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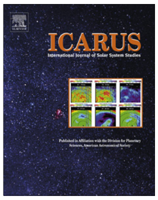

Mercury’s seasonal sodium exosphere: MESSENGER orbital observations

Timothy A. Cassidy [a,*], Aimee W. Merkel [a], Matthew H. Burger [b], Menelaos Sarantos [c,d], Rosemary M. Killen [e], William E. McClintock [a], Ronald J. Vervack, Jr. [f]

[a] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA
[b] Goddard Earth Sciences, Technology, and Research, Morgan State University, Baltimore, MD 21251, USA
[c] Goddard Planetary Heliophysics Institute, University of Maryland Baltimore County, Baltimore, MD 21250, USA
[d] Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[e] Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[f] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

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ABSTRACT

The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) Ultraviolet and Visible Spectrometer (UVVS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft now orbiting Mercury provides the first close-up look at the planet’s sodium exosphere. UVVS has observed the exosphere from orbit almost daily for over 10 Mercury years. In this paper we describe and analyze a subset of these data: altitude profiles taken above the low-latitude dayside and south pole. The observations show spatial and temporal variation but there is little or no year-to-year variation; we do not see the episodic variability reported by ground-based observers. We used these altitude profiles to make estimates of sodium density and temperature. The bulk of the exosphere is about 1200 K, much warmer than Mercury’s surface. This value is consistent with some ground-based measurements and suggests that photon-stimulated desorption is the primary ejection process. We also observe a tenuous energetic component but do not see evidence of the predicted thermalized (or partially thermalized) sodium near Mercury’s surface temperature. Overall we do not see the variable mixture of temperatures predicted by most Monte Carlo models of the exosphere.

1. Introduction

The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) Ultraviolet and Visible Spectrometer (UVVS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft has provided almost daily observations of the exosphere since entering orbit about Mercury on 18 March 2011. UVVS uses a variety of observation geometries during each orbital pass, but this paper focuses on altitude profiles, or “limb scans,” of sodium emission taken above Mercury’s sunlit hemisphere (McClintock and Lankton, 2007). UVVS measures the D_1 and D_2 emission lines near 589 nm wavelength, which are caused by resonant scattering of sunlight. The scattering is so efficient that even the emission visible from Mercury’s nightside (on the order of hundreds of kilorayleighs; Baumgardner et al., 2008) is comparable to Earth’s brightest visible aurorae (e.g., Hunten et al., 1956).

This paper describes the first orbital observations of Mercury’s sodium exosphere. Since its discovery almost three decades ago (Potter and Morgan, 1985) the sodium exosphere has been observed regularly from the ground (see reviews by Domingue et al., 2007 and Killen et al., 2007). The orbital observations described here are quite different from ground-based observations, which can image Mercury’s entire disk and surrounding space. The UVVS observations described here, by contrast, are altitude profiles tangent to the surface (Fig. 2) with limited spatial coverage (Fig. 3). UVVS, however, provides unprecedented spatial resolution and observation cadence. This paper presents 10 Mercury years of near-daily observations that allow us to resolve variations in both local time and true anomaly.

Ground-based observers and modelers have proposed a number of hypotheses to explain their observations. One of the early ideas was that sputter ejection of sodium from Mercury’s poles is responsible for variable polar bright spots (Potter and Morgan, 1990; Sarantos et al., 2001). Another is that thermal desorption of sodium at dawn is responsible for the dawn/dusk asymmetry reported by some observers (e.g., Sprague et al., 1997). These observations led to many modeling efforts. The early models began with a few simple assumptions and explored the dynamics of sodium atoms pushed anti-sunward by radiation pressure (Ip,

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* Corresponding author at: 3665 Discovery Drive, Boulder, CO 80303, USA.
E-mail address: timothy.cassidy@lasp.colorado.edu (T.A. Cassidy).

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1986; Smyth and Marconi, 1995). These were superseded by simulations with an increasing number of interdependent source processes (Leblanc and Johnson, 2003, 2010; Mura et al., 2009; Burger et al., 2010).

A principal focus of the sodium exosphere literature has been temporal variability. Observers have reported *episodic* and *seasonal* (yearly repeatable) variability in the exosphere. Episodic variability is attributed to processes such as short-term changes in solar wind conditions (e.g., Killen et al., 2001; Leblanc et al., 2009; Benna et al., 2010). Seasonal variability is driven by Mercury's changing distance from the Sun, during which the intensities of source, loss, and transport processes change (Lammer et al., 2003; Sarantos et al., 2007; Kameda et al., 2009). In this paper we describe the MESSENGER UVVS results in the context of this previous work, especially with regard to temporal variability. However, a direct comparison with ground-based observations is difficult, and sometimes impossible, because of the differing nature of the two data sets.

This paper is organized as follows. In Section 2, we describe the UVVS observations and discuss conclusions that can be reached by simple inspection of the data, followed by quantitative analysis of UVVS limb scans to estimate exospheric temperature (Section 3) and density (Section 4). We close with a discussion of implications for exospheric source, loss, and transport processes (Section 5).

2. UVVS observations

2.1. Description of UVVS observations

The UVVS is comprised of a telescope feeding a grating monochromator that scans discrete narrow wavelength bands to detect exosphere emission (McClintock and Lankton, 2007). The sodium spectral scan covers a wavelength range of 587.7–591.1 nm with a 0.2 nm step size, allowing both the D_1 (589.8 nm) and D_2 (589.1 nm) emission line centers to fall in the middle of the scan. The detected signal is a combination of sodium emission, solar light scattered off of Mercury's surface, and a dark offset (Fig. 1). The dark offset is from thermionic emission within the detector and is a function of instrument temperature. The dark offset is fully characterized and routinely sampled on the night side of the planet. The scattered sunlight contribution is reflected off of Mercury's surface and scattered into the monochromator. This component is determined by fitting a solar continuum spectrum to the dark-subtracted spectral scan using only wavelengths near the ends of the scan away from the emission lines. The dark and scattered light components are subtracted from the measured signal, and the residual is assumed to be sodium emission from the exosphere. The instrument radiometric sensitivity calibration is applied to convert from counts per second to radiance, and the 11 points around the two line (D_1 and D_2) centers are summed to obtain a total sodium radiance value in kilorayleighs (kR) for each spectral scan. Each limb scan presented in this paper is made up of a series of spectral measurements as the instrument scans in altitude (Figs. 2 and 4). As mentioned earlier, sodium emission is as bright as the Earth's visible aurorae, making it very easy to detect. Therefore the sodium emission dominates the detected signal and the dark and solar scattering components are only small sources of retrieval error as shown in Fig. 1.

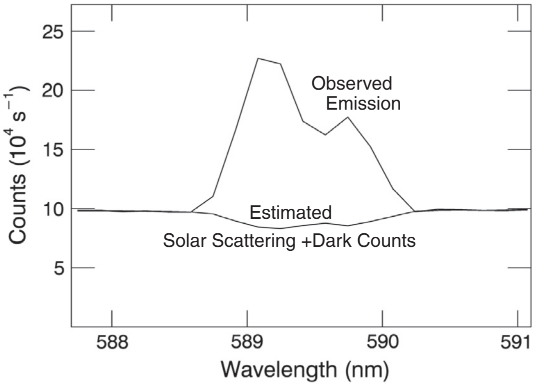

Fig. 1. Example spectrum of sodium D_1 and D_2 emission observed by MESSENGER UVVS at ~100 km tangent altitude near the subsolar point. The graph shows the total observed counts s^{-1} along with the estimated solar scattering and dark offset backgrounds. The observation was taken on 10 April 2011. The true anomaly angle was 124°.

In this paper we describe two MESSENGER UVVS observation types, dayside limb scans and south pole limb scans, obtained between 5 April 2011 and 29 July 2013. Dayside limb scans provide most of the data analyzed in this paper. An example of the observation geometry is shown at the top of Fig. 2. The dayside limb scans are taken when the MESSENGER spacecraft is near apogee and the UVVS line-of-sight points approximately northward. UVVS dayside limb scans provide altitude profiles at primarily low latitudes from dawn to dusk. Each altitude profile extends from just above the surface, as low as 10 km, to several thousand kilometers above the surface.

The other type of observation described in this paper is a south pole limb scan. An example is shown at the bottom of Fig. 2. These are altitude profiles above the south pole that can only be obtained during part of Mercury's year. In these observations the UVVS is scanned back and forth above the south pole terminator. Similar observations are not possible at the north pole because MESSENGER's eccentric orbit has its periapse at high northern latitudes. The spatial coverage, in latitude and local time, of both limb scan types is shown in Fig. 3. The limb scans primarily probe the low-latitude dayside in contrast to ground-based observations that typically include Mercury's entire disk as seen from Earth.

2.2. Qualitative interpretation of limb scan data

In this section we describe some general features of the dayside and south pole limb scans. Examples of UVVS dayside and south pole limb scans are shown in Fig. 4, which shows the observed sodium radiance (sum of D_1 and D_2 emission lines) above Mercury's limb as a function of line-of-sight tangent altitude. The limb scans show a two-temperature structure, which is apparent in Fig. 4 at 6, 12, and 16 h local time by a sharp change in slope between 500 and 1500 km (this change in slope can be seen more clearly in Figs. 6 and 7). The cooler component has a steeper slope and is closer to the surface. It comprises the bulk of the exosphere observed by dayside limb scans. The energetic component has a relatively shallow slope, is relatively tenuous, and has been detected by UVVS up to 4000 km above the dayside surface.

Limb scan observations have been conducted regularly throughout the mission and provide consistent observing geometry, allowing us to search for year-to-year variations in emission. The observations shown in Fig. 4 are very similar from one Mercury year to the next, especially for the near-surface (cooler) component of the exosphere. We do show an example (Fig. 4, 12 h local time) where there is evidence of year-to-year variability above ~700 km altitude. However, because the signal-to-noise level is low in these observations, as indicated by the large error bars in Fig. 4, this variability has yet to be confirmed as real.

This year-to-year repeatability is surprising given the short-term episodic variability reported by ground-based observers. For example, Killen et al. (2001) reported a factor of three increase in total exospheric content over several days. Leblanc et al. (2009) also reported changes in exospheric emission, both in brightness