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Recycling of Ions in Mercury's Magnetosphere

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Abstract. To determine the relative rates of ion recycling to the surface and loss of ions to the solar wind, we followed 3,500 Na ions in a tight grid of magnetic and electric fields at Mercury. We conclude that up to 60% of the photoions launched on the dayside near the surface will re-impact the dayside. For a dawn - dusk electric field, we find that most of the returning ions impact the dayside. This will be the case for a southward IMF. Photoions do not impact the dayside with sufficient energy to cause secondary sputtering, but on the nightside they will be accelerated to keV energies, and may cause secondary sputtering there.

1. Introduction

Photoionization is believed to be the predominant loss process for exospheric neutral sodium atoms in Mercury's exosphere. The efficiency of ion recycling to the surface has implications for the long-term volatile budget, for possible sequestration of volatiles in cold traps or high latitude bands, and for relative enrichment of one volatile over another. It has been suggested that the relative loss rates of Na^+ and K^+ may affect the Na/K ratio in the Hermean exosphere. Generally, it has been assumed that about 50% of these photoions escape by entrainment in the solar wind, and the remaining 50% re-impact the surface, as first suggested by Goldstein et al. (1981). Heretofore, this assumption has never been tested by sampling sodium ion trajectories in a magnetosphere model specifically tuned to Hermean conditions. Therefore, we have developed a full-particle tracing code to map the trajectories of charged particles under gravitational, magnetic and electric forces.

2. Ion Trajectories

Our code is based on the Toffoletto & Hill (1993) model, scaled to the Hermean dipole field, and with the ring current removed. Specifics of the model are given in Sarantos (2000) and Sarantos et al. (2001). We followed 3,500 Na ions in a tight grid of magnetic and electric fields at Mercury. The ions were launched at the surface, with an isotropic angular distribution with respect to the vertical at each launching site. Particles were set in motion at sites sampled every 15 degrees of latitude and 30 degrees of longitude to cover the entire dayside. The initial energy was taken to be ~1 eV. Since we only sampled neutrals produced via photon-sputtering, we let the initial ion spatial distribution vary as $\cos f \cos q$, where f and q are the launching latitude and longitude measured from the sub-solar point. We also ran cases in which ions were launched with an isotropic spatial distribution from the dayside surface. The ions were followed until either they hit the surface of the planet, crossed the magnetopause, or reached 7 Mercury radii (Rm) down the tail. It takes less than 10 seconds for an emitted ion to hit the surface of the planet, 30 seconds to a minute to escape to the solar wind, or up to a few minutes to re-impact the nightside by traveling down the tail and turning around.

In order to determine how the ion and accompanying neutral distributions respond to changes in the IMF, we show two runs using nominal magnetic field values. The coordinate system is Cartesian with +x toward the sun, +z normal to the ecliptic in the direction of north as defined at Earth, and y completes a right-handed coordinate system. We first chose a strong negative Bx: B(x,y,z)= (-30,+15,-10) nT. We then tried a second configuration with B(x,y,z) = (20,-10,-10) nT. These values are consistent with the dominance of the Bx component at the orbit of Mercury. In both cases the IMF was southward, which results in the maximum reconnection between Hermean fields and the IMF.

We chart the net change (ions recovered minus ions launched) per dayside surface element and unit local flux under the two aforementioned IMF configurations in Figure 1. Fifty ions were launched isotropically at every other grid point. Areas color-coded in red retained all ions launched. In both figures, dawn is to the left and dusk is to the right. No ions were launched from areas shown in white. A dawn-dusk asymmetry is evident in the spatial pattern in which ions are retained. Ions launched from dawn-side areas are more likely to be retained, whereas ions launched from the dusk-side have a tendency to escape to the solar wind. This is due to the assumption of a predominantly dawn-dusk electric field and may change for different assumed values of By (i.e. a northward IMF case).

Recycling is found to be very important. In either case roughly 60% of ions launched neutralize by impacting the surface. This result is in good agreement with earlier estimates (Ip, 1987). The IMF configuration and magnitude regulates how much sodium is returned to the surface after each sputtering ionization cycle. That has significant implications for the containment of heavy volatiles over geological times.

Because ions that hit the dayside surface have computed energies of 10 - 100 eV upon impact, no significant Na^+ sputtering occurs on the dayside as a result of returning photo-ions. In contrast, about 5 - 10% of ions launched follow Speiser-type orbits and accelerate up to 10 keV before they impact the surface on the nightside. An example of such trajectories is seen in Figure 2 for Na and Figure 3 for K ions. For both figures the IMF was B(x,y,z)=(-30, 15,-10) nT, and ions are launched with identical energies. The K^+ ions travel farther down the tail, and end up in the evening sector. The Na^+ ions have a tighter trajectory and impact on the dawn-side near 6 AM. These ions, which account for up to a tenth of photoionization losses, are mostly implanted into the regolith, but some cause secondary neutral production.

3. Conclusions and Directions for Future Work

We conclude that up to 60% of the photoions launched on the dayside near the surface will re-impact the dayside. For a dawn-dusk electric field, we find that most of the returning ions impact the dayside. This will be the case for a southward IMF. These photoions do not impact the dayside with sufficient energy to cause secondary sputtering, but on the nightside they will be accelerated to keV energies, and may cause secondary sputtering there. We plan to extend these results by 1) considering northward IMF, and 2) using a more realistic distribution of neutrals, both vertically and distributed around the planet. Our rate of ion retention is expected to decrease as we include ions created at progressively higher altitude, and as we increase the relative number of atoms closer to the terminator.

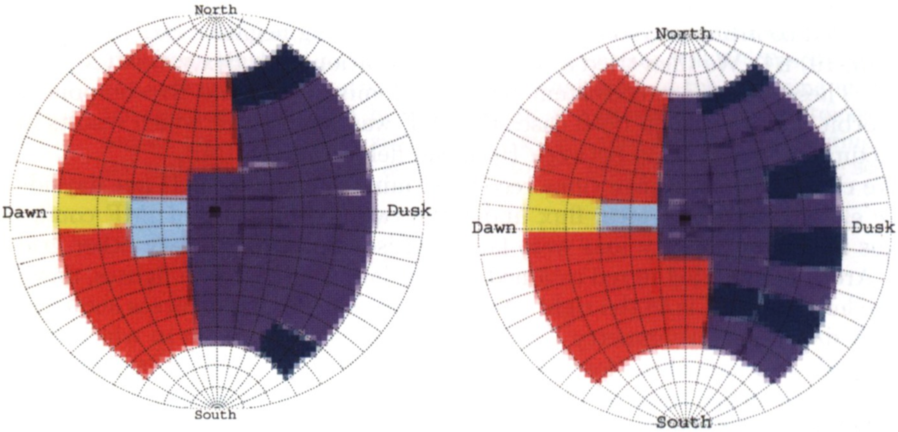

Figure 1. Ion retention pattern for ions launched isotropically from the surface with IMF B(x,y,z)=(-30, 15, -10) nT and B(x,y,z)=(20, -10, -10) nT, on the LHS and RHS, respectively. Red areas retain all ions launched within their boundaries, while dark blue areas lose all ions. Dawn is to the left.

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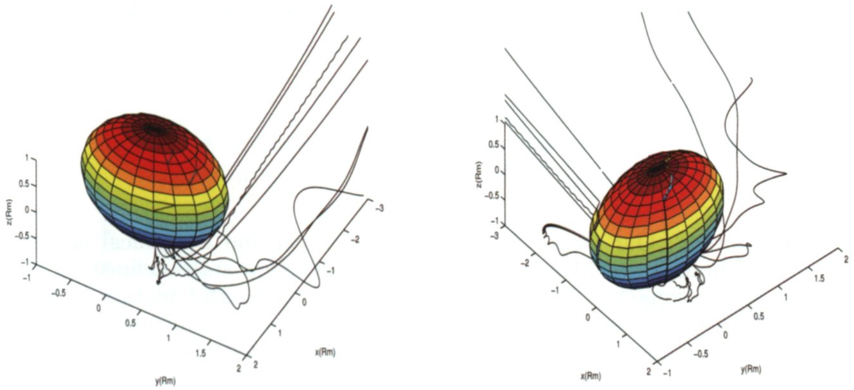

Figure 2. Comparison of the trajectories of K ions (left) and Na ions (right) launched from the same spots with identical IMF configurations B(x,y,z)=(-30,15,-10) nT. Ions have the same initial energy. The K ion ends up on the evening sector, while the Na ion impacts the dawn sector near 6 AM.

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