Detection of Large Exospheric Enhancements at Mercury due to Meteoroid Impacts

T. A. Cassidy1, C. A. Schmidt2, A. W. Merkel1, J. M. Jasinski3, and M. H. Burger4
1 Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA; Timothy.Cassidy@lasp.colorado.edu
2 Center for Space Physics, Boston University, Boston, MA 02215, USA; schmidtct@bu.edu
3 NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
4 Space Telescope Science Institute, Baltimore, MD 21218, USA

Received 2021 May 25; revised 2021 July 20; accepted 2021 July 30; published 2021 August 30

Abstract

The Ultraviolet and Visible Spectrometer (UVVS) on the MESSENGER spacecraft observed three large transient events in Mercury’s nightside “tail” in which the exospheric brightness increased by an order of magnitude. Meteoroid impacts are the best explanation given that the events are brief, can be simulated with instantaneous injections of vapor, and were not associated with unusual solar wind conditions. Data–model comparisons suggest that the impactors are 10–20 cm in diameter and produce vapor temperatures of ~10^4 K, much warmer than usually assumed for impact vapor. We estimate the impact frequency to be on the order of once per Earth day for meteoroids 10 cm diameter and larger, consistent with a pre-MESSENGER prediction. UVVS observed three atomic species during one event: sodium, magnesium, and calcium. Na and Mg brightened simultaneously, and their modeled ejection ratio roughly matches Mercury’s surface abundance. Ca showed no sign of an enhancement, consistent with earlier predictions that Ca in impact vapor is bound in a molecule that is undetectable to UVVS. This event provides an unprecedented opportunity to see three species respond (or not) to a single source and has implications for our understanding of Mercury’s exosphere.

Unified Astronomy Thesaurus concepts: Meteoroids (1040); Space weather (2037); Solar-planetary interactions (1472); Exosphere (499); Mercury (planet) (1024); Impact phenomena (779)

1. Introduction

The Ultraviolet and Visible Spectrometer (UVVS) channel of the Mercury Atmospheric and Surface Composition Spectrometer (MASC) on board the MESSENGER spacecraft observed three large transient events in Mercury’s nightside “tail” in which the exospheric brightness increased by an order of magnitude. Meteoroid impacts are the best explanation given that the events are brief, can be simulated with instantaneous injections of vapor, and were not associated with unusual solar wind conditions. Data–model comparisons suggest that the impactors are 10–20 cm in diameter and produce vapor temperatures of ~10^4 K, much warmer than usually assumed for impact vapor. We estimate the impact frequency to be on the order of once per Earth day for meteoroids 10 cm diameter and larger, consistent with a pre-MESSENGER prediction. UVVS observed three atomic species during one event: sodium, magnesium, and calcium. Na and Mg brightened simultaneously, and their modeled ejection ratio roughly matches Mercury’s surface abundance. Ca showed no sign of an enhancement, consistent with earlier predictions that Ca in impact vapor is bound in a molecule that is undetectable to UVVS. This event provides an unprecedented opportunity to see three species respond (or not) to a single source and has implications for our understanding of Mercury’s exosphere.

Smyth 1986; Potter et al. 2002). The resulting antisunward acceleration can push gravitationally bound Na onto escape trajectories. Mercury’s escape velocity is 4.25 km s^{-1}, but Na atoms ejected at ~2.0 km s^{-1} can escape down the tail at peak radiation pressure (Smyth & Marconi 1995).

The radiation pressure changes over the course of a year owing to Mercury’s eccentric orbit (Smyth & Marconi 1995; Potter et al. 2007; Schmidt et al. 2010, 2012). Mercury’s radial motion with respect to the Sun changes the solar scattering rate by an order of magnitude as explained by, e.g., McClintock et al. (2018, Figure 14.1). Radiation pressure peaks when Mercury is close to the Sun but moving toward (or away) from it, and this is when the tail is brightest (Figure 1). Figure 1 shows the Na tail radiance as a function of Mercury’s angular orbital position, the true anomaly angle (TAA). MESSENGER was beneath Mercury’s south pole during these observations, and UVVS sight lines were above Mercury’s nightside. Typically, the instrument field of view was swept between dawn and dusk as the altitude was slowly varied. Examples of the sight lines are shown in Figure 2.

Figure 1 includes only a subset of the tail data to cut down on scatter introduced by variable spacecraft position and instrument pointing. We describe observation geometry using the Mercury Solar Orbital (MSO) coordinate system in which the XMSO axis points toward the Sun, ZMSO toward the north, and YMSO toward dusk (see diagram in top right panel of Figure 2). Figure 1 included all Na observations taken while the spacecraft was beneath Mercury’s south pole (spacecraft ZMSO < -1.5) and UVVS sight-line tangents satisfied XMSO = -1.4 ± 0.15 R_M (about 0.4 R_M behind Mercury), YMSO = -1 ± 0.15 R_M (dawn), and ZMSO = ± 0.5 R_M. This range of values happened to capture all three episodic events.

The result is a climatology of the Na tail showing its seasonal variability throughout MESSENGER’s orbital mission. The red
points highlight the three bursts of exospheric emission that were well above typical values. The events occurred on 2011 August 4 (TAA 205°), 2012 October 24 (228°), and 2013 April 13 (213°).

Figure 2 shows cross-tail profiles of Na radiance for each exospheric brightening event (red points) compared with normal values (gray points). Each event was seen during several dawn –dusk sweeps of the UVVS field of view, but only the first sweep of each event is shown for clarity. The gray points include all UVVS observations taken during the MESSENGER mission with similar observation geometry (spacecraft $Z_{\text{MSO}} < -1.5$ and sight-line tangent $X_{\text{MSO}} = -1.3 \pm 0.2 R_{\oplus}$) and time of year (TAA within 1°5 of the event shown).

3. Modeling

3.1. Steady-state Model

A sudden brightening in UVVS data could be caused by a changing exosphere, but it could also be due to changing observation geometry. To rule this out, we compared UVVS data to steady-state models created with a publicly available code (Burger 2021). These are meant to be empirical matches to tail data rather than comprehensive simulations of exospheric sources and sinks (e.g., Leblanc & Johnson 2010).

For Na we used uniform dayside ejection and the temperature was set to 1200 K, similar to the speed distributions used for photodesorption in previous Na tail simulations (Burger et al. 2010; Mouawad et al. 2011; Schmidt et al. 2012). Na source rates were scaled to match steady-state data taken before and after the transient enhancements: $7 \times 10^{23} \text{s}^{-1}$ for the 2011 event and $3 \times 10^{23} \text{s}^{-1}$ for the 2012 and 2013 events. For Ca we used an energetic dawn source based on the parameters of Burger et al. (2014): 60,000 K with an ejection rate of $6 \times 10^{22} \text{s}^{-1}$. The Mg model had a source centered on 9:00 local time and a temperature of 6000 K (Merkel et al. 2017) with an ejection rate of $3 \times 10^{23} \text{s}^{-1}$. The sticking coefficient was set to 1 for all three species (this was changed for the Na transient models, as discussed below).

Including dawn/dusk asymmetries in the Na source was not necessary to reproduce steady-state data because dawn/dusk asymmetries in the tail are minimal at these TAA (Cassidy et al. 2016). North/south asymmetries (Burger et al. 2010; Schmidt 2013; Schmidt et al. 2020) were not included because the sight lines look roughly south to north, and so model output was not very sensitive to the source latitude.

3.2. Transient Source Model

To model the transient sources, we used another publicly available code (Schmidt 2021) better suited to time-dependent sources. Anticipating that such short events could be caused by impacts, we ran an ensemble of models that each began with the ejection of Na or Mg atoms from a point on Mercury’s surface. The initial parameter space covered increments of 5 minutes in impact time and 15° in latitude and longitude, with further refinement once approximate source locations and times were found. In the absence of knowledge about the sources’ energy distribution, we used the Maxwell–Boltzmann flux distribution (e.g., Smith et al. 1978) and temperatures of 2000, 3500, 5000, 10,000, 15,000, or 20,000 K.

Transient models were added to the appropriate steady-state model (they add linearly because these emissions are optically thin and the atoms have negligible interactions). The vapor mass was found by scaling the transient model to match the data (radiance is directly proportional to source rate in these models). The parameter set that produced the lowest $\chi^2$ error was chosen for each event. Results are summarized in Table 1.

The uncertainty in impact time is about 5 minutes; for source location it is about 15° in longitude (1 hr local time). These are the minimum differences in impact parameters that make a discernible difference in model output. Source latitude is the least constrained quantity since the sight lines run roughly south to north. High-latitude sources (>45°) can be easily distinguished from low latitude (<15°) by the fraction of ejecta that is in shadow. High-latitude sources are missing the dip due to Mercury’s shadow centered on $Y_{\text{MSO}} = 0$. However, it is difficult to distinguish northern midlatitude sources from southern ones. Note that the apparent precision in local time given in Table 1 is a consequence of Mercury’s spin–orbit resonance, which fixes the local time for a given longitude and TAA. It is not a reflection of the accuracy of the data–model comparison.
Figure 2. Left panels: cross-tail profiles of Na radiance during the exospheric brightening events. The episodic events (red points) are compared with typical observations (gray points) at similar true anomaly angles and observation geometries. The dip in the center of the emission patterns is Mercury’s shadow. Right panels: UVVS sight lines for each event, color-coded by radiance.
3.3. Data

Model Comparisons

Figure 3 shows the Na radiance as a time series for each event. For the 2011 August 4 event, UVVS measured Mg and Ca along with Na. The time series shows simultaneous brightening in both Mg and Na but not atomic Ca. The plots include the steady-state and best-fit transient models (as described in the previous section) for Na and Mg. Since Ca did not show an enhancement, we only performed steady-state simulations. In all three events and species, the steady-state model closely matches the data before and after the enhancements. The best-fit temperature for Na was 10,000 K for all three events. Mg favored a slightly hotter temperature at 15,000 K. At these energies, bulk escape occurs and a few kilograms of vapor can produce a large enhancement. Videos of the transient simulations are available in an online archive (see acknowledgments).

The 2011 and 2013 events each consist of brief spikes in radiance followed by lingering hour-long enhancements (Figure 3). Both were best fit with nightside sources, equatorial midnight for 2011 and the predawn northern hemisphere for 2013. The 2012 event, by contrast, lasted about 2 hr and remains bright throughout. It was fit with a midday southern hemisphere source.

Its length seems to be due to the broad range of transit times from the dayside to the tail and not, as might be reasonably expected, atoms bouncing across the warm surface. We used the temperature-dependent sticking coefficient for Na from Yakshinskiy & Madey (2005), which predicts that atoms will stick on the nightside and have a low chance of sticking on most of the dayside. The accommodation coefficient was allowed to vary. The best-fit run for the 2012 event used 0.1, similar to that used in some Monte Carlo Na models (e.g., Burger et al. 2010; Mouawad et al. 2011), but model output was not especially sensitive to this parameter because accommodated particles are less likely to reach the tail. Simulated particles lose a bit of energy each time they hit the surface, and they are re-ejected in a random direction if they do not stick. Such particles are more likely to stay on the dayside, where they originated.

We did run simulations of the 2011 (midnight) event to see whether nonzero sticking on the nightside could match the data. Atoms were allowed to accommodate, rather than stick to, the nightside surface. The enhancement’s decay time was too long for all such simulations regardless of the thermal accommodation parameters.

4. Discussion

The most likely source for the transient enhancements is meteoroid impacts. In Section 3.3 we show that they can be modeled reasonably well with instantaneous ejections of vapor from single points on Mercury’s surface. This is distinct from the continuous production of vapor over a broad area by micrometeors or sputtering.
Mangano et al. (2007) predicted that meteoroid impacts would frequently enhance Mercury’s exosphere and that these enhancements would be easier to see on the nightside, as we found here. Meteoroids are commonly seen on other solar system bodies: they are detected via flashes on the lunar nightside (Suggs et al. 2014) and at Jupiter (e.g., Giles et al. 2021), and by various methods in Earth’s upper atmosphere (e.g., Brown et al. 2002).

A 10 cm diameter impactor can produce our smallest event (2013) based on the vapor production equations from Cintala (1992). That assumes 2.9 wt. % Na Mercury surface composition (Evans et al. 2012) and an impactor with a speed of 30 km s⁻¹, the average for meteoroids impacting Mercury according to Marchi et al. (2005). The largest event, 2012, requires a ~16 cm diameter.

These large impactors are likely from the main asteroid belt and are distinct from the smaller cometary impactors responsible for the primary impact vapor source to Mercury’s exosphere (Pokorný et al. 2018; Janches et al. 2021). Lack of knowledge of the impactors’ speeds introduces considerable uncertainty in this size estimate. The vapor production is a power-law function of impact velocity, with an exponent ≥2 (Cintala 1992; Collette et al. 2014), and impact speeds range from ~20 to 70 km s⁻¹ in the Marchi model.

We evaluated sputtering as a possible cause, but the solar wind conditions needed for high sputtering rates were not present based on MESSENGER magnetometer data taken just before and during the events. These include a southward-oriented interplanetary magnetic field (IMF) with high field strengths and high solar wind dynamic pressure, which will drive reconnection on the dayside magnetopause to inject plasma into the magnetospheric cusps. Ion precipitation onto the surface is triggered by reconnection, which is favored when the IMF BZ component is negative and the IMF magnitude is greater than 30 nT (Jasinski et al. 2017).

However, conditions during the events were not conducive to reconnection: BZ was small or positive, and IMF magnitudes ranged from 14 to 23 nT. This is within the range of normal variability, 10–30 nT according to James et al. (2017), and nowhere near the extreme space weather events cataloged by Slavin et al. (2019), where BZ was -100 to -400 nT. The events also did not take place during known interplanetary coronal mass ejection passages (Winslow et al. 2015).

### 4.1. Impactor Timing

The events all occurred when Mercury’s Na tail radiance was low (Figure 1). It is unlikely that impactors are more common at this time (Marchi et al. 2005), although Jasinski et al. (2020) also detected a large impactor TAA = 177°. Instead, there is an observational bias that makes it easier to see energetic Na, the kind produced by impacts or sputtering, when radiation pressure is too weak to push low-energy Na down the tail.

To demonstrate this, we plotted two simple steady-state exosphere models in Figure 1, one high energy and one low energy. Both have constant source rates; changes in brightness with TAA are due solely to changes in radiation pressure and solar photon scattering. The high-energy model used a 4000 K globally uniform source (ejection rate of $4.4 \times 10^{23}$ s⁻¹). This temperature was chosen for simulations at the outset of the project, before the data–model comparison effort that found higher temperatures, because it is typical of micrometeoroid source parameters used in past Monte Carlo modeling. The low-energy model used the 1200 K Na source from Section 3.1 with an ejection rate of $7 \times 10^{23}$ s⁻¹.

The 1200 K model reproduces the large drop in emission around aphelion and perihelion, while the 4000 K model is relatively flat. The transients (red points) appear when the low-energy source cannot populate the tail. It is worth noting here that the asymmetry in emission before and after TAA = 180° was also expected (Potter et al. 2007). The tail is brighter for TAA < 180° compared to TAA > 180° because low-energy exospheric Na escapes down the tail more easily when TAA < 180° (Smyth 1986; Smyth & Marconi 1995; Potter et al. 2007; Jasinski et al. 2021).

This helps explain why energetic sources are more apparent when TAA > 180°: the steady-state tail is dimmer. The models in Figure 1 also suggest that energetic sources should be visible between TAA ~ 320° and 360°, but observations are relatively sparse for that TAA range.

### 4.2. Impact Rates

Estimating the impact rate requires the length of time that UVVS took observations similar to Figure 2. The events were all found in data labeled “UVVSExoScan” on NASA’s Planetary Data System (PDS), so we only include those observation types in the total. These were sweeps of the tail region that were ideal for detecting and characterizing episodic events. There are often gaps in these sequences, so we exclude intervals where that gap exceeds 5 minutes.

Because of the bias against impact detection during periods of high radiation pressure, we only count UVVSExoScan data taken when the high-energy model in Figure 1 is above the low-energy model. Mg tail events are difficult to identify in isolation owing to the low signal-to-noise ratio in that data set, so we exclude times when UVVS only observed Mg.

Combining these constraints, UVVS was sensitive to impacts for ~4.7 days, during which it detected three impact events. A possible fourth event was seen in a truncated observation sequence (2011 October 12, TAA = 152°). Assuming that the four impacts are Poisson distributed, the maximum likelihood estimate of the impact rate is 310 per Earth year (e.g., Giles et al. 2021), but the actual impact rate could range from 85 to 795 per Earth year (95% confidence interval). In comparison, Marchi et al. (2005) predicted about 900 impacts per Earth year for diameters 10 cm or larger, reasonably close to the observed rate given the many uncertainties involved (see discussions in Pokorný et al. 2018; Janches et al. 2021).

### 4.3. Impact Vapor Composition in the 2011 Event

The 2011 event allows us to compare the response of three atomic species to a single source. The ratio of Mg to Na for our best-fit transient source is about 3, which roughly matches Mercury’s surface composition (most impact vapor will be from the surface rather than the impactor). This is unusual for Mercury’s exosphere: the Mg ejection rate is normally two orders of magnitude smaller than that of Na.

Globally, the Mg/Na ratio in the surface ranges from 1.3 to 6.2 (McCoy et al. 2018). The exact value at the simulated impact location is not known, but it occurred in the high-Mg region. The Mg/Si ratio there is ~0.6, above the global mean of 0.44 (Merkel et al. 2018; Nittler et al. 2020). The Na/Si ratio averages 0.12 globally, but its value in the high-Mg region is
unknown. Na may be higher than average at this impact location because it coincides with the Na exospheric surface reservoir (Leblanc & Johnson 2010; Cassidy et al. 2016), but it is not clear whether it extends to the depth excavated by an impactor (Sarantos & Tsavachidis 2020).

Ca observations taken during the 2011 event show no obvious enhancement, despite Ca being as abundant as Na in the surface. This is explainable if most Ca is ejected as CaO (Killen et al. 2005; Berezhnoy 2018), which is not detectable by UVVS. On the dayside this molecule is photodissociated into Ca and O, but this was a nightside impact. Ca atoms would not have been produced until CaO molecules reached sunlight, and after that it still takes some time to photodissociate. The CaO photodissociation lifetime is \(\sim 13\) minutes (Valiev et al. 2017). This would have spread the Ca enhancement out in time, making it difficult to detect.

A possible complication is that Mg is also predicted to be ejected as a molecule. MgO (Sarantos et al. 2011). However, MgO rapidly photodissociates to Mg and O, unlike CaO. Valiev et al. (2017) estimated the photodissociation lifetime as \(\sim 15\) s for MgO. It is also possible that Mg was mostly released in atomic form, an outcome for impact vapor cloud simulations with quenching temperatures less than \(\sim 3500\) K in Berezhnoy (2018).

The 2011 event shows that impacts should produce atomic Na and Mg in similar quantities. This has implications for an Na impact vapor source proposed by Suzuki et al. (2020). Their Na source peaks at \((1\text{–}3) \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}\) at the aphelion subsolar point. What they did not consider is that this implies an Mg source of the same magnitude, and that is ruled out by UVVS data. The Mg source peaks at \(10^6 \text{ cm}^{-2} \text{ s}^{-1}\), at midmorning near perihelion (Merkel et al. 2017). The Suzuki impact vapor source would also produce a large Ca population at the subsolar point, via photodissociation of CaO, which was not detected (Burger et al. 2014).

### 4.4. Impact Vapor Temperature

Na and Mg normally have very different speed distributions at Mercury, but the data–model comparison found them to be similar, 10,000–15,000 K. Exospheric modelers often assume temperatures of 3000–5000 K. We also ran simulations with a more typical 3500 K. Those simulations do not give poor results, but they do underestimate the cross-tail width of the ejecta plume.

The higher temperatures might be reasonable given the experiments of Schultz et al. (2007) and references therein. They found impact vapor temperatures of several thousand kelvin, but they also show that centimeter-sized impactors produce bulk flows that are fast enough to boost the total vapor energy far above the thermal energy.

### 5. Conclusion

Exospheric species are usually studied in isolation. In principle, they should share a limited set of source and loss processes, but in practice they do not have much in common. Energy distributions, source rates, spatial distributions, and seasonal variabilities are unique to each species. The 2011 event provides an unprecedented opportunity to see three species respond (or not) to a single source. Model comparisons found something surprising: Na and Mg were ejected in proportion to their surface composition, and their energy distributions are similar. This is to be expected for an exospheric source process like impact vaporization, but it is rarely seen in practice. The lack of a Ca enhancement is interesting and explainable by previous work.

The derived meteoroid impact rate from this handful of events has large uncertainty. The Mercury community could improve on these statistics by observing the Na tail during periods of low radiation pressure when energetic sources should stick out above the normally dim nightside exosphere.

The UVVS data used in this paper are available on the NASA PDS in collection MESS-E/V/H-MASCS-4-UVVS-DDR-V1.0. Exosphere model output is available at doi:10.5281/zenodo.4792827, including videos of the simulations. Work was supported by the NASA ROSES Solar System Workings Program, award No. 80NSSC19K0790, and Discovery Data Analysis Program, award No. NNX16AJ03G.

**ORCID IDs**

T. A. Cassidy  
https://orcid.org/0000-0003-4308-4083

A. W. Merkel  
https://orcid.org/0000-0001-9751-6481

J. M. Jasinski  
https://orcid.org/0000-0001-9969-2884

**References**

Berezhnoy, A. A. 2018, *Icar*, 300, 210

Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., & Worden, S. P. 2002, *Natur*, 420, 294

Burger, M. 2021, Neutral Exosphere and Cloud Model, https://github.com/mburger-stsci/nexoclom

Burger, M. H., Killen, R. M., McClintock, W. E., et al. 2014, *Icar*, 238, 51

Burger, M. H., Killen, R. M., Vervack, R. J., Jr., et al. 2010, *Icar*, 209, 63

Cassidy, T. A., McClintock, W. E., Killen, R. M., et al. 2016, *GeoRL*, 21, 1121

Cassidy, T. A., Merkel, A. W., Burger, M. H., et al. 2015, *Icar*, 248, 547

Cintala, M. J. 1992, *JGR*, 97, 947

Collette, A., Sternovsky, Z., & Horanyi, M. 2014, *Icar*, 227, 89

Evans, L. G., Peplowski, P. N., Rhodes, E. A., et al. 2012, *JGRE*, 117, E00L07

Giles, R. S., Greathouse, T. K., Kammer, J. A., et al. 2021, *GeoRL*, 48, e91797

Ip, W.-H. 1986, *GeoRL*, 13, 423

James, M. K., Imber, S. M., Bunce, E. J., et al. 2017, *JGRA*, 122, 7907

Janches, D., Berezhnoy, A. A., Christou, A. A., et al. 2021, *SSRv*, 217, 50

Jasinski, J. M., Cassidy, T. A., Raines, J. M., et al. 2021, *GeoRL*, 48, e92980

Jasinski, J. M., Regoli, L. H., Cassidy, T. A., et al. 2020, *NatCo*, 11, 4350

Jasinski, J. M., Slavin, J. A., Raines, J. M., & DiBraccio, G. A. 2017, *JGRA*, 122, 153

Killen, R. M., Bida, T. A., & Morgan, T. H. 2005, *Icar*, 173, 300

Leblanc, B., & Johnson, R. E. 2010, *Icar*, 209, 280

Mangano, V., Massetti, S., Milillo, A., et al. 2013, *P&SS*, 82, 1

Mangano, V., Milillo, A., Mura, A., et al. 2007, *P&SS*, 55, 1541

Marchi, S., Morbidelli, A., & Cremonese, G. 2005, *A&A*, 431, 1123

McClintock, W. E., Cassidy, T. A., Merkel, A. W., et al. 2018, in Mercury: The View after MESSENGER, ed. B. J. Anderson, L. R. Nittler, & S. C. Solomon (Cambridge: Cambridge Univ. Press), 371

McCoy, T. J., Peplowski, P. N., McCubbin, F. M., & Weider, S. Z. 2018, in Mercury: The View after MESSENGER, ed. B. J. Anderson, L. R. Nittler, & S. C. Solomon (Cambridge: Cambridge Univ. Press), 176

Merkel, A. W., Cassidy, T. A., Vervack, R. J., et al. 2017, *Icar*, 281, 46

Merkel, A. W., Vervack, R. J., Killen, R. M., et al. 2018, *GeoRL*, 45, 6790

Milillo, A., Mangano, V., Massetti, S., et al. 2021, *Icar*, 355, 114179

Mouawad, N., Burger, M. H., Killen, R. M., et al. 2011, *Icar*, 211, 21

Nittler, L. R., Frank, E. A., Weider, S. Z., et al. 2020, *Icar*, 345, 113716

Pokorny, P., Sarantos, M., & Janches, D. 2018, *ApJ*, 863, 31

Potter, A. E., Killen, R. M., & Morgan, T. H. 2002, *M&PS*, 37, 1165

Potter, A. E., Killen, R. M., & Morgan, T. H. 2007, *Icar*, 186, 571

Sarantos, M., Killen, R. M., McClintock, W. E., et al. 2011, *P&SS*, 59, 1992

Sarantos, M., & Tsavachidis, S. 2020, *GeoRL*, 47, e88930

Schmidt, C. A. 2013, *JGRA*, 118, 4564

Schmidt, C. A. 2021, Surface-Bound Planetary Exosphere Model, https://github.com/CarlSchmidt/Exosphere-Model

Cassidy et al.

Schmidt, C. A., Baumgardner, J., Mendillo, M., & Wilson, J. K. 2012, JGRA, 117, A03301
Schmidt, C. A., Baumgardner, J., Moore, L., et al. 2020, PSJ, 1, 4
Schmidt, C. A., Wilson, J. K., Baumgardner, J., & Mendillo, M. 2010, Icar, 207, 9
Schultz, P., Eberhardy, C., Ernst, C., et al. 2007, Icar, 190, 295
Slavin, J. A., Middleton, H. R., Raines, J. M., et al. 2019, JGRA, 124, 6613
Smith, G. R., Shemansky, D. E., Broadfoot, A. L., & Wallace, L. 1978, JGRA, 83, 3783
Smyth, W. H. 1986, Natur, 323, 696
Smyth, W. H., & Marconi, M. L. 1995, ApJ, 441, 839
Suggs, R. M., Moser, D. E., Cooke, W. J., & Suggs, R. J. 2014, Icar, 238, 23
Suzuki, Y., Yoshioka, K., Murakami, G., & Yoshikawa, I. 2020, JGRE, 125, e06472
Valiev, R. R., Berezhnoy, A. A., Sidorenko, A. D., Merzlikin, B. S., & Cherepanov, V. N. 2017, P&SS, 145, 38
Winslow, R. M., Lugaz, N., Philpott, L. C., et al. 2015, JGRA, 120, 6101
Yakshinskiy, B. V., & Madey, T. E. 2005, SurSc, 593, 202