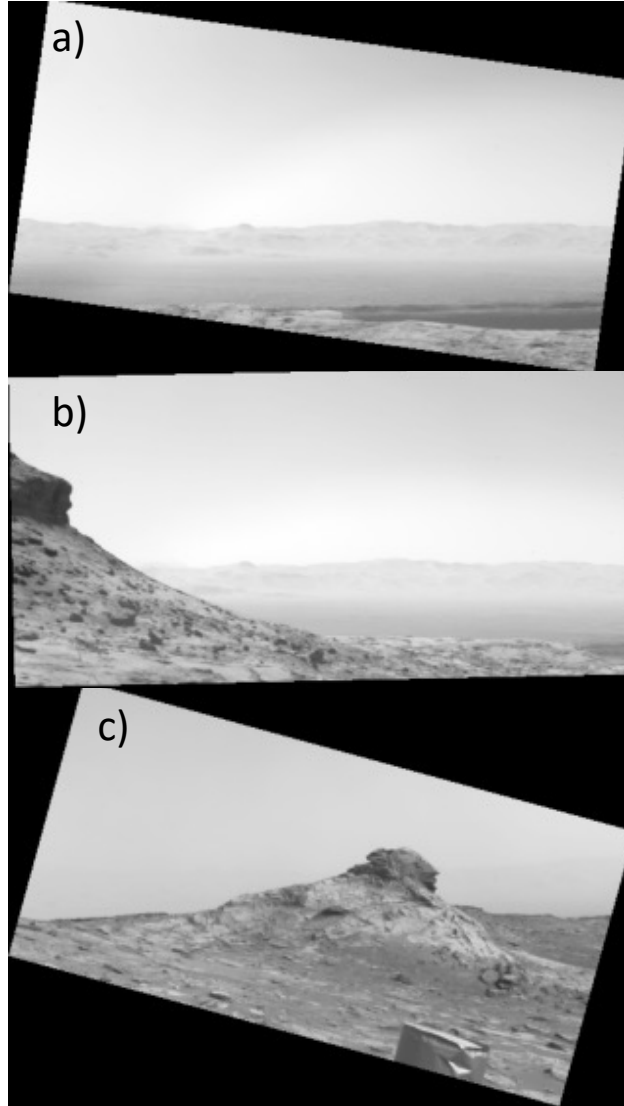


Figure 2.2: Examples of three LOS images on panel (a) sol 3190, (b) sol 3249, and (c) sol 3461. In panel (a), the view to the northern crater rim is completely clear, meaning that the entire frame can be used in this analysis. The left side of the frame in panel (b) is blocked by terrain, so this image was analyzed only on the right side of the frame. Images such as panel (c) were neglected from this analysis because the terrain completely obscured the view to the crater rim.

of crater rim radiances, and $\tau_{[i,j]}$ is the 2D array of dust optical depths which vary both in azimuth and elevation.

In addition to the 2D array of optical depth values across the crater rim, the frame is divided into three distinct sections: center, east, and west, as shown in Figure 2.4. Since the Navcam FOV is 45° wide, we can view $\sim 22^\circ$ on either side of north, which is approximately 15–20 km across the crater rim. Splitting the frame into these three sections allows us to explore the degree to which dust within the Gale Crater is well-mixed horizontally. For each section, the crater rim is divided into 20-pixel sections centered on pixel 70, pixel 260, and pixel 460 for the west, center, and east pointings, respectively, as measured along the crater rim. 20-pixel wide sections were chosen to eliminate terrain-shadowing biases by averaging. Typically, the west section is located at a pointing approximately 18° west in azimuth from north, while the east section is pointed approximately 18° east in azimuth from north.

2.2.3 Correcting for Variable Illumination

A number of assumptions are made to derive Equation 2.1, which are described in more detail in Moores, Lemmon, Kahanpää, et al. (2015). An assumption of note, and the reason this equation holds between 10:00 and 14:00 LTST, is that the sun evenly illuminates the scene captured in the Navcam frame. For times within 2 hours on either side of noon, this assumption is fairly accurate, as the sun sits overhead casting even light onto the sky, crater rim, and ground. Moving outside the 4-hour window, the sun’s movement in the sky causes the scene to be illuminated unevenly — namely, a higher sky brightness is observed in the east during the morning hours and in the west during the afternoon hours.

To address the uneven illumination, the first correction made accounts for uneven light shining on the ground and crater rim. In Equation 2.1, we assume $I_C = I_G$ when $\tau = 0$, which is a reasonable assumption during midday when the sun is overhead. In the morning and evening, the solar incidence angle on the crater rim differs from that on the ground due to a combination of the tilt of the crater rim from the horizontal and the azimuthal curvature of the crater rim. The incidence angles on the ground and crater rim are calculated using

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma) \quad (2.2)$$

where θ is the incidence angle, representing the angle between the radiation beam on a surface and the normal to the surface, θ_z and γ_s represent the solar zenith and solar azimuth angles, respectively. β is the tilt of the surface from the horizontal. Lastly, γ is the horizontally projected azimuth angle.

When calculating the incidence angle on the ground, both β and γ are set to zero. When calculating the

incidence angle on the crater rim, a MOLA-derived digital elevation map showing the angle of the crater rim was created, shown in Figure 2.3, and an average value of $\beta = 18^\circ$ was used. For the azimuth angle of the crater rim, angles between 30° and 15° across the frame are typically chosen, where an angle of 0° points south, with negative angles pointing east and positive angles pointing west. The site-frame solar zenith and azimuth angles are found in the LOS image metadata, and 180° is subtracted from the solar azimuth angle such that 0° is due-south.

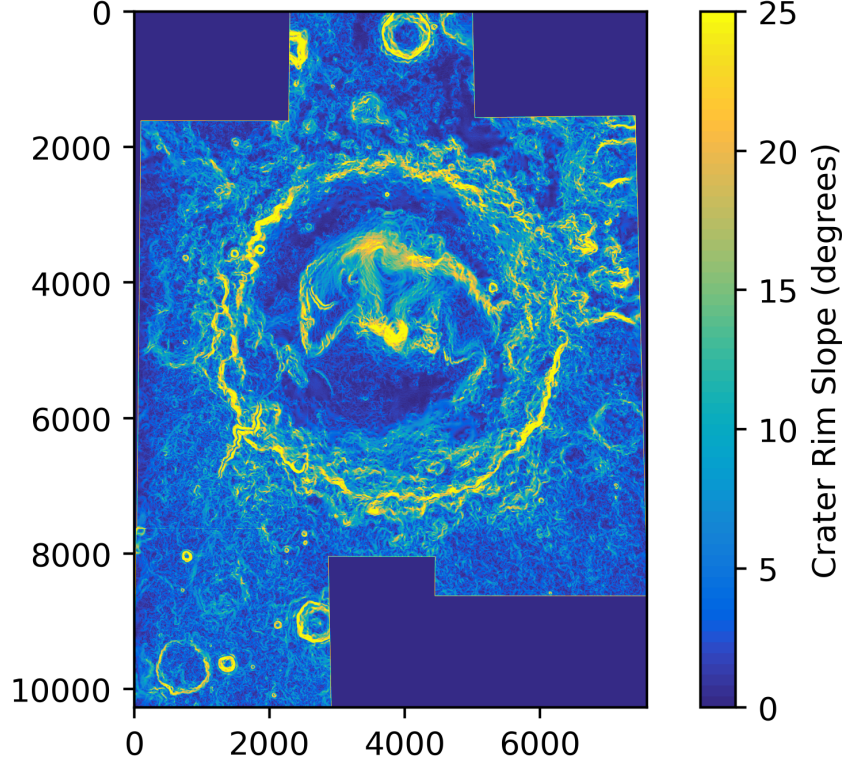


Figure 2.3: MOLA-derived elevation map of Gale Crater, showing the slope of the northern crater rim. Though the slope is not uniform, we use a constant slope of 18° in Equation 2.2

Once the incidence angles of the ground are found, a ratio is taken and applied to I_G , where the assumption is now $I_C = I_G(\frac{\cos\theta_C}{\cos\theta_G})$ at $\tau = 0$, which is applied to Equation 2.1 to get

$$\tau_{[i,j]} = -\ln \left(\frac{1 - \frac{I_{S,[i]}}{I_{C,[i,j]}}}{\frac{I_{G,[i]} \times (\frac{\cos\theta_C}{\cos\theta_G})}{I_{C,[i,j]}} - \frac{I_{S,[i]}}{I_{C,[i,j]}}} \right). \quad (2.3)$$

A further discussion of the ratio of the incidence angles will be discussed in Section 2.2.4.

The second correction that is made to the extinction derivation is finding the lines of constant source angle within the image. At noon when the sun is vertically overhead, lines of constant azimuth within the LOS frame correspond to isophotes from the sun, and are therefore equivalent source functions (see Moores,

Lemmon, Kahanpää, et al. (2015) for the discussion on the source function). In the morning and evening, when the sun is on either side of the frame, these isophotes are no longer vertical. As such, we calculate the angle of these lines of constant light across the frame, hence referred to as the “solar angle”.

To find the solar angle, Equation 2.2 is used, where $\beta = 90^\circ$ and $\gamma = 90^\circ$, setting the surface normal as a horizontal line that runs across the LOS frame. When the sun is directly overhead, the solar angle is equal to 90° , and the lines of constant solar angle are also constant vertical lines of azimuth. When the solar angle diverges from 90° (as in the morning and evening), sections of the image input into Equation 2.3 are selected following the solar angle. This is done by shifting the pixels by the solar angle, causing vertical lines to be constant in solar angle rather than constant in azimuth. An example of the solar angle over one sol is shown in Figure 2.4.

After the pixels are shifted according to the solar angle, and Equation 2.3 is used to find the opacity between the rover and the crater rim, we return to the method of C. Smith et al. (2020) and C. A. Moore et al. (2016, 2019) to account for the distance to the crater rim. This is necessary because driving inevitably changes the amount of atmosphere between the rover and the crater rim. Thus, to compare the amount of dust in the crater throughout the mission, the opacities are divided by the distance to the crater rim to give a value of extinction, with units of km^{-1} . This is done using the Gwinner et al. (2010) digital terrain model (DTM) of the Gale Crater. A simulated image of the crater rim is reconstructed, and using metadata from the images, we can find the distance between the rover and the crater across the Navcam FOV. An example of the DTM is shown in Figure 2.5.

2.2.4 Discussion of Illumination Uncertainty

Since the LOS extinction depends on the radiance of the scene captured by Navcam, a discussion of the illumination in the images is warranted. The cosine ratios are shown in Figure 2.6 as a function of LTST and season for the center, east, and west portions of the crater rim. In the 4-hour window around noon, the cosine ratio is typically close to 1 with a seasonal dependence showing that the crater rim receives more sunlight than the ground in the southern summer and less sunlight than the ground in the southern winter. In the morning, the cosine ratio is much larger, with higher differences between the cosine ratios earlier in the morning and later in the evening, following the same seasonal trend of a higher crater rim incidence angle in the summer.

To examine how the lighting affects the calculation of the extinction, first we examine the radiances in each section of the image, since these are the portions of the image that are input in Equation 2.3. Figure 2.7 shows the change in spectral radiance extracted from the LOS images as a function of LTST for the (a)

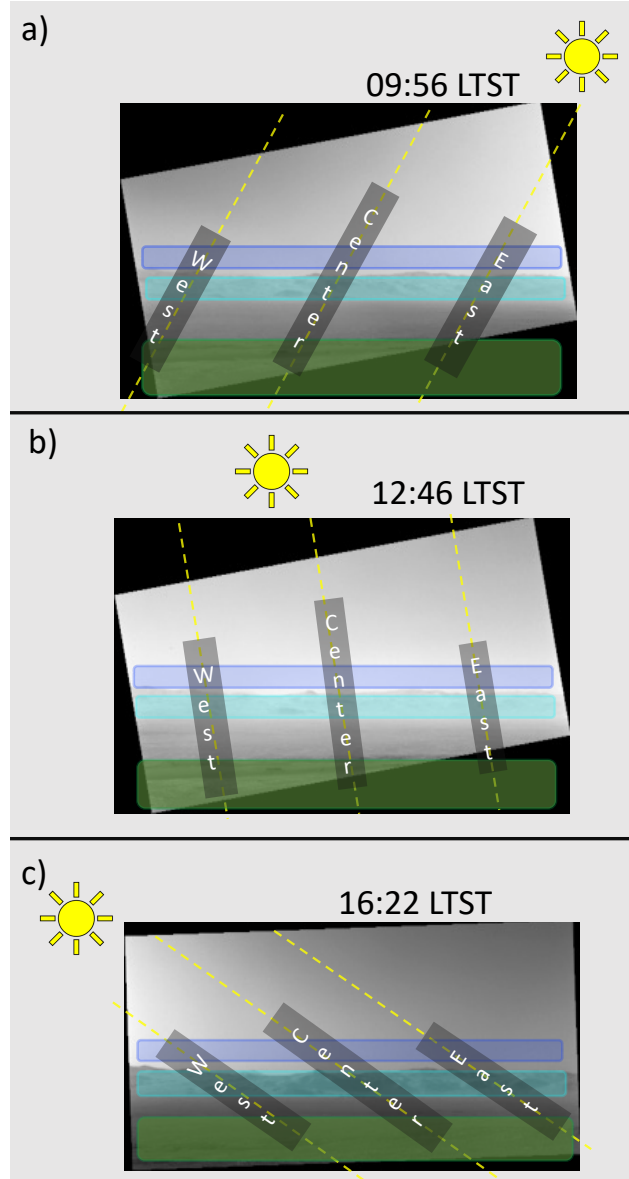


Figure 2.4: Three LOS observations captured on sol 1930 at (a) 09:56, (b) 12:46, and (c) 16:22 LTST. Note that a drive occurred between images (b) and (c), causing the rotation to orient the image into the site-frame to vary slightly post-drive. The blue, cyan, and green sections of each image represent the sky, crater rim, and ground sections, respectively, used in Equation 2.3 The solar angle across the frame is outlined with the dashed yellow lines.

Gray boxes show the west, center, and east portions of the frame used to calculate the extinctions at various pointings, which are tilted according to the solar angle.

sky, (b) crater rim, and (c) ground sections for each direction used in the analyses. The normalized standard deviation in radiances across the frame is plotted in Figure 2.7d–f.

In the sky, an illumination difference occurs between the eastern and western directions. As the sun rises in the east, this portion of the frame is typically brighter than the center and west sides of the frame. Alternatively, the setting sun in the west causes the western side of the frame to be more illuminated than the east. This can be seen in the standard deviations in Figure 2.7d, with typically higher morning and evening

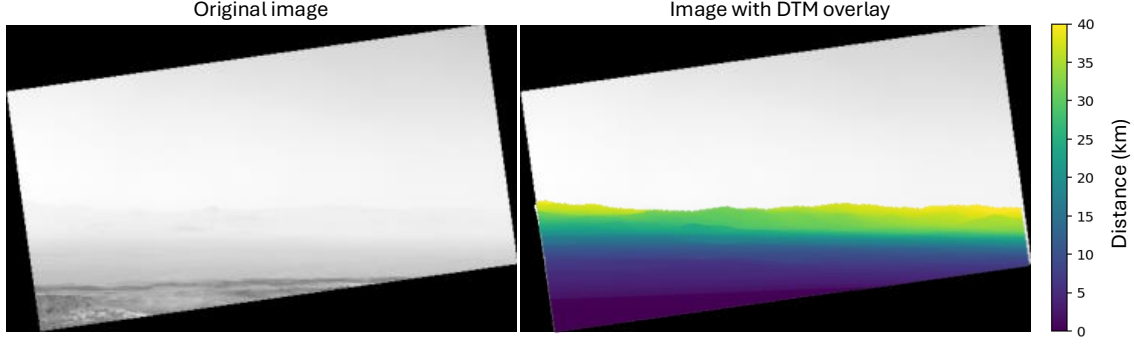


Figure 2.5: The lefthand panel shows an example LOS frame from sol 2705 of the MSL mission. The righthand panel shows the image with the DTM laid overtop. The distances in the frame range from approximately 0 km near the rover to 40 km at the furthest point of the crater rim.

standard deviations than those taken between 10:00 and 14:00 LTST. Across the crater rim, the illumination sees a bias similar to the sky; however, it is slightly less pronounced. Though the eastern radiance on the crater rim is higher in the morning than the western radiance (and vice versa for the evening), the standard deviation (Figure 2.7e) values are lower than those for the sky.

The ground shows a slightly different pattern than the sky or the crater rim. The change in illumination across the frame appears to be highest in the mid-sol period, rather than in the morning or evening. However, despite the spread in ground radiances appearing quite large in Figure 2.7c, this is occurring on an image-by-image basis, and not within a single image between the west-center-east directions. When looking at the standard deviation in each frame, the values are quite low, similar to the crater rim radiances, with no particular diurnal trend. This means that the ground radiances have varied more over the course of the mission than the sky or crater rim, as would be expected, but the variation within a frame is similar to the sky and crater rim.

Without including the cosine correction, a higher crater rim radiance (Figure 2.6), caused by more incident sunlight than on the ground, would carry through Equation 2.3 as an artificially higher amount of dust in

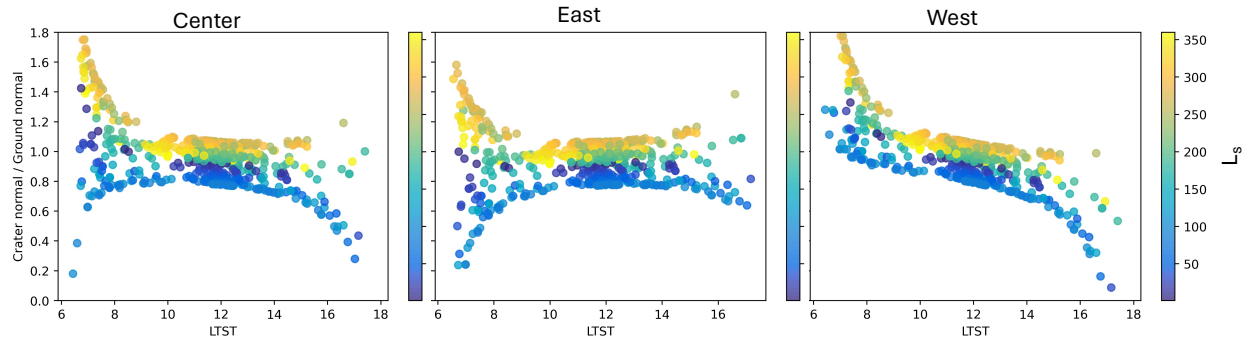


Figure 2.6: The ratio of incidence angles on the crater rim and ground by azimuthal section of a Navcam LOS image as a function of LTST and L_s .

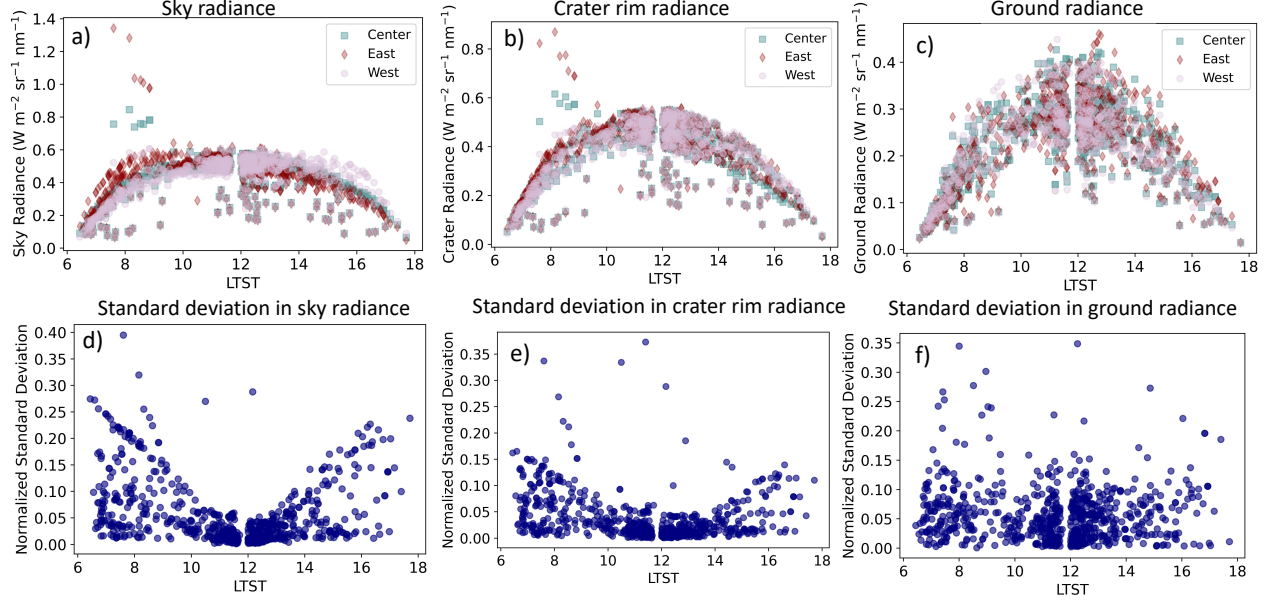


Figure 2.7: Radiance of the (a) sky, (b) crater rim, and (c) ground, for the center (teal), east (red), and west (purple) directions in the LOS images as a function of local true standard time (LTST). The standard deviations for the (d) sky, (e) crater rim, and (f) ground are plotted as a function of LTST for comparison.

the latter half of the year throughout the day (beyond $L_s = 180^\circ$), with this effect being the strongest in the morning and the evening. Alternatively, at the beginning of the year (before $L_s = 180^\circ$), a lower crater rim radiance due to more sunlight on the ground would artificially lower the calculated dust throughout the day, with a stronger effect in the morning and evening.

2.2.5 Uncertainty in the Calculated Extinction

The extinction uncertainty is determined using the method described by C. A. Moore et al., 2016, 2019 and C. Smith et al. (2020). To find the uncertainty for the crater rim-averaged extinction, the crater rim is further subdivided into subsections that are 8 pixels wide. The extinction is found for each subsection, and the 1-sigma standard deviation between all subsections is calculated. The purpose of this step is to average over any effects from shadowed terrain on the crater rim or near the rover, as well as any unevenness in illumination across the sky, ground, and crater rim that may arise due to local changes in slope.

After the standard deviation is calculated, a 95% confidence interval is calculated using Equation 2.4, presented as

$$95\% \text{ confidence} = 1.96 \frac{\sigma}{\sqrt{n}}, \quad (2.4)$$

where σ is the standard deviation in extinctions and n is the number of subsections in the frame, which is

usually 64 subsections. Typically, Equation 2.4 results in a confidence interval that is $<5\%$ of the crater-rim averaged extinction, and the uncertainty from illumination or terrain variability is minimal.

For the uncertainty in the individual north, east, and west directions, the standard deviation is calculated between the extinctions in each direction. Equation 2.4 is not used, as the 95% confidence interval is not relevant for this purpose. Here, we see larger uncertainties, with a typical standard deviation value that is about 10% of the extinction value. It is important to note that a larger standard deviation between the directional extinctions could arise from terrain and illumination effects; however, a genuine difference in dust loading between sections of the image causing the extinction to be higher in one direction will also result in a higher uncertainty.

2.3 Results

2.3.1 Seasonal Results

First, we examine the record of LOS extinction from the beginning of the mission to the end of MY 36 as a function of mission sol (Figure 2.8a) and solar longitude (Figure 2.8b). There is a gap in the record between sols 2066 and 2175 due to the MY 34 GDS (shown with a yellow bar), as well as a couple of gaps after sol 3000 due to occlusion from the near-field terrain the rover was driving through. Figure 2.8 includes crater-rim averaged extinctions, where the images were taken only between 10:00-14:00 LTST to compare to the previously reported LOS extinctions — however, each extinction reported here has been updated using the illumination corrections described in Section 2.2.3. Two additional MYs are now added to the LOS extinction record.

Since the LOS observation was first employed in MY 31, the extinction has followed a yearly pattern, where, starting at the southern fall equinox at $L_s = 90^\circ$, the extinction slowly declines until it reaches a minimum of $\sim 0.025 \text{ km}^{-1}$ around $L_s = 100^\circ$. For three MYs in a row — MY 33, MY 34, and MY 35 — the minimum extinction was shown to rise from year to year, with the minimum extinction in MY 35 dropping to only $\sim 0.04 \text{ km}^{-1}$, a difference of 45% between MY 33 and MY 35.

After the minimum that occurs at $L_s = 100^\circ$, the extinction begins to steadily rise as the season progresses, reaching a peak extinction of 0.1 km^{-1} around $L_s = 300^\circ$ shortly after southern summer, with a small local peak around $L_s = 200^\circ$. In contrast to the trend observed in the minimum extinction, the maximum extinction saw a slight decline from MYs 32 to 34. This suggests that during the dustier time of year, more dust is concentrated near the surface — consistent with observations from C. A. Moore et al. (2019) during the southern summer — resulting in less dust to look through as the rover climbs higher in elevation up Mount

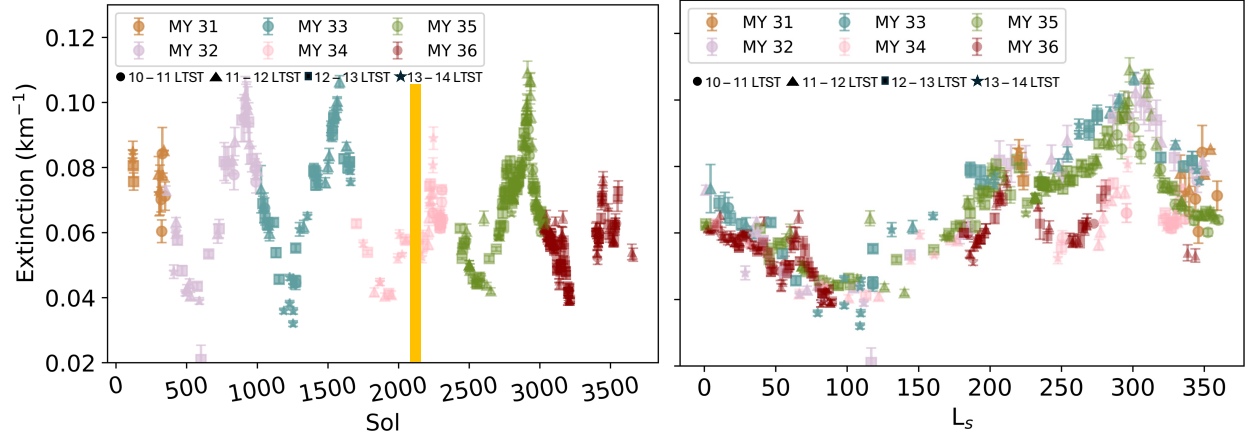


Figure 2.8: The midsol (10:00–14:00 LTST) LOS extinctions as a function of panel (a) mission sol and (b) L_s . The error-bars represent the 95% confidence interval described in Section 2.2.5. Marker types represent the time interval when the image was taken: 10–11 LTST (circles), 11–12 LTST (triangles), 12–13 LTST (squares), and 13–14 LTST (stars). These data span from the end of MY 31 to the end of MY 36, with over 1000 mission sols and two MYs added from the most recent LOS extinction publication of C. Smith et al. (2020). The sols spanning the MY 34 global dust storm (GDS) have been removed from this analysis, and the time of the GDS is indicated by the yellow bar.

Sharp. However, this trend does not seem to hold in MY 35 when the maximum extinction rises back to the level seen in MY 32. Unfortunately, data during the dustiest time of year in MY 36 could not be used in this analysis due to terrain occlusion.

We examine if a sampling bias is skewing the maximum and minimum extinction values for each MY. As will be discussed in Section 2.3.2, a diurnal trend exists in the LOS data, where the highest extinctions are observed at noon. Splitting Figure 2.8 into 1-hour intervals between 10–14 LTST, we see that in MY 34 and 35, the peak extinctions were sampled between 11–12 LTST, whereas the MY 34 peak extinction was sampled between 13–14 LTST, when extinctions are typically lower than the noontime values. In general, MY 34 had fewer 11–13 LTST LOS images captured, potentially contributing to the lower peak of MY 34. At the time of minimum dustiness, MYs 32 and 33, which had lower minimums than the following years, had their minimum extinctions sampled between 13–14 LTST. In MY 33, the minimum extinction was sampled between 11–13 LTST, where extinctions are typically slightly higher.

In addition to the variations in maximum and minimum extinctions, small variations exist year-to-year in the transitions between the non-dusty and dusty seasons. For example, an uptick in extinctions during MY 36 after $L_s = 50^\circ$ was observed. This may be caused by an increase in dust lifting from the surface during this period in MY 36, which was not seen in MY 34 or MY 35 (Guzewich et al., 2023). This uptick was not captured in the MY 36 Mastcam column opacities; however, a similar uptick was observed in MY 35 at this time (Lemmon, Guzewich, et al., 2024).

For the reasons above, it is difficult to draw specific conclusions from the variations in maximum and

minimum extinction from year-to-year when the variation is small and sol-to-sol variability as well as sampling biases could be a driver of the changes seen between years. Largely, interannual variability in the LOS dust extinction is minimal, with repeated trends in the maximum and minimum extinctions in Gale Crater. Nevertheless, the broadly repeating yearly cycle follows the seasonality of dust globally as a result of regional dust events (J. M. Battalio et al., 2023; M. Battalio & Wang, 2019, 2021; Guzewich, Toigo, & Wang, 2017; Guzewich et al., 2015; Kass et al., 2016; Montabone et al., 2014; Montabone et al., 2020; Wang & Richardson, 2015; Wang et al., 2023).

2.3.2 Diurnal Results

With the updated method for the LOS processing, we present the results for the dust extinctions as a function of LTST (Figure 2.9 for $L_s = 0\text{--}180^\circ$ and Figure 2.10 for $L_s = 180\text{--}360^\circ$). These data are divided into 30-degree bins of L_s to show the changes with respect to time more clearly. Additionally, the data are presented using the extinctions from each of the three directions shown in Figure 2.4 — the center (north), east, and west portion of the LOS frame, as well as the average over the entire crater rim. In Figures 2.9 and 2.10, the data for each bin are fit to a half-period sine wave, shown with the dashed black line for each image. A sine wave, parabolic, and a linear fit were compared to determine which fit best describes the data. The sine wave and parabolic fit consistently produced a better R value than the linear fit with two exceptions: the eastern-pointing directions in three L_s -bins and the three directional fits in the $L_s = 330\text{--}360^\circ$ bin. To describe a diurnal cycle, a sine wave is more intuitive than a parabola. In addition, the sine wave fit used here resembles the shape of diurnal dust opacity described in Jezero Crater (M. D. Smith et al., 2023). For further discussion of the sine wave fit, see Section 2.4.1.

Here we see a trend that persists through each season, where the extinction is lower in the morning hour, peaks near solar noon, and declines into the evening. These data are constrained to when the sun is in the sky to image the crater rim, which typically falls between 06:00 and 18:00 LTST at the near-equatorial region of Gale Crater. In the less-dusty season ($L_s = 0\text{--}180^\circ$), the morning and evening extinctions go as low as $\sim 0.02\text{ km}^{-1}$ to 0.04 km^{-1} , while the noon extinctions are around $\sim 0.04\text{ km}^{-1}$ to 0.06 km^{-1} , depending on the seasonal bin. This represents a 1.5 to 2 factor change between the lowest and highest extinctions. In the dustier season ($L_s = 180\text{--}360^\circ$), the morning and evening extinctions are typically around 0.04 km^{-1} and reach as high as 0.1 km^{-1} during the dustiest time of the year. This is a factor of 2.5 variation. Note that Figures 2.9 and 2.10 show the extinction calculated for each direction in the LOS frame, expanding on the average data presented in Figure 2.8. The increasing extinctions in the mid-sol period and subsequent decrease in the evening are seen in each section of the image. The diurnal trend shown here suggests that

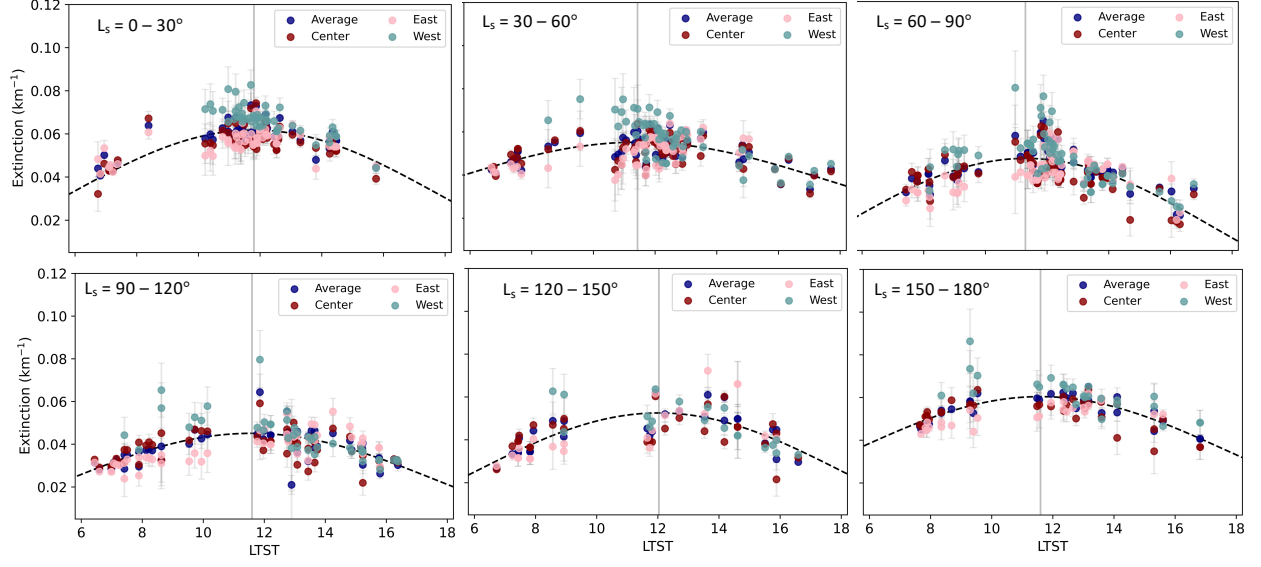


Figure 2.9: LOS extinctions as a function of LTST in 30-degree bins of L_s between $L_s = 0-180^\circ$. Crater rim-averaged (navy), center (red), east (pink), and west (teal) extinctions are shown here. The black curve is the data fit to a sine wave. The vertical gray line shows the time of peak extinction according to the sine curve fit. The extinctions appear to increase from the morning into the mid-sol, where there is a peak near noon, and then decrease into the afternoon.

dust is moving in the crater on shorter timescales than originally thought, with a diurnal component to the dust cycle in Gale Crater.

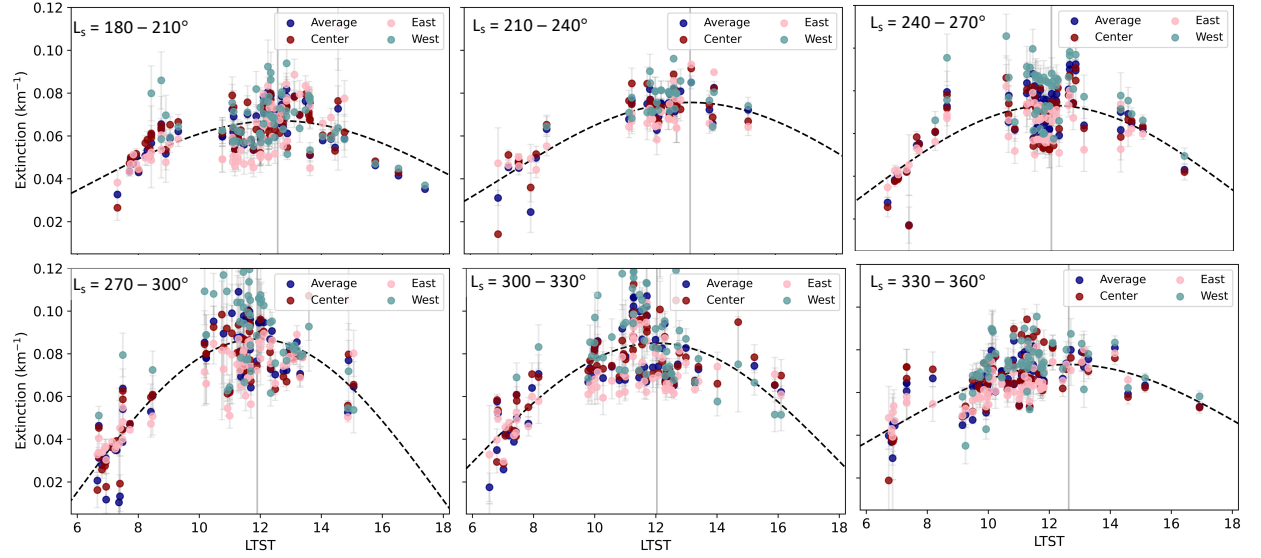


Figure 2.10: LOS extinctions as a function of LTST, as described in Figure 2.9, between $L_s = 180-360^\circ$.

2.3.3 Geographic Results

Next, we analyze the geographic inhomogeneity in the LOS extinctions using the three sections in each Navcam frame. Figure 2.11 shows the extinctions as a function of L_s , with markers representing the center, east, and west portions of the frame. Error bars show the standard deviation between the directions. Since this analysis includes extinctions taken outside the 10:00–14:00 LTST window, we show the geographic extinctions three times: earlier than 10:00 LTST (a), between 10:00 and 14:00 LTST (b), and later than 14:00 LTST (c).

Following the images taken sequentially throughout the day, Figure 2.11a shows a higher extinction in the western portion of the LOS frame compared to the eastern side, with the center of the frame typically between the east and west, except for a deviation around $L_s = 250\text{--}300^\circ$, when the center extinction is the lowest. It is important to note when looking at Figure 2.11a that due to the solar angle in the morning coming from the eastern side of the Navcam frame, the western portion of the image is often shifted such that an extinction on the west side of the frame cannot be derived for every morning image because the needed ground element is out-of-frame to the left. Therefore, there could be differences in dust loading from this time of day in this direction that are not captured in this analysis.

At noon (Figure 2.11), a similar geographic trend is seen, with the western side of the frame having higher extinctions, and the eastern and center portions showing lower values. With season, the inhomogeneity appears to be at a minimum in the $L_s = 50\text{--}170^\circ$ range, with values across the frame appearing closest in the southern winter period. After $L_s = 200^\circ$, the western side of the frame has a clear increase in extinction compared to the center and eastern sides.

After 14:00 LTST, the extinction values across the frame are largely homogeneous. Particularly in the southern autumn and winter, between $L_s = 0\text{--}180^\circ$, the extinctions in each direction are extremely similar. Moving into southern spring and summer, the spread across the frame begins to increase, similar to the noon extinctions. Despite this increase, other than a handful of exceptions, the extinctions in the evening typically differ by no more than $\sim 0.01 \text{ km}^{-1}$, meaning that the crater can be considered to be well-mixed in this period. However, due to the observational bias of most LOS images being captured in the mid-sol period, there are fewer data points to examine the geographic trend.

Examining the directions from 10:00 to 14:00 LTST as a function of mission sol (Figure 2.12), an interesting trend is seen. For the first ~ 900 sols of the mission, the extinction does not appear to favor any particular direction, with each direction higher on some sols and lower on others. After sol ~ 1000 , the highest extinctions are usually observed on the western side of the frame. For the first ~ 1200 sols of the mission, the rover drove in the southwest direction, meaning that the 45° view as seen from the Navcam was different at the beginning

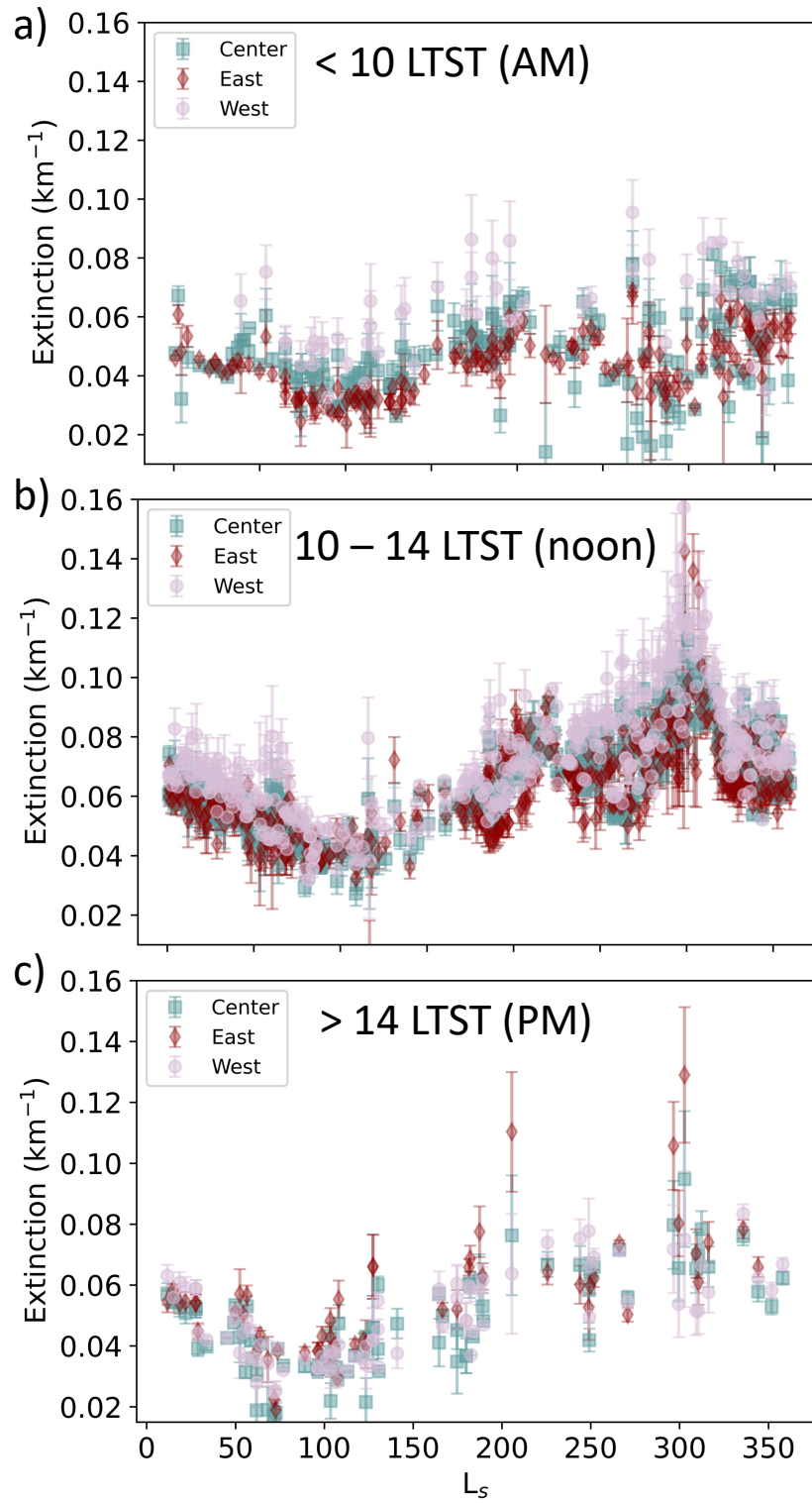


Figure 2.11: Center (teal squares), east (red diamonds), and west (purple circles) extinctions as a function of L_s for panel (a) times earlier than 10:00 LTST, (b) times between 10:00–14:00 LTST, and (c) times later than 14:00 LTST.

In general, extinctions on the west side of the frame are higher in the morning and noon periods, with eastern extinctions slightly higher in the afternoon. Particularly in panels (a) and (b), the dusty season sees a wider spread of extinctions across the frame.

of the mission than when the rover began driving in the southern direction after sol ~ 1200 . Images at the beginning of the mission would have seen more of the north-eastern crater rim, which shifted to the north-west as driving occurred during the mission. Differences in dust-loading across the frame over the course of the mission can therefore provide insight into discrepancies in dust-loading across a wider swath of the crater rim. It is possible that initially the dust loading within the Navcam frame was well-mixed horizontally; however, as we began to see a wider view of the western side of the crater rim, the dust-loading became noticeably higher on the western side of the frame due to some dust lifting source. The topography of Gale Crater is complex (Figure 2.13) with various topographical features (such as the Bagnold Dunes) that are particularly conducive to dust lifting (Guzewich et al., 2023).

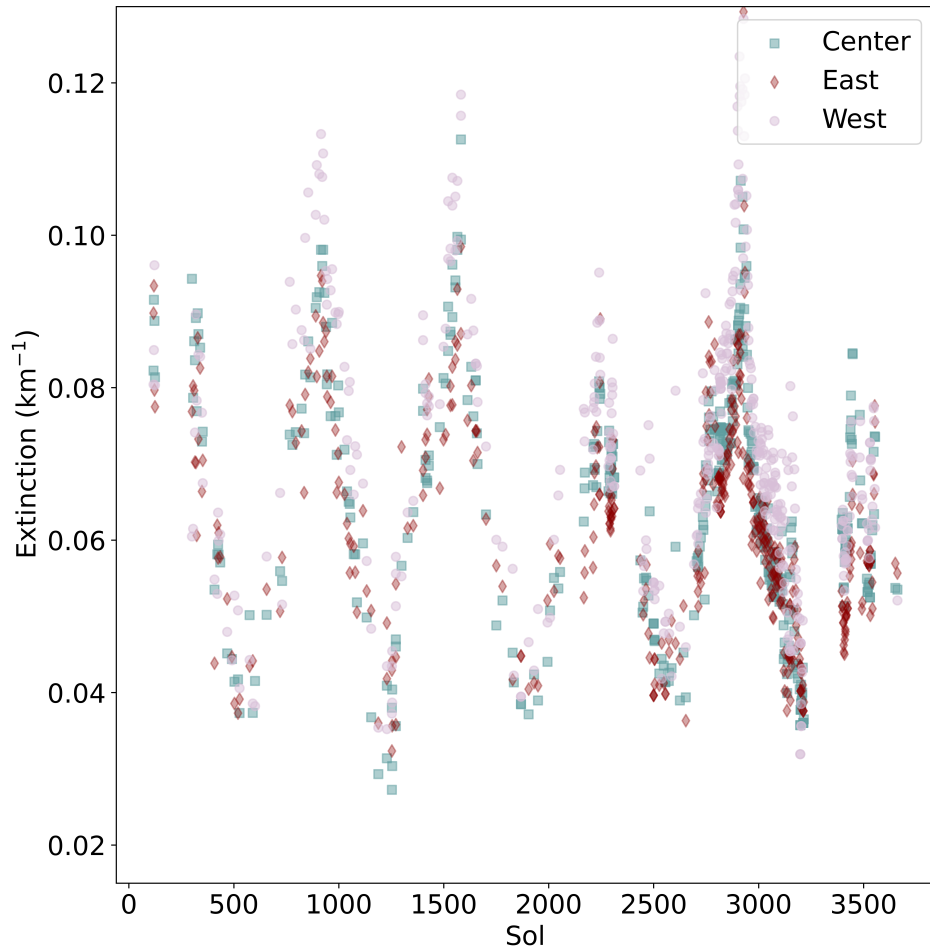


Figure 2.12: Center (teal), east (red), and west (purple) extinctions as a function of mission sol. These data show the extinctions between 10:00 and 14:00 LTST. The errorbars are removed from this image to better see the trend in extinctions.

Fortuitous dust lifting regions on the north-west side of Gale Crater may cause the dust loading to be favored on one side of the LOS frame. It is also possible that geographical inhomogeneities in dust-loading



Figure 2.13: The northern half of Gale Crater (retrieved from <https://science.nasa.gov/mission/msl-curiosity/location-map/>). The rover's traverse can be seen in white. The complex topography within Gale may contribute to the higher dust loading seen on the west side of the LOS images.

occurred as we began to climb Mt. Sharp around sol 800. Looking on a sol-by-sol basis, the differences in extinctions across the frame are typically quite small—usually differing by no more than $\sim 0.02 \text{ km}^{-1}$, which is a smaller difference than the daily change in dust loading seen in Figures 2.9 and 2.10.

Recall that the LOS derivation method is sensitive to lighting effects, which are discussed in Section 2.2.4. Particularly for extinctions that appear to be much higher or much lower than usual, especially when compared to the other directional pointings (around sol 1,000 in Figure 2.12, for example), it is possible that shadowing on the crater rim or the topography within the frame can cause the extinction to vary more than expected. However, the horizontal inhomogeneity, particularly in the images taken between 10:00–14:00 LTST, is likely a real effect independent of lighting. Within this 4-hour window, the sun moves from the eastern sky to the western sky, with a steep solar angle on each side of noon. Shadowing on the crater rim and ground as well as a brightness bias on one side of the sky would change over this time, yet a consistent trend of higher extinction on the western side of the frame for the majority of the year is seen regardless of the solar angle.

Additionally, the behavior of the directional extinctions between the morning and evening differs from what would be expected if these were only being driven by illumination effects. In the morning, when the sun is on the eastern side, a higher western extinction is calculated, which seems as though it could be driven by illumination. In the evening, when a similar but opposite brightness occurs on the western side of the

frame occurs, the strong bias toward the east is not seen as we would expect if the directional extinctions were driven only by illumination. At this time of the day, the extinctions in each direction are closer than in the morning and at noon, indicating that mixing has occurred within Gale to homogenize the dust loading in the atmosphere. With that in mind, the inhomogeneity in dust loading appears to be typically a small effect, with an increase in variation in the southern-summer season.

2.4 Discussion

2.4.1 Dust Lifting and the Diurnal Trend in Dust Extinction

The diurnal trend in dust extinctions, where higher dust extinctions are observed at noon, was noted by C. Smith et al. (2020); however, they did not determine a cause or correct for illumination effects within the images, leading to uncertainty if the diurnal trend was truly caused by differences in dust loading or due to lighting. By reanalyzing C. Smith et al. (2020) and C. A. Moore et al. (2016, 2019) Navcam LOS images with a correction to account for illumination, we find that the diurnal trends hold in the LOS extinction, where the dust extinction is at a maximum around solar noon, and at its lowest in the morning and evening.

In Figures 2.9 and 2.10, the extinctions were fit to a half-period sine wave $(t) = A \sin(B(t - C) + D)$, where the parameter, A , is the amplitude of the sine wave, describing the variation in extinction throughout the day. Figure 2.14 shows the value of A for each 30° - L_s bin as a function of solar longitude, shown with the vertical axis on the left. On the righthand axis, for comparison, are the average extinctions across the LOS frame.

From Figure 2.14, we can see that the variation in extinction across a sol appears to change with respect to season. In the southern winter, the diurnal variation is lower. As the extinctions start to increase moving into the southern spring, peaking at $L_s = 300^\circ$, the diurnal variation also increases, with a peak at a similar time.

The parameter, C , which represents the shifting of the amplitude along the x-axis, is examined to determine if there is a seasonal dependence. This would determine if the daily peak in dust extinction occurs at a different time throughout the year. C is found for each 30° -bin of L_s and the coefficient of variation (the standard deviation of the values, divided by the mean of the values) was calculated. The coefficient of variation was calculated to be 0.07, indicating that the variation of the standard deviation from the mean is very low. This suggests that there is no seasonality to the time at which the daily peak in dust extinction occurs, which we observe to be typically at solar noon from Figures 2.9 and 2.10.

Studies of dust lifting at the Gale Crater can partly inform the diurnal trend seen here. Guzewich et al.

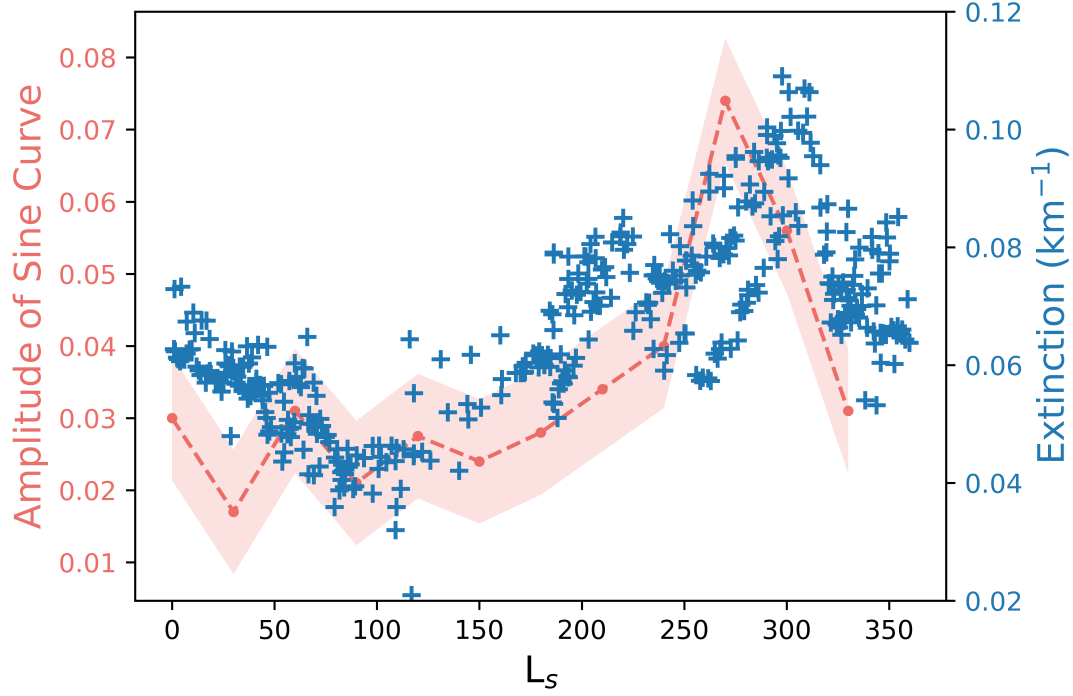


Figure 2.14: Left ordinate axis: Parameter A as determined by the sine wave fit of each 30°-bin of L_s as a function of season. This describes the diurnal variation in the LOS extinction. The shaded region represents the 95% confidence interval. Right ordinate axis: Crater rim-averaged extinctions for comparison.

(2023) analyzed the dust lifting events observed by the Navcam on Curiosity in Gale Crater. Though a lack of dust lifting events was observed early in the mission (Moore, Lemmon, Kahanpää, et al., 2015), a marked increase occurred after sol 1500 (Guzewich et al., 2023). The frequency of dust lifting events peaked at solar noon, with a gradual decline on either side of noon, which can be expected with strong solar heating at noon (Newman et al., 2019). Since the work by Guzewich et al. (2023) did not seek to calculate the amount of dust lofted into the atmosphere but rather the frequency and characteristics of such events, it cannot be determined if the noon dust lifting events are lifting more dust than those in the morning and afternoon. However, if the frequency of dust lifting increases near solar noon, we can expect to see an increase in opacity around this time as more dust is lofted into the atmosphere, potentially within the LOS of the Navcam.

With respect to season, the trend in dust lifting as observed by Guzewich et al. (2023) appears more variable, though some of this variability is introduced by inherent observation biases based on rover location due to the convolution of LOS observations with the zonal-mean dust seasonality (Montabone et al., 2015; Montabone et al., 2020). In general, the dust lifting frequency is lowest in the southern winter and highest in the southern summer (Guzewich et al., 2023), which is a pattern also observed at the Spirit Rover landing site, Gusev Crater (Greeley et al., 2010).

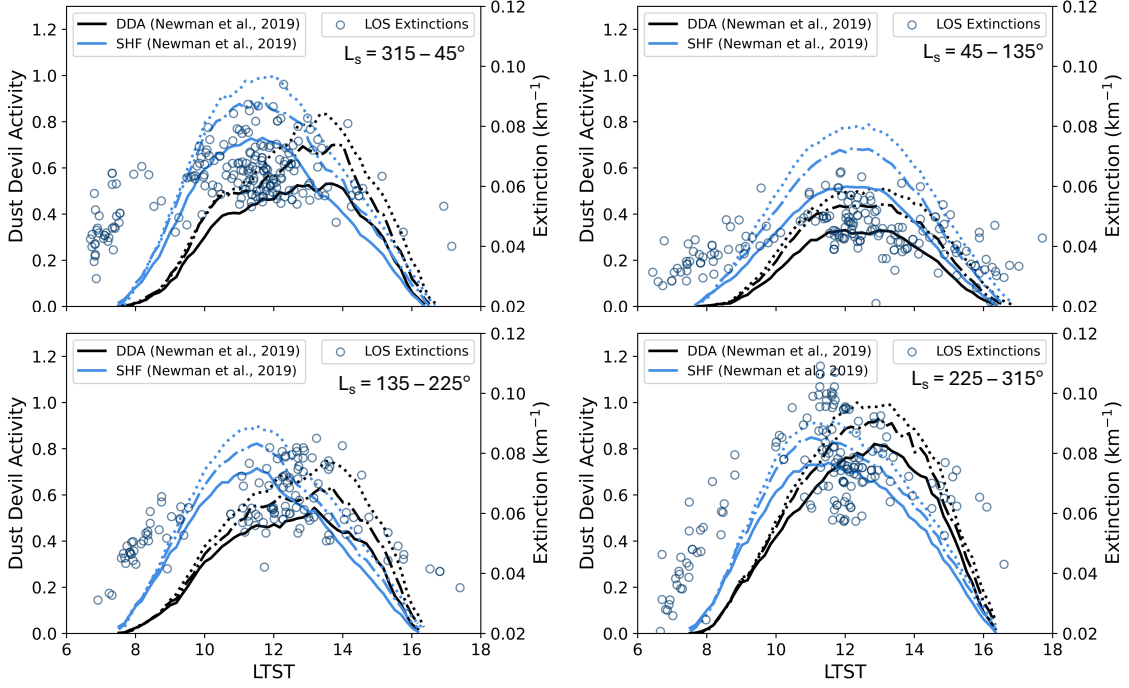


Figure 2.15: Normalized dust devil activity and sensible heat flux as a function of local true standard time retrieved from Newman et al. (2019) compared against the diurnal LOS extinctions for four seasonal periods: $L_s = 315-45^\circ$, $L_s = 45-135^\circ$, $L_s = 135-225^\circ$, and $L_s = 225-315^\circ$. The solid black and blue lines represent year 1, the dashed lines represent year 2, and the dotted lines represent year 3 from simulations by Newman et al. (2019).

Newman et al. (2019) modeled the sensible heat flux (SHF) and dust devil activity (DDA) as a function of LTST and season within Gale Crater using MarsWRF. Figure 2.15 shows the SHF and DDA compared with the LOS extinction for four seasonal periods: $L_s = 315-45^\circ$, $L_s = 45-135^\circ$, $L_s = 135-225^\circ$, and $L_s = 225-315^\circ$. The SHF and DDA were retrieved from Newman et al. (2019), with a note that the DDA and SHF have been normalized between a range of 0 and 1 for Figure 2.15. The equation $DDA_{normal} = \frac{DDA_i - \min(DDA)}{\max(DDA) - \min(DDA)}$ is used where DDA_i is the i th element of the DDA set, and $\min(DDA)$ and $\max(DDA)$ are the smallest and largest values within the set, respectively. The same process is done for the SHF set. Here, we can see that the LOS extinctions follow a similar trend to the SHF, where a peak occurs at solar noon, which is strongest in the southern summer season ($L_s = 225-315^\circ$). The increase in DDA activity is similar to the LOS extinction with respect to season; however, the peak in DDA tends to occur up to two hours later than noon, with the exception of $L_s = 45-135^\circ$ where the peak is still at noon. This offset is not observed in the LOS extinctions (component B in the sinusoidal fit).

A diurnal trend in the column optical depth was observed using Mastcam solar imaging in the Gale Crater (Lemmon, Guzewich, et al., 2024). With the column opacities split into bins of 30° of L_s , Lemmon, Guzewich, et al. (2024) observed a decrease in opacity throughout a sol, with a larger morning-evening opacity difference in the second half of each MY, with MY 31 as the only exception. In opposition to the

LOS analysis, a maximum in opacity at solar noon is not observed, rather a decline throughout the day, with the morning having the highest opacity. It is suggested by Lemmon, Guzewich, et al. (2024) that differences in the pressure variations within the crater (Haberle et al., 2014) are causing the change in diurnal opacity. This may explain, in part, the decline in LOS extinction in the evening period as shown in Figures 2.9 and 2.10. However, it is important to note inherent differences in these observations — the column opacities will include contributions from dust and other aerosols within the column, such as water-ice clouds, both inside and outside the crater. Meanwhile, the LOS extinction is examining dust exclusively within the crater, and there is no evidence of water-ice fog in Gale Crater (Martínez et al., 2017). An increase in water-ice cloud formation in the morning could explain the higher column opacities at a time when the LOS is seeing a lower dust extinction. Interestingly, results from TIRS on the Perseverance Rover agree with our diurnal dust trend (M. D. Smith et al., 2023) with a broad peak in opacity at noon. However, the increase observed by TIRS is wider, meaning that the LOS extinctions rise and fall more rapidly throughout the day.

2.4.2 Comparison with Mastcam Solar Imaging

As a complement to the Mastcam solar disc imaging, we plot the Navcam LOS extinctions with the 880 nm Mastcam column opacities, also referred to as Mastcam taus, in Figure 2.16 for comparison between the two observations. The column opacities are divided by 11.1 km, representing the typical pressure scale height of the atmosphere, as carried out in previous LOS investigations (C. Smith et al., 2020).

The agreement between the Mastcam taus and Navcam LOS extinctions is quite good throughout the mission; however, comparisons at the dustiest time of MY 36 cannot be made due to LOS data omission caused by terrain occlusion. A regional dust storm was observed much earlier in the season than usual in MY 36 at $L_s = 150^\circ$ (Lemmon, Guzewich, et al., 2024). Unfortunately, this storm occurred within the period when LOS images were removed from analysis because of terrain in the image, and this dust storm was not captured within the extinction data.

During each MY, a lag between the LOS extinctions and taus can be observed. During the southern winter, when there is generally less dust in the atmosphere, the Navcam LOS reaches its minimum before the Mastcam tau. Then, during the dustier southern summer, the Mastcam tau peaks before the Navcam LOS, which is especially clear in the period around sol 3100 in MY 35. For the lag in minimum, the LOS extinction typically reaches its lowest value about 10° of L_s sooner than the Mastcam taus, whereas the maximum in LOS extinction occurs nearly 65° of L_s after the peak in column opacity. Typically, Gale Crater appears to be less dusty than the air outside the crater, in part determined by comparisons to the Spirit landing site, where column opacities are similar in value to those in Gale Crater despite Curiosity seeing through

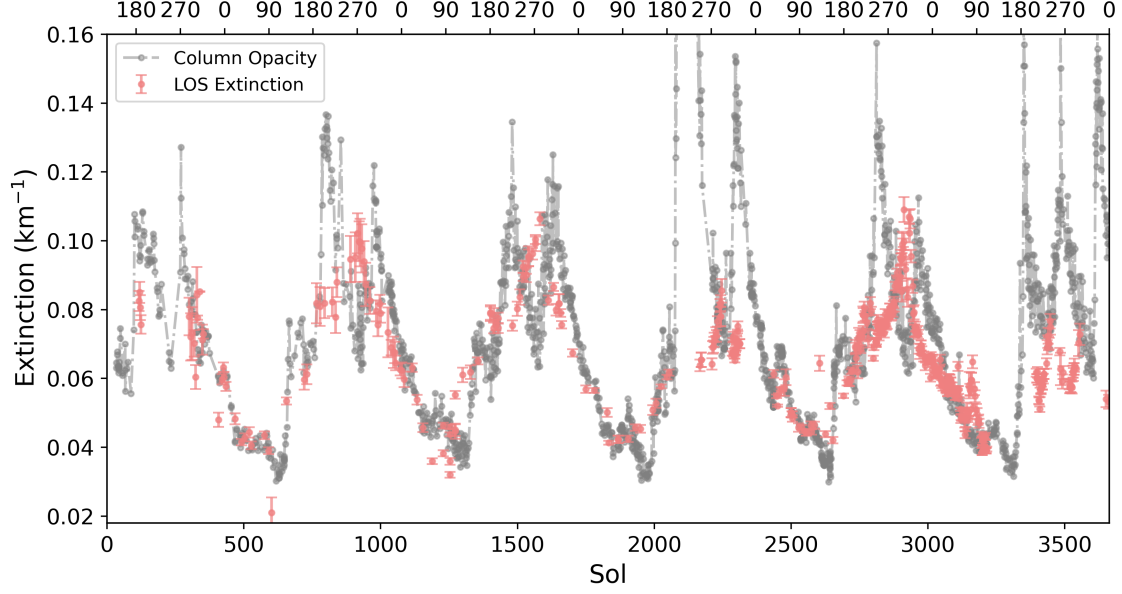


Figure 2.16: Navcam LOS extinctions (pink) and Mastcam column opacities (gray) throughout the MSL mission (L_s values shown on the top x-axis). The Mastcam opacities are divided by 11.1 km to convert to extinction for comparison with the Navcam extinctions. The extinctions from the MY 34 global dust storm are not included here but are discussed in detail in C. L. Smith et al. (2019).

an extra 2 km of atmosphere (Martínez et al., 2017). Splitting the atmosphere into three vertical layers, Guzewich, Newman, et al. (2017) found that the contribution of near-surface dust extinction to the Mastcam τ_{aerosol} varied by season. At the time of minimum extinction around $L_s = 100^\circ$, the near-surface opacity was only 10% of the total column opacity, and the crater is expected to be a sink of dust at this time of year (C. A. Moore et al., 2019), explaining why the crater becomes less dusty before the air above. At $L_s = 270^\circ$, the near-surface opacity made up 50% of the total column opacity (Guzewich, Newman, et al., 2017), aligning with observations of increased vertical mixing during the southern summer (Rafkin et al., 2016). Combining increased vertical mixing with increased dust lifting from the surface at $L_s = 270^\circ$, both dust entering from outside the crater and dust lifting from the surface might contribute to the later peak in LOS extinctions compared to the Mastcam column opacities.

Chapter 3

Optical Depths of Dust Devils Observed in Gale Crater, Mars

3.1 Overview and Author Contributions

As shown in Chapter 2, a diurnal trend in the line-of-sight (LOS) dust extinction, which probes dust loading in the bottom ~ 2 km of the atmosphere in Gale Crater, was observed. The dust extinction was shown to peak at local noon, with lower extinctions in the morning and evening. The amplitude of the diurnal variation, which is defined as the difference between the minimum and maximum extinction, was larger in the southern summer, indicating a seasonal cycle to the diurnal trend. In Chapter 2, it was hypothesized that the increased frequency of dust devil activity contributes, at least in part, to this observed diurnal LOS trend. However, it was noted that the amount of dust lofted in each dust devil was unknown, and variations in the amount of dust lofted may affect the diurnal trend.

While previous studies examined when and where dust lifting occurs, the amount of dust lofted by these events remains poorly understood. This limits our understanding of how dust devils contribute to the background dust abundance and to boundary layer processes. In this work, we quantify the optical depths of dust devils in Gale Crater observed by Navcam to constrain the role of dust lifting events in the Martian dust cycle. By examining trends in dust devil optical depth as a function of time of sol, season, and rover location, we investigate whether changes in dust devil optical depth align with known diurnal and seasonal patterns of dust loading in Gale Crater. We also compare our optical depth estimates with convective pressure vortices measured by REMS to explore the relationship between vortex strength and dust lifting.

This work was carried out in collaboration with S.D. Guzewich, E.L. Mason, and J.E. Moores, and is currently under review at *Journal for Geophysical Research: Planets*, from which the text for this chapter was adapted. Author contributions are as follows: G. Bischof (author of this dissertation): conceptualization, data curation, formal analysis, investigation, methodology, writing (original draft), writing (review and editing); S. D. Guzewich: conceptualization, validation, writing (review and editing); E.L. Mason: validation, writing

(review and editing); and J. E. Moores: funding acquisition, validation, supervision, writing (review and editing).

3.2 Methods

3.2.1 Navcam Dust Devil Sequences

There are several sequences used to search for dust devils on Mars (see Guzewich et al. (2023)). In this work, we use the dust devil surveys and the dust devil movies to derive optical depths. The dust devil surveys consist of 3 image-sequences pointing in eight azimuthal directions, totaling 24 images. The azimuthal pointings are spaced such that a 360° FOV around the rover is observed. The images in each 3-image sequence are taken every 13 s, and the time between sequences is 32 s. Dust devil movies consist of 2 types of sequences: long and short sequences. Each dust devil movie is fixed in azimuth and elevation, where short movies consist of 21 images with 13 s between each frame, and long movies consist of 45 images with 13 s in between. In this work, only the short sequence dust devil movies are used. Figure 3.1 shows the dust devil observations with positive detections used in this work as a function of mission sol and LTST.

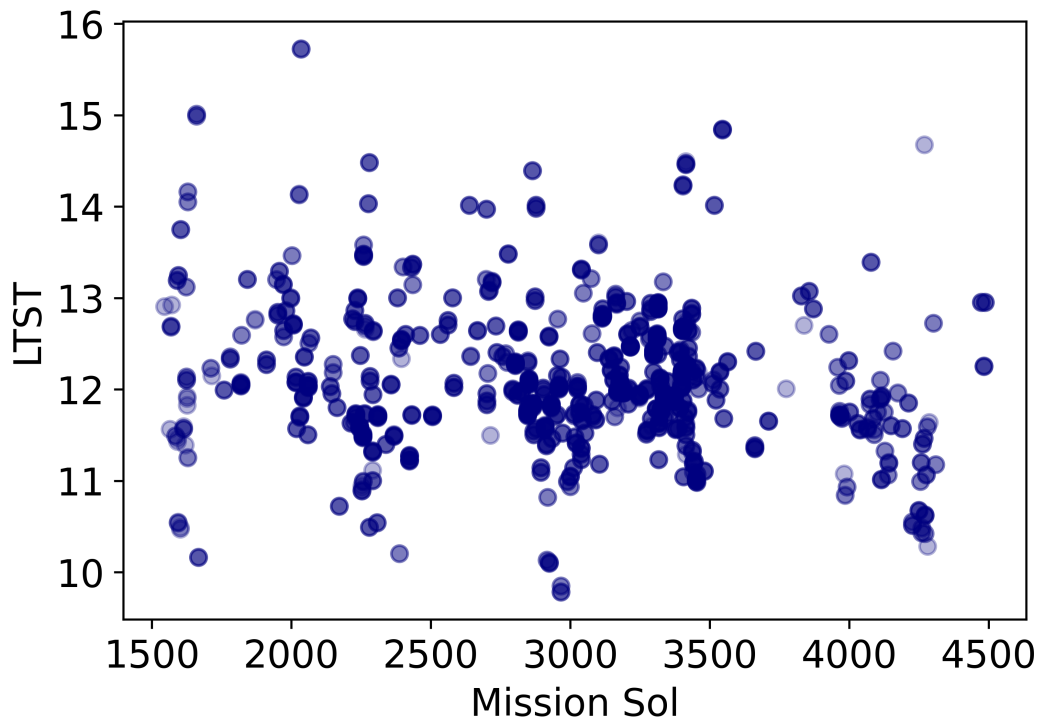


Figure 3.1: The spread of dust devil observations with positive detections through sol 4500 used in this work. For the first ~ 1500 sols of the mission, dust devils were not observed in Gale Crater. Most frequently, dust devil images are acquired around the mid-sol period between 11-13 LTST.

3.2.2 Derivation of Dust Devil Optical Depth

Dust lifting events were identified using the standard technique presented in Guzewich et al. (2023). Since most dust devils have low-optical depth and are difficult to detect by eye, a mean-frame subtraction (MFS) technique was used to identify the dust devils. For each dust devil sequence, the average value of each pixel was computed across all frames, producing a single “mean frame” with the same dimensions as an individual frame in the sequence. The mean frame was subsequently subtracted from each individual frame to isolate motions associated with dust lifting. Figure 3.2 shows an example dust devil movie from MSL mission sol 2847 (MY 35, $L_s = 253^\circ$). The top panel displays a standard Navcam frame in which dust lifting is difficult to observe by eye. The bottom panels show the MFS-processed movie, where the dust devil is clearly visible and highlighted in red. Dust tends to be bright against the surface and dark against the sky used in this methodology.

To derive the optical depth of each identified dust devil, the method of Lemmon, Lorenz, et al. (2022) was applied. The derived optical depth represents a “delta optical depth” as the method accounts for background dust and returns only the additional optical depth contributed by the dust devil. Under a low-opacity approximation, the optical depth of the dust devil is given by

$$I = I_0 e^{-\tau} + J_0 (1 - e^{-\tau}), \quad (3.1)$$

where I is the radiance of each pixel in a standard frame, I_0 is the radiance of each pixel in the mean frame, τ is the optical depth of each pixel, and J_0 is a source term that accounts for dust scattering properties. In practice, J_0 was taken to be the radiance of the sky following standard practice in similar dust optical depth calculations (Bischof et al., 2024; Lemmon, Lorenz, et al., 2022; Moores, Lemmon, Kahanpää, et al., 2015; C. Smith et al., 2020). The number of pixels used for J_0 varied between movies depending on the amount of sky visible in the frame. Typically, J_0 was computed from approximately 200×50 pixels, though movies containing more or less sky used correspondingly larger or smaller regions. When possible, only sections of the sky that did not include a dust devil were used for J_0 , so the radiance of the section did not change with time. An example of the region used to calculate J_0 is indicated by the navy box in the top panel of Figure 3.2.

Equation 3.1 was used to generate a “ τ -map” of the entire scene for each frame in the sequence. The dust devil was then isolated from each frame by manually tracing its spatial extent using the Matplotlib Lasso Selector tool. This step inherently introduces some degree of human error. For example, if the edges of a dust devil are poorly defined, regions of weak dust lifting may be excluded because they fall below the threshold

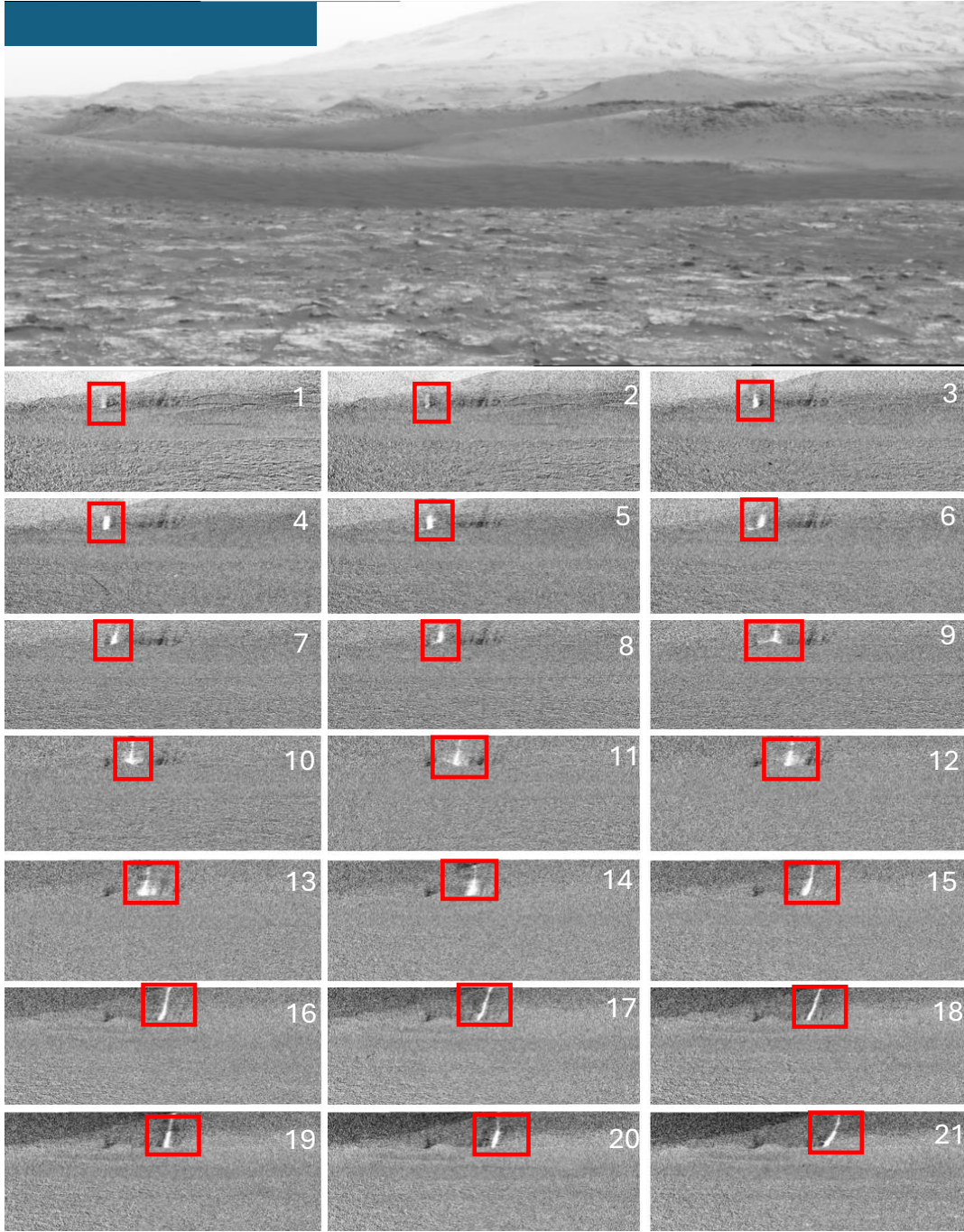


Figure 3.2: (top panel) Frame 1 of a sol 2847 dust devil movie with no additional processing. (bottom panels) The dust devil tracked through the 21 frames of the sequence using the MFS technique. The blue bar in the left corner of the top panel indicates the area used for J_0 in Equation 3.1

of visual detectability, despite exceeding the background dust. Variations in optical depth less than $\sim 5 \times 10^{-4}$ are no longer distinguishable from regular noise in the τ -map. After isolating the dust devil in each frame, an average optical depth was calculated for that frame. This process was applied to every dust devil movie or survey taken between sols 1500 to 4500.

To calculate the uncertainty on each reported dust devil optical depth, we calculate the standard error on the mean, which is given by

$$uncertainty = \frac{\sigma}{\sqrt{n}}, \quad (3.2)$$

where σ is the standard deviation of the per-pixel dust devil optical depth and n is the number of pixels in each isolated dust devil. If the optical depths of all the pixels in a dust devil are similar, the reported uncertainty is low. If the dust devil has pixels with optical depth that vary substantially, the uncertainty is higher.

3.3 Results

3.3.1 Example of an Isolated Dust Devil on Sol 2847

Figure 3.3 shows the result of applying the method described above to calculate the optical depth of the dust devil observed on sol 2847. The dust devil was isolated across 21 frames of the sequence, and the average optical depth of each frame is displayed in the lower right corner of each panel. The frame-averaged optical depth ranges from 0.00513 and 0.0236, with the minimum in frame 2 and the maximum in frame 16. In general, the optical depth is lower at the beginning of the sequence and increases toward the end, with fluctuations in optical depth throughout the intermediate frames.

As indicated by the colour map in Figure 3.3, the base of the dust devil typically exhibits the highest optical depth, which decreases with increasing distance from the dust devil core. For example, in frame 20, the dust devil is relatively compact, with a well-defined core of optical depth greater than 0.05 and minimal spatial extent beyond the centre. In contrast, frame 10 shows a less well-defined core, with additional dust distributed around the core and a lower overall optical depth.

Figure 3.4 shows the distribution of pixel optical depths for the sol 2847 dust devil in each frame of the sequence. Overall, the optical depths are low, with 34% of pixels exhibiting values below 0.01. Only a small fraction of pixels have optical depths exceeding 0.06, and all pixels with optical depth greater than 0.09 occur in frame 13 or beyond, highlighting the increase in overall optical depth toward the end of the sequence. It is interesting to note that the classic threshold for dust devil visibility by eye is taken to be an optical depth

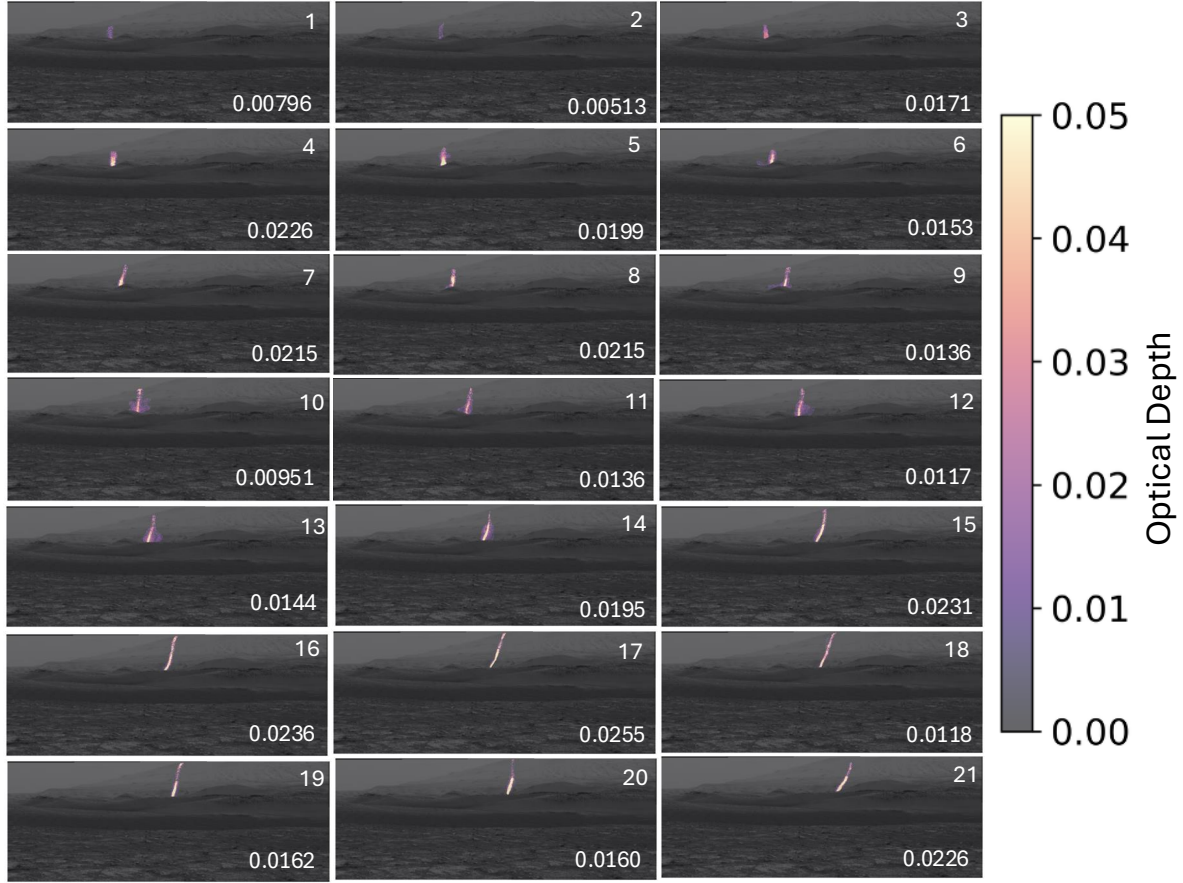


Figure 3.3: The calculated optical depth of the isolated dust devil for each frame of the sol 2847 dust devil movie. The dust devil is characterized by a well-defined core with higher optical depth, with the optical depth lowering away from the core. The dust devil increases in average optical depth toward the end of the movie.

of 0.1. The sol 2847 dust devil, which is just barely visible by eye in the raw frames, has only a fraction of pixels above this typical threshold.

The observed optical depth distribution is fitted with a gamma distribution, shown by the black curve in Figure 3.4a. The goodness of fit is evaluated using a Q-Q plot (Figure 3.4b). For opacities below ~ 0.08 , the gamma distribution described the data well as indicated by the close agreement between the blue data points and the red 1:1 line. At optical depths greater than ~ 0.08 , the gamma distribution increasingly overestimates the number of higher-optical depth pixels, which is shown by the downward curvature of the data relative to the 1:1 line. This bias is reflected in the difference between the arithmetic mean optical depth of the dust devil through all frames (0.0171) and the mean derived from the gamma fit (0.0218), due to the overestimation of the high optical depths.

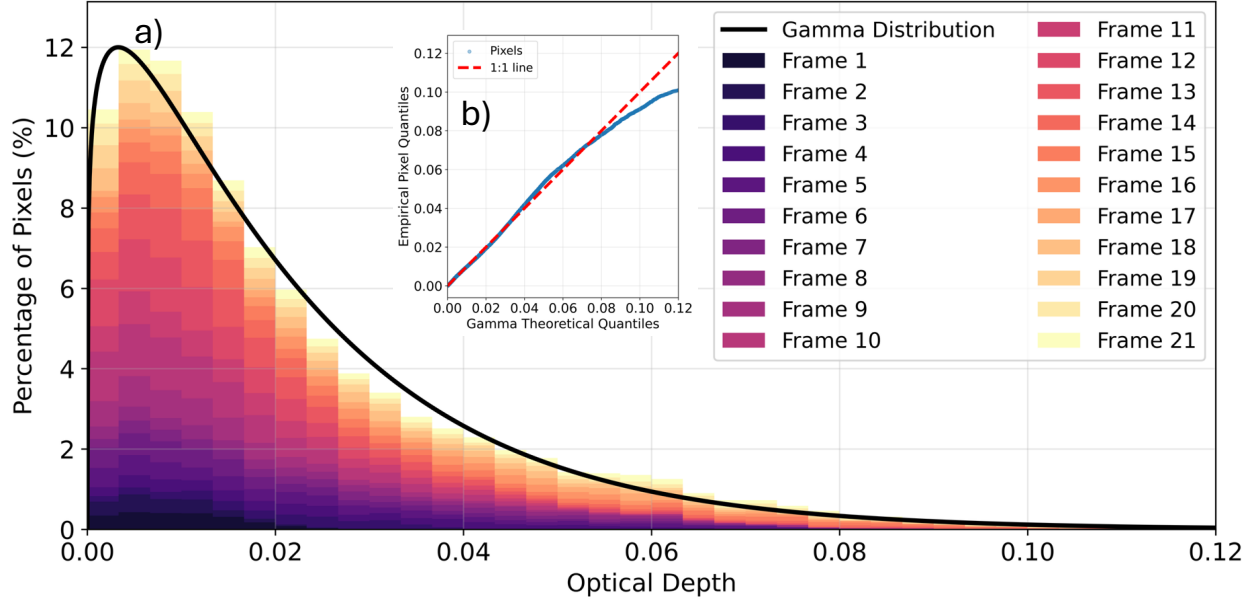


Figure 3.4: (a) Per-pixel optical depth distribution of the sol 2847 dust devil through 21 frames. A gamma distribution is fit to the data, which describes the distribution well at low-optical depth, but overestimates the number of high-optical depth pixels, shown by the inset plot (b).

3.3.2 Seasonal Results

The frame-averaged dust devil optical depths are shown in Figure 3.5 as a function of mission sol and solar longitude, divided into MY by the coloured markers. The period of the MY 34 global dust storm is highlighted by the orange bar. The first derived optical depth occurs on sol 1545, corresponding to the first instance of a dust devil imaged with Navcam. Overall, optical depths are low, with 98% of the derived values less than 0.1. A small number of optical depths are greater than 0.1, and the maximum derived optical depth is 0.32. The lowest derived optical depth is 1.2×10^{-4} , which is the approximate lower limit for isolating additional dust compared to background noise as discussed in Section 3.2.2.

As shown in Figure 3.5a, there is substantial interannual variability in the derived optical depths. For example, MYs 34 and 36 had fewer optical depths greater than 0.1 compared to MYs 33, 35, and 37. In particular, MY 35 had many dust devils with optical depths exceeding 0.1 at multiple times of year. During MY 35, Curiosity was in the Glen Torridon valley and there were frequent dust devils (Guzewich et al., 2023; Mason et al., 2025). During the MY 34 global dust storm, which occurred between sols 2066 and 2175, dust devil optical depths were both rare in occurrence (Guzewich et al., 2019), as well as characterized by low optical depth. After the end of the dust storm, the optical depths returned to their typical values. This decrease in optical depth during the MY 34 dust storm was similarly observed by Mason et al. (2026), and attributed to a decrease in convection during times of high atmospheric optical depth.

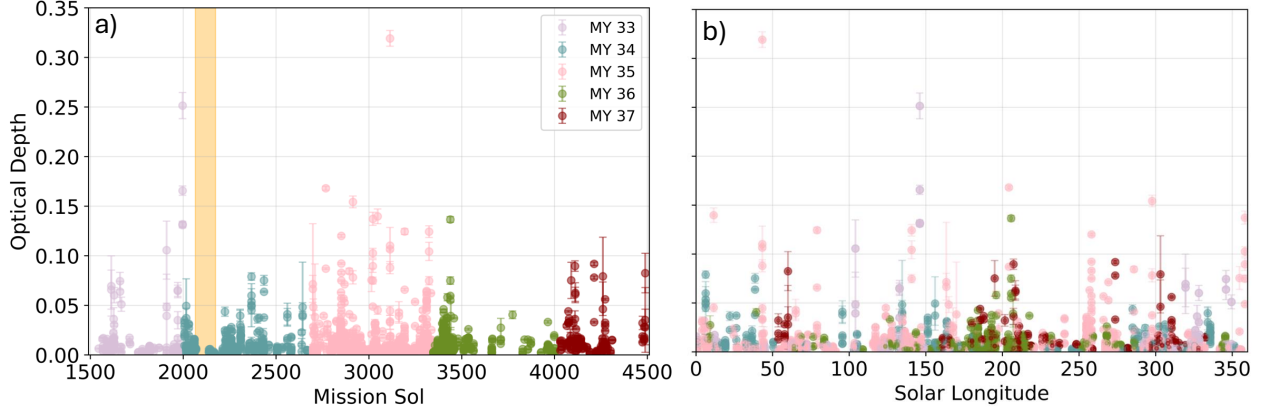


Figure 3.5: Derived optical depths as a function of (a) mission sol, (b) solar longitude. The orange bar depicts the period of the MY 34 global dust storm. Error bars represent the standard error of the mean. Substantial interannual variability in optical depth is seen.

Seasonal variations in dust devil optical depth are presented in Figure 3.5b. Periods of relatively higher and lower optical depth are seen throughout the MY. In general, the optical depths are lowest between $L_s \approx 50\text{--}125^\circ$, corresponding to southern hemisphere fall and winter. Optical depths increase again from $L_s = 150^\circ$ and remain relatively high until the end of the year, with a dip to winter values around $L_s = 200\text{--}250^\circ$. The interannual variability noted above is reflected in the seasonal cycle. For example, MYs 33 and 35 exhibited high optical depths around $L_s = 150^\circ$ which is not observed in the other MYs.

3.3.3 Diurnal Results

Dust devil optical depths exhibit a diurnal pattern, shown in Figure 3.6. In the morning, optical depths are generally low and begin increasing around 11 LTST. Dust devil optical depth peaks between 12 and 13 LTST, before dropping down to the lower levels observed in the morning. The rarer optical depths > 0.1 are only observed in the hours between 11–13 LTST, which is the time of sol when the solar heating is strongest. In addition, REMS pressure drops are largest at this time, which is discussed further in Section 3.4.2. These optical depth values are consistent with REMS UV sensor-derived dust devil optical depths shown in Mason et al. (2026).

There are fewer data points at times before 11 LTST and after 13 LTST, which could potentially skew results to suggest a diurnal trend that does not exist. However, the lack of points outside of the 11–13 LTST period is not fully due to an observational bias. While the Curiosity rover does execute dust devil observations more frequently in the mid-sol period (Figure 3.1), normalized histograms of dust lifting frequency in Guzewich et al. (2023) to include sequences without any observed dust lifting show that dust lifting naturally occurs more frequently during the mid-sol period when the heating is the strongest. This is corroborated by

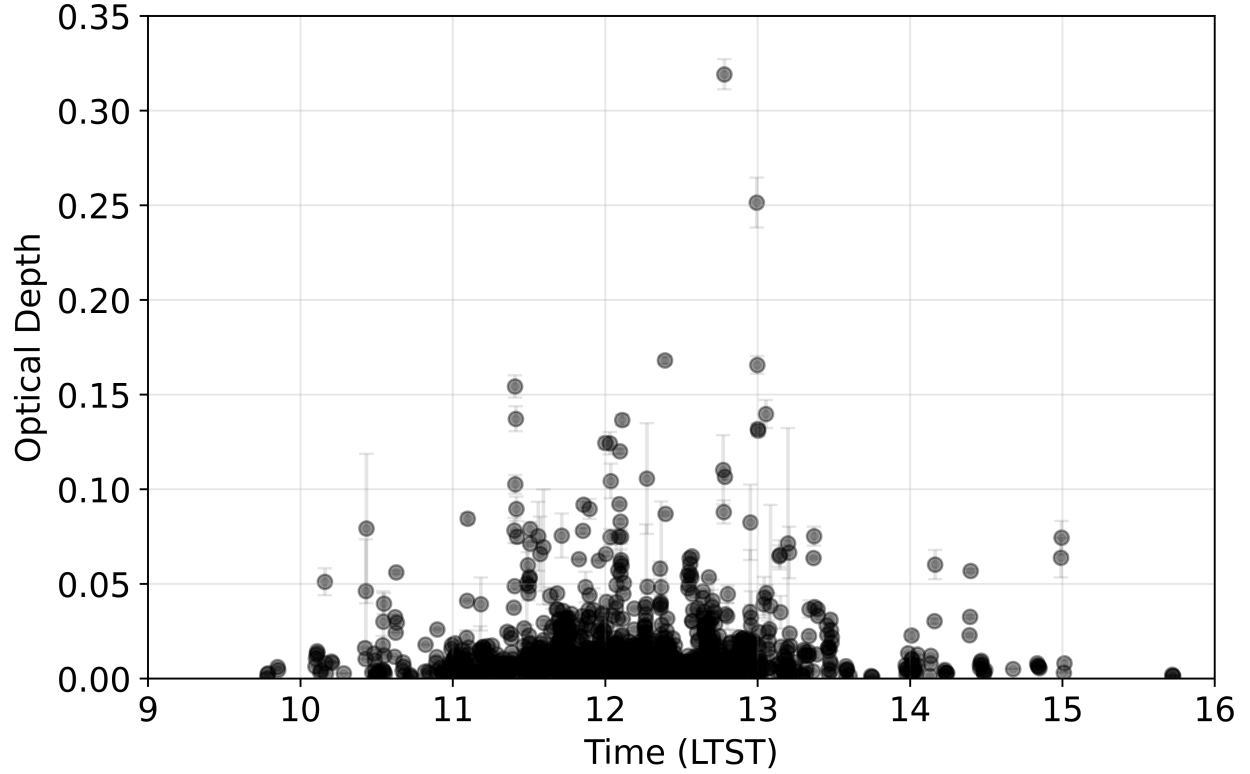


Figure 3.6: Dust devil optical depth as a function of LTST. Optical depth typically peaks between the mid-sol hour of 11-13 LTST, with lower optical depth values in the morning and evening.

the diurnal pattern in REMS convective pressure vortex detections (Mason et al., 2025). Therefore, while there may be instances of dust devils that have had higher dust devils outside 11-13 LTST, we believe Figure 3.6 is representative of the diurnal changes in dust devil optical depth.

3.4 Discussion

3.4.1 Comparison to the LOS Dust Extinction

In Chapter 2, we derived the horizontal dust extinction in the bottom 2 km of Gale Crater using the LOS extinction observation. A diurnal trend was found, where the extinction was lowest in the morning, increased to a peak around local noon, and then decreased in the evening. Seasonal variations were also evident, with the largest diurnal change in extinction occurring in the southern summer and the smallest change occurring in the southern winter. While the mixing of air from outside Gale Crater likely contributes to this trend, it was hypothesized in Chapter 2 that the increase in the dust lifting observed at local noon (Guzewich et al., 2023) adds to the additional extinction observed by Navcam. However, it remained unclear whether these more frequent midday dust lifting events also lifted more dust per event, potentially contributing further to

the mid-sol increase in atmospheric dust. Note that in this section we assume dust devils with greater optical depths lift more dust, which is a simplification due to the lack of information on the size of each dust devil. The actual amount of dust lifted in kg will depend on both the optical depth and the size of the dust devil, which we do not consider here.

Figure 3.7 shows a histogram of all dust devil optical depths as a function of LTST analyzed in this work. Each bin is divided into three colours (gray, navy, and light blue) to represent low, medium, and high optical depth dust devils, respectively. The cutoffs for these categories were determined using the standard deviation of all optical depths. Dust devils with optical depths below one-half a standard deviation from the mean (0.0036) are classified as low, and those above one-half a standard deviation above the mean (0.024) are classified as high.

From Figure 3.7a, it is apparent that dust devils occur much more frequently between 11 – 13 LTST (note that this histogram is not normalized to include non-detections to remove observational biases), with the majority in the medium optical depth category between 0.0036 and 0.024, and similar numbers of low and high optical depth dust devils. In Figure 3.7b, for each time bin, the number of events in each optical depth category is divided by the total number of events in that bin, converting the counts into percentages. This means that, for any given time bin, the three optical depth categories together sum to 100%, showing the relative contribution of each category rather than the absolute counts. Missing bars in Figure 3.7b (for example, between 9–11 LTST in the $L_s = 0 - 90^\circ$ panel) are due to there being no data for that time and season.

The diurnal trend in Figure 3.7b is offset from the trend in LOS dust extinction. Throughout the day, the percentage of high optical depth dust devils increases, but the maximum percentage of high optical depth events occurs at 13–14 LTST in all seasons, except for $L_s = 270-360^\circ$, where the peak percentage is at 14–15 LTST. These peaks in the percentage of high optical depth dust devils are all later than the maximum dust extinction observed at local noon. Additionally, while the greatest diurnal change in the LOS extinction occurring in the southern summer around $L_s = 270^\circ$, no high optical depth dust devils are present in the 12–13 LTST bin in the $L_s = 270-360^\circ$ panel of Figure 3.7b. However, despite the percentage of dust devils in the high optical depth category reaching a maximum later than seen in the LOS extinction record, the raw count of high optical depth dust devils is still much larger between 11–13 LTST than 13–14 LTST by almost an order of magnitude. These results suggest that even though relatively less dust is lofted per event in the mid-sol hours, the greater occurrence of dust devils of all strengths near local noon is the main contributor to the diurnal LOS extinction trend.

It is important for the reader to note that the peak in dust devil optical depth occurs at the same time in the midsol as the peak in dust extinction, which leads to additional questions regarding boundary layer

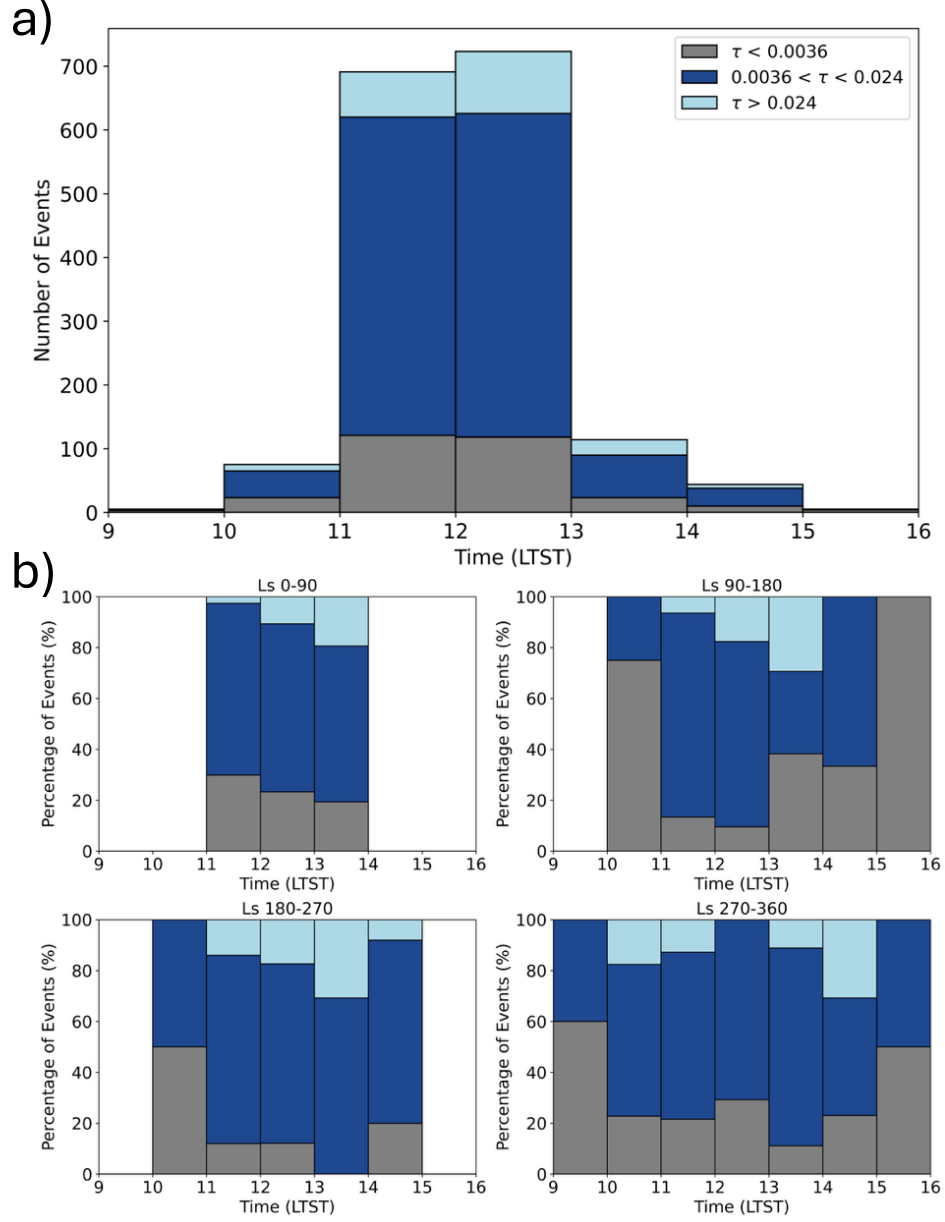


Figure 3.7: (a) A histogram of the total number of dust lifting events as a function of LTST divided into high (light blue), medium (navy), and low (gray) optical depths. (b) Each time bin from panel a is normalized to show the relative contribution of each optical depth category, split into four L_s bins

dynamics. If dust devil optical depths begin to decline around 13 LTST, we would not necessarily expect to see a similar decline in extinction at the same time due to the time it takes for dust to resettle onto the surface. Instead, one might expect an offset between dust devil optical depth and LOS extinction, which was not observed in this work. However, direct dust injection and settling are not the only two processes at play. As mentioned, at certain times of year, dust mixes between the crater and the air above the crater (Guzewich, Newman, et al., 2017), which may result in dust getting lifted higher into the atmosphere and out

of the view of the relatively shallow LOS extinction observation. Additionally, the complex topography of Gale may circulate the lifted dust to other locations in the crater which are not probed in the north-pointing LOS images. Connecting the LOS extinction and dust devil optical depth trends requires further work to understand circulation in Gale Crater.

3.4.2 Comparison to REMS Pressure Drops

Atmospheric pressure drops associated with convective vortices have been monitored using REMS since the beginning of the mission, and the frequency of both pressure and UV sensor drops were reported in Mason et al. (2025) to compare Navcam detections with pressure and UV drop detections. Here we compare the pressure drop data from Mason et al. (2025) with the dust devil optical depths reported in this work to assess the relationship between the derived optical depth and vortex strength.

Figure 3.8a shows a histogram of pressure drops as a function of LTST, split into weak, medium, and strong pressure drops. The same cutoff method used in Section 3.4.1 was applied here, with the low pressure-drop cutoff at a value of 0.63 Pa and the high-pressure drop cutoff at 1.1 Pa. Only pressure drops greater than 0.5 Pa were used to calculate the mean, which was chosen in previous work as the minimum depth needed to definitively and positively attribute the pressure drop to a passing vortex (Mason et al., 2025). The pressure cutoffs of 0.63 and 1.1 Pa do not correspond directly to the thresholds that lift dust devils at the optical depths discussed in Section 3.4.1. Instead, they provide a convenient way to compare datasets using their respective standard deviations. A detailed description of the filters applied to the pressure data can be found in Mason et al. (2025).

Figure 3.8a shows the largest number of pressure drops occur in the 11–13 LTST period, consistent with the dust devil optical depth analysis. In Figure 3.8b, where each time bin shows the relative contribution of the pressure drop categories (as described for Figure 3.7b), the pattern differs from that observed for dust devil optical depth. In the first two seasonal plots ($L_s = 0-180^\circ$), the highest percentage of strong pressure drops are observed in the mid-sol period. In the southern spring and summer from $L_s = 180-360^\circ$, the strongest pressure drops do not exhibit a clear mid-sol peak, nor do they coincide with the peak in the percentage of high-optical-depth dust devils, which occurs around 13–14 LTST. Note that the data presented in Figure 3.8 combine pressure drops detected between MYs 33 – 37 to represent the same period used in Figure 3.7. Substantial interannual variability is present in the pressure drop data, described in Mason et al. (2025), and each MY may exhibit distinct behaviour. However, because the optical depth data also has large interannual variability, we use the combined MY approach for consistency.

Comparisons of Figures 3.7 and 3.8 indicate that while an increase in the number of pressure drops

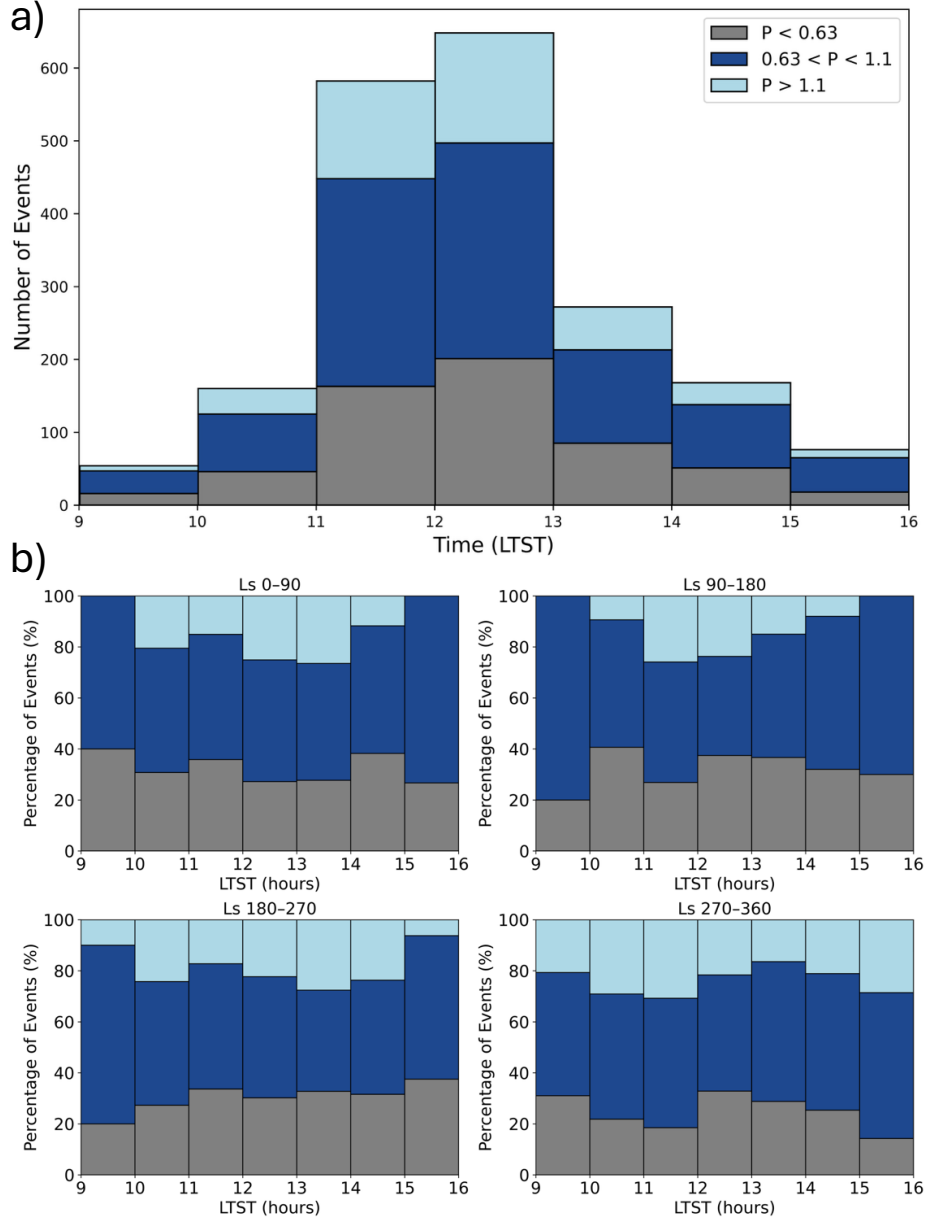


Figure 3.8: a) A histogram of the number of pressure drops as a function of LTST divided into weak (light blue), medium (navy), and strong (gray) drops. (b) Each time bin from panel (a) is normalized to show the relative contribution of each pressure drop category, split into four L_s bins.

increases the number of dust lifting events, the percentage of strong pressure drops does not fully correlate with the percentage of dust devils with high optical depths. Other mechanisms, such as the availability of dust to be lifted, must be, in part, responsible for the reason some vortices lift large amounts of dust while some do not lift any at all.

For the discussion in this section, it is important to note that the pressure drops reported in Figure 3.7 are measured locally near the rover, whereas Navcam images dust devils both near and far from the rover.

As a result, the pressure drops reported here are not directly associated with the dust devil optical depths shown in Figure 3.7. However, Mason et al. (2026) reported coincident pressure drops and UV sensor drops, from which optical depths were derived, and found a similar conclusion showing that pressure drop strength is not well-correlated with optical depth.

3.4.3 Localization of Dust Devils

Figure 3.9 shows the record of dust devil optical depths localized through Curiosity’s traverse. For Navcam dust devil observations, the pointing of a dust devil movie is biased to where dust lifting has been previously observed, as chosen by the MSL science team at the time of scheduling the observation, which means we observe dust devils both close to and far from the rover. Figure 3.9b shows the azimuthal pointing of the instrument at the time of the observation, where 0° is due north, 90° is due east, and so on. A more detailed description of the precise azimuthal locations of the observed dust devils can be found in Guzewich et al. (2023).

In Figure 3.9a, the markers are colour-coded based on dust devil optical depth, and the size of the marker similarly increases with higher optical depth. The azimuthal pointings are shown in Figure 8b, with a colour-coded line based on sol groupings. From the time of the first derived dust devil optical depth on sol 1545 to sol 1900 (grey line in Figure 3.9b), the dust devil optical depths are relatively low. The first grouping of high optical depths occurs between sol 1900 and sol 2000 (black line), when the rover moved across Vera Rubin Ridge. At this time, many of the dust devil detections were pointed upslope of Mt. Sharp or toward Bagnold Dunes (Guzewich et al., 2023), which have been shown to have active sediment transport based on observed ripple patterns (Baker et al., 2018), as well as low dust coverage on rocks (Henley et al., 2025). As the rover traversed Glen Torridon (white line) between sols 2000 to 2700, optical depths were relatively lower.

The next area of high dust devil optical depth occurred around sols 2700 to 3300 (blue line), when the rover drove around the Sands of Forvie. At this time, many high optical depths greater than 0.1 were observed, with most movies pointed toward the Sands. After sol 3500 (pink line), the rover drove toward the Gediz Vallis channel, which is a time characterized by lower dust devil optical depths.

Figure 3.9 highlights the importance of the terrain in determining the dust devil optical depths. It has been shown previously that low thermal inertia surfaces are conducive to more frequent and larger pressure drops (Mason et al., 2025; Newman et al., 2019), and an increase in observed dust devils (Guzewich et al., 2023; Hueso et al., 2023). From Figures 3.7 and 3.8, it was shown that larger pressure drops are not necessarily correlated with higher optical depths. However, it is possible that at sandier locations, the combination of more convective activity associated with low thermal inertia and saltation of larger sand particles that can

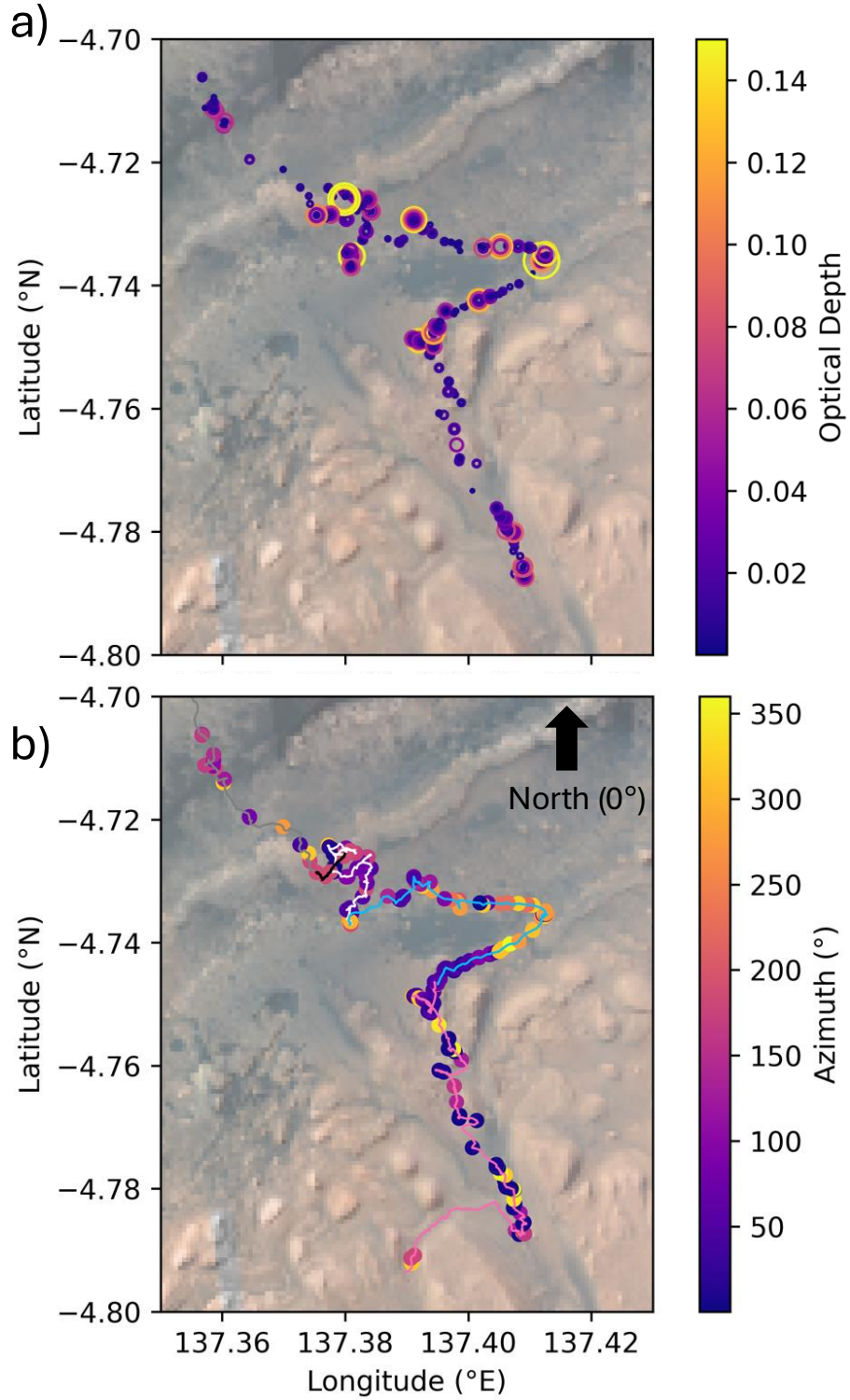


Figure 3.9: (a) Dust devil optical depths along the rover traverse. (b) Azimuthal pointings of the Navcam movies, with the line breaking the traverse into sol groups: sols 1545 – 1900 (grey), sols 1900 – 2000 (black), sols 2000 – 2700 (white), sols 2700 – 3300 (blue), and sols 3300 to 4500 (pink).

“kick-up” available dust particles on the surface (Kok et al., 2012; Neakrase et al., 2016), contributes to dust devils with higher optical depths. At locations without large sand grains available to “loose” the dust particles, it is possible that less dust becomes airborne even with strong pressure drops, resulting in lower optical depths.

3.4.4 The role of Background Terrain in the Calculation of Dust Devil Optical Depth

Navcam observations of dust devils are relatively sensitive to the background behind the dust devil. Using the MFS technique, a dust devil will appear as a bright feature compared to terrain in the background and dark in comparison to the sky (Lemmon, Campbell, et al., 2024). Since the apparent brightness of the dust devil depends on the brightness of its background, our results may be biased toward dark terrains which emphasize the brightness of the dust devil. For example, when tracing the spatial extent of a dust devil by eye, as described in Section 3.2.2, a dust devil with poor contrast will potentially be lost in the noise of the image, and the full extent of the dust devil may not be included in the average optical depth calculation.

However, importantly, the equation used calculate dust devil optical depth (Equation 3.1) does not depend on the reflectance of the surface, which removes an element of potential bias caused by the background terrain. As shown in Figure 3.9, the highest dust devil optical depths observed throughout the mission typically occurred when imaging regions of low thermal inertia, and therefore darker material. It is possible that these optical depths are being enhanced by the contrast with the background. However, because a correlation between thermal inertia and optical depth has been observed by other studies which do not rely on images (Mason et al., 2026), we do not fully attribute the higher optical depths to background terrain.

Chapter 4

A Mars Microbial Survival Model: Calculating Bioburden Reductions for Past Mars Spacecraft to Estimate Forward Contamination on Mars

4.1 Overview and Author Contributions

Mars is a natural laboratory for studying the geology, climate, and environment of a planet similar, yet very different, to our own through landed spacecraft. Though stringent planetary protection protocols exist to limit the bioburden on a spacecraft prior to launch, most spacecraft are not completely sterilized before leaving Earth, and therefore have the potential to contaminate the surface of Mars with terrestrial microorganisms. Previous studies have examined the biocidal nature of the moon (Schuerger et al., 2019) and interplanetary space travel (Moores & Schuerger, 2020) to create models estimating microbial survivability. This chapter strove to extend these models to create a Mars Microbial Survival (MMS) model to estimate the forward contamination of Mars. Here we considered nine biocidal factors that contribute to the inactivation of microorganisms brought to the surface of Mars at several mission landing sites, giving an estimate of the likelihood of Earth-based viable contamination present today on the surface. We assess the sterility of the spacecraft after some amount of time on the surface using the concept of the Sterility Assurance Level (SAL; defined as a -12 log reduction in bioburden with initial viable spore counts at approximately 1×10^6 spores per replicate; Craven et al. (2021)).

The text for this chapter is adapted from the paper titled, “A Mars Microbial Survival Model: Calculating Bioburden Reductions for Past Mars Spacecraft to Estimate Forward Contamination on Mars” published in *The Planetary Science Journal* in 2026. Coauthors on this work are J.E. Moores, R. Ordinaria, and A.C. Schuerger. Using the CRediT framework, author contributions are as follows: G. Bischof (author of

this dissertation): data curation, formal analysis, investigation, methodology, visualization, writing (original draft), writing (review and editing); J. E. Moores: conceptualization, funding acquisition, methodology, supervision, writing (review and editing); R. Ordinaria: formal analysis, visualization, writing (review and editing); A.C. Schuerger: conceptualization, data curation, validation, writing (review and editing).

4.2 Methods

Similar to the LMS (Schuerger et al., 2019) and CPMS (Moores & Schuerger, 2020) models, the current work largely focused on adapting laboratory studies modeling the inactivation of the spore-forming microorganism *B. subtilis*, which was present in most Spacecraft Assembly Facility samples (Hendrickson et al., 2020, 2021). *B. subtilis* has been shown to be more resistant to space biocidal factors than non-spore-forming species (Horneck et al., 2010; Nicholson et al., 2000; Rummel et al., 2014), so it can be assumed that by inactivating *B. subtilis* spores the other non-spore-forming species are similarly inactivated. It is also assumed that the spores are present as monolayers composed of individually spaced spores (Schuerger & Headrick, 2023; Schuerger et al., 2019). Other studies, such as the planetary protection probability risk assessment for the Europa Clipper mission, used multiple microorganism groups with varying lethality rates to consider the contamination risk of Europa (McCoy et al., 2021). For this work, the aim was to use data on microorganism survivability under Mars surface conditions specifically (see, e.g., Schuerger and Nicholson (2006) and Schuerger et al. (2003, 2008)). There are very limited data for microorganisms other than *B. subtilis* under Mars surface conditions; thus, we constrained the model to only one microorganism, as opposed to using multiple microorganism groups as in McCoy et al. (2021). For some of the biocidal factors, there are a limited number of published experiments studying the inactivation rate of *B. subtilis* under specific Mars surface conditions, and thus there are limited data for some of the deleterious factors on the surface of Mars. Therefore, the current work should be considered a first-order estimate of microbial survival on Mars.

The MMS model is split into two key phases: the cruise phase and the surface phase. During the cruise phase, we considered the decrease in bioburdens on the outer shells of spacecraft launched to Mars, as well as the protected internal surfaces of landers and rovers. In the cruise phase, the deleterious effects of UVC, synergistic temperature and vacuum, vacuum alone, and ionizing radiation — namely, solar wind particles (SWPs) — were considered. Subsequently, during the surface phase, bioburden reductions were calculated for each spacecraft that reached the surface of Mars. The surface phase of the MMS model considered the effects of UVC, synergistic temperature and pressure, desiccation, low pressure alone, high-salt regolith, acidic regolith, and perchlorate-rich regolith. Appendix Table A1 shows the bioburden reductions and references for the surface-phase factors.

The cruise-phase trajectories for the eight Mars-bound spacecraft that successfully landed on the surface were considered here; data were retrieved using the Jet Propulsion Laboratory Horizons system. The heliocentric distances of the spacecraft as functions of time were used as the spacecraft traveled from Earth to Mars. During cruise, each Mars-bound rover/lander was contained within a protective spacecraft structure, known as the aeroshell. The aeroshells are composed of two components: the heat shield and the back shell. Unlike the heat shield, which ablates during entry into Mars and completely reduces viable bioburdens on the heated surface, the back shell lands on the surface generally unheated. Therefore, modeling the bioburden reduction during cruise was important for quantifying the ability of the back shell to contaminate Mars after landing on the surface.

4.2.1 Mars Mission Landing Sites

This work considered eight spacecraft that landed on Mars and operated through the duration of the intended missions, as well as six unsuccessful missions (Table 4.1). The first successful lander to reach the surface of Mars was the Viking 1 lander in 1976 at a location of 22.2°N, 312.0°E in Chryse Planitia. Viking 2 landed shortly thereafter at a location of 47.9°N, 134.3°E in Utopia Planitia. The landers operated for 2245 and 1281 sols, respectively. However, both Viking landers were heat sterilized prior to launch at 112°C for 23–30 hour after the coolest internal portions of the landers reached 112°C (Puleo et al., 1977). Thus, the two Viking landers were considered to be free of viable bioburdens at landing.

Pathfinder successfully landed on Mars in 1997, containing both a stationary base and a small rover. Pathfinder landed just southeast of Viking 1 at 19.3°N, 326.4°E, operating for 83 sols on the surface. Following Pathfinder, the twin Spirit and Opportunity rovers landed in 2004 at 14.5°S, 175.4°E and 1.9°S, 354.4°E, respectively. Spirit is the southernmost rover to land on the surface of Mars, while Opportunity is the rover closest to the equator. The Phoenix lander is the most northern-based lander on Mars, landing in 2008 in Green Valley (68.2°N, 234.2°E). The Phoenix lander was active through the northern summer, with a mission duration of 150 sols. In 2012, the Curiosity rover landed in Gale crater, situated 4.5°S, 137.4°E. Gale crater has the lowest elevation of the 10 landing sites on Mars (−4.5 km below the datum). The InSight lander (4.5°N, 135.9°E) arrived at Mars in 2018 in Elysium Planitia, resembling the Phoenix lander with large solar arrays on either side of the main body. The Perseverance rover landed in Jezero crater in 2021 (18.4°N, 77.4°E), with a similar rover design to that of Curiosity. The elevation of Jezero crater (−2.6 km below the datum) lies between that of Gale crater and that of Gusev crater (∼−1.9 km), where Spirit landed. Lastly, the Zhurong rover landed in 2021 shortly after the Perseverance rover at 25.1°N, 109.9°E. The Zhurong rover is smaller in size than the Curiosity and Perseverance rovers but slightly larger than Spirit and Opportunity.

Details of the location and time of landing for each of the eight spacecraft are given in Table 4.1.

A number of Mars spacecraft either crashed on Mars or ceased operations shortly after landing. The Mars 2 mission saw the first impact of a human-made spacecraft on Mars on 1971 November 27 — however, the lander failed to deploy properly and was inoperable. The Mars 3 lander, identical in design to Mars 2, soft-landed on the surface of Mars at 45°S, 202°E in December 1971, but transmission to Earth stopped after 20 s on the surface. In 1974, after losing contact during its descent, Mars 6 impacted the surface at approximately 23°S, 340°E and was inoperable. The Mars Polar Lander attempted landing at 76°S, the most southern landing site for a Mars mission; however, contact was not reestablished after landing, and the lander was considered lost. Similarly, Beagle 2 was expected to reach the surface of Mars on 2003 December 25; however, contact with the lander was never made, deeming it lost. Most recently, the Schiaparelli Entry, Descent, and Landing Module (EDM) malfunctioned during descent and crashed into the Martian surface at 300 km hour⁻¹. Details of the approximate landing/crash sites of these missions are given in Table 4.1.

Table 4.1: Spacecraft Landing Site Details

Spacecraft Name / Status	Landing Coordinates	L_s (deg)	Local Time
Successful Landings			
Pathfinder (lander + rover); nonoperational	19.3°N, 326.4°E	142°	03:00
Spirit (rover); nonoperational	14.5°S, 175.4°E	327°	14:25
Opportunity (rover); nonoperational	1.9°S, 354.4°E	339°	13:15
Phoenix (lander); nonoperational	68.2°N, 234.2°E	76°	17:12
Curiosity (rover); operational	4.5°S, 137.4°E	150°	15:30
Insight (lander); nonoperational	4.5°N, 135.9°E	295°	14:00
Perseverance (rover); operational	18.4°N, 77.4°E	5°	15:53
Tianwen-1 (lander + rover; Zhurong); nonoperational	25.1°N, 109.9°E	45°	13:48
Unsuccessful Landings			
Mars 2	45°S, 47°E	300°	N/A
Mars 3	45°S, 202°E	303°	N/A
Mars 6	23.9°S, 340°E	19°	N/A
Mars Polar Lander	76°S, 165°E	255°	N/A
Beagle 2	11.5°N, 90.4°E	321°	N/A
Schiaparelli EDM	2°S, 353°E	244°	N/A

Table 4.2 shows the estimated bioburdens on each spacecraft at the time of launch, which were calculated based on published data or the dry masses of the spacecraft and the formalism of Schuerger et al. (2019) (Table 4.1, column (6)). Aside from the heat-sterilized Viking landers, each spacecraft had a spore-forming bioburden of approximately $10^4 - 10^5$ spores. The MMS model described here includes spore-forming, non-spore-forming, and nonculturable species according to the assumptions given by Schuerger et al. (2019) and by the assumptions described below. The bioburdens for landed Mars spacecraft will thus rise to approximately

$10^8 - 10^9$ organisms per vehicle at launch (Table 4.2).

Table 4.2: Bioburden Estimates on Each Mars-bound Spacecraft at the Time of Launch

Mission	Mars Landing Date	Total Estimated Spore Bioburden	Total Viable Organisms ^a	Dry Mass ^a (kg)	Total Launched Bioburden ^c	References
Mars 2	1971 Nov 27	–	–	358	1.39×10^9	Debus (2005)
Mars 3	1971 Dec 02	–	–	358	1.39×10^9	Debus (2005)
Mars 6	1974 Mar 12	–	–	635	2.47×10^9	Debus (2005)
Viking VL1	1976 Jul 20	0	0	576	0	Debus (2005)
Viking VL2	1976 Sept	0	0	576	0	Debus (2005)
Pathfinder + Sojourner	1997 Jul 04	2.94×10^4	1.40×10^8	360	1.40×10^9	Barengoltz (1997) Debus (2005)
Mars Polar Lander	1999 Dec 03	–	–	429	1.67×10^9	Debus (2005)
Beagle 2	2003 Dec 25	1.01×10^5	4.82×10^8	71	2.76×10^8	Pillinger et al. (2006) Debus (2005)
Spirit	2004 Jan 03	1×10^5	4.78×10^8	820	3.19×10^9	Kazarians et al. (2017) Debus (2005)
Opportunity	2004 Jan 24	2.1×10^5	1.00×10^9	820	3.19×10^9	Kazarians et al. (2017) Debus (2005)
Phoenix	2008 May 25	3.46×10^4	1.65×10^8	350	1.36×10^9	Kazarians et al. (2017)
Curiosity	2012 Aug 06	5.64×10^4	2.69×10^8	899	3.50×10^9	Benardini et al. (2014)
InSight	2018 Nov 26	1.50×10^5	7.16×10^8	358	1.39×10^9	Hendrickson et al. (2020)
Perseverance	2021 Feb 18	3.73×10^5	1.78×10^9	1025	3.99×10^9	M. Cooper et al. (2023)
Zhurong rover	2021 May 14	–	–	240 ^f	9.34×10^8	Ding et al. (2022)
Schiaparelli EDM	2016 Oct 19	2.9×10^5	1.38×10^9	576	2.24×10^9	Ball et al. (2022)
Misc. landed hardware ^d	–	–	–	2000 (est) ^d	7.78×10^9	see text
Total bioburden^e	–	1.05×10^6	5.03×10^9	–	3.81×10^{10}	–
Average bioburden^e	–	1.05×10^5	5.03×10^8	–	2.12×10^9	–

^a A VO-to-spore ratio of 4776:1 was based on averaging the upper ranges of three spacecraft and cleanroom assay techniques (see text here and Hendrickson et al. (2017)). Total VOs for each spacecraft at launch were estimated by multiplying the spacecraft dry mass by the VO:spore ratio of 4776.

^b Dry masses of spacecraft were adopted from Debus (2005) and Wikipedia pages for specific spacecraft.

^c LMS = Lunar Microbial Survival model. The LMS model predicted a bioburden of 3.89×10^6 total culturable and nonculturable microorganisms per kilogram of spacecraft dry mass based on 16 assumptions. Values in column (6) were estimated by multiplying the dry masses of spacecraft (column (5)) by this value (see Schuerger et al. (2019)).

^d Miscellaneous hardware included heat shields, back shells, parachutes, and other miscellaneous debris impacting the Martian surface during entry, decent, and landing. Precise data for the miscellaneous hardware were not readily available, and thus this is a first-order estimate

^e Means for columns (3), (4), and (6) were derived from the available date given in the columns. Not all spacecraft were characterized for prelaunch spore bioburdens.

^f Mass of the Tianwen-1 lander was estimated based on data posted on the Wikipedia website for the lander (<https://en.wikipedia.org/wiki/Tianwen-1>; last accessed on 11–11–24).

4.2.2 Effects of UVC

4.2.2.1 Cruise-phase UVC Calculation

The UVC reaching the spacecraft was calculated in a similar manner to that presented in the CPMS model (Moores & Schuerger, 2020), though only considering UVC instead of UVC + UVB. Biocidal effects by ultraviolet irradiation are dominated by exposures to UVC (200–280 nm; see A. L. Santos et al. (2013)), allowing us to neglect the small contribution of UVA and UVB. The intensity of light, S , hitting the spacecraft was considered as a function of the spacecraft’s distance from the Sun and the attitude angle of the spacecraft with respect to the Sun. This was calculated using

$$S(\hat{s}, \hat{n}, \hat{t}) = 6.68 \text{ Wm}^2 \hat{s} \cdot \hat{n} \left(\frac{r_{Earth}}{r(t)} \right)^2, \quad (4.1)$$

where 6.68 W m^{-2} is the solar constant for UVC (200 to 280 nm) at 1 astronomical unit (AU), $\hat{s}$ is the solar vector, $\hat{n}$ is the surface normal (which is defined as a vector perpendicular to the surface of the spacecraft),

r_{Earth} is 1 AU, and $r(t)$ is the distance of the spacecraft from the Sun in units of AU at time, t , for the duration of the cruise.

4.2.2.2 Surface-phase UVC Calculation

4.2.2.2.1 UVC Radiative Transfer Model To calculate UVC irradiances incident on the Martian surface, a one-dimensional, doubling-and-adding (DA) radiative transfer model was used. The DA model has been used extensively in the atmosphere of Titan (Griffith et al., 2012) and has been adapted for use in the Martian atmosphere (Moores et al., 2007; Tomasko et al., 1999). The model used here derives from the Griffith et al. (2012) lineage, which was subsequently adapted to Mars and further refined by validating the output against REMS UV data (Moores et al., 2017; Smith & Moores, 2020). The model splits the Martian atmosphere into two layers, where the bulk of dust loading and CO₂ is present in the bottom layer, with gaseous absorption in the top layer.

The UVC flux at the top of the atmosphere was found using the E490 ASTM solar spectrum (ASTM, 2000) for Earth, which was scaled to Mars’s distance in accordance with its orbital position at various L_s values. On Mars, the CO₂-rich atmosphere attenuates wavelengths less than 200 nm (Kuhn & Atreya, 1979), so only wavelengths between 200 and 280 nm were used in the study. The UVC irradiance in the model was split into four 20 nm wide spectral wave bands: 200–220 nm, 220–240 nm, 240–260 nm, and 260–280 nm.

Spatially (i.e., zonally averaged) and seasonally dependent aerosol abundances were retrieved from the Mars Climate database, and a map of these opacities can be found in Figure 2 of Moores et al. (2017). The aerosol abundance at a particular latitude and season was used for each corresponding spacecraft. Wavelength-dependent parameters for light-aerosol interactions, such as single scattering albedo, asymmetry parameter, and real and imaginary index of refraction, were selected from Wolff et al. (2010). Other variables relevant for the model, such as particle size, size distribution variance, and the limit for where the particles are considered “large”, were obtained from Tomasko et al. (1999).

4.2.2.2.2 UVC on the Tops and Sides of Spacecraft Using the DA model, the UVC irradiance was modeled for the first 24 hours at the surface of each of the eight successful missions in 30-minute increments at the solar longitude and corresponding LTST at landing. For a flat surface on the spacecraft body, the UVC hitting such a surface was the sum of the direct and diffuse irradiances from scattering in the atmosphere output by the model.

To include surfaces tilted away from the horizontal, surfaces with an angle of 90° from the Martian surface, with its face pointed in each of the cardinal directions (north-east-south-west), were considered. The direct UVC irradiance striking a tilted surface was calculated as

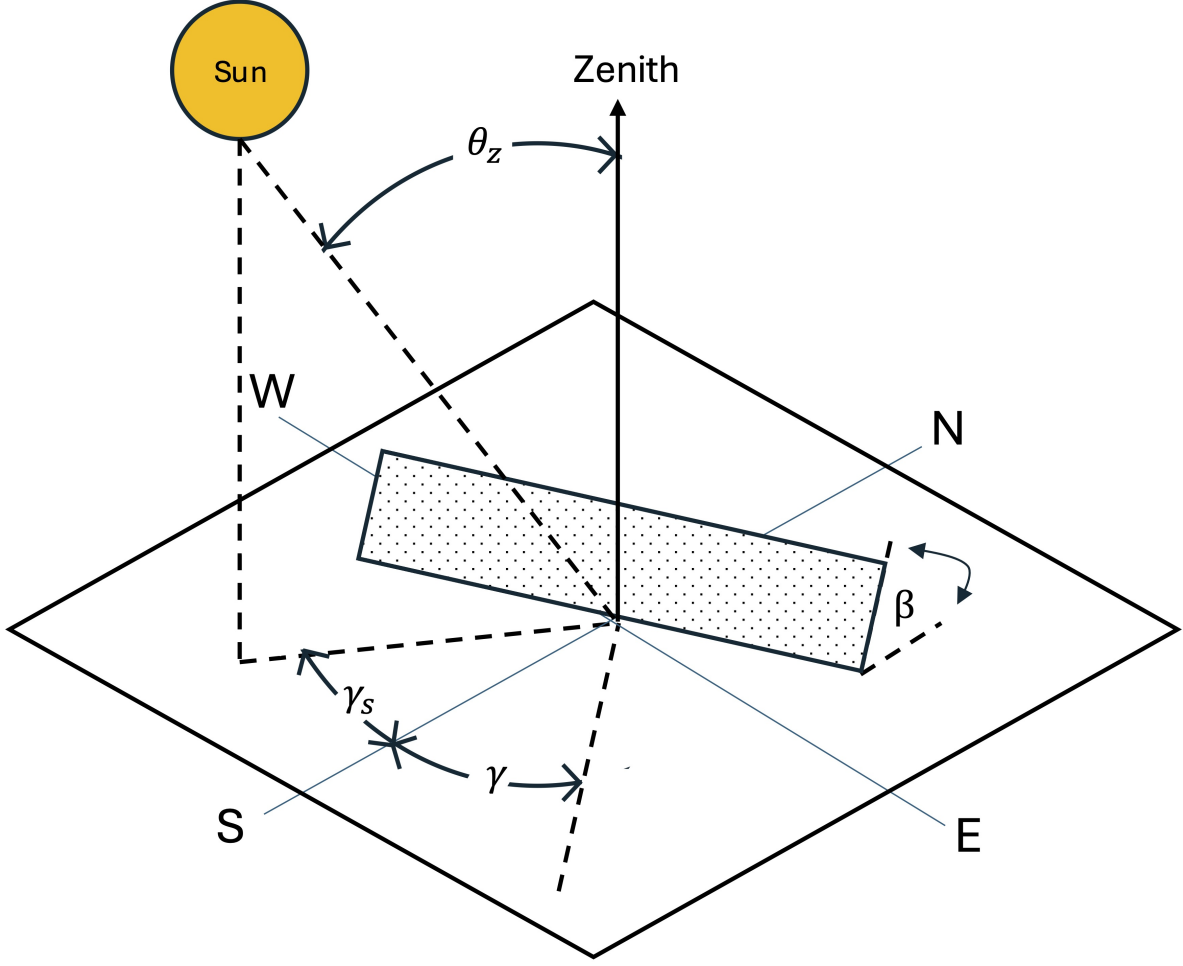


Figure 4.1: Configuration of incident sunlight on non-horizontal surfaces on a spacecraft's body. For vertical surfaces facing the cardinal directions, β is set to 90° . (Adapted from Duffie et al. (2020), Figure 1.6.1.)

$$S_{\text{tilted surface}} = S_0 \times [\cos \theta_s \cos \beta + \sin \theta_s \sin \beta \cos(\gamma - \gamma_s)], \quad (4.2)$$

where S_0 is the total direct UVC irradiance, θ_s is the solar zenith angle, β is the angle of the titled surface from the ground (which was set to 90°), γ is the azimuth angle, and γ_s is the solar azimuth angle. Figure 4.1 shows the various components of this equation in a schematic.

For diffuse UVC irradiances incident on the tilted surface, the gridded sky outputs given from the DA model were used. Here 64 points in zenith and 38 points in azimuth were returned from the model. The azimuthal points were interpolated and regridded to give 180 points, in 2° increments, where 0° represented north. The portions of the sky behind the tilted surface were removed, such that only sections of the sky within the surface's field of view were considered (similar to the method in Kerr et al. (2023)). Each point was then summed to give the diffuse UVC irradiance contribution to the tilted surface for each of the cardinal

directions. The direct and diffuse irradiances were similarly added together to give the total UVC irradiance on the angled surfaces.

In addition to modeling the first 24 hours at the eight successful mission landing sites, the UVC fluence rates over a Mars year at all 14 sites were modeled. Starting at $L_s = 0^\circ$, which corresponds to spring equinox, the UVC irradiance over 1 sol was modeled in 30-minute increments. This was repeated in increments of 10° of L_s , ending at $L_s = 350^\circ$. The UVC irradiance was interpolated between the 10° - L_s increments to give a full year's worth of modeled UVC irradiance. The UVC irradiance incident on both flat surfaces and tilted surfaces was considered.

4.2.2.2.3 UVC on the Undersides of Spacecraft To model the UVC fluence rates on the undersides of spacecraft, a similar method to Schuerger and Moores (2023) was used, based on Moores et al. (2007). The “geometric shielding ratio” (GSR; defined as the width of the spacecraft divided by the height of the spacecraft above the ground) for eight spacecraft was calculated. Figure 6 (bottom right) of Moores et al. (2007) was used to find the log reduction in the incident irradiance for each spacecraft according to its latitude and GSR. The reduction was applied to the irradiance calculated in Section 4.2.2.1, starting at $L_s = 0^\circ$ for each spacecraft.

4.2.2.2.4 UVC Attenuation due to Dust/Regolith Dust on Mars is known to settle onto the surfaces of the landers. This has been shown to decrease the power available for landers operating with solar arrays, such as the Pathfinder and InSight missions (Lorenz et al., 2021). Since dust attenuates the solar UV, there is a possibility that settled dust on a lander will decrease the resulting bioburden reduction. To calculate the attenuated UVC due to dust, the UV absorption coefficients for Mars JSC-1 with grain sizes of 150, 250, 350, 500, 600, and 850 μm were retrieved from Godin et al. (2023).

The reduced light intensity, $S_{reduced}$, was calculated by

$$S_{reduced} = S_0 e^{-L\sigma}, \quad (4.3)$$

where S_0 is the initial irradiance (which was modeled in Section 4.2.2.1), L is the thickness of the dust layer, and σ is the absorption coefficient. For each of the grain sizes, the regolith was assumed to be a monolayer. That is, for the 150 μm grains, L was also 150 μm , and so on with the other sizes. The reduced light intensity was then used to calculate the bioburden reductions over one Mars year.

4.2.2.3 UVC Bioburden Reduction

The bioburden reduction from UVC was handled similarly to that in the LMS (Schuerger et al., 2019) and CPMS (Moores & Schuerger, 2020) models. In both the LMS and CPMS models, the inactivation of *B. subtilis* had a biphasic response (adapted from Schuerger and Nicholson (2006)). The fractional reduction over time is given by

$$\Delta N_{UV}(t) = \frac{N_{UV}(t + \Delta t)}{N_0(t)} = 10^{-3.374 \times S \Delta t / 217 \text{ J m}^{-2}} \quad (4.4a)$$

$$\Delta N_{UV}(t) = \frac{N_{UV}(t + \Delta t)}{N_0(t)} = 10^{-0.062 \times S \Delta t / 217 \text{ J m}^{-2}}, \quad (4.4b)$$

where Equation 4.4a is the primary response to UVC light and spores are rapidly inactivated. Equation 4.4b is the refractory secondary response, with slower inactivation kinetics (see Schuerger et al. (2019)). The term ΔN_{UV} is the fractional reduction at time, t , in seconds starting at an initial bioburden of N_0 . Since the current work considers only UVC and not UVC+UVB, the irradiance needed to reach the secondary phase response in the LMS and CPMS models (i.e., 590 J m^{-2}) was converted to 217 J m^{-2} .

It has been suggested that the fast inactivation rate of the first phase is the inherent biological response to the stress induced on a spore in a high UV environment, while the slower inactivation rates of the second phased captures outliers, some of which may be in multi-layers or shadowedI on the spacecraft (Schuerger, 2024).

4.2.3 Effects of Temperature and Vacuum

4.2.3.1 Calculating the Temperature of the Spacecraft

To calculate the temperature of external surfaces of spacecraft for a surface normal on the spacecraft and pointing toward the Sun (similar to the UVC calculation), the energy balance between the incoming sunlight that is absorbed and the outgoing thermal emission was modeled:

$$T(\hat{s}, \hat{n}, t) = \left(\frac{L_{\odot}(1 - A)\hat{s} \cdot \hat{n}}{4\pi r(t)^2 \epsilon \sigma} \right)^{\frac{1}{4}}. \quad (4.5)$$

Here, $L_{\odot}$ is the solar luminosity, 3.828×10^{26} , passing through the area of a sphere centered on the Sun with a radius $r(t)$. A is the albedo of the spacecraft material, ϵ is the thermal emissivity of the spacecraft material, and σ is the Stefan–Boltzmann constant, set to $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$. See the CPMS model (Moores & Schuerger, 2020) for a full derivation of these terms.

In the CPMS model, gold multilayer insulation (MLI) blankets were used as the spacecraft material, with a high albedo of $A = 0.72$ (Finckenor & Dooling, 1999) and a low emissivity of $\epsilon = 0.03$ (Gilmore, 2002). However, for missions to Mars that touch down on the surface of the planet, a more common material used is an ablative heat shield material, namely SLA-561V, developed by Lockheed Martin. For SLA-561V, an emissivity of 0.85 was used in Equation 4.5 (Meurisse et al., 2018), which is much higher than the gold MLI blanket. We select an albedo value for typical white paint of $A = 0.25$ on spacecraft (Henninger, 1984).

4.2.3.2 Synergistic Temperature and Vacuum Bioburden Reduction

Above temperatures of 210 K, the synergistic effects of temperature and vacuum will be the dominant biocidal factor over the effects of temperature or vacuum acting alone (See Figure 3 of Schuerger et al. (2019) and Moores and Schuerger (2020)). Simultaneous exposure to elevated temperatures and vacuum may enhance dehydration within the spore, which is known to influence spore resistance and survivability when the spore reaches a state of extreme desiccation (Nicholson et al., 2000; Setlow, 2006).

Here the reduction follows an Arrhenius process as outlined in the CPMS and LMS models and was calculated by

$$\Delta N_{T+V}(t) = \frac{N_{T+V}(t + \Delta t)}{N_0(t)} = \exp(-\lambda \Delta t) \quad (4.6a)$$

$$\lambda(T) = 308 \text{ s}^{-1} \exp\left(\frac{-4988 \text{ K}}{T}\right). \quad (4.6b)$$

In addition to surfaces on the outside of the spacecraft that are above 210 K, the insides of the spacecraft are typically temperature controlled such that the internal temperature remains within a range of 220–320 K (Novak et al., 2005). At these temperatures, synergistic temperature and vacuum would be the dominant biocidal factor for microorganisms on internal surfaces of the spacecraft.

4.2.3.3 Isolated Vacuum Bioburden Reduction

Below 210 K, vacuum alone becomes the dominant factor over synergistically acting temperature and vacuum. The bioburden reduction due to vacuum alone (which is independent of distance during the cruise, since vacuum is present everywhere in interplanetary space) was found using

$$\Delta N_v(t) = \frac{N_v(t + \Delta t)}{N_0(t)} = \exp(-1.15 \times 10^{-7} \text{ s}^{-1} \Delta t) \quad (4.7a)$$

$$\Delta N_v(t) = \frac{N_v(t + \Delta t)}{N_0(t)} = \exp(-1.82 \times 10^{-8} \text{ s}^{-1} \Delta t), \quad (4.7b)$$

representing the two-phase response where the inactivation slows after 94 days of exposure to vacuum (Schuerger et al., 2019). Vacuum acting alone is relevant for external portions of the spacecraft that are not heated by the Sun, as well as internal components that are not temperature controlled.

4.2.4 Effects of Solar Wind Particles

4.2.4.1 Solar Wind Particle Bioburden Reduction

Solar wind particles (SWPs) ejected from the Sun may contribute a small bioburden reduction during cruise. SWPs are composed of 96% protons and 4% helium ions and do not penetrate deeply into the surface of the spacecraft (Smithers et al., 2007). Based on the CPMS model, the bioburden reduction from SWPs was given by

$$\Delta N_{SWP}(t) = \frac{N_{SWP}(t + \Delta t)}{N_0(t)} = \exp(-2.67 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \frac{\Delta t \hat{s} \hat{n}}{r(t)^2}), \quad (4.8)$$

where the effect from SWPs has an inverse square dependence similar to the UVC flux (Kayser et al., 1984).

4.2.5 Effects of Desiccation, Low Pressure, Acidic Regolith, Perchlorates, and High-salt Regolith

Due to the limited data on the remaining surface-phase biocidal factors, the fractional reduction for each factor was modeled as a linear reduction. The data for the effects of desiccation, acidic regolith, perchlorates, and high-salt regolith were retrieved from Schuerger et al. (2012), where a series of biotoxic geochemical scenarios were set up under Mars surface conditions using *B. subtilis* spores. In each of these scenarios, the bacterial spores were buried under a layer of regolith that blocked the presence of UV light, such that only the interaction with the soil and low pressure affected the inactivation of the spores (Schuerger et al., 2012). The data for low-pressure effects come from Schuerger et al. (2003).

4.2.5.1 Desiccation Bioburden Reduction

$$\Delta N_D(t) = \frac{N_D(t + \Delta t)}{N_0(t)} = 10^{-0.30 \frac{\Delta t}{86400 \text{ s}}}, \quad (4.9)$$

where Δt is in units of seconds. Schuerger et al. (2012) calculated the bioburden reduction for *B. subtilis* using Earth-days, hence the division by 86,400 s. When calculating the reduction on Mars, Δt was set to 88,642 s, to include the additional ~ 39 minutes in a Martian day. This applied to the following equations for low pressure, high-salt regolith, acidic regolith, and perchlorate-rich regolith

4.2.5.2 Low-pressure Bioburden Reduction

The bioburden reduction due to the low pressure on the surface of Mars, between 8 and 10 mb, was derived by

$$\Delta N_P(t) = \frac{N_P(t + \Delta t)}{N_0(t)} = 10^{-8.6 \times 10^{-4} \frac{\Delta t}{86400 \text{ s}}}. \quad (4.10)$$

Similar to the vacuum during cruise, the low pressure will affect microorganisms on internal surfaces within the rover/lander body.

4.2.5.3 High-salt Regolith Bioburden Reduction

The bioburden reduction due to high-salt regolith on the surface of Mars was derived by

$$\Delta N_{HS}(t) = \frac{N_{HS}(t + \Delta t)}{N_0(t)} = 10^{-0.071 \frac{\Delta t}{86400 \text{ s}}}. \quad (4.11)$$

The high-salt regolith in Schuerger et al. (2012) was composed of 80.17 wt% basalt, 0.87% calcium phosphate, 5.9% ferric sulfate, 5.4% gypsum, 5.1% kieserite, and 2.6% magnesium chloride. The particles sizes ranged from sub-micron grains to larger grains less than 200 μm (Schuerger et al., 2012).

4.2.5.4 Acidic Regolith Bioburden Reduction

The bioburden reduction due to acidic regolith on the surface of Mars was derived by

$$\Delta N_A(t) = \frac{N_A(t + \Delta t)}{N_0(t)} = 10^{-0.0014 \frac{\Delta t}{86400 \text{ s}}}. \quad (4.12)$$

The acidic regolith was composed of 53.5 wt% basalt, 8.0% anhydrite, 27.0% ferric sulfate, 1.0% jarosite, and 8.0% sodium sulfate, with the same grain sizes as above (Schuerger et al., 2012).

4.2.5.5 Perchlorate-rich Regolith Bioburden Reduction

The bioburden reduction due to perchlorate in the regolith on the surface of Mars was derived by

$$\Delta N_{per}(t) = \frac{N_{per}(t + \Delta t)}{N_0(t)} = 10^{-0.014 \frac{\Delta t}{864000 \text{ s}}}. \quad (4.13)$$

The perchlorate-rich regolith was composed of 63.5 wt% basalt, 2.0% anhydrite, 4.0% calcium carbonate, 3.75% ferrihydrite, 0.5% hematite, 2.0% kieserite, 2.25% Ti-magnetite, 2.0% magnesite, 9.75% olivine, 8.75% pyroxene, and 1.5% sodium perchlorate (Schuerger et al., 2012).

4.3 Results

4.3.1 Cruise-phase Results

Before any spacecraft reaches the surface of Mars, the deleterious effects of space reduce the bioburdens as the spacecraft cruise from Earth to Mars. For surface-based missions en route to Mars, the main surface rover or lander was enclosed within the aeroshell, which was exposed to the effects of solar UVC, solar heating, and SWPs. After each cruise, the back shell landed on the surface and was a potential source of contamination. The lander or rover encased within the aeroshell was protected from the deleterious effects of UVC, solar heating, and SWPs but was exposed to synergetic vacuum and temperature effects from internal heating, as well as vacuum acting alone. Here we considered two cruise-phase results: external bioburden reductions on the aeroshell, including the back shell that landed on the surface, and internal results that were relevant for the robotic lander that acted on the surface of Mars.

4.3.1.1 External Cruise-phase Results

Figure 4.2 panels (a) and (c) show the modeled instantaneous UVC fluence rates incident on the Opportunity and Phoenix aeroshells during their respective cruises. These were chosen to represent the shortest and longest travel times to Mars, respectively (outside of the Viking landers, which traveled longer but were launched with zero bioburdens, as well as the failed Mars 3 mission). The y-axis represents the angle from the solar vector (i.e., the Sun’s rays), where 0° indicates a surface normal on the aeroshell (i.e., a vector from the spacecraft surface that is perpendicular to the surface) that is aligned with the Sun’s rays and will receive the sunlight full on. While 90° indicates a surface normal that is pointing completely perpendicular to the Sun’s rays, the light is parallel to the surface and “glancing” the surface rather than striking it directly. For surfaces between 0 and 40° , within 50 days of each respective cruise start time, up to 6 W m^{-2} (i.e.,

per second by definition) of solar UVC was incident on each aeroshell. The UVC fluence rates on aeroshell surfaces were reduced as the surface tilted away from the Sun and as the aeroshells traveled farther from the Sun

The cumulative bioburden reduction throughout the cruise due to the exposure to UVC for the Opportunity and Phoenix aeroshells can be seen in Figures 4.2(b) and (d). On the Opportunity aeroshell, surfaces with a surface normal parallel to the solar vector received a reduction of -2×10^4 logs. The Phoenix cruise, which lasted ~ 94 days longer than the Opportunity cruise, had a -3×10^4 log bioburden reduction for similar surfaces facing the Sun. Even surfaces that received minimal sunlight owing to the attitude of the spacecraft had a bioburden reduction between 0 and -5000 logs throughout the flight. An SAL level of -12 logs was achieved very quickly, meaning that sterility of the aeroshell due to UVC alone occurred in days on all external Sun-facing surfaces for each mission.

The temperature of the aeroshell's external surfaces from solar heating for the Opportunity and Phoenix cruises can be seen in Figures 4.3(a) and (c). Here we assumed that the aeroshell was covered in white-colored SLA-561V. Due to the thermal properties of this material, the outside of the aeroshell may have reached a maximum temperature of ~ 350 K for Sun-facing surfaces during cruise. Surfaces pointed away from the Sun were cooler, with temperatures around 200 K.

At the observed temperatures, the bioburden reductions (Figures 4.3(b) and (d)) were smaller than that of UVC but still significant. Over the entire Opportunity cruise, Sun-facing surfaces had a bioburden reduction of -1200 logs. Phoenix had a higher reduction owing to its longer cruise time, seeing a -2500 log reduction during flight. For both aeroshells, temperature and vacuum acting together had a minimal effect on surfaces with a surface normal greater than 70° , since these surfaces did not get hot enough for vacuum and temperature synergism to be relevant.

Additionally, SWPs encountered throughout the cruise were modeled using Equation 4.13 to produce a reduction of -12 logs on the Opportunity aeroshell and -17.5 logs on the Phoenix aeroshell. The effects of SWPs were small compared to UVC and solar heating on the external aeroshells of spacecraft.

Throughout the cruise phases, UVC on the surface of the aeroshell contributed the most to bioburden reductions. Each spacecraft reached 1 SAL very quickly from UVC alone. Opportunity, with the shortest cruise time, experienced 1666 SALs on Sun-facing surfaces and approximately 208 SALs on surfaces pointing away from the Sun. Combining the UVC reductions with reductions from vacuum-temperature synergism, vacuum, and SWPs, the external surfaces of the back shell should have been effectively sterilized by the time the spacecraft began the entry, descent, and landing (EDL) phase of the mission.

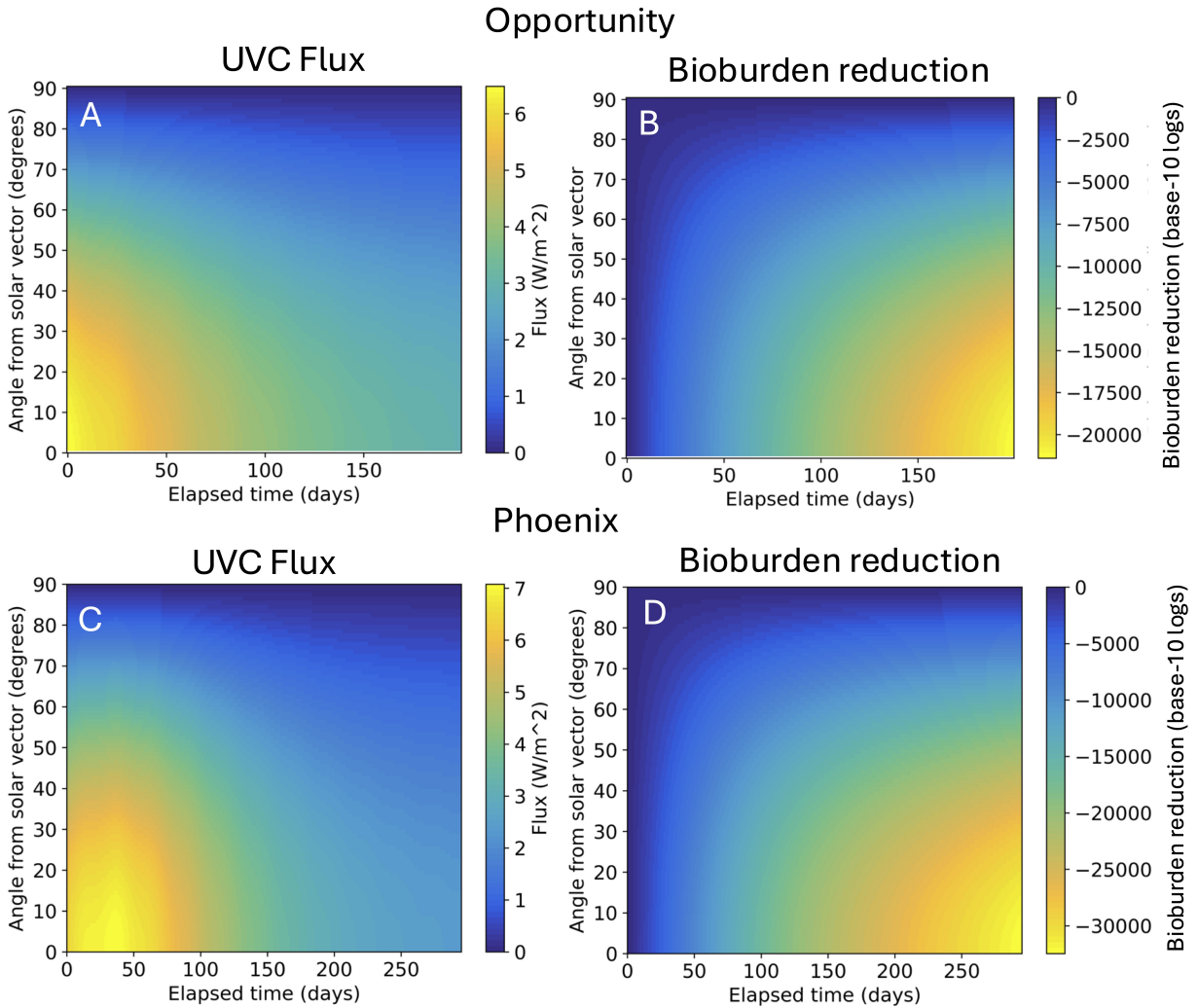


Figure 4.2: Panels (a) and (c) Instantaneous UVC irradiance incident on the surface of the Opportunity aeroshell (shortest flight duration) and the Phoenix aeroshell (longest flight duration) at spacecraft surface normals pointing directly at the Sun or pointing 90° away from the Sun (i.e., the Sun rays would be parallel to such a surface). (b) and (d) The bioburden reduction from biocidal UVC during flight. For surface normals less than 80° , a cumulative bioburden reduction of -2500 logs for Opportunity and -5000 logs for Phoenix was observed, far surpassing the SAL of -12 logs.

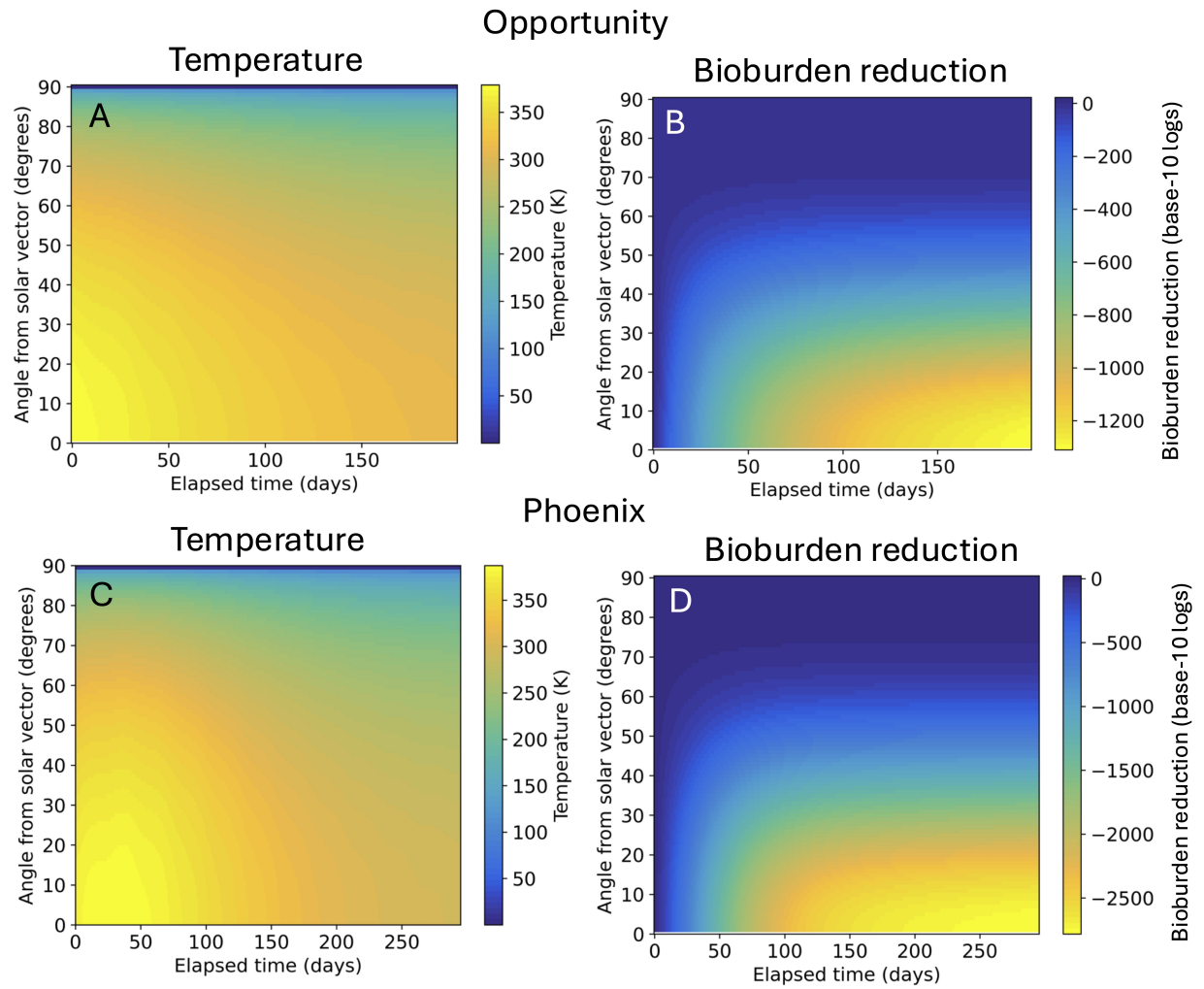


Figure 4.3: (a, c) External temperature of the Opportunity and Phoenix aeroshells, composed of SLA-561V. (b, d) The bioburden reduction from synergistic high temperature and vacuum during flight. Sun-facing surfaces reached one SAL very quickly owing to the high temperatures.

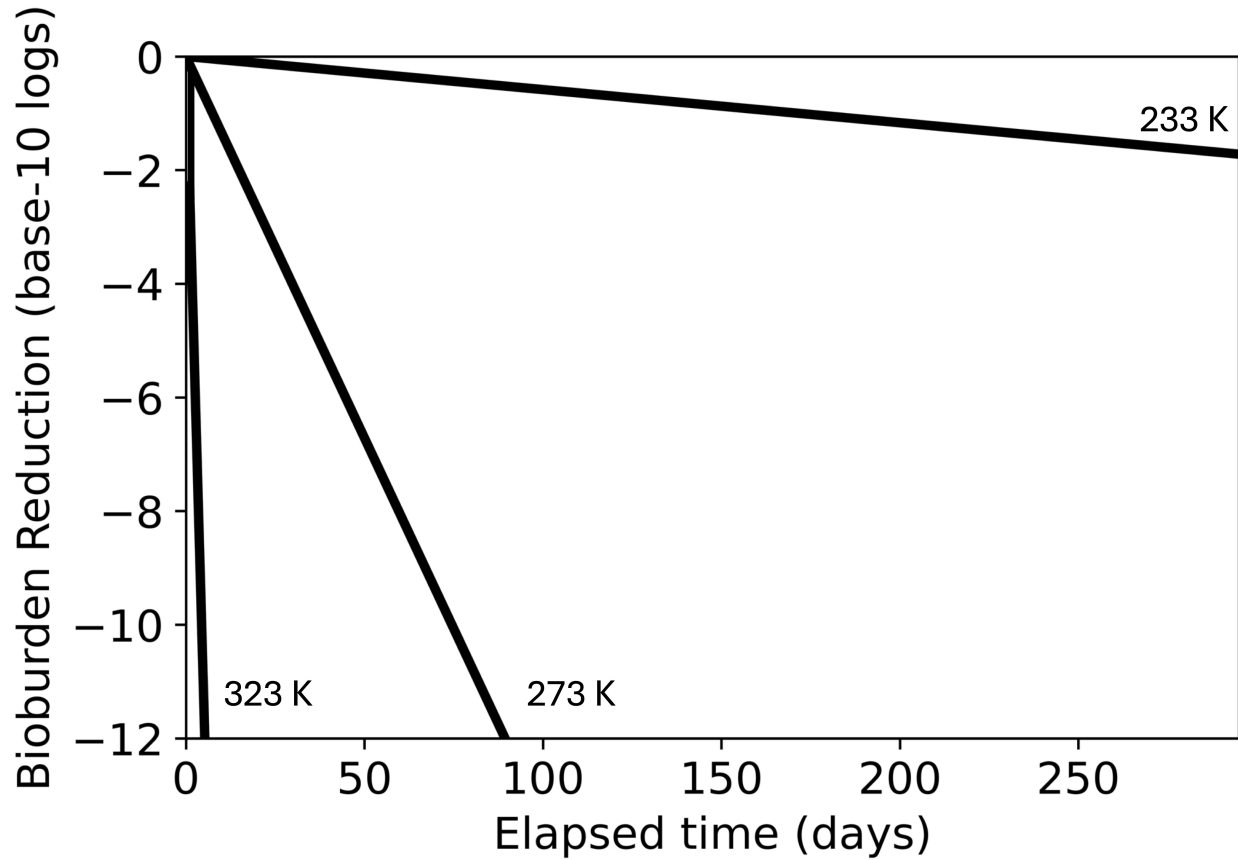


Figure 4.4: Bioburden reductions due to synergistically acting temperature and vacuum during the duration of the Phoenix cruise. Internal components kept at 323 K reached 1 SAL after approximately 10 days into the cruise, while colder components kept at 233 K had a bioburden reduction of -2 logs after approximately 300 days in cruise.

4.3.1.2 Internal Cruise-phase Results

The rovers and landers within the Opportunity and Phoenix aeroshells, respectively, were sheltered from the effects of UVC, solar heating, and SWPs during cruise; however, the insides of the aeroshells where the landers were stored were not pressure controlled, and therefore synergistic vacuum and temperature from internal heating and vacuum acting alone contributed to bioburden reductions. The internal components of a spacecraft are typically kept between -40°C and 50°C (or ~ 233 and 323 K) during cruise (Novak et al., 2005). The bioburden reductions on the internal components kept within three diverse temperature ranges over the duration of the Phoenix cruise are shown in Figure 4.4.

The bioburden reductions inside the aeroshells depended on the internal temperatures held throughout the cruise phases of the missions. Warmer components, such as radioisotope thermoelectric generators for missions that included this component (both Phoenix and Opportunity were solar powered), reached 1 SAL within a few days of the cruise and were sterilized by the time the aeroshell reached Mars. Colder components, however, experienced only a -2 log bioburden reduction throughout the Phoenix cruise, which was reduced

to a -1.5 log reduction for the Opportunity cruise, which was about 100 days shorter.

At temperatures below 210 K, the synergism between vacuum and temperature ceases, and vacuum becomes the dominant process. For Opportunity, vacuum acting alone reduced the bioburden by -0.5 logs during the cruise phase. For Phoenix, the reduction was slightly larger at -0.6 logs for the cruise phase. Vacuum alone had a minimal effect on reducing the bioburdens on the landers encased within the aeroshells.

Unlike the external components of the aeroshell, the internal components containing landers that operate on Mars may not have been sterilized by the time the spacecraft reached the surface. Missions with longer cruises, such as Phoenix, experienced a higher reduction by the time of landing compared to missions with shorter cruises, such as Opportunity.

4.3.2 Mars Surface Predictions

4.3.2.1 External Bioburden Reductions from UVC

Once on the surface, the spacecraft were no longer encased within their aeroshells and were exposed to the biocidal conditions in the Martian atmosphere and on the surface, including the UV environment. Figure 4.5 shows the first 24 hours of modeled UVC exposure on flat surfaces at the relevant L_s at landing for each of the eight successfully landed spacecraft given in Table 4.1. Each curve in Figure 4.5 was integrated to give the total UVC exposure in 24 hours. The Spirit rover had the highest total UVC exposure, with 64.9 kJ m^{-2} accumulated over the first sol. Alternatively, Curiosity had the lowest total UVC exposure, with 51.9 kJ m^{-2} accumulated on the first sol. The maximum instantaneous UVC irradiance and total accumulated UVC dosage per sol for the first sol on the surface are shown in Table 4.3.

Table 4.3: Maximum Instantaneous UVC Irradiance and Total Accumulated UVC Dosage within the First 24 hr after Landing

Spacecraft Name	Maximum UVC Irradiance (W/m^2)	Accumulated UVC Dosage (kJ/sol)
Pathfinder	2.11	58.7
Spirit	2.45	64.8
Opportunity	2.32	59.5
Phoenix	1.34	56.0
Curiosity	2.01	51.9
InSight	2.27	56.8
Perseverance	2.22	58.8
Zhurong	2.08	59.7

The bioburden reductions for Sun-facing horizontal surfaces on the landed spacecraft can be seen in Figure 4.6. Here the modeled UVC that was inputted into the bioburden reduction Equations (4.4a) and (4.4b) started at the landing time for each individual spacecraft and ran for 24 hours. For example, Pathfinder landed at 03:00 LTST; therefore, the UVC was modeled from 03:00 on the first sol to 03:00 on the next

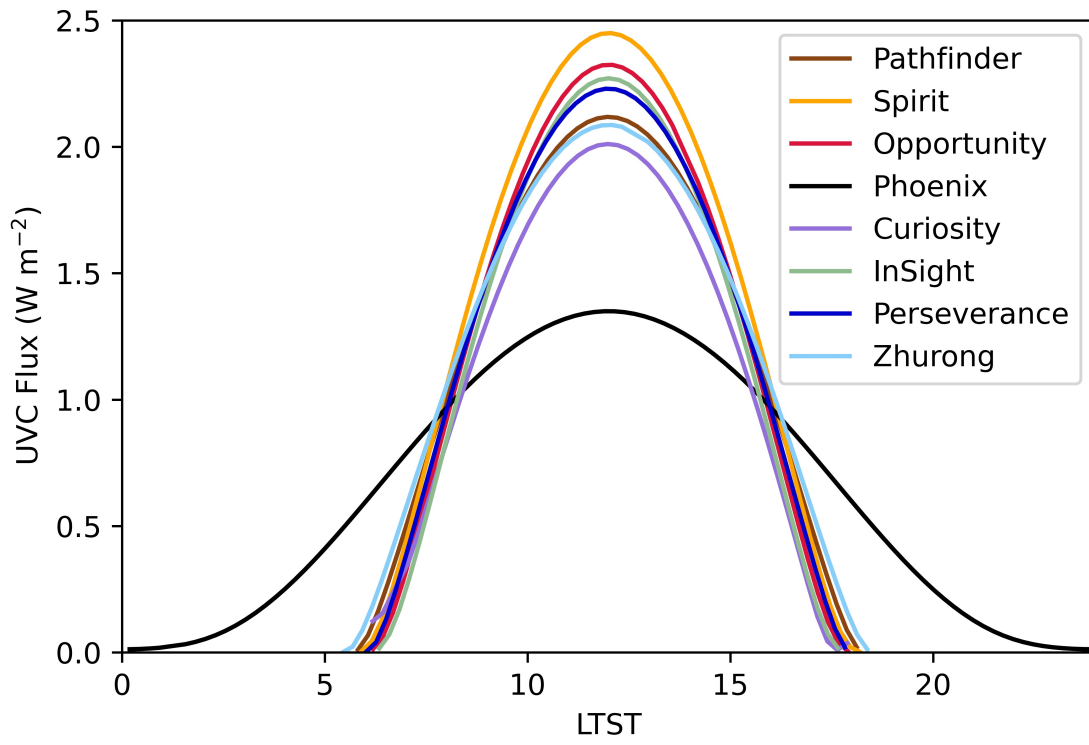


Figure 4.5: The modeled UVC irradiance incident on a flat surface for the first full 24 hours of sunlight at each spacecraft location and L_s of landing (Table 4.1).

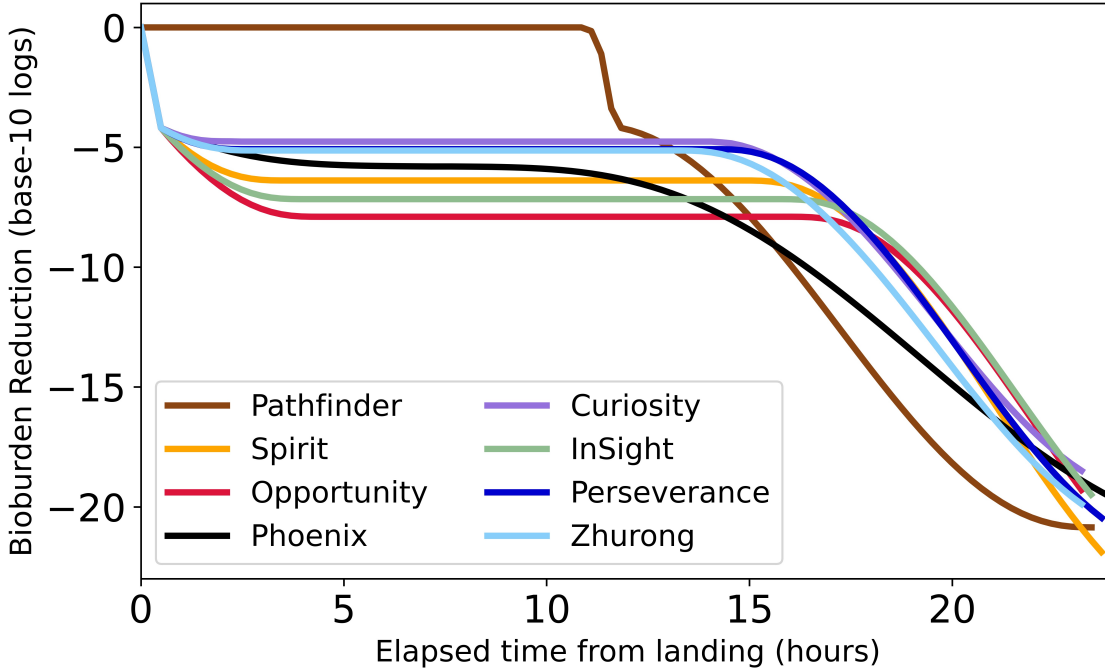


Figure 4.6: The bioburden reductions from UVC on flat spacecraft surfaces, considering the time of landing for each spacecraft and the UVC modeled in Figure 4.5 After the first 24 hours on the surface, all horizontal Sun-facing surfaces had a bioburden reduction greater than 1 SAL.

sol. As noted in the LMS and CPMS models, the bioburden reduction due to UVC alone has two phases: a rapid inactivation phase occurs until a reduction of approximately -4.196 logs is achieved, and then a second more refractory inactivation phase occurs. The biphasic biocidal effects of solar UV are clearly illustrated in Figure 4.6, in which the spacecraft that landed during the afternoon (Spirit, Opportunity, Phoenix, Curiosity, InSight, Perseverance, and Zhurong) all experienced immediate and rapid inactivation rates. At the seven sites where the landers touched down in the afternoon, the Sun set shortly after landing, causing the inactivation to slow, before it began again the next morning when the Sun rose. Pathfinder landed in the middle of the night, meaning that once the Sun rose, rapid inactivation occurred and then slowed to the refractory second-phase biocidal inactivation kinetics. Despite differences in timing, the upper surfaces of all spacecraft received at least -15 logs of bioburden reductions throughout their respective first sols, reaching greater than 1 SAL within 24 hours.

Although upward Sun-facing surfaces on each lander received 1 SAL within 24 hours (Figure 4.6), most other surfaces of the spacecraft received lower SAL levels of UVC irradiation. Figure 4.7 shows the bioburden reduction on four vertical faces pointing in each of the cardinal directions for the Pathfinder, Spirit, Opportunity, and Phoenix landers. The vertical faces are intended to represent end-member cases, such that surfaces

on the spacecraft that are slightly elevated, but not vertical, undergo a bioburden reduction between the flat-facing surface and the vertical surface. Since each spacecraft landed at different latitudes and times of year, the amounts of UVC hitting each vertical surface would have varied. For example, north-facing surfaces at the Pathfinder, Spirit, and Opportunity sites had a much smaller bioburden reduction (approximately -5 logs) compared to north-facing surfaces at the Phoenix landing site (-10 logs). For each lander, east- and west-facing surfaces ultimately underwent the same bioburden reductions; however, differences in Sun exposures due to the Sun rising in the east and setting in the west caused asymmetry in the bioburden reductions throughout the modeled sols. Despite the differences in latitude and Sun exposure at each landing site, a significant reduction occurred for each surface within the first 24 hours.

Figure 4.8 shows the bioburden reduction for horizontal and vertical faces pointed in the cardinal directions for the Curiosity, InSight, Perseverance, and Zhurong missions. Similar to Figure 4.7, not all surfaces reached 1 SAL within 24 hr, due to the differences in UVC exposure. However, even the smallest bioburden reduction within 24 hours was -5 logs, indicating that UVC rapidly inactivated microbes on spacecraft after landing.

After the first 24 hours of landing, UVC continued to be the dominant biocidal factor for spacecraft on the surface of Mars. Figure 4.9 shows the bioburden reduction over one Mars year for flat surfaces on all 14 spacecraft that reached the surface of Mars. After one Mars year, the landers closest to the equator received the highest bioburden reduction, with values over -1×10^4 logs (i.e., 833 SALs; Figure 4.9). As landing sites move toward the poles, the reductions lessened. The Phoenix lander and Mars Polar Lander underwent the smallest bioburden reduction owing to their northern and southern locations. However, even though the landers closer to the poles had a smaller reduction, after one Mars year, approximately -4000 logs of bioburden reductions were observed for the Phoenix lander and Mars Polar Lander, which is equivalent to 333 SALs. Results indicate that flat horizontal surfaces on every landed spacecraft would be sterilized after one Mars year.

Bioburden reductions on vertical surfaces of each landed spacecraft after one Mars year are shown in Figure 4.10. Similarly to flat surfaces, the latitudinal placement of the spacecraft affected the bioburden reductions. For east- and west-facing surfaces, the landers closer to the equator had higher bioburden reductions than those closer to the poles. Alternatively, north-facing surfaces had higher bioburden reductions for landers south of the equator, while south-facing surfaces had higher bioburden reductions for landers north of the equator. This is caused by differences in the UV fluence rates in the northern and southern hemispheres due to the axial tilt of the planet. Though there are differences in the bioburden reduction depending on the direction the surface faced and the latitude of the lander, all surfaces had at least -1000 log reductions, and some surfaces had reductions up to -5500 logs. Thus, every Sun-exposed surface on every spacecraft would likely be sterilized after 1 year on the surface of Mars.

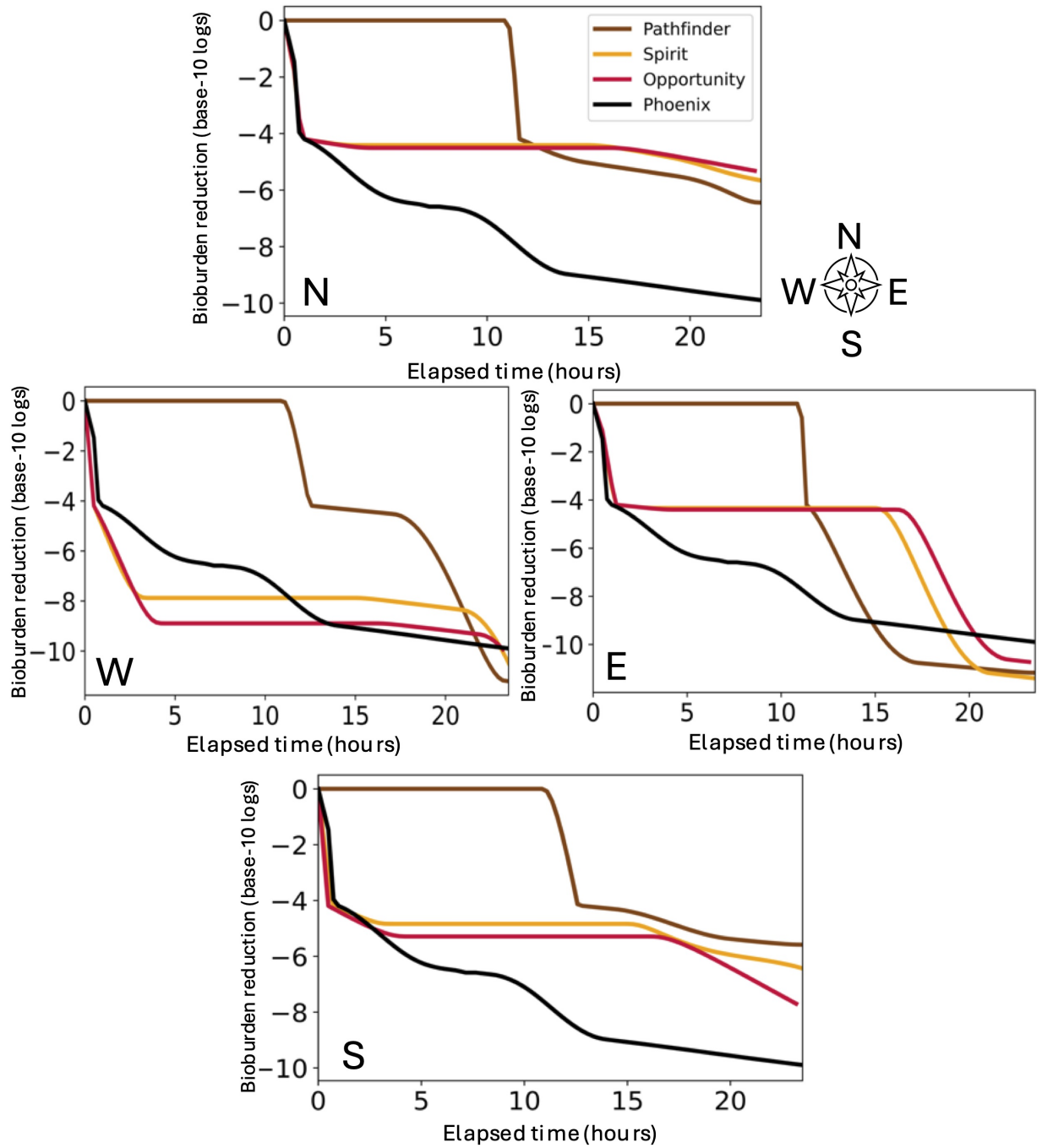


Figure 4.7: The bioburden reduction from UVC on north-, east-, south-, and west-facing surfaces for the first 24 hr after landing at the Pathfinder, Spirit, Opportunity, and Phoenix landing sites. Unlike the flat surfaces, not all vertical-facing surfaces reached 1 SAL within 24 hr; however, bioburden reductions greater than -6 logs for all surfaces were seen.

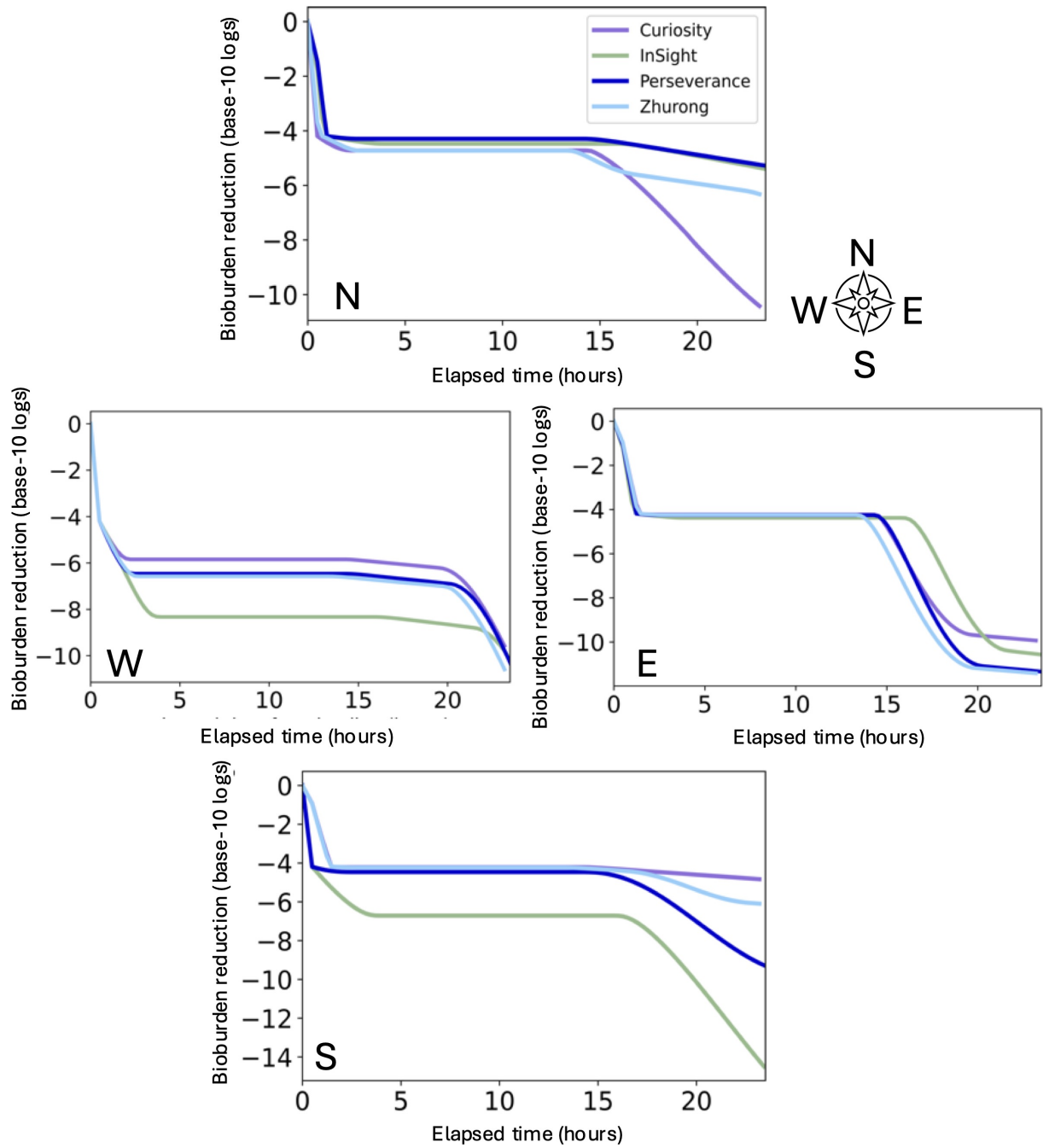


Figure 4.8: The bioburden reduction from UVC on north-, east-, south-, and west-facing surfaces for the first 24 hr after landing at the Curiosity, InSight, Perseverance, and Zhurong landing sites. Unlike the flat surfaces, not all vertical-facing surfaces reached 1 SAL within 24 hours.

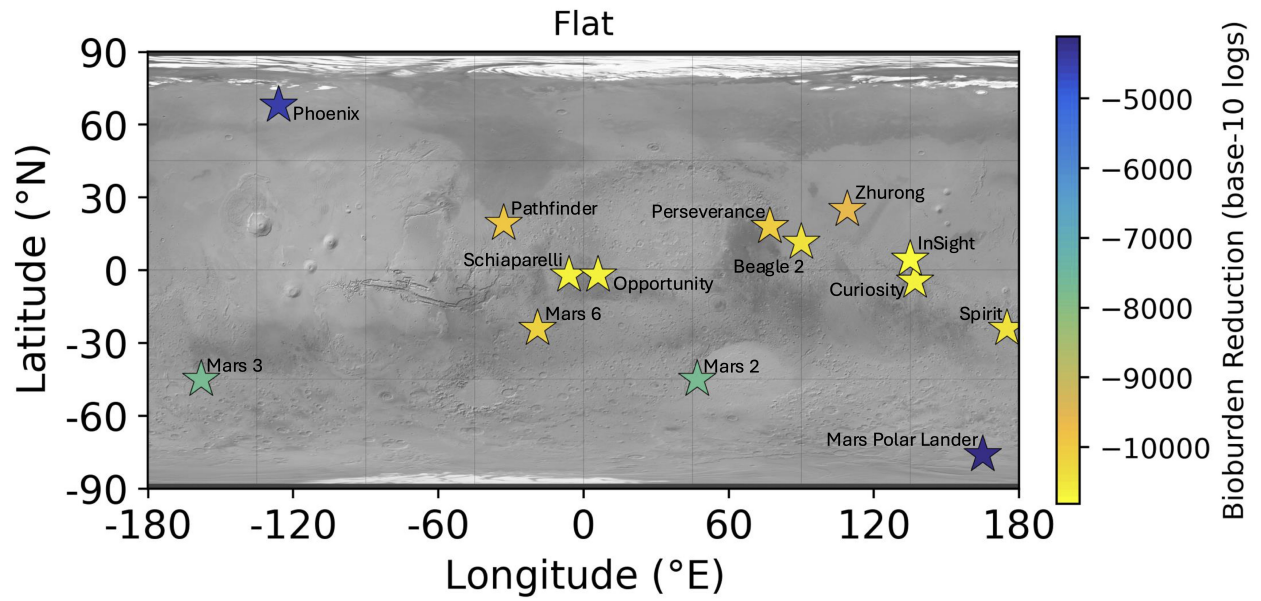


Figure 4.9: Bioburden reductions for flat surfaces on all missions that reached the surface of Mars after one Mars year. Equatorial missions had a higher bioburden reduction, while polar missions had a lower reduction. Every mission reached at least 333 SALs after one Mars year. (Map credit: NASA, USGS.)

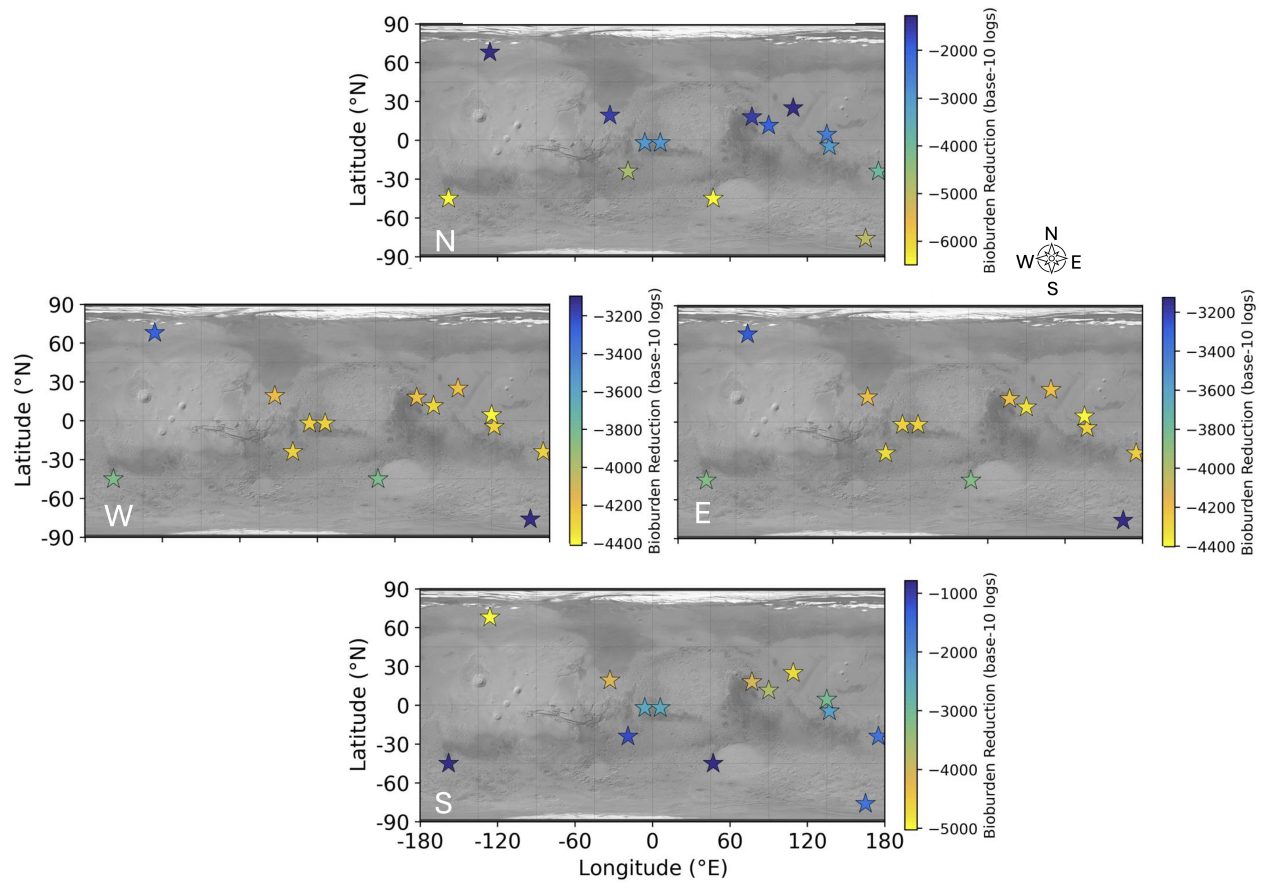


Figure 4.10: Bioburden reductions for north-, east-, south-, and west-facing surfaces on all missions that reached the surface of Mars after one Mars year. Bioburden reductions on all surfaces ranged between -1000 and -5500 logs, indicating high sterility from UVC on the external surfaces of the landers. (Map credit: NASA, USGS.)

Figures 4.6–4.10 assume that surfaces were in full sunlight for the durations of the sols, which is not an assumption that holds for all parts of the rovers and landers considered here. For example, the upper deck of many of the landers contained instruments that cast shadows onto the upper decks, shielding portions of the landers from direct sunlight. Thus, the results in Figures 4.6–4.10 are the maximum reductions achieved assuming no shielding from the UVC. Schuerger and Moores (2023) tested the ability for spacecraft materials to reflect UVC light for reaching shaded portions of a spacecraft. In this work, we find that over the course of a Mars year, the surfaces with the smallest bioburden reductions were north-facing surfaces on the Phoenix lander, as shown in Figure 4.10. If we assume that surfaces on the Phoenix spacecraft were completely shielded from direct sunlight by a spacecraft material—and the adjacent surfaces reflected 10% of the incident UVC—north-facing surfaces would still accumulate 8.3 SALs over one Mars year. For such a surface to receive less than 1 SAL, a completely vertical north-facing wall at the Phoenix site would have to be shaded at all hours of the day by a surface that reflects only 1.12% of the UVC (Schuerger & Moores, 2023).

The undersides of the landers are shielded from direct sunlight, causing significantly lower bioburden reductions. Figure 4.11 shows the times to 1 SAL for the undersides of eight spacecraft based on the methods of Schuerger and Moores (2023). The fastest time to sterility of the underside of a lander or rover occurred at the Opportunity landing site in 46 sols. The slowest time to sterility was 140 sols at the Zhurong landing site, due to a combination of the rover’s low underside clearance and more northern location. In Figure 4.9, the UVC was modeled starting arbitrarily at $L_s = 0^\circ$, which is not necessarily the time of year where each lander would receive the highest UVC irradiance. Thus, the times to sterility are not necessarily the fastest times at specific sites, but the results in Figure 4.11 show that approximately 4.78 SALs on the undersides of every spacecraft were likely achieved within one Mars year (i.e., 669.4 sols per Mars year divided by 140 sols for the Zhurong rover in Figure 4.11).

While UVC has a very strong sterilizing effect on landers on the surface of Mars, the presence of dust settled on the landers can attenuate the UVC shining on the lander. The bioburden reduction on sun-facing surfaces underneath a layer of Martian regolith is shown in Figure 4.12 for the Phoenix landing site (solid lines) and the InSight landing site (dashed lines) for each JSC-1 grain size used in Godin et al. (2023). As shown in Figure 4.12, the bioburden reductions were significantly diminished owing to the presence of regolith. At the Phoenix landing site, when no regolith was present, the sun-facing surfaces had nearly -5000 log reductions throughout the year. With the addition of UV-attenuating regolith, the reductions dropped to -250 logs for regolith with 500 μm grain sizes. For regolith with grain sizes of 250 μm , just over -12 logs (1 SAL) were accumulated in a year, severely reducing the deleterious effect of UVC. At the InSight landing site, more than -500 log reductions were accumulated for 500 μm regolith, but similar to Phoenix, the 250

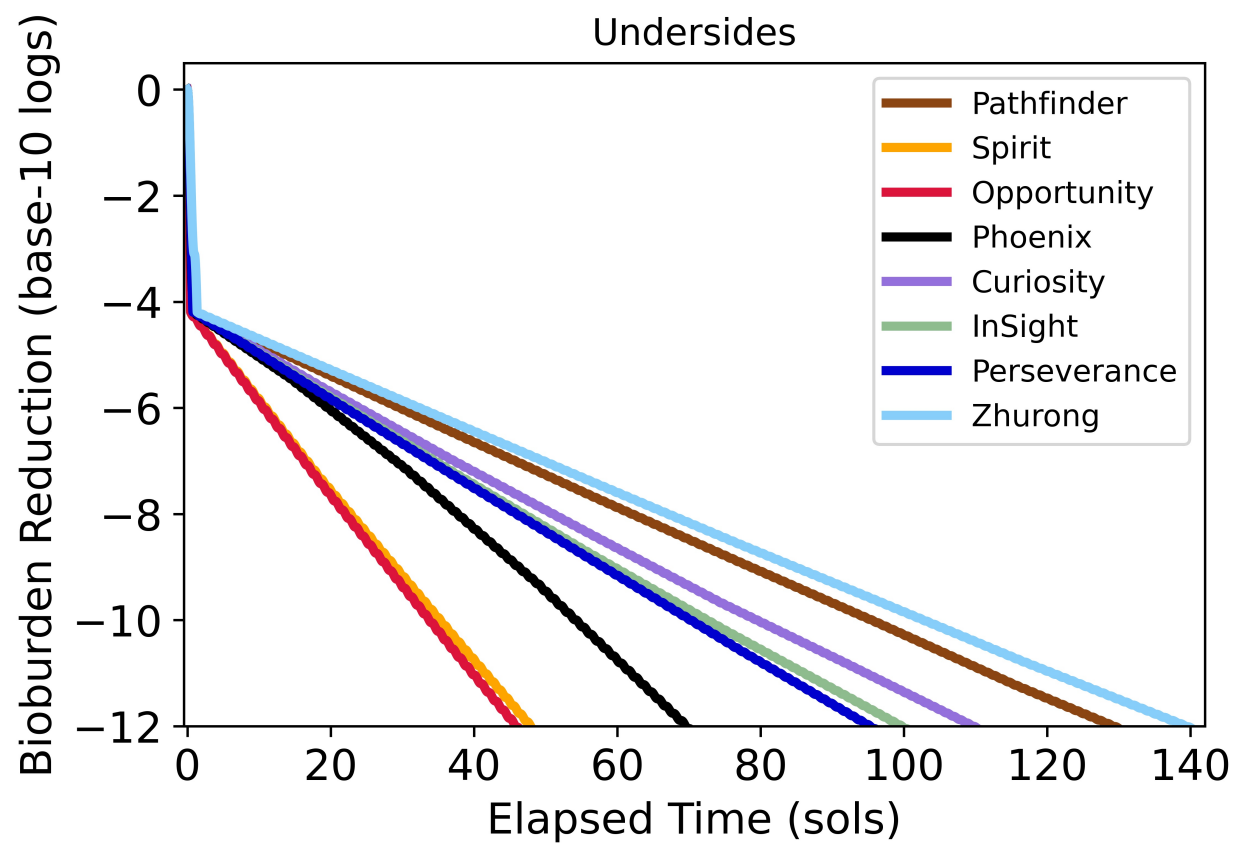


Figure 4.11: The bioburden reduction from UVC on the undersides of the spacecraft at all landing sites. The shortest time to 1 SAL was the Opportunity rover at 46 sols, and the longest time was the Zhurong rover at 140 sols.

μm -sized grains severely attenuated the UVC, resulting in just over -12 logs throughout the year. Note that the analysis in Figure 4.12 assumed dust accumulated rapidly on the spacecraft surface, which is discussed further in Section 4.4.2, however it is likely that dust accumulates more slowly than considered above.

4.3.2.2 Bioburden Reduction from Desiccation, High-salt Regolith, Acidic Regolith, and Perchlorates

Although UVC contributes the most to bioburden reductions on external surfaces of Mars landers, additional factors such as desiccation, high-salt regolith, acidic regolith, and perchlorates will additionally contribute to the inactivation of microorganisms on Mars. Here we used linear models to determine the bioburden reductions from these factors over 669 sols (i.e., one Mars year).

Desiccation and high-salt regoliths are two factors that could contribute an additional 1-17 SALs over a single Mars year. For example, -50 to -200 logs in bioburden reductions were predicted for high-salt soils and desiccation, respectively, after 669 sols. The presence of perchlorates had the next highest contribution, with an additional -10 logs per Mars year. Acidic regolith had the lowest contribution, with an additional -1.0 logs per Mars year. It is important to recall that these data were retrieved from Schuerger et al. (2012), which have only one reduction data point after 7 days, meaning that the data must be extrapolated out to 669 sols and may not be entirely reflective of the bioburden reductions after extended periods of time. Further data on these parameters under long-term Mars simulations are required to refine their contributions to the MMS model.

4.3.2.3 Bioburden Reductions on the Internal Surfaces of Spacecraft

While the external components of the landers are likely to be sterilized quickly by UVC, with small additions from biotoxic soils, the internals are shielded from UVC and regolith. Microorganisms on the insides of the landers are affected by synergistically acting temperature and low pressure, as well as low pressure alone. Though the air temperature of Mars is often below 210 K Martínez et al. (2017), the temperature at which the synergism becomes unimportant and low pressure alone becomes the dominant factor, the internals of each lander are typically kept between 233 and 313 K to ensure instrument functionality (Kempenaar et al., 2018). Figure 4.13 shows the bioburden reductions for internal surfaces of spacecraft when kept at temperatures of 313, 273, or 233 K for one Mars year.

If the internal temperature of a lander was modeled at 313 K, the internal components reached 1 SAL within 8 sols. However, at the lower end of the temperature range, the time to sterility becomes greatly extended. At 233 K, 1 SAL was reached after 2000 sols. When considering low pressure acting alone, a maximum reduction of -0.6 logs was achieved throughout one Mars year.

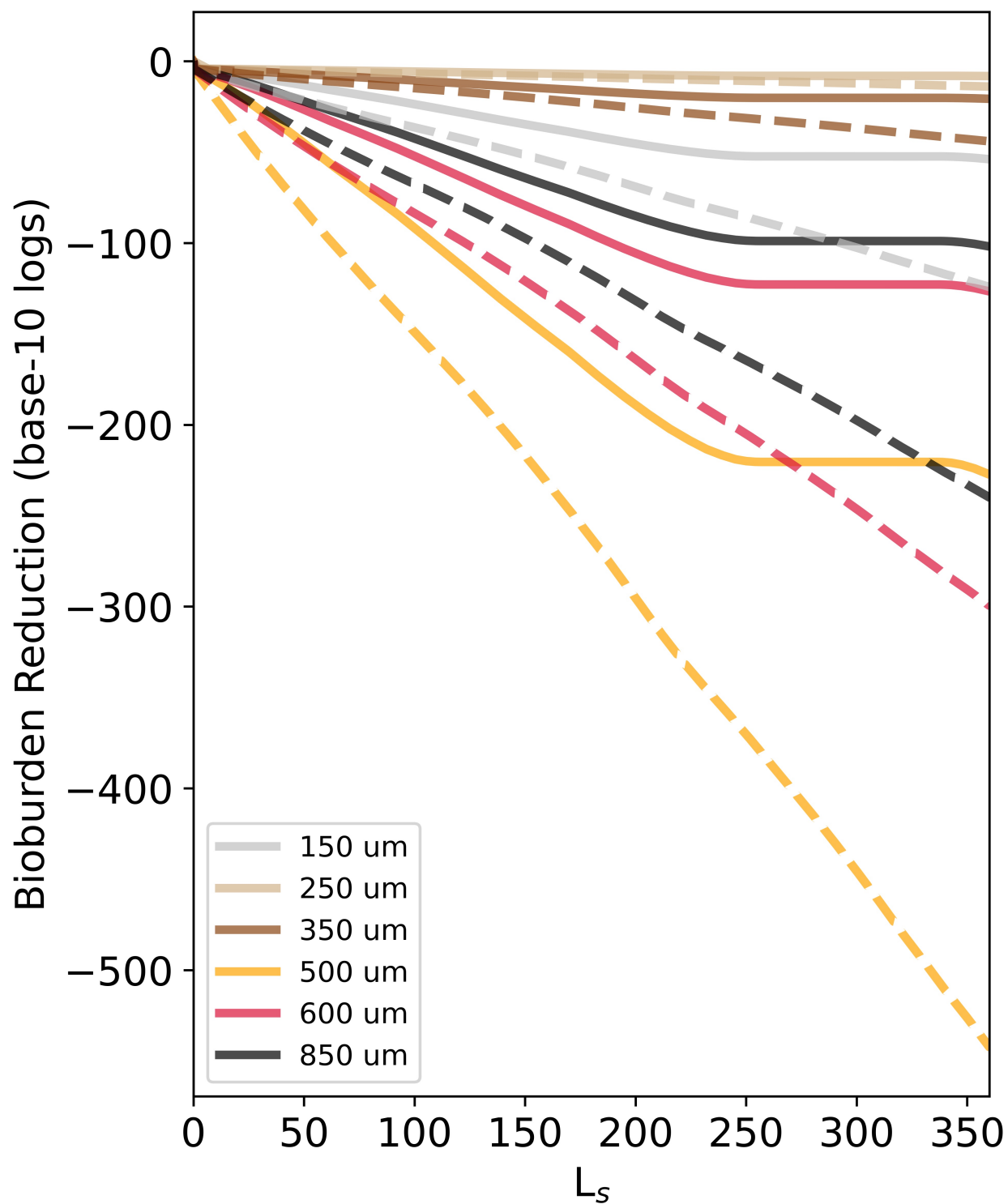


Figure 4.12: Bioburden reductions at the Phoenix (solid lines) and InSight (dashed lines) landing sites due to regolith-attenuated UVC. The most UVC was attenuated with 250 μm grain sizes, significantly diminishing the yearly bioburden reduction. Less UVC is attenuated with the 500 μm grains, though the bioburden reductions are still significantly less compared to a regolith-free scenario.

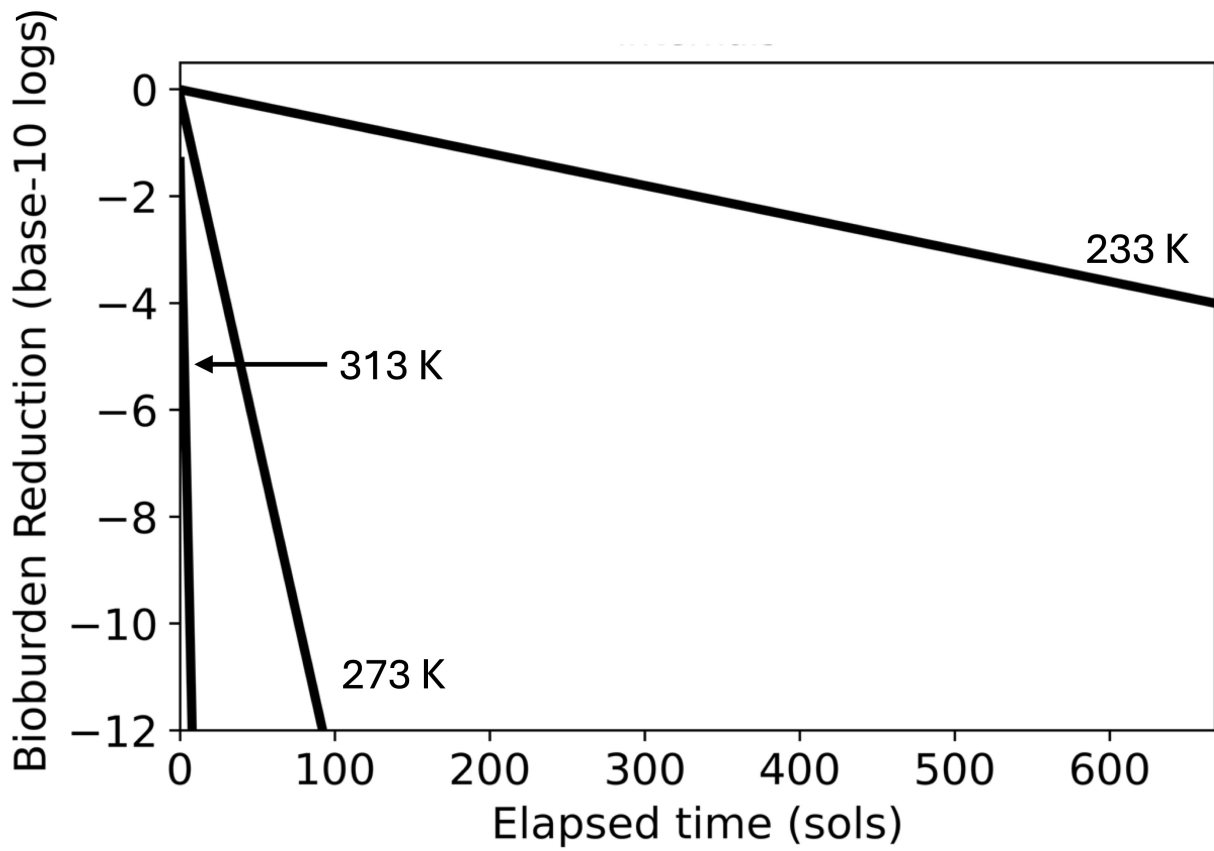


Figure 4.13: The bioburden reductions on the internals of the landers from synergism between low pressure and temperature over one Mars year. The internals are typically kept between 233 and 313 K, which significantly affects the resulting reduction, with high temperature rapidly leading to 1 SAL and lower temperatures not reaching sterilization within a year.

4.4 Discussion

4.4.1 Are Earth-based Microbes Alive on the Surface of Mars Today?

The MMS model combined biocidal effects during cruise and on the surface of Mars to estimate the bioburden reduction rates on 14 spacecraft landed or crashed on Mars. As of this writing (2025 January 15), are there any viable Earth microorganisms on any of the spacecraft on Mars? Table 4.2 shows the estimated bioburdens on the Mars-bound spacecraft considered in this work at the time of launch. With the overall average bioburden per spacecraft of 2.12×10^9 viable microorganisms at launch (Table 4.2), a bioburden reduction of 1 SAL (-12 logs) is sufficient to sterilize each spacecraft and lander within one Mars year when considering bioburden reductions during cruise phase and post-landing.

Throughout cruise, Sun-facing external surfaces of each aeroshell underwent greater than -2×10^5 log reductions from UVC and -1200 log reductions from synergetic effects of temperature and pressure (based on the Opportunity rover with the shortest cruise time). Although surfaces angled away from the Sun received fewer reductions, spacecraft adjust their pointing for communication purposes and orbital dynamics. If spacecraft are spin-stabilized—or mission operations might even choose to rotate spacecraft to expose different surfaces to the Sun for temperature management or intentional bioburden reduction—then their shaded areas may come into the solar beam periodically throughout cruise. Due to the highly biocidal environment and the total bioburden at launch, it is likely that all external surfaces of the aeroshells were sterilized by the time the back shells landed on the surface of Mars.

The bioburden reductions on the internal components of both the aeroshells, as well as the external and internal components of the landers—which were shielded throughout the cruise phases from solar UVC and heating—depended on the internal temperature of the spacecraft, as discussed in Section 4.3.1.2. If the internal temperatures were kept within the lowest temperature range close to 233 K, only a -2 log reduction would have occurred during cruise. In such a case, with the bioburden estimates in Table 4.2, millions of viable spore-forming organisms would still be present on the protected external and internal components of the robotic landers. Unlike the aeroshells and back shells in which the Sun-facing surfaces were sterilized during flight, the landers themselves likely landed on the surface with an appreciable bioburden.

As discussed in Section 4.3.2.2, the exposed surfaces of landers on the surface of Mars were likely sterilized quickly owing to the strong effect of UVC on the surface of Mars. Within 1 sol, a -12 log reduction on Sun-facing surfaces would likely sterilize the remaining bioburden remaining after cruise. Within one Mars year, all external components would be sterilized from the UVC reflected off lander components or Martian regolith. Based on the discussion above, the two places where microbes are most likely to survive the longest are on

the internal surfaces of the landers or underneath a layer of regolith.

If the internal surfaces of the Perseverance rover, for example, have been kept at 233 K for the duration of their missions, the bioburdens on the internal structures of the rover would not yet have been effectively sterilized (i.e., the mission has been active for fewer than 1400 sols at the time of writing). It is more likely, however, that the internal systems are not held consistently at the minimum or maximum of the temperature range. At 273 K, between the highest and lowest temperatures, -12 log bioburden reductions are achieved within 100 sols, meaning that, over 1300 sols into the mission, it is likely that most of the internal surfaces of Perseverance have been sterilized.

Shorter missions, such as the Pathfinder or Phoenix missions, or missions that failed upon landing, may not have reached the -12 log reduction needed for 1 SAL within their active lifetimes. Once a mission ends and the internal components are no longer heated, low pressure acting alone is the relevant biocidal factor for the inactivation of internal microbes. A -12 log reduction from low pressure alone would take over 16,500 sols, equivalent to nearly 25 Mars years. Using nominal Mars time-keeping conventions (where Mars Year 1 began on 1955 April 11), Mars 2 and 3 reached the surface of Mars during Mars Year 9 and have now been on the surface for 29 Mars years. Mars 6 has been on the surface for 27 Mars years. Outside of these three missions, no other landers considered in the MMS model have been on the surface for the 25 Mars years needed to deactivate microbes from low pressure alone. This means that it is possible that there are Earth-based microbes still alive today on some internal surfaces of the rovers and landers, particularly for Pathfinder, Phoenix, Mars Polar Lander, Beagle 2, and the Schiaparelli EDM.

Microbes dislodged from the rovers will have a similar survivability compared to those exposed only to low pressure. If the microbes are under a layer of regolith 1 mm thick with the same absorption coefficients as Figure 4.12, after 25 Mars years, the 150, 250, and 350 m grain sizes will have blocked enough UVC such that microbes under the regolith will not have reached 1 SAL for any latitude on Mars. However, the microbes will still be subjected to low-pressure effects and will be sterilized after the 25 yr without UVC irradiation. Though the biotoxic soils will only add a small addition to the bioburden reduction, the presence of additional deleterious effects means that it is likely that microbes under a 1 mm thick layer of regolith will be sterilized in approximately 25 Mars years or less.

4.4.2 Bioburden Reductions under Regolith/Dust

The bioburden reduction due to UVC attenuated by a layer of regolith was explored in Section 4.3.2.1. We found that, using laboratory-derived values for the absorption coefficient of JSC-1 Mars (Godin et al., 2023), the bioburden reductions were reduced greatly when a layer of regolith was present compared to regolith-free

surfaces. The actual grain sizes of the regolith vary at each landing site depending on the material present, though grains between 100 μm and 1 mm are common, meaning that the grain sizes in Figure 4.12 are representative of the landscape (Golombek et al., 2008; H. J. Moore & Jakosky, 1989; H. J. Moore et al., 1999; Rivera-Hernández et al., 2019; Vaughan et al., 2023). Even when assuming that the microbes were under only a monolayer of regolith grains, the bioburden reductions decreased significantly. If microbes end up under several layers of regolith, the attenuation of UVC could be strong enough that UVC no longer reduces the bioburden. It is interesting to note, however, that it is unlikely that many spores are dislodged from spacecraft if they encounter the Martian surface as high-velocity impacts with contact g-forces greater than 60g (Schuerger & Borrell, 2023).

On the spacecraft itself, it is unlikely that regolith grain sizes as large as in Figure 4.12 will be present. Here finer dust is expected to accumulate, where dust particle sizes are typically between 1 and 4 μm (Lemmon et al., 2019; Tomasko et al., 1999). Though the particles sizes are smaller, dust has been shown to accumulate on solar panels such that power output is significantly reduced (Lorenz et al., 2021). At the Curiosity landing site, an analysis of horizontally mounted instruments (such as the REMS) in comparison to vertically mounted instruments (such as the Mars Hand Lens Imager (MAHLI)) showed that the REMS sensor had dust on 49% of its surface, while MAHLI was only 4.7% covered (Yingst et al., 2020). This indicates that horizontal surfaces, such as the vertical “wall” in Figures 4.7 and 4.8, will have bioburden reductions similar to what was reported owing to a limited dust deposition on such surfaces.

A dust correction factor on the REMS UV sensor was calculated throughout the mission that determines the fractional decrease in UV irradiance due to dust accumulation. As of Mars Year 34, the minimum dust correction factor was 0.7 (a correction factor of 1 indicates that the UV radiation incident on the UV sensor is not attenuated by dust), meaning that a 30% reduction in UV irradiance was observed at that time (Vicente-Retortillo et al., 2018). At the Curiosity landing site, a maximum UVC reduction of 30% for an entire Mars year would still accumulate a -7000 log bioburden reduction for flat surfaces. However, dust accumulation is landing site dependent. The Opportunity rover underwent many dust-cleaning events, while the InSight lander had virtually none (Lorenz et al., 2021), meaning that the UVC attenuation would be stronger at InSight. Although dust was shown to rapidly accumulate up to 0.82 μm within the first 10 mission sols on the Phoenix telltale mirror (Moores, Ha, et al., 2015), the MMS model shows that 1 SAL was reached within the first 24 hr at every landing site (Figure 4.6), likely before dust would have an impact on attenuating the UVC.

4.4.3 Biotoxic Soils on Mars

Though the effects of high-salt regolith, acidic regolith, and perchlorates are small, they may still contribute a cumulative -60 log bioburden reduction per year. This reduction will vary depending on the landing site. Perchlorates, for example, have been detected at multiple landing sites on Mars. Perchlorates were measured in several locations near the Phoenix lander at 0.4–0.6 wt% (Hecht et al., 2009). In Gale crater, Curiosity measured perchlorates at several locations along its traverse (Glavin et al., 2013; Ming et al., 2014; Sutter et al., 2017), with a variation of concentrations between 0.05 and 1.05 wt% (Sutter et al., 2017). Despite the presence of perchlorates at several landing sites, the concentrations vary greatly between locations (Rzymiski et al., 2024), meaning that the effectiveness of perchlorates at reducing bioburdens on landers may be limited, and the reduction values in Section 4.3.2.2 are predicted to be higher than practical. The same may be true of salt- and acidic-rich soils. While these do exist on Mars (Bell III et al., 2000; Gellert et al., 2004; Klingelhöfer et al., 2004; Morris et al., 2004), their spatial variability and concentrations will limit their biocidal effectiveness. As such, a -60 log reduction from biotoxic soils is certainly an upper limit, and the actual reduction is likely lower.

4.4.4 Implications for Future Mars Missions

While this work focused on estimating the viability of Earth-based microorganisms on previously landed spacecraft on Mars, these results can additionally inform the likelihood of forward contamination during future missions.

The missions considered in the MMS model spanned a large range of latitudes between 68°N and 76°S, giving insights into global bioburden reductions on Mars. At equatorial latitudes, between -20°S and 20°N, reductions greater than -10000 logs can be achieved over one Mars year on almost all spacecraft external surfaces, as seen with the Opportunity rover (Figure 4.10). Moving away from the equator, the bioburden reductions decrease owing to lower incident solar UVC irradiation caused by the axial tilt of Mars. However, spacecraft at the southernmost and northernmost latitudes still underwent reductions of approximately -4000 logs over one Mars year. Figure 4.14(a) shows the accumulated UVC energy per sol as a function of L_s , and the cumulative bioburden is shown in panel b. By the end of the MY, all locations on Mars underwent several thousand bioburden reductions.

The Mars Life Explorer (MLE) is a mission concept designed to search for signatures of life on Mars by digging into subsurface ices. Due to its concept, maintaining strict bioburden limits would be important when considering a mission searching for life on the subsurface of Mars. The MLE spacecraft was proposed to land in one of three locations on Mars, Arcadia Planitia (40°N), Utopia Planitia (45°N), or Phlegra Montes (35°N).

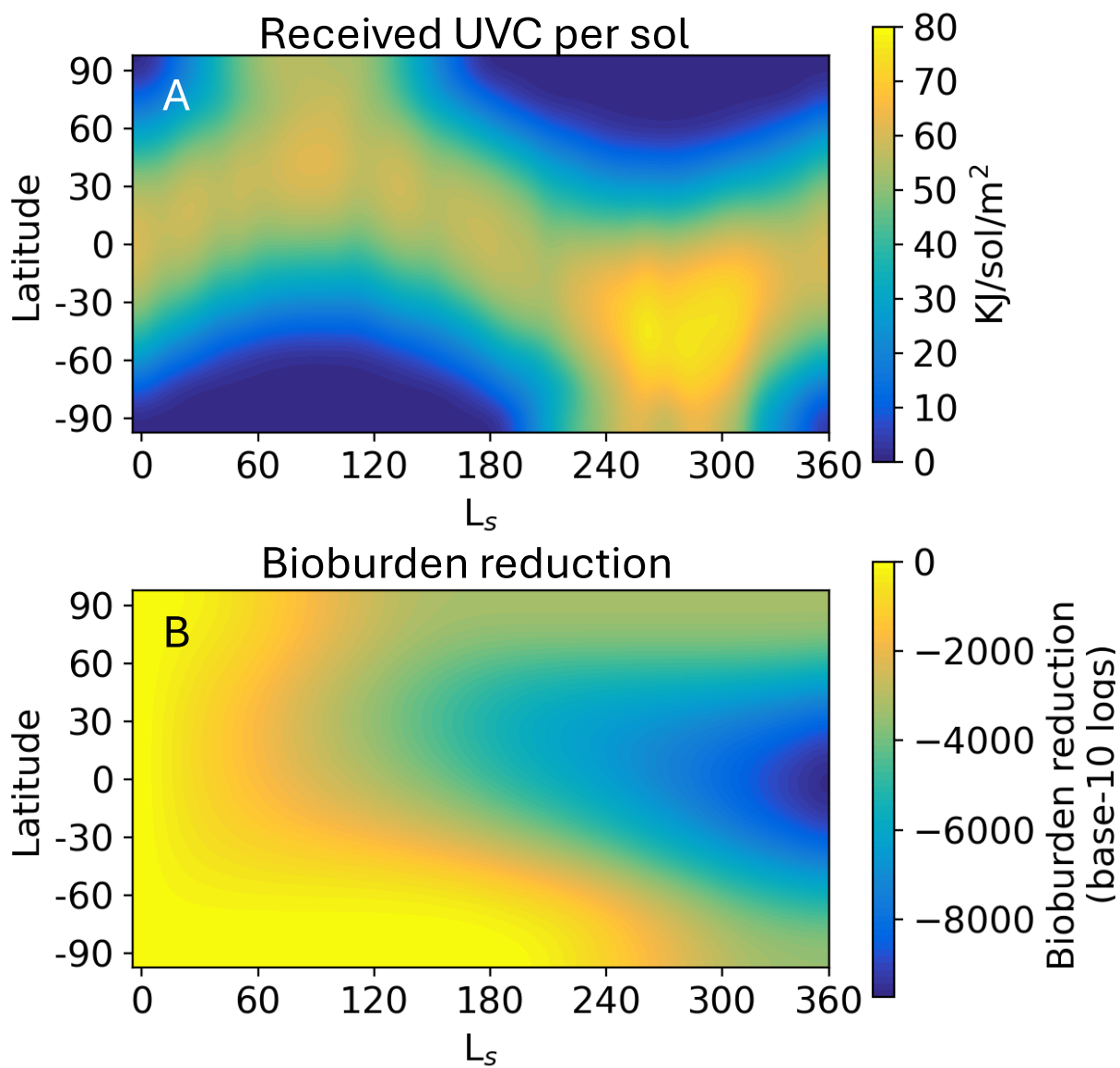


Figure 4.14: (a) UVC energy at all latitudes on the Martian surface as a function of L_s . (b) The cumulative bioburden reduction over the entire MY, showing high sterility at all locations on the surface of Mars.

Between 35°N and 45°N, horizontal, Sun-facing surfaces on the MLE lander would have a bioburden reduction of approximately -8000 and -6000 logs, respectively. Sun-exposed surfaces on the MLE that undergo the smallest bioburden reductions would be those surfaces facing north, though a reduction of approximately -1000 logs is likely to occur for these latitudes.

Depending on the dimensions of the lander, which affect the GSR (Moores et al., 2007), the range of bioburden reductions on the underside of the MLE lander might be approximately -5000 logs for shielding ratios of 0.1, down to approximately -4.5 logs for GSRs of 100. With a lander concept similar to that of InSight (Williams & Muirhead, 2021), the expected bioburden reduction on the underside of the lander over the course of one Mars year would be approximately -45 logs. Thus, within a single Mars year, all external surfaces of the MLE would likely surpass multiple SALs. Additionally, if the internal components of the MLE are held near 310 K, all internal areas of the lander would likely be sterilized within 8 sols. However, as discussed above, components of the lander not exposed to UVC irradiation — or elevated synergism between temperature and low pressure— might maintain a viable bioburden for 25 Mars years. For a lander with the expressed purpose of searching for life, Earth-based microorganisms existing for so long may result in false positives of microbial activity for Martian samples.

4.4.5 Caveats and Next Steps for Modeling Microbial Survival on Mars

The current paper intended to provide a point of reference for first-order estimates of microbial survival on Mars by considering the UV environment, as well as additional biocidal factors that may affect the survivability of Earth-based microorganisms. Expanding modeling elements in the future will allow for a more thorough understanding of microbial inactivation under such biocidal conditions and give a more precise length of time estimation for microbial survival.

The UV environment was modeled for several surface orientations, including surfaces tilted away from the horizontal and the undersides of the landers, giving a maximum biocidal reduction caused by UVC irradiation. However, rover surfaces are intricate, which may cause components to shield other components from UVC radiation. As mentioned in Section 4.3.1.2, a north-facing component of the Phoenix lander shaded at all hours of the day by a spacecraft component that reflects only 1.12% of the incident UVC would fail to reach 1 SAL in one Mars year. Modeling the intricate geometry of the lander deck, including on mated surfaces that contain small crevices, would give a better understanding of the fraction of the lander that is shadowed throughout the day. While UVC has been shown to be effective in reducing *B. subtilis* spores in experiments aboard the International Space Station, when spores were not arranged as monolayers, self-shielding from UVC resulted in an 8% survival rate in low Earth orbit conditions and 100% survival rate in Mars-simulated

conditions (Wassmann et al., 2012). With the prelaunch bioburden densities on spacecraft being very low, the self-shielding effect is likely minimal; however, it is important to keep in mind that these results would vary drastically under conditions where layers of spores are present.

The number of VOs present on the spacecraft was estimated according to the formalism of Schuerger et al. (2019) using a spore-to-VO ratio of 1:4776, found by combining results from Hendrickson et al. (2017). Using a higher spore-to-VO ratio of 1:50,000 will increase our total bioburden estimates by approximately one order of magnitude from those found in Table 4.2. Ultimately, the bioburden reductions on the surface of Mars are so high that the specific choice of spore-to-VO ratio has little effect on the conclusions of this work.

In this paper, a survivability of 25 Mars years was found for microbes shielded from all other biocidal factors except for low-pressure effects. It is this factor that provides an upper limit for the time microbes may survive on the surface, because if all other factors are negligible owing to the locations of the microbes (e.g., deeply embedded in the spacecraft or under layers of regolith), low pressure will certainly always be present. In this work, low-pressure effects were modeled using data that included only two time points — after 100 and 2100 days (Supplementary Table A1) — and the bioburden reduction was linearly modeled over time. Additional laboratory studies to examine the effects from low pressure over a prolonged time would help make this estimate more accurate. Crucially, if low-pressure effects on microbial populations become null after prolonged periods, the upper limit on the survivability of Earth-based microbes may far extend 25 Mars years. In such a case, all landed and crashed spacecraft on the surface of Mars would contain living microbes to this day.

Chapter 5

Characterization of Rocky Planet Atmospheres from Lyman- α Transit Observations

5.1 Overview and Author Contributions

Radiative transfer in the upper atmosphere contributes immensely to atmospheric escape, which can shape populations of exoplanetary atmospheres. Observing ongoing mass loss using Lyman- α transits has been successful for larger planets, but so far has yielded only non-detections for smaller, rocky planets. Observations of mass-loss in our own solar system highlights that hydrogen escape from rocky planets is a function of atmospheric and planetary parameters, including temperature and hydrogen mixing ratio, which would ultimately affect an observed Lyman- α transit of these planets. Currently, we have no wider framework for determining these bulk planetary properties from the observation of a Lyman- α transit for rocky exoplanets. This work models hydrogen escape from rocky planets, varying parameters such as planet mass, temperature, hydrogen mixing ratio, and stellar photoionization rate to assess the impact on the Lyman- α transit depth to aid in interpretation of future positive detections, as well as guide future observations by determining which planets are most easily detectable.

This work was carried out with coauthors R.D. Wordsworth, J.E. Moores and C. Cherubim. Using the CRediT framework, author contributions are as follows: G. Bischof (author of this dissertation): conceptualization, data curation, formal analysis, investigation, software, methodology, visualization, writing (original draft), writing (review and editing); R.D. Wordsworth: conceptualization, methodology, supervision, validation, writing (review and editing); J. E. Moores: conceptualization, funding acquisition, writing (review and editing); and C. Cherubim: Validation, writing (review and editing).

5.2 Methods

The model used in this work contains two regions: the heterosphere and the escape region. First, we model a two-component isothermal heterosphere starting at the homopause. The homopause is defined as the

atmospheric boundary where the molecular diffusion coefficient becomes greater than the eddy (turbulent) diffusion coefficient (Catling & Kasting, 2017). Since both molecular and eddy diffusion depend on the pressure and number density of the atmosphere, the homopause altitude is set by the hydrostatic profile. Above the homopause, which we fix to 100 km altitude in our model consistent with Earth’s homopause altitude¹ (Lehmacher et al., 2011), species are no longer effectively mixed. They instead separate out depending on their molecular/atomic masses, with H extending to higher altitudes than heavier species such as N₂. The region above the homopause is what we define as the heterosphere region, where the stratification of the species occurs.

The second region is the escape region. H escape from the atmosphere is simulated as Jeans or hydrodynamic escape, determined by the properties of the heterosphere. In the Jeans escape regime, the escape region starts at the exobase, which is defined as the boundary between the thermosphere and the exosphere, where the mean-free path exceeds the local scale height and collisions between atoms are negligible. In the hydrodynamic regime, the escape region starts at the R_{XUV} level, defined as the radius where the **optical depth** at XUV wavelengths is equal to 1 (Murray-Clay et al., 2009; Watson et al., 1981). The calculation to determine the location of the exobase and R_{XUV} level is described in Section 5.2.1. The radial number density of H from the escaping region is modelled according to a Jeans or hydrodynamic escape profile, from which the Lyman- α transit depth is calculated. A schematic depicting the two regions of the model is shown in Figure ??.

5.2.1 Modelling the Upper Atmosphere: Determining Jean’s or Hydrodynamic escape

To determine whether an atmosphere is escaping on an atom-by-atom basis as Jean’s escape or as a hydrodynamic outflow, we first consider diffusion of H through the heterosphere. The homopause is assumed to occur at an altitude of 100 km, where H and atomic oxygen (O) are present. These constituents represent a simplified, water-rich lower atmosphere, where H and O result from the photodissociation of water vapour. The total number density of both species is set to 10^{19} atoms m⁻³, consistent with the number density of Earth’s homopause, and within a few orders of magnitude of homopause densities across other Solar System bodies (Pierrehumbert, 2010).

The changing composition of the upper heterosphere with radius is modelled considering molecular diffusion, where the species gravitationally separate out based on their mass. The number density, n , of each species as a function of radius is given by

¹The homopause altitude will not vary by orders of magnitude for rocky exoplanets, so the precise selection of homopause altitude is insignificant (Pierrehumbert, 2010)

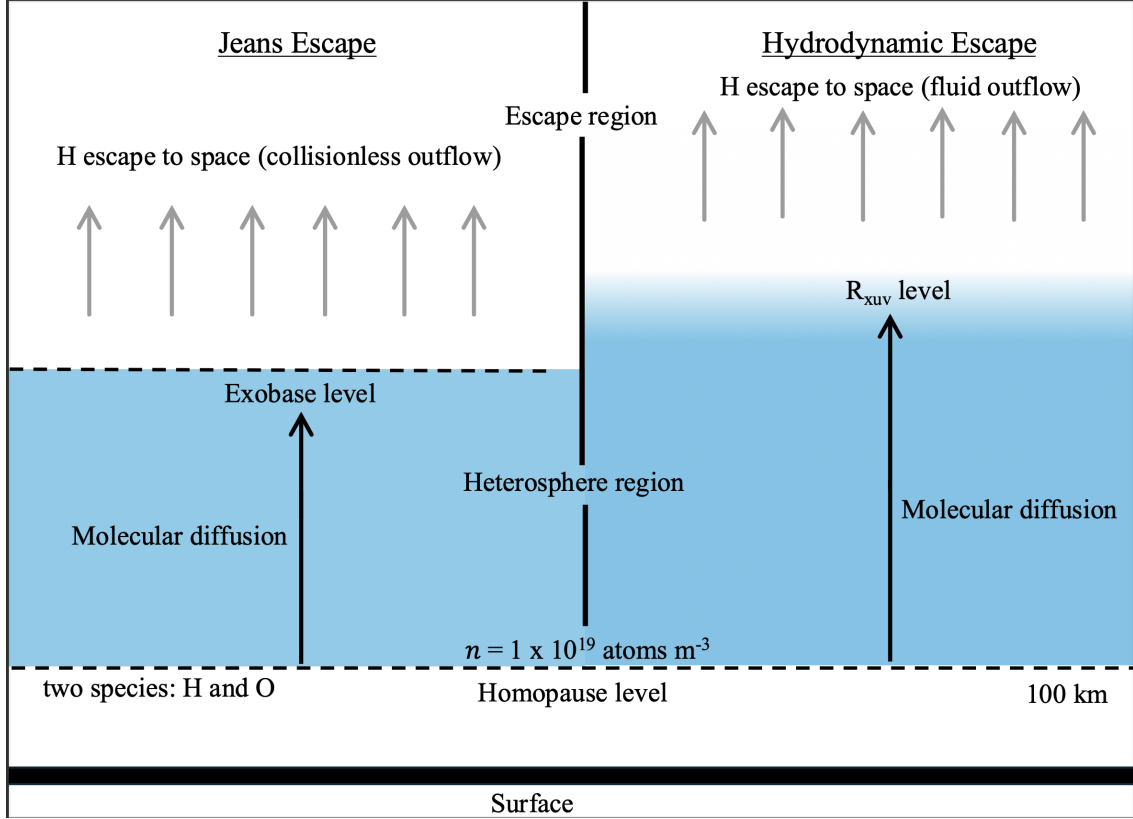


Figure 5.1: Schematic depicting the diffusion of H and O from the homopause up to exobase (Jeans escape) or R_{XUV} region (hydrodynamic escape) in our model. The blue shading indicates the heterosphere region of the model and the white shading indicates the escape region of the model. If the Jeans parameter at the exobase > 3 , H escapes from the exobase according to Jeans escape. If the Jeans parameter < 3 , hydrodynamic escape occurs.

$$n(r) = n(r_0) \exp \left(\frac{r_s}{H_s} \left(\frac{r_s}{r} - \frac{r_s}{r_0} \right) \right), \quad (5.1)$$

where r is radius from the planet's center, r_s is the radius of the planet, r_0 is the homopause radius, set to 1×10^5 m in altitude plus the value of r_s , and H_s is the scale height at the surface for each species (Pierrehumbert, 2010). Since the homopause altitude is much smaller than the planet radius, r_0 is approximately equal to r_s .

The surface scale height, H_s , is calculated with

$$H_s = \frac{kT_0}{mg_s}, \quad (5.2)$$

where k is the Boltzmann constant, T_0 is the isothermal heterosphere temperature, g_s is the gravity at the surface, and m is the mass of the species (either O or H) in kg.

At every radius level in the model, the number density of both species is calculated according to Equation (5.1) and Equation (5.2). Then, the mean-free path of the atmosphere, l , for a given species is

$$l(r) = \frac{1}{\chi n(r)}, \quad (5.3)$$

where χ is the effective collision cross section area of the species. Since the atmosphere has two components, the cross section is taken as an average of the individual cross sections of H and O, similar to Evans et al., 2025. Equation (5.3) indicates the average distance an atom will travel in the atmosphere before colliding with another atom.

The mean-free path at radius r is compared with the local scale height $H(r)$, which varies with distance from the center of the planet due to the changing gravitational acceleration, $g(r)$. The local scale height is thus given by

$$H(r) = H_s \left(\frac{r}{r_s} \right)^2. \quad (5.4)$$

When the mean-free path of the atmosphere is equal to the local scale height, the exobase level has been reached. We assume the exobase to be a sharp boundary between the thermosphere and exosphere. This assumption is not necessarily true in reality, but it has been shown to have minimal impact on studies of thermal escape (Chamberlain, 1963).

Next, we calculate the Jeans parameter, λ_{Jeans} , which describes how tightly an atmosphere is bound to the planet. λ_{Jeans} is defined by the ratio of gravitational energy to thermal energy, written as

$$\lambda_{\text{Jeans}} \equiv \frac{GMm}{kT_0 r}, \quad (5.5)$$

where G is the gravitational constant, M is the mass of the planet, m is the mass of H, and r is the radius where λ_{Jeans} is evaluated. A higher Jeans parameter indicates a more tightly bound atmosphere.

The value of the Jeans parameter that dictates the transition between slower, collisionless Jeans escape and bulk-outflow hydrodynamic escape has been debated in the literature (Erkaev et al., 2015; Evans et al., 2025; Gronoff et al., 2020; Guo, 2024; Volkov, Tucker, et al., 2011). Here we adopt the Volkov, Johnson, et al., 2011 transition value of $\lambda_{\text{Jeans}} = 3$. If an exobase level is found and $\lambda_{\text{Jeans}} > 3$, the atmosphere is in the Jeans regime, escaping from the exobase level. If $\lambda_{\text{Jeans}} < 3$ before an exobase level is found, the planet is in the hydrodynamic regime.

The hydrodynamic escape level, R_{XUV} , is the radius where **optical depth** at XUV wavelengths is equal to unity (Murray-Clay et al., 2009; Watson et al., 1981). Without prior knowledge of the outflow structure, R_{XUV} cannot be determined self-consistently, which is a well-known limitation of atmospheric escape models (Broome et al., 2025; Schreyer et al., 2024). As we discuss further in Section 5.2.2.3, we attempt to remain as

agnostic to R_{XUV} as possible, employing an energy-limited escape equation that does not require prescribing an R_{XUV} value. Only in solving for the diffusion-limited mass loss rate is an R_{XUV} level required. Here we choose a value of $R_{\text{XUV}} = 1.5 R_{\text{P}}$, which is similar to modelled values for rocky exoplanets Broome et al., 2025; Yan and Guo, 2019. The implications of selecting this value are discussed in Section 5.2.2.3.

After it has been determined which escape regime the atmosphere is in, the density of H as a function of distance from the planet is simulated. For Jeans escape, we model an H exosphere using a Chamberlain model as described in Section 5.2.3. For the hydrodynamic escape regime, we model the outflow of H based on an isothermal Parker wind model, as described in Section 5.2.4. For both cases, the H profile is then used to model the Lyman- α transit. The reader should note that the purpose of this model is not to investigate the time-dependent evolution of the atmosphere under Jeans or hydrodynamic escape, rather we assess the ability to characterize an atmosphere based on the snapshot in time given by the Lyman- α transit depth.

5.2.2 Limiting Factors for Escape: Diffusion-limited, Exobase-limited, and XUV Energy-limited Escape

Once the escape regime is determined, we calculate the primary factor limiting H escape. In the Jeans regime, escape can be limited by conditions at the exobase or by the ability for H to diffuse through the background gas from the homopause to the exobase. In the hydrodynamic escape regime, escape may be similarly limited by the diffusion of H, or by the available XUV energy.

5.2.2.1 Diffusion-limited Escape

For both hydrodynamic and Jeans escape, the diffusion of H through a static background of O may limit the ability for H to escape. To introduce the concept of diffusion-limited escape, we first discuss the concept of the “cross-over flux” (Watson et al., 1981; R. D. Wordsworth et al., 2018; Zahnle et al., 1990).

In the hydrodynamic escape regime, the cross-over flux, ϕ_c , is the value that determines if heavier species are entrained in the outflow of H. Below the cross-over flux, only H atoms escape. Above the cross-over flux, heavier atoms, such as the background atomic oxygen, will be dragged along with the outflow of H and escape.

The cross-over flux is defined as

$$\phi_c = \frac{bf_1}{H_1}(m_2 - m_1), \quad (5.6)$$

where the b is the binary diffusion coefficient (here for H and O), which varies with temperature as $4.8 \times 10^{19} \text{ T}^{0.75} \text{ m}^{-1} \text{ s}^{-1}$. The mixing ratio of the lighter species (H, species 1 in this work) is given by f_1 . H_1

is the scale height of the lighter species and m_2 and m_1 are the masses of the heavier and lighter species, respectively.

If the background gas is static, and therefore not escaping with the diffusing H, the diffusion-limited flux, in units of atoms $\text{m}^{-2} \text{s}^{-1}$, can be derived from Equation (5.6) as

$$\Phi_{\text{diff}} = \frac{\phi_c}{m_1}. \quad (5.7)$$

Though the cross-over flux is only relevant in the hydrodynamic escape regime, because the slower Jeans escape will never drive the escape of heavier atoms, the diffusion-limited escape flux is important for both regimes. The ability for H to reach the exobase region or the R_{XUV} region will affect the mass loss rates for both regimes. Therefore, in both regimes, the diffusion-limited flux is calculated to determine if the diffusion of H through O is a bottleneck for escape.

5.2.2.2 Exobase-limited Escape

In the Jeans escape regime, if H escape is not limited by diffusion, it is limited by the thermal energy at the exobase, here referred to as exobase-limited escape. The Jeans escape flux, in units of atoms $\text{m}^{-2} \text{s}^{-1}$, is given by

$$\Phi_{\text{jeans}} = \frac{n_{\text{exo}}}{2\sqrt{\pi}} (1 + \lambda_{\text{exo}}) \exp(-\lambda_{\text{exo}}) U, \quad (5.8)$$

where n_{exo} is the number density of H atoms at the exobase, λ_{exo} is the Jeans parameter evaluated at the exobase, and

$$U = \sqrt{\frac{2kT_{\text{exo}}}{m}}, \quad (5.9)$$

where U is the thermal speed of the H atoms considering a Maxwell-Boltzmann distribution.

If the atmosphere is in the Jeans escape regime, Φ_{diff} is compared to Φ_{Jeans} . If Φ_{diff} is greater than Φ_{Jeans} , H diffuses to the exobase faster than it is removed by Jeans escape, making this scenario exobase-limited. If Φ_{jeans} is greater than Φ_{diff} , H is removed from the exobase faster than it can diffuse through the background gas. This is the diffusion-limited case. In our model, Jeans escape will always be limited by one of these two processes.

5.2.2.3 Energy-limited Escape

In the hydrodynamic escape regime, the escape can similarly be limited by one of two factors: the ability for H atoms to diffuse through the atmosphere as discussed, or by the XUV energy from the host star deposited into the atmosphere to drive the outflow. The maximum escape rate, $\dot{M}$ in units of kg s^{-1} based on incoming energy is set by

$$\dot{M}_{\text{XUV}} = \eta \frac{3F_{\text{XUV}}}{4GK\rho_p} \quad (5.10)$$

where η is the evaporation efficiency, F_{XUV} is the incident XUV flux, ρ_p is the mean planetary mass density, and K is a potential energy reduction factor which accounts for the gravity of the host star. The reader is directed to Caldiroli et al., 2021 for details on Equation 5.10, including the calculation of η .

Using Equation (5.10) allows us to calculate the energy-limited flux without prescribing an R_{XUV} value. However, since Equation (5.10) gives a mass-loss rate in kg s^{-1} and Equation (5.7) gives a flux in units of $\text{atoms m}^{-2} \text{s}^{-1}$, a radius is needed to compute the diffusion-limited mass loss rate ($\dot{M}_{\text{diff}}$) to compare to the energy-limited mass loss rate. As mentioned in Section 5.2.1, the value is selected to be $1.5 R_p$. The minimum diffusion-limited mass loss rate for a given Φ_{diff} occurs if $R_{\text{XUV}} = 1 R_p$, while our choice of R_{XUV} will increase the mass-loss rate by a factor of 2.25 for the same value of Φ_{diff} .

Similarly to the Jeans escape regime, $\dot{M}_{\text{diff}}$ and $\dot{M}_{\text{XUV}}$ are compared, and the smaller of the two mass loss rates determines by which mechanism the escape is limited. In particular, if Φ_{diff} is less than Φ_{XUV} , the escape is diffusion limited. If $\dot{M}_{\text{diff}}$ is greater than $\dot{M}_{\text{XUV}}$, the escape is energy limited. In reality, there are instances when the incoming XUV energy is able to heat the atmosphere to a point where the background gas is no longer static. In such a case, the O atoms would escape with the H atoms. In this work, we only consider cases where H escapes alone, necessarily requiring that the escape flux is always less than the cross-over flux described in Equation (5.6). This assumption is discussed further in Section 5.4.3.

To give the reader a sense for the parameter space where these regimes would be important, Figure 5.2 shows the escape rates and corresponding regimes for a $1 R_{\oplus}$ and $1 M_{\oplus}$ planet orbiting at 1 AU from a GJ 436 type star. The white line indicates the set of heterosphere temperatures and H mixing ratios at which the atmosphere transitions from the Jeans escape regime to the hydrodynamic escape regime. Within the hydrodynamic escape regime, the blue line indicates whether the escape is XUV energy limited or diffusion limited. If the value of R_{XUV} used to calculate $\dot{M}_{\text{diff}}$ was less than $1.5 R_p$, the blue line would move further up, making the XUV-limited phase space smaller. If the value of R_{XUV} was selected to be less greater than $1.5 R_p$, the blue line would move down, increasing the XUV-limited phase space.

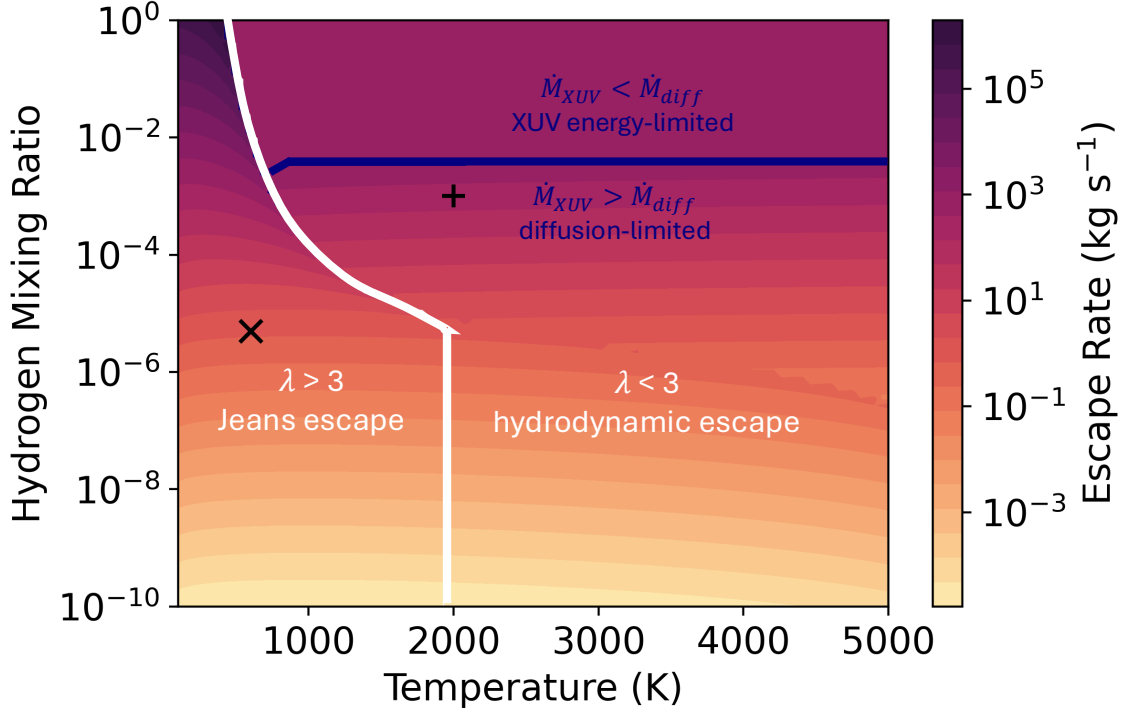


Figure 5.2: Escape rate as function of H mixing ratio and heterosphere temperature for a $1 R_{\oplus}$ and $1 M_{\oplus}$ planet. The white line indicates the transition from the Jeans to hydrodynamic escape regime. The blue line in the hydrodynamic regime indicates the transition from diffusion-limited to energy-limited escape. The 'x' marker indicates the Jeans regime example used in Section 5.3.1, while the + marker indicates the hydrodynamic regime example.

5.2.3 Density of Hydrogen in the Exosphere: Jeans Escape

To simulate the radial profile of H atoms in the exosphere for a planet in the Jeans escape regime, we use a modified Chamberlain profile, which has been shown to accurately recreate the H exosphere around Earth (Baliukin et al., 2019; Kameda et al., 2017). The number density of H in the exosphere, as described in Chamberlain, 1963, is given by

$$n(r) = n_{\text{exo}} \exp\left(\frac{-E_r}{k T_{\text{exo}}}\right) \zeta(\lambda_{\text{Jeans}}) \quad (5.11)$$

where r is the radius from the center of the planet and n_{exo} is the number density of H at the exobase. In the exobase-limited case, n_{exo} is the number density value calculated from Equation (5.1) at the exobase radius. If the escape is diffusion limited, hydrogen reaches the exobase slower than it can be removed. In this case, the number density of H at the exobase is calculated by taking the ratio of the diffusion-limited flux to the Jeans escape flux as

$$n_{\text{exo,diff}} = \frac{\Phi_{\text{diff}}}{\Phi_{\text{Jeans}}/n_{\text{exo}}}. \quad (5.12)$$

In Equation (5.11), E_r is the difference in potential energy between a radius, r , and the exobase, written as

$$E_r = \frac{GMm}{r_{\text{exo}}} - \frac{GMm}{r}. \quad (5.13)$$

In Equation (5.11), T_{exo} is the temperature of the exobase. Since the temperature of the exobase is a complex function of number density, the various species in the upper atmosphere, and irradiation from the host star, we consider the exobase temperature to be a free parameter in the model.

Finally, $\zeta(\lambda)$ is a partition function evaluated using Equation (5.5) at the exobase. The partition function describes three trajectories that H atoms can take after escaping the exobase: satellite trajectories, ballistic trajectories, and escaping trajectories. These trajectories are described in detail in Chamberlain, 1963. Similarly to Kameda et al., 2017, we consider only the ballistic and escaping components, where $\zeta(\lambda) = \zeta_{\text{ballistic}}(\lambda) + \zeta_{\text{escape}}(\lambda)$.

The exosphere is extended to a distance corresponding to the smaller of R_{star}/R_p or the planet’s Hill radius, **which is defined as the region around a planet where its own gravitational force is the dominant force for attracting satellites (or in this work, retaining H atoms) compared to a larger body, such as the host star that the planet orbits**. Described below in Section 5.2.6, the Lyman- α transit is simulated for a mid-transit planet with an impact parameter of 0. In this case, the largest possible extent of the exosphere observed from the Earth’s line-of-sight is out to the edge of the star’s radius. However, for close-in planets, the Hill radius can be smaller than this ratio. Beyond the Hill radius, interactions with the stellar environment can produce an extended H tail (Bourrier et al., 2015; Owen et al., 2023; Schreyer et al., 2024). Since this work neglects the formation of a tail, if the Hill radius is less than R_{star}/R_p , the exosphere is cut at the Hill radius. For a planet with a small Hill radius, the measured transit depth may represent a lower limit because additional absorption from an extended tail is not accounted for.

5.2.4 Density of Hydrogen in the Outflow: Hydrodynamic Escape

To simulate the hydrodynamic outflow of H, we use the hydrodynamic escape model *Sunbather* (D. Linssen et al., 2024), which calls the isothermal Parker wind model, *p-winds* (L. A. D. Santos et al., 2022). We discuss our choice of using an isothermal model below. *P-winds* models a hydrodynamically escaping atmosphere, calculating a density and velocity profile assuming a constant speed of sound, as discussed in L. A. D. Santos et al., 2022 and Lampón et al., 2020.

Inputs into *Sunbather*, which are passed on to *p-winds*, are the planet’s mass and radius, the host star’s mass and radius, the semi-major axis of the planet, the transit impact parameter, and the spectral energy distribution (SED) of the host star. For all simulations in this work, the GJ 436 stellar spectrum is used (France et al., 2013, 2016), since most rocky planets to date have been detected around M-stars, which have unique XUV environments since their XUV luminosity to bolometric luminosity is typically very large (e.g. Behr et al., 2023; France et al., 2016; Loyd et al., 2016; Wheatley et al., 2017; Wilson et al., 2021, 2025; Youngblood et al., 2016).

To give the reader a sense of the energy emitted from various types of stars, Figure 5.3 (upper panel) shows the spectral energy distribution (SED) at 1 AU out to mid-IR wavelength for GJ 436, GJ 876, Epsilon-eri, the sun, and WASP 17 (Wilson et al., 2025; Youngblood et al., 2016). These represent a quiet M-dwarf, an active M-dwarf, a K-type star, a G-type star, and an F-type star. As shown in the upper panel, the M-type stars emit orders of magnitude less light compared to the K, G, and F-type stars.

Between the XUV and FUV, Figure 5.3 (bottom panel) shows the SED for both M dwarfs and the sun. The y-axis has been truncated to be able to see the differences more clearly and therefore, the flux from the sun is much greater than both M-type stars above 1500 Å. However, in portions of this wavelength range, the M-type stars emit more UV than the sun. For example, GJ 436 has the highest Lyman- α flux of the three stars. This figure demonstrates that even though the overall flux of the M-dwarfs is much lower than than the other stellar types, the relatively strong UV flux gives rise to the unique XUV environment of these stars, where the ratio of XUV flux to bolometric flux exceeds that of other stellar types.

The final three inputs into *Sunbather* are the chemical composition of the outflow, the mass-loss rate, and the isothermal outflow temperature. In our work, we utilize the isothermal Parker wind solution only. Though the outflow parameters, such as temperature and velocity, can be altered significantly at high metallicity (D. Linssen et al., 2024), this work only considers the outflow of H which allows us to use the simplifying assumption of the isothermal Parker wind. The mass loss rate found in the heterosphere region of the model, as described in Section 5.2.2.3, is used as input into *Sunbather*. The isothermal outflow temperature is a free parameter in this work, similar to the exobase temperature in the Jeans escape regime.

Similarly to the Jeans escape regime, we simulate the hydrodynamic outflow to a distance that is the smaller of R_{star}/R_p or the Hill radius, acknowledging that this may underestimate the transit depth due to excluding absorption from a potential H tail.

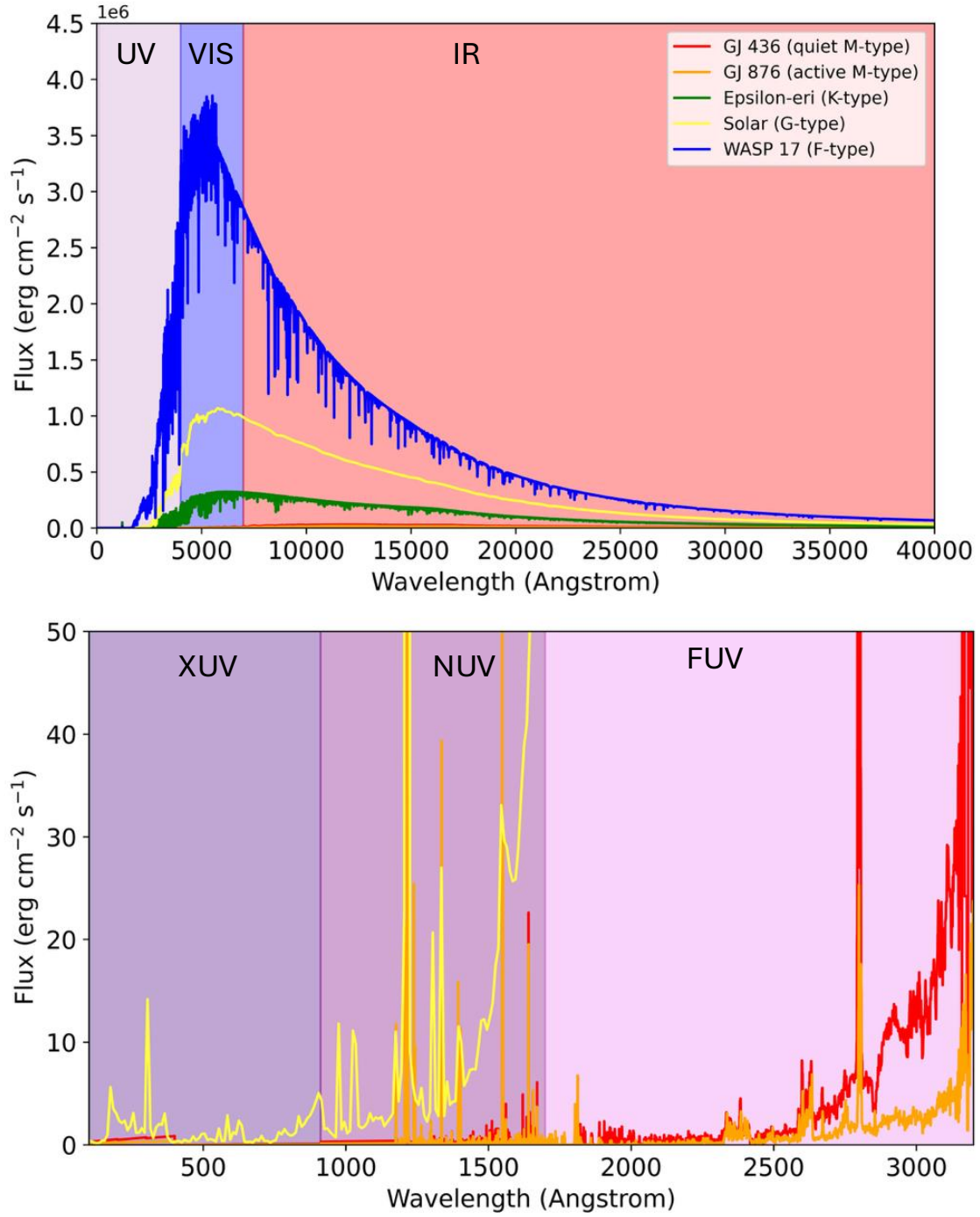


Figure 5.3: Upper panel: SEDs at 1 AU for GJ 436, GJ 876, Epsilon-eri, the sun, and WASP 17 through the Mid-IR. Lower panel: SEDs for the UV wavelengths for the two M-dwarfs and the sun.

5.2.5 Photoionization of H

Lyman- α photons are absorbed only by H atoms with a neutral charge, highlighting the significance of interactions with the circumstellar environment. For example, a lack of positive Lyman- α detections from

highly irradiated sub-Neptunes, such as π Men C (Muñoz et al., 2020), suggest that the photoionization of H atoms can play a large role in the detectability of a planet’s Lyman- α transit (Owen et al., 2023).

In the hydrodynamic escape regime, the photoionization of H in the outflow is included in *p-winds*, affected by the stellar spectrum (GJ 436, in this work), distance to the host star, and density of the hydrogen outflow. See L. A. D. Santos et al., 2022 for full details on the photoionization calculations included in the model.

To include photoionization in the Jeans escape regime, we use the formalism presented in Chamberlain, 1963. As mentioned in Section 5.2.3, only ballistic and escaping trajectories are considered in this work. Atoms on ballistic trajectories will fall back to Earth on timescales shorter than the time to photoionization, meaning only escaping particles will be photoionized. The radius where photoionization becomes important, r_{ion} , as a function of the time it takes to photoionize a fraction of $1/e$ of the H atoms, τ_{ion} , is described as

$$r_{\text{ion}} = r_{\text{exo}} \left(\frac{3\xi v_{\text{esc}} \tau_{\text{ion}}}{2r_{\text{exo}}} \right)^{2/3} \quad (5.14)$$

where v_{esc} is the escape velocity at the exobase level, r_{exo} (see Chamberlain, 1963 for the full derivation). ξ is a scaling factor to include the time needed to ionize a fraction of H atoms greater than $1/e$.

If a host star outputs photoionizing radiation at a rate of β (in units of s^{-1}), we can substitute this rate in Equation (5.14) as $\tau_{\text{ion}} = \frac{1}{\beta}$. Equation (5.14) can then be rearranged to find the fraction of ionized H, ξ , as a function of distance from the planet,

$$\xi = \frac{2}{3} \left(\frac{r}{r_{\text{exo}}} \right)^{3/2} \frac{r_{\text{exo}} \beta}{v_{\text{esc}}}, \quad (5.15)$$

and the number density ionized as a function of distance is now

$$n_{\text{ion}}(r) = n(r)e^{-\xi}. \quad (5.16)$$

The photoionization rate, β , used for the Jeans escape regime is calculated using the *radiation processes* function in the *hydrogen* module of *p-winds* (L. A. D. Santos et al., 2022), with inputs including the GJ 436 spectrum and the distance to the planet.

5.2.6 Simulating the Lyman- α transit

For both the hydrodynamic and Jeans escape scenarios, we utilize the *RT* module from *Sunbather*, described in D. Linssen et al., 2024 to simulate the Lyman- α transit. For hydrodynamic escape, the inputs needed to run the *RT* module are the planetary and stellar parameters described above in Section 5.2.4, the number density of H in the outflow, the velocity of the atoms in the outflow, and the temperature of the

outflow, which are given by the *p-winds* simulation.

For the Jeans escape regime, we modify the *RT* module, since the temperature of the exosphere and the velocity of the atoms are not given by the Chamberlain model. For the temperature of the exosphere, we assume that the temperature at the exobase is the maximum temperature, which decreases linearly with radius from the planet to a minimum temperature of 50 K at a radius of R_{star} . A model of Jeans escape from Pluto’s atmosphere shows a decrease in temperature with radius from the exobase temperature of 68 K to 45 K at a radius of 2000 km (Evans et al., 2025). While the temperature of the exosphere affects the Lyman- α line width due to thermal broadening, the broadening due to the Doppler shift of the atoms moving at high velocity is more significant.

The velocities of the atoms in the exosphere have a significant effect on the line broadening. For Lyman- α transits observed using HST, the line center is typically obscured by absorption from the interstellar medium (ISM) within the range of -50 to 50 km s^{-1} (Wood et al., 2005), therefore exospheres that are Doppler-shifted outside of the contamination zone are more easily observable. The thermal velocity of H atoms at the exobase temperatures considered in this work results in speeds ranging from ~ 1.5 to 5 km s^{-1} . However, observations from the sub-Neptune GJ 436 b showed that the velocities of atoms in the H outflow exceed the thermal velocity (Bourrier et al., 2015), reaching up to 100 km s^{-1} in the star-Earth line-of-sight due to interactions with the circumstellar environment. For this work, we prescribe a velocity profile in which atomic velocities increase from the thermal velocity at the exobase temperature up to 25 km s^{-1} at the outer boundary of the exosphere, based on Figure 4 of Bourrier et al., 2015, which shows maximum velocities of 25 km s^{-1} within an exospheric radius of $1 R_{star}$. While additional interactions with the stellar environment can produce a significant effect on the Lyman- α line by broadening the line width further, these considerations are outside the scope of this work.

We model the planet at mid-transit, with an impact parameter of 0. The *RT* model returns a value of F_{in}/F_{out} , which is the ratio of the in-transit Lyman- α flux compared to the out-of-transit flux.

5.2.7 Population-Level Sampling

For our population-level analysis plots, the heterosphere-escape-transit model was run for 5000 simulated planets to observe trends between key planetary properties and the resulting Lyman- α transit. We randomly sampled from a grid of planetary masses, M_p , between 0.45 to $6.5 M_{\oplus}$. Radii of the planets were determined from the mass-radius relationship derived in Müller et al., 2024, where planets with masses $\leq 4.4 M_{\oplus}$ are considered to be rocky, and planets with masses between 4.4 and $137 M_{\oplus}$ are gaseous with H-He envelopes. Heterosphere temperatures were sampled from a distribution between 100 to 5000 K . To span the parameter

space between planets with H-depleted secondary atmospheres to H-rich enveloped atmospheres, the H mixing ratios were sampled from a grid with values between 10^{-10} to 1. The planet’s semi-major axis — which ultimately affects the photoionization rate and the F_{XUV} flux input into Equation (5.2.4) — was sampled from a grid between 0.01 to 1 AU. For planets undergoing Jeans escape, the exobase temperature was sampled from a grid ranging from 100 to 1000 K. The outflow temperature for planets in the hydrodynamic regime was sampled from a distribution between 2000 to 9000 K. For each simulated planet, the transit occurred in front of a star with a radius of $0.46 R_{\odot}$, consistent with the radius of GJ 436 (Torres, 2007).

5.3 Results

5.3.1 Planetary Escape Regime Examples

To illustrate the function of the model, Figure 5.4 shows examples of an atmosphere in the Jeans escape regime and an atmosphere in the hydrodynamic escape regime. The planets in both scenarios had masses and planetary radii set to $1 M_{\oplus}$ and $1 R_{\oplus}$, respectively, each orbiting a $0.46 R_{\odot}$ star at 1 AU. For the Jeans escape atmosphere, the heterosphere temperature was set to 600 K, with a H mixing ratio of 5×10^{-6} . These values are approximations for the thermosphere temperature (Liu et al., 2023) and H mixing ratio at Earth’s homopause (Catling & Kasting, 2017). In the hydrodynamic escape scenario, the heterosphere temperature was set to 2000 K with an H mixing ratio of 10^{-3} .

As shown in Figure 5.4a, the H and O atoms diffuse through the atmosphere in both the Jeans escape and hydrodynamic escape regimes. In the Jeans escape regime, the mean-free path of the atmosphere becomes equal to the scale height at a distance 536 km from the surface. The Jeans parameter evaluated at this level yields $\lambda_{\text{Jeans}} = 11.64$. In the hydrodynamic case, the atmospheric scale height becomes so large that the exobase region is beyond the modeled range. In Figure 5.4b, the atmosphere in the Jeans escape case remains predominately oxygen, with an H mixing ratio of 0.38 at the exobase. In the hydrodynamic escape case, the upper atmosphere becomes H-dominated at altitudes greater than 1200 km.

With an exobase temperature of 1000 K, consistent with Earth’s oxygen-dominant exobase (Kameda et al., 2017), Figure 5.4c shows the resulting Chamberlain profile. The modelled Chamberlain profile matches well with previous observations of Earth’s geocorona (Baliukin et al., 2019; Kameda et al., 2017), though the model places the exobase at a slightly higher altitude compared to the actual exobase altitude of 500 km. H diffusion limits the escape to $1.43 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$, consistent with Earth’s diffusion-limited escape flux (Joshi et al., 2019), and corresponding to a mass loss rate of 0.86 kg s^{-1} . In the hydrodynamic case, the escape is diffusion limited with a mass loss rate of $2.4 \times 10^2 \text{ kg s}^{-1}$. With an outflow temperature of 3000

K, the resulting H outflow profile is shown in Figure 5.4c.

In the Jeans escape regime, the Chamberlain profile was used to simulate the Lyman- α transit shown in panel d, resulting in a maximum transit depth of 4.9×10^3 ppm, or 0.49%. Since atomic velocities were capped at a maximum of 25 km s^{-1} , the wings of the Lyman- α line are not significantly broadened. The outflow in the hydrodynamic regime produces a maximum transit depth of 3.9×10^4 ppm, or 3.9%. The velocities calculated by *Sunbather* result in greater Doppler broadening compared to the Jeans case, with the Lyman- α wings extending from approximately -30 km s^{-1} to 30 km s^{-1} , as shown in Figure 5.4d.

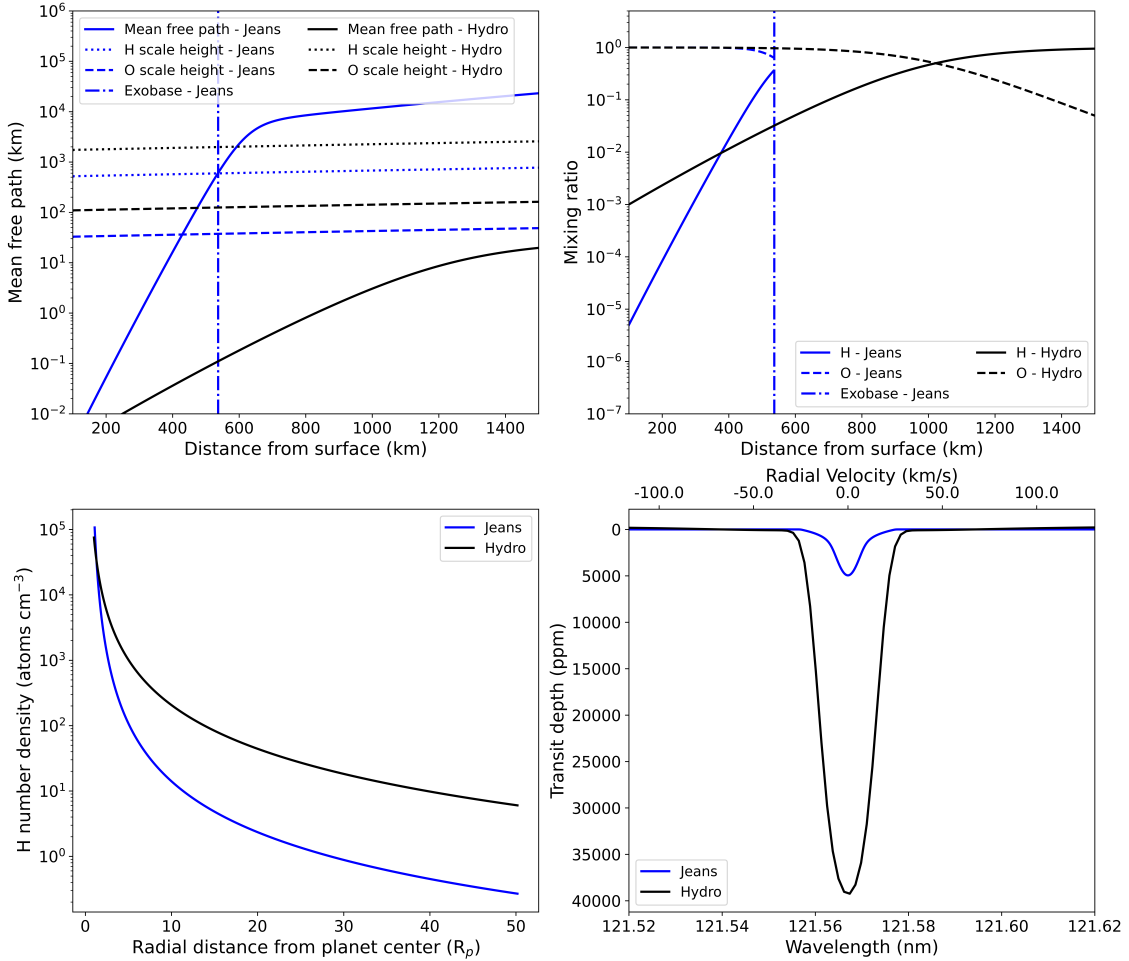


Figure 5.4: (a) The mean free path of the atmosphere based on the molecular diffusion of H and O used to calculate the exobase altitude. In the Jeans escape regime, the exobase is denoted by the dash-dotted blue line. In the hydrodynamic escape regime, no exobase is found and the atmosphere escapes hydrodynamically. (b) Mixing ratios of H and O in the upper atmosphere as a function of radius. (c) The radial number density of H in both regimes as a function of R_p (d) The associated Lyman- α transit depths.

5.3.2 Model Simulations: Population-level view

5.3.2.1 Escape Regime Results

Figure 5.5 identifies atmospheres which fall into either the Jeans escape or hydrodynamic escape regime based on the value of λ_{Jeans} evaluated at the exobase or the R_{XUV} level. The escape regime depends on the planet’s mass, the heterosphere temperature, and the H mixing ratio at the homopause. Of the 5000 sampled planets, 42% are predicted to be in the hydrodynamic escape regime and the remaining 58% are in the Jeans escape regime.

As shown in Figure 5.5a, hotter, lower mass planets are more likely to undergo hydrodynamic escape, while cooler, higher mass planets tend to be in the Jeans escape regime. If two planets are of equivalent mass and temperature, the H mixing ratio determines which regime the planets fall, shown in Figure 5.5b. A planet with a high H mixing ratio, above approximately 10^{-4} , will maintain a lower mean free path with radius compared to a planet with less H. When the mean free path stays small with radius, an exobase is not found in the model and the planet therefore falls into the hydrodynamic escape regime.

Figure 5.5c presents a density plot showing the individual contribution of each parameter on λ_{Jeans} . Heterosphere temperature has the greatest effect for determining the escape regime, with mass and H mixing ratio mostly affecting λ_{Jeans} when the mass is low and the hydrogen mixing ratio is greater than 10^{-4} .

5.3.3 Lyman- α Transit Depth Results

To assess whether observing a Lyman- α transit can constrain atmospheric properties, Figure 5.6 presents the modelled transit depths as a function of planet mass, H mixing ratio, and heterosphere temperature for all planets in both escape regimes. The overall transits are potentially lower limits compared to a real-life scenario since we do not model beyond the planets’ Hill radii and neglect additional absorption from an H tail. However, note that the maximum depth of each modelled transit is reported here. As described in Section 5.3.1, the hydrodynamic escape model self-consistently calculates outflow velocity, setting the broadening of the Lyman- α line. Faster outflows broaden the line and result in a shallower transit, whereas slower outflows yield deeper transits. In the Jeans escape regime, the exospheres are given similar velocity profiles, therefore the line widths are all very similar.

Across both panels in Figure 5.6, it is evident that H mixing ratio is the dominant factor controlling the transit depth of a planet, with high H mixing ratios generally producing a strong absorption. In such cases with abundant H, the escape rate is typically higher because it is not limited by the ability of H atoms to diffuse through the background gas, but is instead limited by either the temperature of the exobase in the

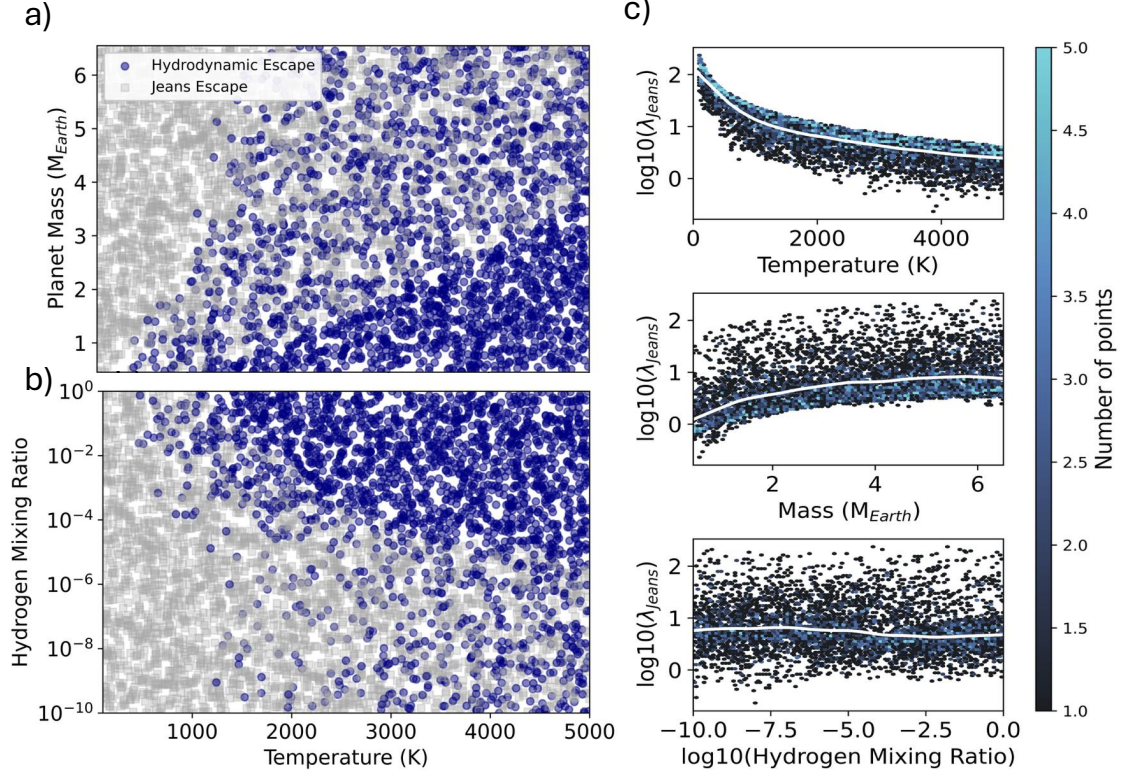


Figure 5.5: (a) Escape regime as a function of heterosphere temperature and planet mass, (b) Escape regime as a function of heterosphere temperature and H mixing ratio, and (c) a density plot showing the dependence of λ_{Jeans} on each variable.

Jeans escape regime or by the XUV irradiation in the hydrodynamic regime. Competing effects between heterosphere temperature and H mixing ratio can lead to similar Lyman- α transits. For example, a planet with a high heterosphere temperature of 5000 K, but a lower H mixing ratio (on the order of 10^{-3}) can produce a transit depth exceeding 10^5 ppm. Conversely, a planet with a lower heterosphere temperature of 1000 K can produce a similar 10^5 ppm transit depth once the H mixing ratio approaches unity.

Planet mass minimally affects the transit depth, shown in the left panel of Figure 5.6. The effect of H mixing ratio is much more significant than planet mass in the majority of cases.

Though the upper atmosphere temperature has only a marginal effect on the transit depth, the competing effect between temperature and H mixing ratio becomes more apparent in the Jeans escape regime (Figure 5.7), where the transit depth varies with exobase temperature. Here, at a fixed H mixing ratio, transit depths can span two to three orders of magnitude as the exobase temperature increases from 100 K to 1000 K. Even for atmospheres that are nearly pure H, low exobase temperatures produce only modest signals that are typically no more than a few thousand ppm.

In the hydrodynamic escape regime, the dependence of transit depth on temperature is more subtle. Holding all other atmospheric properties constant, a lower outflow temperature will result in a larger transit

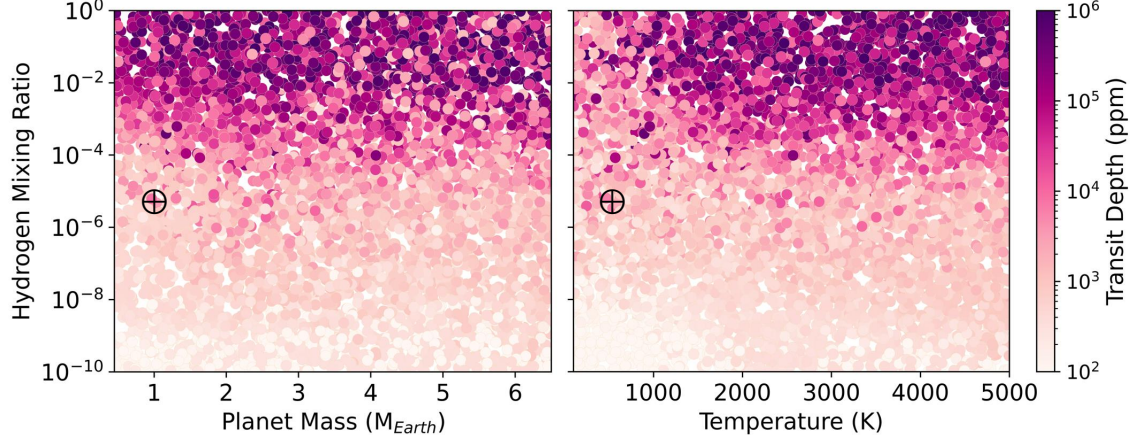


Figure 5.6: Lyman- α transit depths as a function of H mixing ratio, planet mass, and heterosphere temperature for planets in both escape regimes. The black markers indicate Earth-like values for mass, temperature, and H mixing ratio. The H mixing ratio is the most significant factor controlling the transit depth in both panels.

depth. Specifically, a transit for an atmosphere escaping with the minimum outflow temperature of 2000 K will be approximately $6\times$ deeper than the same atmosphere escaping with the highest outflow temperature of 9000 K. The bulk velocity of the atoms is higher at higher outflow temperature, causing the Lyman- α line to broaden and become shallower. Conversely, slower-moving atoms at lower temperatures result in deeper, narrower transits. Transit depth variations on this order are not apparent in Figure 5.7 due to the logarithmic color scale.

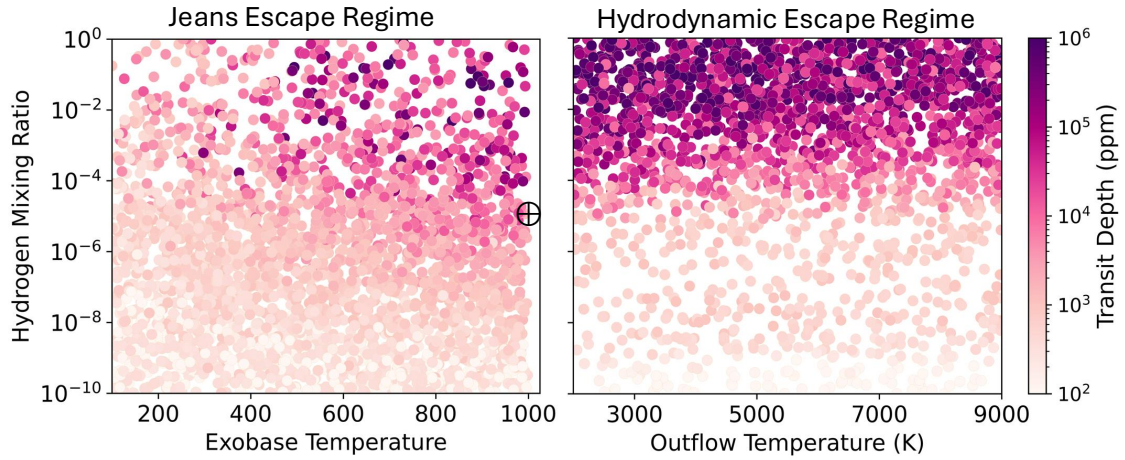


Figure 5.7: Lyman- α transit depths for Jeans escape regime planets (left) and hydrodynamic escape regime planets (right), based on the H mixing ratio, exobase temperature, and isothermal Parker wind outflow temperature. The black marker on the left panel indicates Earth-like values for H mixing ratio and exobase temperature.

Assessing the influence of each parameter on the transit depth individually in Figure 5.8, it becomes apparent that the factor with the largest influence on the transit depth is the H mixing ratio of the atmosphere. Individual variables can have an additional influence on the transit depth, with variations typically between

one or two orders of magnitude. For example, on the individual planet level, parameters such as the exobase temperature may have a large 2-order magnitude impact on the transit depth. However, when considering the whole population of planets, the H mixing ratio establishes the baseline transit depth, while the remaining factors impose smaller variations.

A notable feature of Figure 5.8 is the concentration of transit depths between ~ 100 -1000 ppm, indicated by the high-density blue regions. These cases typically represent planets that have very little escape — for instance, high-mass planets with low exobase temperatures. Despite a weak outflow, enough H diffuses upward from the homopause to produce a small absorption in the line core. Consequently, even planets that begin with low H mixing ratios at the homopause can be H dominant by the escape level.

5.4 Discussion

5.4.1 Effect of photoionization on the Lyman- α transit depth

Photoionizing radiation from the host star will dampen a planet’s transit signal by ionizing the escaping H atoms, which can no longer absorb Lyman- α photons. The importance of considering photoionization on the Lyman- α transit depth has been explored in detail in both observations (Bourrier et al., 2018; Ehrenreich et al., 2015) and modelling studies (Bourrier et al., 2016; Owen et al., 2023; Schreyer et al., 2024).

Figure 5.9 shows the Lyman- α transit depth as a function of H mixing ratio, distance to the star, and photoionization rate. Distance and photoionization rate are linked in this work because all modelled planets orbit the same star, GJ 436. Consequently, a planet with a smaller semi-major axis will receive photoionizing flux at a higher rate than a planet with a larger semi-major axis, with a $1/r^2$ dependence. From Figure 5.9, it is clear that planets orbiting closer to their host stars, and therefore receiving more ionizing radiation, have a smaller transit signal than those further from the host star. Though the photoionizing flux can make a 1 to 2 order of magnitude difference in transit depth at the highest rate, the H mixing ratio remains the most influential factor controlling the transit depth.

It is important to keep in mind when assessing Figure 5.9 that the escaping H is modelled out to either a ratio of R_{star}/R_p or the planet’s Hill radius, depending on which is smaller. Planets orbiting closely to their star have a small Hill radius, on the order of a few planetary radii, whereas planets orbiting further away have very large Hill radii, and the escaping H is modelled out to $\sim 100 R_p$. Therefore, the trend shown in Figure 5.9, where short-period planets have lower transit depths, can partly be a modelling artifact caused by the size of the H cloud available to absorb Lyman- α photons, which consequently produces a smaller signal.

Figure 5.10 shows the ionized-H fraction as a function of radial distance from the planetary surface for

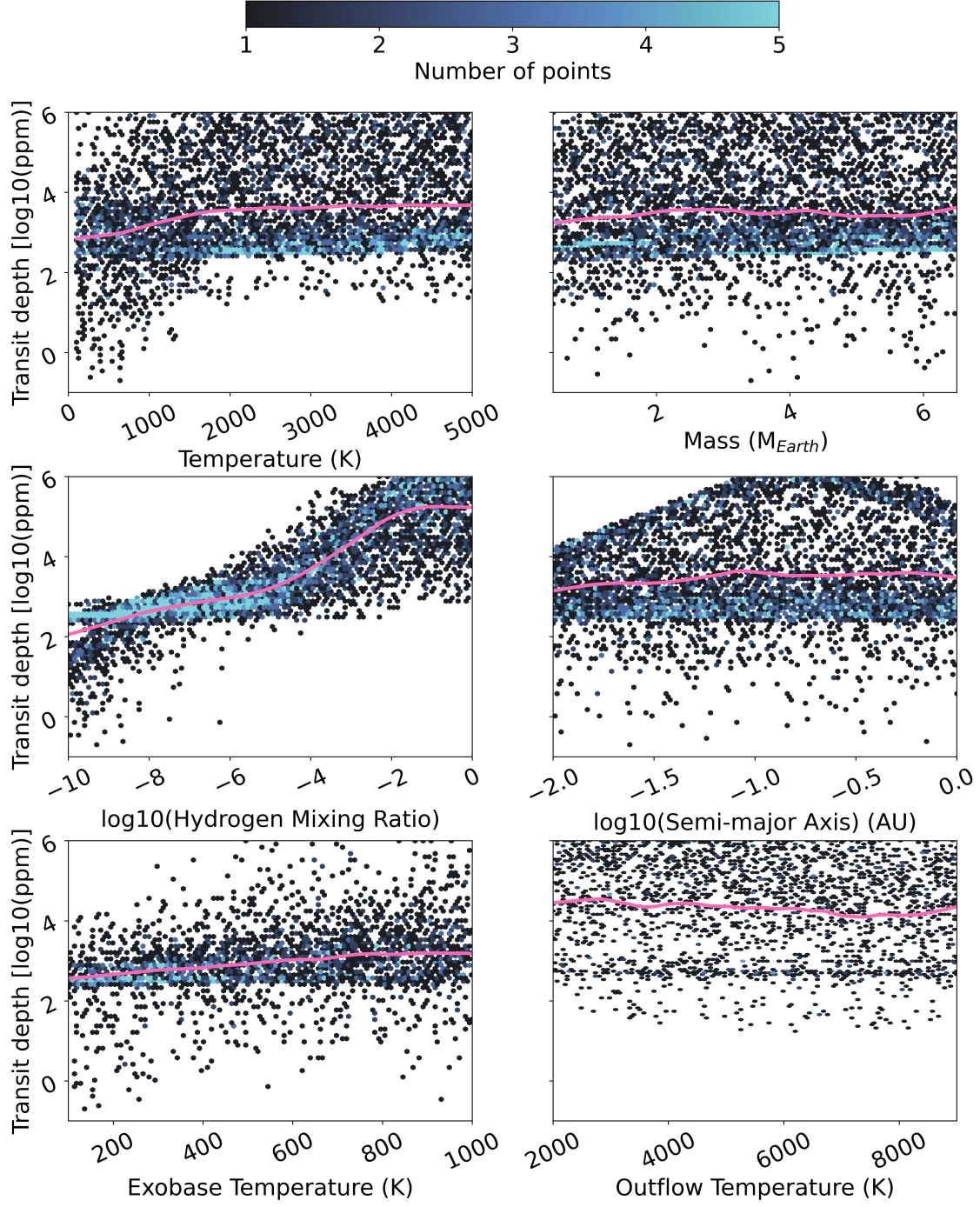


Figure 5.8: Density plot showing the dependence of transit depth on heterosphere temperature, planet mass, H mixing ratio, semi-major axis, exobase temperature in the Jeans regime, and outflow temperature in the hydrodynamic regime. The pink line indicates the locally weighted regression with a smoothing fraction of 0.2 to show variations in the transit depth trend.

planets orbiting at a range of distances around GJ 436 (upper panel) and HD 97658 (lower panel), which is a K1V-type star. For GJ 436, planets located between 1 and 0.1 AU retain nearly all neutral H, allowing Lyman- α photons to be absorbed. At a semi-major axis of 0.01 AU, the photoionizing radiation emitted from

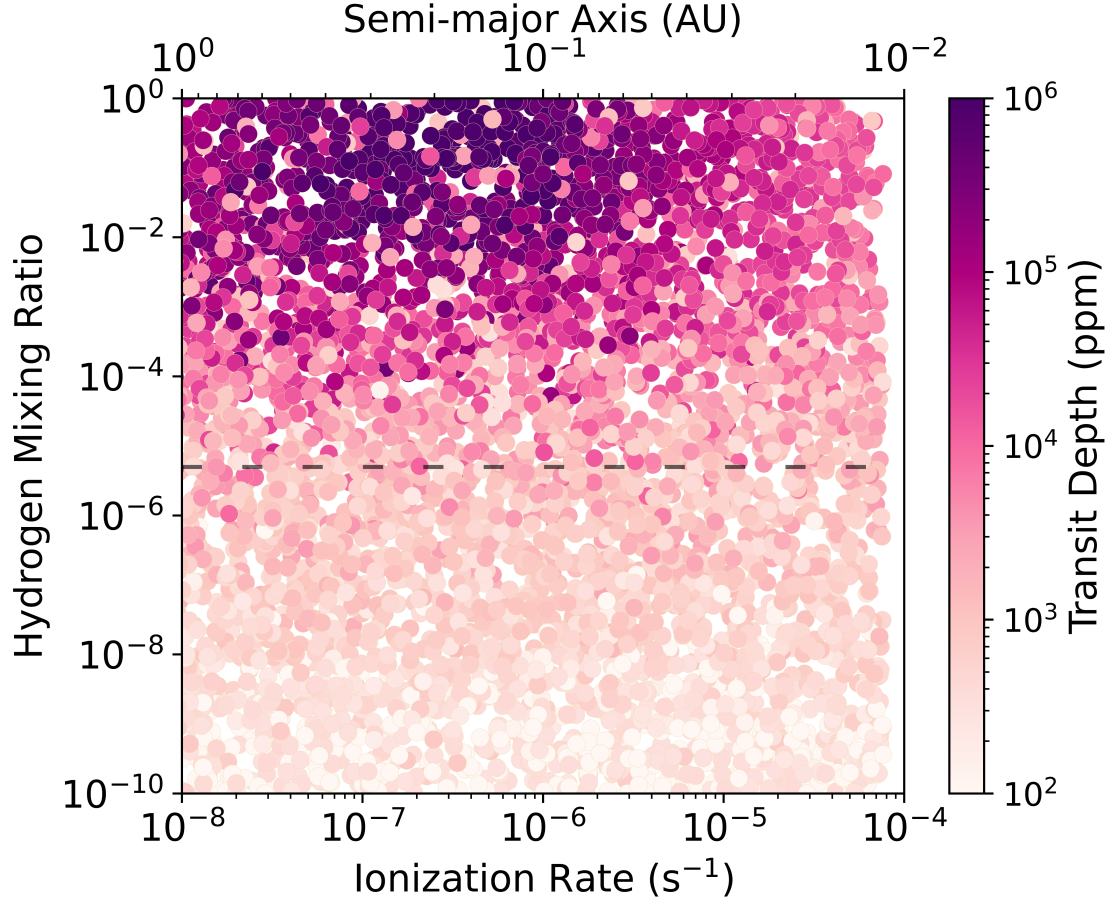


Figure 5.9: Lyman- α transit depths as a function of H mixing ratio, stellar ionization rate (bottom axis) and orbital semi-major axis (top axis). The dashed line indicates an Earth-like hydrogen mixing ratio.

GJ 436 is strong enough to ionize nearly all H atoms past $\sim 50 R_p$. At this orbital distance, the Hill radius, which is used in this work to truncate the outer boundary of the H cloud, varies from approximately $2.5 R_p$ to $5 R_p$, depending on the mass of the planet. Even at these very small Hill radii, the ionization fraction is between 20% — 40%, respectively. If the escaping H was not truncated at the Hill radius, the total neutral H column could be somewhat larger, potentially increasing the predicted transit depth. However, the steep rise in ionization fraction with radius indicates that truncation at the Hill radius does not significantly impact the resulting Lyman- α transit depth.

The lower panel of Figure 5.10 shows a star with a higher photoionizing flux, HD 97658, where the ionized H fraction is significantly larger at smaller radii from the planet. A planet orbiting at 1 AU would still retain the majority of the neutral H, as in the GJ 436 case, however the ionized fraction is significantly increased for a planet orbiting at 0.1 AU. At 0.01 AU, all H is fully ionized almost immediately upon escaping from the atmosphere. Under these conditions, a planet may experience a very high mass-loss rate while producing

no detectable Lyman- α transit signature because neutral H cannot survive long enough to absorb Lyman- α photons. This behavior is consistent with the non-detection of a Lyman- α transit for HD 97658 b (Bourrier, Ehrenreich, King, et al., 2017), which orbits at 0.08 AU and is likely subject to a strong photoionization environment.

It is interesting to consider the competing effects of mass-loss rate and ionization fraction for planets undergoing hydrodynamic escape. As orbital distance decreases, the rising XUV irradiation enhances the atmospheric escape rate, as long as the outflow is not diffusion limited, which increases the amount of neutral H available to produce a deeper Lyman- α transit. At the same time, the stronger ionizing flux more efficiently removes neutral H, reducing the observable signal. For planets orbiting stars with relatively weak photoionization, the boost in mass-loss rate can outweigh the simultaneous increase in ionization, allowing a detectable transit to persist. In contrast, planets around stars with strong ionizing fluxes will have their H atoms ionized so rapidly that even large escape rates cannot compensate, suppressing the Lyman- α transit signature.

5.4.2 Detectability of Lyman- α transits and Applications to Exoplanetary Systems

This work evaluates the feasibility of characterizing rocky exoplanet atmospheres from their Lyman- α transit signatures. In Section 5.3, we show that the H mixing ratio at the homopause is generally the dominant factor governing the transit depth, while parameters such as temperature and photoionization rate tend to play a smaller role at the population level. Whether these trends can be applied to real systems ultimately depends on the detectability of the transits, particularly for planets with low H mixing ratios that may possess secondary atmospheres.

There are several barriers to detecting Lyman- α transits. First, the ISM can completely absorb stellar Lyman- α flux in the range of approximately -50 km s^{-1} to 50 km s^{-1} , removing access to the line core (Wood et al., 2005). As a result, nearly all Lyman- α transits detected to date rely on the blue wing of the line (e.g. Ehrenreich et al., 2015), where the H atoms are accelerated to large negative velocities by interactions with stellar winds and radiation pressure (Owen et al., 2023). Progress mapping the ISM is being made (Youngblood et al., 2025), improving the accuracy of reconstructed stellar Lyman- α lines.

A second limitation is that HST is currently the only UV telescope capable of observing Lyman- α at sufficiently high spectral resolution to detect planetary absorption. HST operates in Low Earth Orbit, introducing contamination from Earth’s own H exosphere, though processing exists to remove this contamination (Cruz Aguirre et al., 2023). For Lyman- α observations, the Space Telescope Imaging Spectrograph (STIS)

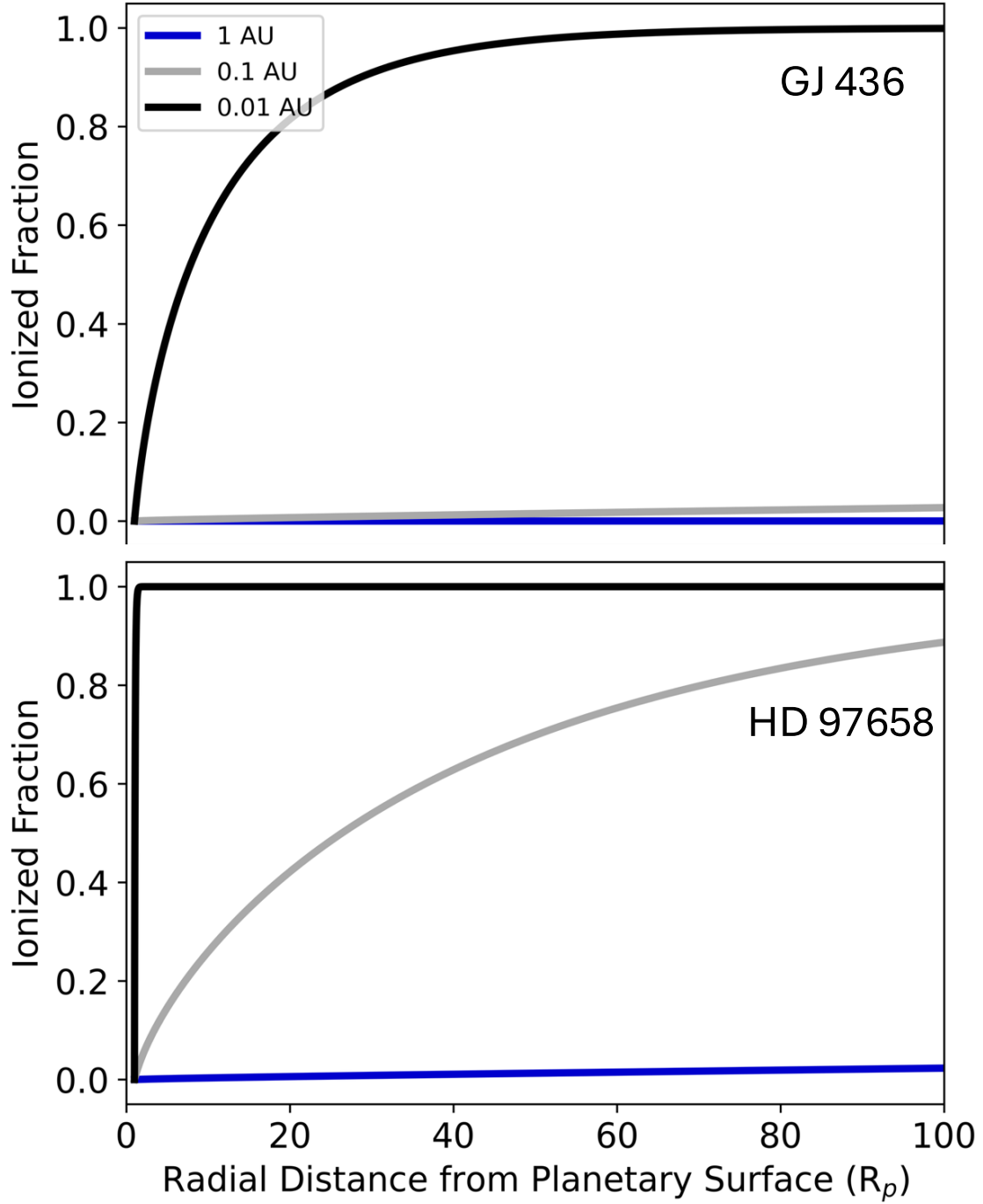


Figure 5.10: Ionized H fraction as a function of radius for planets orbiting at 1 AU, 0.1, and 0.01 AU around GJ 436 (top panel) and HD 97658 (bottom panel).

with the G140M grating has a throughput of $\sim 1.5\%$, corresponding to an effective area of $\sim 680 \text{ cm}^2$ near 121.6 nm (L. A. d. Santos et al., 2019). This relatively small effective area makes the detection of transits around dimmer stars challenging.

Figure 5.11 illustrates the number of transits needed to achieve a signal-to-noise ratio (S/N) of 5, using the

formalism of Castro et al., 2018 and the effective area for HST/STIS. Each panel in Figure 5.11 corresponds to a star with a different peak intrinsic Lyman- α flux between 10^{-13} and 10^{-15} $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, representative of typical M dwarf fluxes observed from Earth (Youngblood et al., 2016). Note that the S/N threshold of 5 is applied only to the peak transit depth at the line core, and, therefore, the S/N on the wings would be lower because both Lyman- α flux and absorption depth decrease away from the line center. Though the line center is typically obscured by ISM absorption, it can be Doppler shifted out of the peak ISM absorption region for stars with high radial velocities, allowing access to these core wavelengths (Peacock et al., 2025).

Overall, Figure 5.11 demonstrates that detecting escaping H from rocky planets with HST is challenging. At the lowest flux levels, only planets with transit depths exceeding 10^5 ppm (i.e. upwards of 10%) are detectable within 10 or fewer transit observations at our S/N threshold. At the highest stellar flux, planets with transit depths of 10^4 ppm (1%) can be observed with 10 or fewer visits. Comparing with Figures 5.6 and 5.7, the detectable cases correspond to Jeans escape atmospheres with high H mixing ratios and high exobase temperatures, or hydrodynamic escape atmospheres with H mixing ratios $> 10^{-4}$. Despite only 42% of the 5000 modelled planets undergo hydrodynamic escape, up to 59% of these planets are detectable in under 10 transits at highest stellar flux value, whereas only 7.2% of the planets in the Jeans escape regime reach the same detectability threshold.

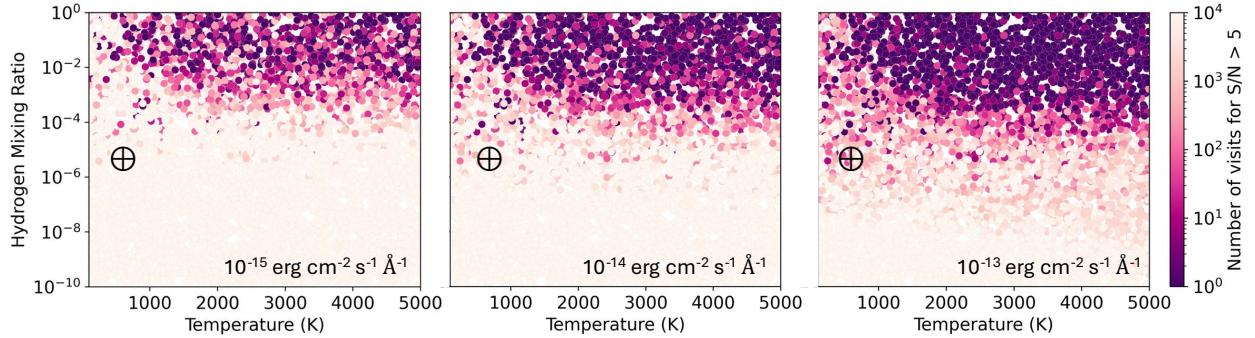


Figure 5.11: The number of transits needed to observe each planet in Lyman- α at a S/N of 5 with HST/STIS, as a function of H mixing ratio and temperature. Each panel corresponds to a peak stellar Lyman- α flux from 10^{-13} and 10^{-15} $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$. The black markers indicate Earth-like values for H mixing ratio and temperature. Only transits $> 10^5$ ppm for the dimmest stars are observable in 10 or fewer transits, however future telescopes may be able to detect transit depths of 10^4 ppm with 10 or fewer transits.

Adopting UV telescope parameters with a much larger effective area increases the detectability. For an effective area of $130\,000 \text{ cm}^2$, based on previous estimates of the LUVOIR telescope concept (see L. A. d. Santos et al., 2019 for details), the minimum transit depth needed to reach a S/N of 5 at all flux levels decreases by approximately one order of magnitude. At a stellar flux of 10^{-15} $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, transit depths of 10^4 ppm can be detectable, while around a brighter star with a 10^{-13} $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ flux, transit depths as low as 1000 ppm can be measured. This detection threshold probes a large range of the parameter

space, such as Jeans escape planets with H mixing ratios as low as 10^{-6} at high exobase temperature and 10^{-4} at lower exobase temperature. From our Earth-like Jeans escape example in Figure 5.4, an Earth analogue would be detectable in fewer than 10 transits.

In the current technological era, rocky planets in the hydrodynamic escape regime remain the best targets for Lyman- α transit observations. These planets typically produce a deeper transit depth than planets in the Jeans escape regime, in part because the outflow temperature has a smaller role than the exobase temperature in shaping the transit signal. As shown in Figures 5.9 and 5.10, the semi-major axis of a planet must be well-balanced, where the planet is close enough to receive sufficient XUV heating to sustain hydrodynamic escape, yet not so close that the upper atmosphere is fully ionized. Simultaneously, shorter orbital periods are favorable, as more transits can be observed in a reasonable time.

Importantly, an entire class of rocky planets may lie within the range of currently detectable Lyman- α transits: those hosting water-vapour-dominated atmospheres inside the runaway greenhouse limit (Ingersoll, 1969; Kasting, 1988). Planets in this regime are expected to transport substantial H_2O to the upper atmosphere, where photolysis can lead to H-enriched upper atmospheres above the homopause (R. D. Wordsworth & Pierrehumbert, 2013), and thus result in strong Lyman- α absorption. Our results suggest that rocky planets residing within the runaway greenhouse limit, particularly those with moderately warm upper atmospheres, should more readily satisfy the conditions for detectable Lyman- α transit absorption with HST, potentially producing a large increase in observable signals near the runaway greenhouse threshold.

Additionally, rocky planet targets orbiting stars with large radial velocities should be prioritized. When the Lyman- α line core is not accessible, observations are restricted to the blue wing, which primarily traces the interaction of the escaping H with the stellar environment (Owen et al., 2023; Schreyer et al., 2024). Targeting stars with high radial velocities that shift more of the intrinsic line core into view allows us to probe the H outflow/exosphere without the secondary interaction with the stellar environment.

Lastly, multi-wavelength observations can help break degeneracies when observing a Lyman- α transit. For example, a planet in the Jeans escape regime exhibiting a shallow transit may be interpreted as a H-poor planet. However, observations at longer wavelengths that reveal a high CO_2 abundance would indicate strong radiative cooling in the upper atmosphere, suggesting the planet may have a higher H mixing ratio but cool exobase temperature. In addition, observing the metastable helium triplet at 1083.3 nm would be extremely informative. If both escaping H and He were observed, the planet would very likely be in the hydrodynamic escape regime, as the typical temperatures associated with Jeans escape are too low to produce strong helium absorption signatures (Kirk et al., 2020). The width of the helium absorption feature would give insight into the temperature of the escaping atmosphere. These multi-wavelength observations put additional constraints on the system, helping to further characterize the atmospheres.

5.4.3 Impacts of hydrogen-only escape

This study considers planets with atmospheres ranging from theoretical secondary atmospheres, containing very little H, to H-dominated envelopes. By design, only H is permitted to escape, as described in Section 5.2. This restriction is justified because H is the primary species responsible for producing Lyman- α transit signatures, which is the main purpose of this work. In the Jeans escape regime, the exobase temperatures considered are too low for additional species to escape with H in any consequential manner. In the hydrodynamic escape regime, limiting the model to H-only escape simplifies the calculations by allowing the outflow to be modelled as an isothermal Parker wind, therefore avoiding uncertainties associated with multi-species hydrodynamic escape and ensuring that the results directly correspond to the observable transit signal.

Despite these justifications, H-only escape can influence the results presented in this work. First, by restricting the mass-loss rate to always be lower than the cross-over flux (Equation (5.6)), we are potentially underestimating the mass loss in certain cases. For instance, diffusion-limited escape rates are often lower than the energy-limited rates, particularly for close-in planets. In reality, these planets, upon very high heating, may reach a regime where the background gas is no longer static and is able to escape with the H, contributing to a much higher mass-loss rate ultimately constrained by the XUV energy. These mass-loss rates could be very different than those predicted in this study, which could result in a deeper Lyman- α transit.

Additionally, restricting heavier species from escaping alters the compositions of the outflow. For a given mass-loss rate, if metals are present, the temperature structure of the outflow can be altered significantly (Huang et al., 2023; Koskinen et al., 2013; D. C. Linssen & Oklopčić, 2023), which ultimately impacts the density and velocity outflow structures. In the outflow, radiative cooling by heavier molecules can significantly reduce the radial extent to which H escapes Yoshida et al., 2024, suppressing a Lyman- α transit depth.

5.4.4 Using Lyman- α transits to probe the lower atmosphere

As demonstrated in this work, observing a planet’s Lyman- α transit can constrain the mixing ratio of H at a planet’s homopause within a couple orders of magnitude. This gives important insights into the potential nature of the atmosphere, particularly when determining if a planet has a secondary atmosphere and estimating its potential composition. For example, extremely large transits are typically only possible with H mixing ratios exceeding 10^{-3} , indicating the planet has an upper atmosphere that is H-dominant, while a shallower transit may imply that H is a minor atmospheric constituent and the mean molecular weight of the atmosphere is higher.

To link the Lyman- α transit to the composition of the lower atmosphere below the homopause to the

surface, additional physical and chemical modeling is required. For instance, Earth's homopause has an approximate H mixing ratio of 10^{-5} , despite abundant water at the surface, due to the atmospheric cold trap at the boundary of the troposphere and stratosphere (Danielsen, 1982). Observing Earth's Lyman- α transit and inferring an H mixing ratio of 10^{-5} could misleadingly suggest that Earth is water-poor. Whole atmosphere models with processes such as photochemistry and vertical mixing are required to assess how the atmospheric composition below the homopause influences the Lyman- α transit depth. We leave this interesting challenge to future work.

Chapter 6

Conclusions

This dissertation consisted of four projects examining radiative transfer processes in the atmospheres of Mars and rocky exoplanets to better understand planetary climate and habitability. Together, these studies demonstrate how interactions between radiation and the atmosphere influence planetary environments, from controlling atmospheric dust distributions and microbial survival on Mars to driving atmospheric escape from rocky exoplanets. The following sections summarize the key findings of each project.

6.1 Dust Dynamics and Lifting in Gale Crater Observed by the Curiosity Rover

In Chapter 2, we used Curiosity Rover Navcam images of the northern crater rim of Gale Crater, spanning over 3600 sols, to calculate the dust loading in the crater. For the first time, a new method was developed to calculate the dust extinction which included the ratio of sunlight on the crater rim in comparison to the near-field ground as well as the direction of the sun’s rays in the image. We updated the previously published LOS extinctions using this new method and added an additional 1000 sols of data, extending the record through the end of MY 36.

The LOS extinctions saw minimal interannual variability, with MYs 35 and 36 following the same trend as prior MYs. During the southern autumn, the extinction begins to decline, reaching a minimum around $L_s = 100^\circ$. After the minimum, the extinctions begin to rise steadily until a maximum is reached near the southern summer between $L_s = 270\text{--}300^\circ$. The extinctions then begin to drop again. There was a small amount of variability in the minimum extinctions seen year-to-year, with the minimum extinction increasing between MYs 33 to 35; however, in MY 36, the minimum dropped back down to levels observed in MY 33.

For the first time, a diurnal trend in LOS dust extinctions was investigated. Through each season, the extinctions observed in the morning were lower and gradually rose to a maximum near solar noon before declining in the evening. Though this was seen consistently throughout the year, the dusty season saw a more pronounced difference in extinctions over the sol. An increase in dust lifting frequency has been observed at

local noon (Guzewich et al., 2023), which may, in part, cause the increase seen in the dust extinction during this period. Additionally, Guzewich et al. (2023) saw an increase in dust lifting activity in the southern summer, which aligns with a larger variation in the diurnal LOS extinction in the southern summer compared to the winter. Pressure changes within Gale Crater driven by atmospheric tides, potentially responsible for a diurnal trend in the Mastcam column opacities (Lemmon, Campbell, et al., 2024), may also play a role in the diurnal LOS extinction trend.

In this analysis, the extinctions on the center, east, and west of the frame were reported in addition to the average extinctions. In the morning, the extinctions were typically higher on the western side of the frame, with lower extinctions on the central and eastern sides. At noon, the western side of the frame continued to show higher extinctions, with the inhomogeneity more pronounced in the dustier season. In the evening, the extinctions were often extremely close in value across the image frame, with a couple of instances of high eastern extinctions, suggesting that by the evening the crater had become well-mixed. Due to the unevenness in illumination in the sky in the morning and evening, the extinctions may be influenced by such illumination. However, at noon, the illumination across the sky and crater is even, with some unevenness in ground illumination due to local topography, but the strong preference for higher western extinctions indicates a generally higher dust loading in that region.

Ultimately, Chapter 2 shows that there are dust dynamics occurring within Gale Crater on smaller timescales than those reported in prior LOS extinction studies. Not only is dust increasing and decreasing as a function of season but throughout the day and with geographic inhomogeneities that become well-mixed by the evening. Additionally, comparing the LOS extinctions to the Mastcam column opacities shows that a combination of dust-lifting from the surface and vertical mixing between the air inside and outside the crater contributes to the dynamicism occurring within the Gale Crater, particularly around $L_s = 270\text{--}300^\circ$ when the dust extinction within the crater is higher than outside the crater.

In Chapter 3, the record of dust devil events observed with the rover’s Navcam were analyzed to uncover trends in optical depth with season, time of sol, and location of the rover. This allows us to better understand the link between dust devils and the dust-loading trends in Gale Crater reported in Chapter 2. In addition, we compared the trends in dust devil optical depth to the REMS pressure drop catalogue.

Seasonally, dust devil optical depths were shown to be the lowest in the southern winter and increased into the southern summer, with a local minimum around $L_s = 250^\circ$. A fair amount of interannual variability was present, with MYs 33, 35, and 37 having a larger number of high optical depth dust devils than MYs 32 and 34. During the MY 34 global dust storm, the dust devil optical depths were low, and returned to seasonal values after the end of the storm.

Diurnally, dust devil optical depths were shown to be low in the morning, to increase to a maximum in the

period between 11-13 LTST, and to decrease into the evening, providing a mechanism to explain the extra dust in the lower layer of the atmosphere as observed in Chapter 2. When examining the diurnal trend in the percentage of dust devils with high optical depth, the period between 13-14 LTST was the time of sol with the highest percentage of high optical depth, though the actual raw count of high optical depth dust devils at this time is much lower than between 11-13 LTST. These results suggest that the diurnal LOS extinction trend observed in Chapter 2 is caused more by the increased frequency of dust devils observed at local noon (Guzewich et al., 2023), rather than each event picking up more dust.

When compared to REMS pressure drops, the time of day with the largest number of pressure drops (11 – 13 LTST) is consistent with the time of the highest frequency of dust devils. However, the percentage of large pressure drops does not fully align with the pressure of high optical depth dust devils, suggesting another mechanism must be present for dust devils to have high optical depths. When examining optical depth trends with rover location, the highest optical depth dust devils occur in low thermal inertia, sandy locations, such as the Bagnold Dunes and the Sands of Forvie. These results suggest such a combination of large convective pressure drops and saltation are required to kick up dust from the surface, generating dust devils with high optical depths.

6.2 The Mars Microbial Survival Model for Estimating the Forward Contamination of Mars

The effects of several biocidal factors — both during cruise and on the surface of Mars — were modeled in Chapter 4 to generate an MMS model to predict short- and long-term survival of Earth microorganisms present on spacecraft at launch. The MMS model was based on published data for *B. subtilis* spores exposed to diverse and interactive biocidal conditions found on the Martian surface. During the cruise phase, solar UVC was the main factor responsible for reducing microbial bioburdens on cruise aeroshells, causing several thousands of log reductions on the Opportunity spacecraft, which had the shortest cruise to Mars and quickly sterilizing the external surfaces of its aeroshell. The effects of vacuum alone contributed small bioburden reductions for internal components of all spacecraft during the cruise phases of the missions.

Once on the surface, robotic landers are freed from their aeroshells and deployed on the surface. Within the first 24 hour of each mission, flat, Sun-facing surfaces were likely to have bioburden reductions of at least 1 SAL (-12 logs). Vertical surfaces facing north, east, south, and west did not all reach 1 SAL after the first 24 hr. However, within one Mars year, every surface of each lander would have been effectively sterilized by UVC irradiation, even on shaded surfaces and underneath the landers. If microbes were dislodged from

the lander during the EDL phase and covered by regolith, UVC was modeled to be less effective at reducing the bioburdens, depending on the sizes of the regolith grains. Regolith with smaller particles ($<350\ \mu\text{m}$) reduced the UVC such that the microbes may survive under the surface for much longer than those that are not as effectively shielded by larger grain sizes. Dust on the rover itself reduces the UVC that reaches the rover surfaces; however, even with moderate dust coverage, each surface achieved at least 1 SAL before a sufficiently thick layer of dust accumulated to reduce the UVC fluence rates on spacecraft surfaces.

Within the lander itself, the synergism between low pressure and high temperature likely had the strongest biocidal effect. If internal components were held at 273 K, 1 SAL was likely accumulated after 100 sols. Lowering the temperature, however, increased the time to sterility. For microbes that were at approximately 210 K (such as those on spacecraft that crashed or had a short mission duration), low pressure would be the dominant biocidal factor. To reach 1 SAL from low pressure alone, the microbes would have had to be on the surface of Mars for 25 Mars years.

For bioburden reductions under regolith, biotoxic soils may contribute to quicker sterilization rates. However, the spatial variability and varied concentrations of the biotoxic chemicals mean that biotoxic soils likely only had a small contributing effect on the bioburden reductions modeled here. It is plausible that Earth microorganisms are present on some internal surfaces of a few spacecraft — with the exception of the Mars 2, 3, and 6 landers — due to the amount of time required to accumulate 1 SAL under non-UVC exposed and low-temperature conditions.

The MMS model predicts very low survival rates for bioburdens on both cruise-phase aeroshells and landed spacecraft at each of the 14 landing sites examined. All external spacecraft surfaces were likely sterilized by UVC alone, with small contributions from other biocidal factors. The bioburdens on the internal surfaces of spacecraft will mostly likely be reduced by temperature and low-pressure effects acting synergistically, although it might take up to 25 years for sterility when considering low pressure alone.

While maintaining high planetary protection standards is crucial for successful Mars science missions, we estimate that only a very small number of microorganisms on cold internal surfaces of spacecraft might persist for several decades on Mars. These results suggest we have very little chance of contaminating the Martian surface, and therefore can send spacecraft to special regions of astrobiological interest.

6.3 Characterizing Rocky Planet Atmospheres with Lyman- α Transit Observations

By modelling the escape of H from atmospheres in the Jeans and hydrodynamic escape regimes, we have shown that Lyman- α transits can be used to constrain the H mixing ratio of an atmosphere, giving insight into the potential presence of a secondary atmosphere. Within the parameter space explored, we saw that colder, higher-mass planets fall into the Jeans escape regime, while hotter, lower-mass planets undergo hydrodynamic escape. Within both regimes, the H mixing ratio at the homopause had the largest effect on the transit depth, with temperature, planet mass, and photoionization introducing variations on the order-of-magnitude level. In the Jeans escape regime, the influence of the exobase temperature is more significant than the effect of the outflow temperature in the hydrodynamic escape regime.

Our findings suggest that with current telescope technology, planets in the hydrodynamic regime provide the best targets to observe a Lyman- α transit. These planets, particularly when they are in the energy-limited regime, produce very large transit signals. With HST, only transits between ~ 1 to 10% at the line core, depending on the brightness of the star, are observable. However, with future UV telescope technology, Earth-like planets with small H mixing ratios that produce transits on the order of 0.1%, can be detected, giving insight into planets with secondary, potentially water-rich atmospheres. Targeting planetary systems with a high systemic radial velocity is crucial to ensure access to the Lyman- α line core.

Future modelling efforts that include atmospheric escape of species heavier than H would help probe the additional effects on the Lyman- α transit. For example, when heavy species are included, an isothermal Parker wind may no longer be valid; future studies may assess what impact this has on the Lyman- α transit. Additionally, a whole-atmosphere model that links the surface to the escape region, combined with additional physics such as photochemistry and vertical mixing, is essential for connecting lower-surface composition to upper-atmospheric escape. Currently, our results show that observing the Lyman- α transit can constrain the H mixing ratio down to the homopause.

Overall, our results show that the Lyman- α transit can be a powerful tool for probing the upper atmospheric H content of rocky exoplanets with secondary atmospheres. Though various combinations of parameters can produce similar transit depths, H mixing ratio can be constrained within a couple orders of magnitude by observing a Lyman- α transit, allowing H-rich and H-poor planets to be distinguished. Future technology, especially when combined with multi-wavelength observations, will allow us to place constraints on the H content of a wide range of secondary atmospheres.

Chapter 7

Future Work

7.1 Expanding the LOS Dust Extinction Observation with Connections to Dust Lifting

The LOS dust extinction observation has used a single-frame Navcam image pointed at Gale crater’s northern rim for several thousand sols of the MSL mission. The first method for better characterization of dust-loading in Gale Crater as a whole involves expanding the field of view of these images to capture a wider swath of the crater rim. Expanding the observation horizontally gives insight into the spatial transport of dust around Gale Crater, which crucially can be used to validate general circulation models of the region, for which validation is currently limited due to the rover’s broken wind sensor. To address this, a wider LOS extinction observation has been developed and implemented on the rover, consisting of four Navcam images with overlapping boundaries that can be stitched together into a mosaic, thereby capturing a broader section of the crater rim. In addition, any images taken throughout the mission that include the ground, crater rim, and sky may be used to derive LOS extinctions, adding scientific value to previously-captured images.

Though Chapter 2 updated the LOS extinction method to allow for observation at times outside of the 10-14 LTST window by accounting for changes in illumination, these updates may be insufficient for deriving the LOS extinction at pointings very far from north. As such, to derive the LOS extinction over the entire crater rim, an updated method including a 3D radiative transfer model must be implemented. By recreating the scene in Gale Crater, adding dust into the model until the radiances in the model output match the radiances in the Navcam image, the amount of dust-loading in any image can be derived.

The expansion of the LOS dust observation complements the investigation in Chapter 3, analyzing the optical depths of dust devils in Gale Crater. First, continuing dust devil observations with Navcam is crucial for continuing to build the record of dust lifting for further characterization. As the rover drives over new terrain, calculating optical depths in areas of varying thermal inertia potentially validates the concepts discussed in Chapter 3 regarding the need for saltation to observe high optical optical depth dust devils. Additionally, since only one major dust storm has occurred throughout the MSL mission in MY 34,

our understanding of dust devil behaviour during these storms is lacking. Capturing the behaviour of dust devils during additional dust storms in the future can validate the current understanding of the shutdown of convective activity in the atmosphere. Lastly, if the LOS extinction is expanded horizontally, we may have a better understanding of major sources and sinks for dust in Gale Crater. Targeting those source regions with dust devil observations could then validate if dust loading in Gale Crater is driven more by the frequency of dust lifting events at a given time versus the amount of dust lifted by any single event.

Lastly, the results in Chapter 2 and 3 focus exclusively on the dynamics of dust in Gale Crater. While these findings provide valuable validation for local-scale models, a better understanding of the Martian dust cycle as a whole requires extending these investigations to other landing sites. For example, Jezero Crater sits above 18°N, where the seasonal cycles differ from Gale’s near-equatorial location. Variations in solar insolation and topology could have a large effect on dust-loading and lifting in Jezero Crater. By comparing temporal changes in dust extinction at Jezero with the observed frequency and magnitude of dust lifting, and contrasting these with the spatial and temporal variations observed in Gale Crater, a more complete understanding of dust transport on Mars can be achieved.

7.2 Next Steps for the Mars Microbial Survival Model

As mentioned in Chapter 4, the MMS model provides a first-order estimate of microbial survival on Mars. There are several important ways this model can be extended in the future to ensure a higher accuracy of modelling bioburden reductions, which would give increased confidence in the results that indicate there is a very small likelihood of forward contamination on Mars due to the highly biocidal nature of the environment.

One of the most crucial next steps involves increased laboratory measurements of microbial survival under Mars-analog conditions. In this study, only *b. Subtilis* is used, in part because *b. subtilis* serves as a proxy for other microorganisms. Due to its high resistance, its inactivation implies that less resistant microbes would be similarly inactivated. However, it is possible that other microbes may be less susceptible to the specific biocidal conditions of Mars. In addition, one of the biggest caveats of the MMS model concerns low-pressure effects, since the laboratory experiments included only two time points.. Microbes buried under dust or regolith would likely only be inactivated by low-pressure conditions, and therefore more laboratory experiments are needed to see if the inactivation from low-pressure changes over time, rather than linearly as suggested in the MMS model. These experiments could potentially alter the estimate for the longest surviving microbes, which we suggest could be up to 25 Mars Years.

Lastly, modelling the UVC irradiance on more intricate sections of the landers could be useful for determining the sterilization from UVC on mated surfaces. If microbes can be sheltered from UVC for prolonged

periods of time, this may effect our estimate that all external surfaces are sterilized within one Mars Year.

7.3 Further Investigations of Lyman- α Transit Observations to Characterize Rocky Exoplanet

The model used in Chapter 5 to simulate H escape from rocky exoplanets has been simplified in many ways, and future work can involve adding additional physics to this model.

Two of the main places where the model can be extended is by including additional species other than H and O at the homopause, allowing species other than H to escape, and relaxing the assumption of an isothermal atmosphere and outflow. As mentioned in Section 5.4.3, we allowed only H to escape to simplify the model and justify the use of an isothermal Parker wind. However, introducing additional species and allowing them to escape could potentially affect our results by changing the temperature structure of the outflow, thereby changing the Lyman- α transit depth. Additionally, if species other than H and O are included at the exobase, the results may vary due to the scale height of the atmosphere being altered depending on the mass of the species.

Another avenue for future work is to include additional interactions with the stellar environment. In this work, the transit is truncated at the Hill radius or the ratio of R_s/R_p and we do not consider the effects of interactions that could shape the H exosphere into a tail, as described in Owen (2019). Including these interactions could affect the results in several ways. Firstly, when considering the implications on detectability, the study would not be constrained to only stars with radial velocities that are shifted outside of ISM contamination. If we could carry out this same study, finding links between the Lyman- α transit and the atmospheric properties (such as H mixing ratio) when including additional stellar interactions, the possibilities for detectable planets become much larger.

Lastly on the modelling side, while we may be able to constrain H mixing ratio down to the homopause based on this work, we remain ignorant to the species further down in the atmosphere. For example, if we observed the Lyman- α transit of a planet with an Earth-like atmosphere, we may assume it is H-poor, due to the H mixing ratio being low at the homopause based on the relatively small transit depth. However, Earth clearly has abundant water on its surface and in its atmosphere, though most of it gets cold-trapped at the tropopause. A whole-atmosphere model that includes physics such as cold-trapping, photochemistry, and vertical mixing would be extremely advantageous for linking the near-surface atmosphere to upper atmosphere products, which can then be viewed during a transit. Implementing a whole-atmosphere model over a similarly wide parameter space and observing how this affects the Lyman- α transit depth could help

us determine if the low H mixing ratio at the homopause is due to a genuinely H-poor planet, or a planet that keeps H in the lower atmosphere, such as a potentially water-rich planet.

Finally, this work can be extended to the interpretation of observed Lyman- α transits. Currently, an ongoing program with HST called “STELa” (Loyd et al., 2024) is aiming to observe Lyman- α transits from ~ 12 planets with radii near the radius valley. Though many of these planets may be considered sub-Neptunes rather than rocky planets, having a large sample of transits helps to gain statistics on the factors influencing the Lyman- α transit, which is applicable to this work.

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Appendix A

Surface Phase Biocidal Factors References

Table A.1: Surface-phase Biocidal Factors Included in the Mars Microbial Survival Model

Mars Surface Biocidal Factor	Species	Mars Sims Log Reductions	Mars Sims Time Steps	Estimated UVC Flux (kJ m ⁻²)	References
Direct UVC beam (200–280 nm)	<i>Bacillus subtilis</i> HA101	[–] 6 logs	30 minutes	6.51	Schuerger et al. (2019)
	<i>B. pumilus</i> SAFR-032	[–] 5.5 logs	18 minutes	39.0	Schuerger et al. (2006)
	<i>B. subtilis</i> HA101	[–] 6 logs	60 minutes	13.0	Schuerger et al. (2006)
	<i>B. subtilis</i> HA101	[–] 4 logs	55 minutes	13.2	Mancinelli & Klovstad (2000)
	<i>B. subtilis</i> HA101	[–] 6 logs	180 minutes	39.0	Schuerger & Headrick (2023)
	<i>B. pumilus</i> FO-36B	[–] 6 logs	60 minutes	13.0	Schuerger et al. (2006)
	<i>B. licheniformis</i> KL-196	[–] 6 logs	60 minutes	13.0	Schuerger et al. (2006)
	<i>B. nealsonii</i> FO-092	[–] 6 logs	30 minutes	6.51	Schuerger et al. (2006)
	<i>B. megaterium</i> KL-197	[–] 6 logs	15 minutes	3.255	Schuerger et al. (2006)
	<i>B. subtilis</i> 42HS1	[–] 6 logs	5 minutes	1.085	Schuerger et al. (2006)
	<i>B. subtilis</i> HA101	[–] 6 logs	15 minutes	3.255	Schuerger et al. (2003)
	<i>B. pumilus</i> SAFR-032	[–] 3 logs	5 minutes	1.085	Osman et al. (2008)
	<i>B. subtilis</i> WN648	[–] 3 logs	40 minutes	8.0	Tauscher et al. (2006)
	<i>B. pumilus</i> SAFR-032	[–] 6 logs	10 minutes	2.0	Vaishampayan et al. (2012)
Desiccation	<i>B. subtilis</i> HA101	[–] 0.01 logs	7 days	—	Schuerger et al. (2012)
	<i>Clostridium</i> sp. MASE-IM-4	[–] 7 logs	30 days	—	Beblo-Vranesevic et al. (2018)
Low P + high T	<i>B. subtilis</i> HA101	[–] 10 logs	8 hr	—	Schuerger et al. (2019)
Low P (8–10 mb)	<i>B. subtilis</i> (multiple species)	[–] 0.5 logs	100 days	—	Schuerger et al. (2003)
	<i>B. subtilis</i> (multiple species)	[–] 2 logs	2100 days	—	Schuerger et al. (2003)
High-salt regolith	<i>B. subtilis</i> HA101	[–] 0.5 logs	7 days	—	Schuerger et al. (2012)
Acidic regolith	<i>B. subtilis</i> HA101	[–] 0.01 logs	7 days	—	Schuerger et al. (2012)
Perchlorate regolith	<i>B. subtilis</i> HA101	[–] 0.1 logs	7 days	—	Schuerger et al. (2012)