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Tomographic Reconstruction of Mercury's Exosphere from MESSENGER Flyby Data

Menelaos Sarantos (1,2), Rosemary M. Killen (3), William E. McClintock (4), James A. Slavin (1), Sean C. Solomon (5), Ronald J. Vervack, Jr. (6).
(1) Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; (2) University of Maryland, Baltimore County, Baltimore, MD 21251, USA; (3) Planetary Magnetospheres Laboratory, Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; (4) Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA; (5) Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; (6) The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (menelaos.sarantos-1@nasa.gov).

1. Introduction

The exosphere of Mercury is among the best-studied examples of a common type of atmosphere, a surface-bounded exosphere. Mercury's exosphere was probed in 2008–2009 with Ultraviolet and Visible Spectrometer (UVVS) measurements obtained during three planetary flybys by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [*1-3*]. The measurements detailed the distribution of two previously known metallic constituents of Mercury's exosphere, Na and Ca, and indicated the presence in the gas phase of yet another metallic species, Mg. Such measurements can answer fundamental scientific questions regarding the relative importance of possible source and loss processes for exospheric species ejected from a surface boundary [*4*].

The trajectory of MESSENGER during the last of its three flybys provided the best spatial coverage prior to orbit insertion. The measurements by MESSENGER of Na, Ca, and Mg during the third flyby have been analyzed with a novel tomographic method. This approach maximizes the amount of information that can be extracted from line-of-sight measurements because it yields three-dimensional distributions of neutrals consistent with the data.

2. Method

To develop and validate the tomographic method, boresights from MESSENGER's UVVS spectrometer were passed through a test model of the sodium exosphere [*5*]. The resonant scattering emission of sodium atoms was simulated along each line of sight. Then, such synthetic data (with and without noise) were inverted to reconstruct densities of the underlying neutral sodium distribution. To this end, an optimization technique based on Tikhonov regularization [*6*] was implemented. A Chamberlain model was initially fitted to the measurements; then, this spatially uniform fit was adjusted during an iterative process in order to best match the data. Inversions using synthetic data that simulate the effects of noisy measurements were very good, especially when the signal-to-noise ratio of the synthetic data exceeded five. Hence, our algorithm is stable to propagation of measurement uncertainty.

3. Synthesis of MESSENGER Third Flyby Measurements

A synthesis of MESSENGER data from its third flyby is shown in Fig. 1. The Ca tail in these reconstructions has a pronounced enhancement on the dawn side as previously surmised [*1-3*]. Furthermore, our reconstructions suggest that Ca at dawn is not confined to the equatorial plane but also extends to higher latitudes. Second, the entire Ca tail appears to be shifted towards dawn. The suggested distribution of Mg is also intriguing: the Mg tail appears to be elongated in the equatorial plane and to exhibit polar enhancements that are asymmetric in the north-south direction. At the time of this writing these results should be considered preliminary. Nevertheless, Mg and Ca have clearly different distributions.

A number of source processes could be consistent with these pictures. The measurements suggest that Ca atoms are put in flight by a process that exhibits a pronounced dawn-dusk asymmetry. An extended equatorial emission, such as that suggested for Mg, could be related to sputtering by ions that precipitate onto Mercury's nightside [*7*]. A related cause might be the exposure to solar wind plasma of even the equatorial dayside surface region at the time of the third flyby as inferred by MESSENGER Magnetometer measurements [*8*]. Polar enhancements such as those evoked by our method have been hypothesized as signatures of solar wind precipitation onto Mercury's surface through the magnetospheric cusps at high latitudes [*9*]. The spatial extent of the source or sources of Ca and Mg and the required production rates must be determined with models of particle transport.

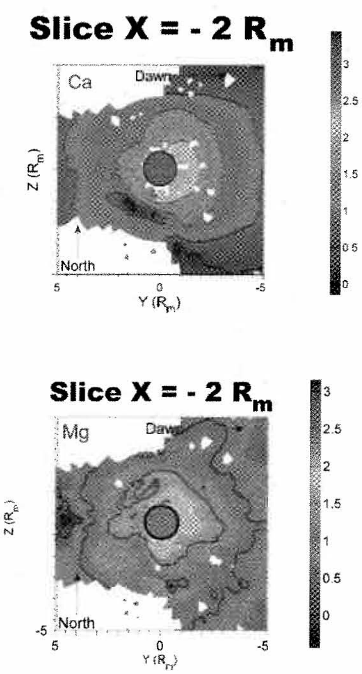

Figure 1: Reconstruction of the Ca tail (upper panel) and Mg tail (lower panel) using line-of-sight measurements during MESSENGER's third flyby. Shown is a section perpendicular to the Sun-Mercury line and located at 2 Mercury radii (R_M) downstream of the planet, where the data coverage is good. Colors are in units of $\log_{10}$ intensity (in Rayleighs). The Sun is behind the plane of this figure. North is up, and dawn is to the right.

4. Conclusion

A tomographic approach can reveal the three-dimensional distribution of exospheric neutrals at Mercury, information that is latent in line-of-sight measurements of scattered light by exospheric particles. This information can help constrain the physical mechanisms that promote and deplete a planetary atmosphere.

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