During MESSENGER’s third flyby of Mercury, the Mercury Atmospheric and Surface Composition Spectrometer detected emission from ionized calcium concentrated 1–2 Mercury radii tailward of the planet. This measurement provides evidence for tailward magnetospheric convection of photoions produced inside the magnetosphere. Observations of neutral sodium, calcium, and magnesium above the planet’s north and south poles reveal altitude distributions that are distinct for each species. A two-component sodium distribution and markedly different magnesium distributions above the two poles are direct indications that multiple processes control the distribution of even single species in Mercury’s exosphere.

Mercury lacks the familiar collision-dominated atmosphere of the other terrestrial planets. It is instead surrounded by a tenuous surface-bounded exosphere composed primarily of atoms and molecules released from the planet’s surface. Understanding the processes that generate and maintain the exosphere provides insight into the composition of Mercury’s surface and the transport of material about the planet. Moreover, quantifying how these processes have modified the optical properties of the surface over Mercury’s lifetime is important in understanding the planet’s geologic history. Observations made by the Ultraviolet and Visible Spectrometer (UVVS) (1) on the MERCURY Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (2) during the first two flybys of the planet (M1 on 14 January 2008; M2 on 6 October 2008) revealed different spatial distributions for three exospheric species: sodium (Na), calcium (Ca), and magnesium (Mg) (3,4). Here we report results from MESSENGER’s third flyby (M3 on 29 September 2009).

As during M1 and M2, most of the M3 exospheric observations were made as MESSENGER approached Mercury, enabling the UVVS to map the tail region that extends anti-sunward from the planet. The M3 trajectory also allowed the UVVS to obtain altitude scans above Mercury’s north and south poles, which had not been possible during the earlier flybys because of spacecraft pointing constraints. Near closest approach, a roll maneuver as MESSENGER entered Mercury’s shadow carried the UVVS field of view in an arc perpendicular to the Sun-Mercury line. The instrument view during these “fantail” observations began southward and rolled through the dawn direction to northward, at which point measurements were interrupted by a spacecraft safehold event. Throughout M3 the UVVS scanned for emission lines from four species (vacuum wavelengths): Na at 589.2 and 589.8 nm, Mg at 285.3 nm, Ca at 422.8 nm, and Ca+ at 393.5 nm (5).

Ionized calcium (Ca+) emission was observed above noise levels only in a relatively small region (Fig. 1A) approximately 1–2 \( R_M \) (where \( R_M \) is Mercury radius, 2440 km) tailward of the planet, with most of the emission close to the equatorial plane. In contrast, neutral Ca emission was more uniformly distributed (Fig. 2B). Line-of-sight column density estimates for Ca+ and Ca 1–2 \( R_M \) downtail were of the same order of magnitude (see Table 1). Because Ca+ velocities — up to hundreds of km s\(^{-1}\), consistent with the signatures of strong magnetospheric convection observed by the MESSENGER Magnetometer during M3 (6–9) — are generally much larger than the several km s\(^{-1}\) velocities expected for Ca (10), local production of Ca+ from Ca is unlikely to yield either comparable column densities or the apparent localized nature of the Ca+ emission.

The observed Ca+ distribution can likely be explained by a combination of magnetospheric convection and centrifugal acceleration. The lifetime of Ca against photoionization is short, \( \sim 1500 \) s (11), so exospheric Ca+ ions are formed close to the planet (within 2.5 \( R_M \)) where much of the Ca+ pick-up process occurs (e.g., 12). Magnetospheric convection was particularly intense during M3 (9), implying that planetary
ions created over the poles would be swept by anti-sunward convection into the magnetotail and down into the plasma sheet (cf. 6,7). Pick-up Ca\(^+\) would also experience centrifugal acceleration as the magnetic field convects over the poles (13). This combination of convection and acceleration acts to transport Ca\(^+\) to the region tailward of the near-planet reconnection line (the so-called X-line), which was located ~0.6 \(R_M\) anti-sunward from Mercury during M3 (9), concentrating Ca\(^+\) that is produced over a relatively large volume into the near-equatorial region at higher altitudes than it originates (Fig. 1C). Consistent with the observations (Fig. 1A), the transported Ca\(^+\) ions would be expected to have their highest densities near the equator tailward of the X-line and would fill the entire width of the magnetotail, approximately 5–6 \(R_M\) at the region of Ca\(^+\) emission. In this scenario, most of the Ca\(^+\) (~65%) is in sunlight and thus observable by the UVVS. This mechanism has been studied in detail for Na\(^+\) ions (14). Because pick-up velocity is independent of mass and centrifugal acceleration depends only on the magnetic field convection, Ca\(^+\) would participate in the same process. Moreover, the convection/acceleration mechanism is most effective for ions picked up at low altitudes over the poles (13), where Ca emissions during M3 were observed to be intense (Fig. 2B).

Observations of the volatile Na showed relatively high abundances over the north and south poles (Fig. 2A), but these abundances decreased by a factor of 1000 only ~1 \(R_M\) anti-sunward from the polar regions. Because radiation pressure effects on Na were relatively small during M3 (15, Table 1), the observations suggest that most of the Na atoms near the poles were produced at low energy and that Na in the tail originated from a high-energy source. In contrast, the refractory species Ca and Mg showed more gradual declines in emission from the poles to the tail region (Figs. 2B,C). This fall-off, coupled with the much smaller response of Ca and virtually negligible response of Mg to radiation pressure in general (16, Table 1), requires that these species derive from higher-energy sources sufficient to eject Ca and Mg directly to the observed radial distances, particularly in the tail region. These UVVS observations are approximately comparable to previous ground-based observations of both Na (e.g., 17) and Ca (10,18), whereas Mg has been observed only by UVVS. However, more detailed comparisons of ground-based and spacecraft datasets require that the observations be made nearly simultaneously and along similar lines of sight owing to the high degree of spatial and temporal variability exhibited by Mercury’s exosphere.

Atoms of Na are particularly sensitive to radiation pressure (17), which varies with Mercury’s position in its elliptical orbit (e.g., 19). The control that radiation pressure exerts over the Na distribution is illustrated through a comparison of M2 and M3 observations (Fig. 3). During M2 radiation pressure effects on Na were stronger, producing a substantially more populated tail with emission as much as 20 times more intense at similar downtail distances during M2 than M3. Although a change in the Na release rate between M2 and M3 cannot be completely ruled out, previous studies have shown that the Na tail effectively vanishes for radiation pressure effects less than about 112 ± 24 cm s\(^{-2}\) (15). The radiation pressure during M3 (Table 1) and our observations of a greatly diminished tail are consistent with that conclusion. This large change is an example of seasonal-style exospheric variability that can occur throughout Mercury’s orbit.

Over the polar regions, Na exhibited a two-component structure during M3 (Fig. 2D). Exponential fits yield e-folding distances (i.e., the altitude change required for intensities to drop by a factor of e) of 202 km (north) and 205 km (south) for altitudes less than 800 km, and 514 km (north) and 468 km (south) for altitudes greater than 900 km. These two components are consistent with a mix of low- (e.g., photon-stimulated desorption) and high-energy (e.g., ion sputtering, meteoroid impact vaporization) processes. No previous observations of Mercury’s Na exosphere have explicitly shown this structure, although ground-based observations have implied multiple source processes for Na (e.g., 15,20) and a two-component distribution has been observed at the Moon (21).

The polar profiles for Ca and Mg (Figs. 2E–F) are characterized by much larger scale heights than for Na, implying much higher energies for the source processes of these two species. In the south, e-folding distances of 1621 km and 2160 km for Ca and Mg, respectively, suggest that similar processes act on the two species. In the north, both species exhibited higher radiances indicating larger release rates. However, whereas the Ca profile has an e-folding distance (1878 km) consistent with the processes acting in the south, the Mg profile is strikingly different and indicates that there may have been an additional source process at work. One possibility is that the northern Mg profile represents the combination of Mg derived directly from the surface [for instance, by heavy ion sputtering or electron-stimulated desorption (ESD)] and dissociation of MgO at higher altitudes [dissociation of CaO has been suggested as a source of high-energy Ca (10)]. A resonance effect related to sputtering or ESD would also affect individual species differently. Alternatively, the north-south differences in the Mg profile may reflect variations in the spatial distribution of Mg-bearing minerals on the surface. Smooth plains units are more common in the north (22), and volcanic deposits associated with Caloris basin (23) and Rachmaninoff basin (24) are also located at northern latitudes and could represent a source of Mg-rich materials.

It is interesting to note that, unlike the Ca and Mg profiles, the Na polar profiles exhibited no substantial north-south
asymmetry in the release rates even though some of the released Na should also derive from the high-energy processes that release Ca and Mg. The lack of a north-south Na source-rate asymmetry could result from differences in the ways various processes affect volatile and refractory species. It could also reflect spatial variations in the distribution of Na-, Ca-, and Mg-bearing minerals on the surface.

The Na, Ca, and Mg distributions in the tailward near-planet region (Fig. 4) are markedly distinct from one another. The Na fantail observations (Figs. 4A,D) showed weak emission peaks in the south and north that are consistent with a symmetric source plus polar enhancements. However, in line with the reduced radiation pressure for Na during M3, these enhancements were less pronounced than the larger peak observed in the north during M2. An equatorial, dawnside peak in the nightside near-planet Ca distribution, suggested by M1 and M2 observations, is firmly established by the M3 fantail observations (Figs. 4B,E), which probed the southern latitudes not sampled in the earlier flybys. The Ca distribution is remarkably consistent in both intensity and location during all three flybys, and a high-energy process is required to release Ca with sufficient energy to produce the dawnside peak at the observed distances tailward of the planet. The Mg distribution observed in the fantail region (Figs. 4C,F) shows a weak, double-peaked concentration, with one peak near the equator and the second near 50°N. The apparent variations in the Mg distribution from M2 to M3, in contrast to the more steady Ca distribution, support the hypothesis that the dominant release processes act differently upon Mg and Ca.

The persistent location and intensity of the Ca dawnside peak in the near-planet tail region during all three flybys, which spanned highly variable magnetospheric conditions, argues against ion sputtering as the dominant process. Meteoroid-impact vaporization is also an unlikely cause unless a systematic, and perhaps large, dawn-dusk asymmetry is shown to exist in the meteoroid flux. It also is difficult to understand why the above processes would not affect Na and Mg in a similar manner. Ca may be preferentially deposited on the nightside because Ca ions in the magnetosphere impact the midnight sector on Mercury’s surface. Such a mechanism was suggested to explain an observed strong dawn enhancement in potassium (K) (25), but the high-energy release process necessary to produce the observed Ca distribution is currently unknown. Transport and loss are also factors that shape the distributions. In particular, the photoionization lifetime for Mg is approximately 10 times longer than that for Na and 100 times longer than for Ca (11). Photoionization losses undoubtedly play a role, but they are not likely to dominate over release in producing the distributions observed close to the planet.

Observations obtained during the MESSENGER flybys, particularly during M3, demonstrate that our knowledge of the source, transport, and loss processes controlling Mercury’s exosphere is incomplete. The concentrated nature of Ca+ in the near-planet tail region, the two-component polar profiles for the volatile species Na, and the striking differences in the polar and fantail observations for the two refractory species Ca and Mg indicate Mercury’s exosphere is both more varied and more intertwined with the magnetospheric environment than previously thought and that multiple, possibly complex, source processes may be important for ejecting both volatile and refractory material into the exosphere. The Ca+ observations provide evidence of magnetospheric convection effects on planetary ions, and the observed differences among the Na, Ca, and Mg distributions argue that the mix of processes at work in the exosphere not only affects volatile and refractory species differently but may be distinct for a given element or mineral. The MESSENGER flyby observations have revealed a complex exospheric system in which the observed spatial distributions suggest multiple processes are at work in ways not yet understood.

References and Notes
5. Detected photon counts were converted to column emission, expressed in rayleighs (1 R = 10⁶ photons cm⁻² s⁻¹ emitted into a solid angle of 4π steradians), using instrument calibration coefficients determined during ground tests (1).

26. We thank M. Lankton and M. Kochte for their contributions to the acquisition and analysis of the data reported here, and J. Slavin and D. Blewett for insightful comments. The MESSENGER project is supported by the NASA Discovery Program under contracts NAS5-97271 to The Johns Hopkins University Applied Physics Laboratory and NASW-00002 to the Carnegie Institution of Washington. RJV, RMK, and ALS are supported by the MESSENGER Participating Scientist Program.

19 February 2010; accepted 24 May 2010
Published online 8 July 2010; 10.1126/science.1188572
Include this information when citing this paper.

Fig. 1. Observations of Ca\(^+\) emission in Mercury’s tail region. (A) The image shows observed column emissions projected onto the plane containing the Sun-Mercury line and Mercury’s spin axis, interpolating to fill in unobserved regions. To clearly show the full region scanned, all observations below 10 R (1 on the color scale) have been set equal to 10 R, leading to the blue background. Beyond 6 R\(_M\) downtail, no observations are above the noise level. (B) The red spectrum is an average of the Ca\(^+\) emission-line observations between 1.5–3.5 R\(_M\) (one-standard-deviation uncertainties are shown); the green line is a Gaussian fit to the average Ca\(^+\) line. (C) Schematic illustration of the magnetospheric convection pattern (blue arrows) that concentrates Ca\(^+\) in the observed narrow region before the ions are ejected down the tail. The large arrow indicates the approximate position of the observed Ca\(^+\) emission tailward of the magnetospheric X-line.

Fig. 2. (A to C) Na, Ca, and Mg emission observed in the polar, nightside, and tail regions of Mercury during MESSENGER’s third flyby. Each observation is an average over the indicated region, which is the projection of the UVVS rectangular field of view onto the plane defined by the Sun-Mercury line and the spin axis of Mercury. The horizontal dimension indicates the projected slit length and becomes smaller as MESSENGER approaches Mercury. The vertical dimension indicates the range the UVVS slit moved through during the integration time (~ 2 s); shorter distances correspond to slower spacecraft slew rates. Owing to the spacecraft location while inbound, the lines of sight are not perpendicular to the plane but are directed sunward by 5-10°. (D to F) Na, Ca, and Mg emission profiles over Mercury’s north and south poles (shown with one-standard-deviation uncertainties). Exponential fits to the data indicate the general behavior of each species. The lone exception is Mg over the north pole, which cannot be fit with such a simple model as discussed in the text.

Fig. 3. Comparison of observations from the third (left) and second (right) MESSENGER flybys illustrating the markedly lower Na tail emission during M3. The images show observed column emissions projected onto the plane containing the Sun-Mercury line and Mercury’s spin axis, interpolating to fill in unobserved regions. The greater degree of point-to-point variation during M3 results from there being approximately six times as many observations as during M2, leading to a lesser degree of smoothing by the interpolation. The region 1–2 R\(_M\) anti-sunward from the planet was not sampled during M2.

Fig. 4. (A to C) Illustrations of the geometry during the “fantail” observations of Na, Ca, and Mg tailward of Mercury during MESSENGER’s third flyby. The UVVS line of sight started in the southward-pointing direction and rolled through dawn toward northern look directions. Colored lines represent the line-of-sight vector for each observation, with the brightness indicating the relative intensity. Lines are black within Mercury’s shadow to emphasize that atoms not excited by sunlight do not emit and cannot be observed by UVVS. The yellow line indicates the spacecraft trajectory. (D to F) Observed Na, Ca, and Mg emission corresponding to the geometry in (A) to (C). Data from M3 are shown with one-standard-deviation uncertainties; data from the first (Ca only) and second flybys are also shown for comparison (uncertainties in these data are slightly smaller owing to longer integration times but are omitted for clarity).
Table 1. Relevant parameters during the three MESSENGER flybys.

<table>
<thead>
<tr>
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<th>M1</th>
<th>M2</th>
<th>M3</th>
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<tbody>
<tr>
<td>True anomaly angle (degrees)</td>
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<td>293</td>
<td>331</td>
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<tr>
<td>Heliocentric distance $r$ (AU)</td>
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<td>0.34</td>
<td>0.31</td>
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<tr>
<td>Radiation acceleration*</td>
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<tr>
<td></td>
<td>Ca</td>
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<tr>
<td>(cm s$^{-2}$)</td>
<td>Mg</td>
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<td>1.8</td>
</tr>
<tr>
<td>g-value† (photons s$^{-1}$ atom$^{-1}$)</td>
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<td>22.89</td>
<td>23.30</td>
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<tr>
<td></td>
<td>Mg (589.2 nm)</td>
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<tr>
<td>(λ in vacuum)</td>
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<tr>
<td></td>
<td>Ca$^+$ (393.5 nm)</td>
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<td>2.95</td>
</tr>
</tbody>
</table>

*Radiation acceleration for atoms at rest with respect to Mercury.
†g-values, or emission probabilities, for atoms at rest with respect to Mercury (16). As atoms accelerate anti-sunward, the presence of deep absorption lines in the solar spectrum causes first a decrease in these values followed by an increase. Without detailed modeling, only approximate (order-of-magnitude) column densities can be inferred from the observed radiances because g-values will be different for atoms and ions at different velocities along the line of sight.