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Observation of neutral sodium above Mercury during the transit of November 8, 2006

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ABSTRACT

We mapped the absorption of sunlight by sodium vapor in the exosphere of Mercury during the transit of Mercury on November 8, 2006, using the IBIS Interferometric BIdimensional Spectrometer at the Dunn Solar Telescope operated by the National Solar Observatory at Sunspot, New Mexico. The measurements were reduced to line-of-sight equivalent widths for absorption at the sodium D_2 line around the shadow of Mercury. The sodium absorption fell off exponentially with altitude up to about 600 km. However there were regions around north and south polar-regions where relatively uniform sodium absorptions extended above 1000 km. We corrected the 0–600 km altitude profiles for seeing blur using the measured point spread function. Analysis of the corrected altitude distributions yielded surface densities, zenith column densities, temperatures and scale heights for sodium all around the planet. Sodium absorption on the dawn side equatorial terminator was less than on the dusk side, different from previous observations of the relative absorption levels. We also determined Earthward velocities for sodium atoms, and line widths for the absorptions. Earthward velocities resulting from radiation pressure on sodium averaged 0.8 km/s, smaller than a prediction of 1.5 km/s. Most line widths were in the range of 20 mA after correction for instrumental broadening, corresponding to temperatures in the range of 1000 K.

1. Introduction

In 1985, sodium was discovered in emission in the exosphere of Mercury by resonance scattering of sunlight from the atoms (Potter and Morgan, 1985). It was realized that during a transit, the exospheric sodium should be detectable by absorption of sunlight. An attempt was made at the Hida Solar Observatory west of Osaka, Japan, to measure Mercury's sodium exosphere in absorption while Mercury transited the Sun's disk on 6 November, 1993. Observations were made at very high spectral resolution using a CCD detector, but no absorption was detected, probably due to seeing blur (Potter et al., 1994). The first successful observations of Mercury's sodium exosphere in absorption above the solar disk were made during the transit of Mercury May 7, 2003 using a 2-dimensional Fabry–Perot spectrograph with adaptive optics at the Vacuum Tower Telescope at Izana, Tenerife (Schleicher et al., 2004). The success of those observations, and availability of new instrumentation, prompted us to observe the Mercury sodium exosphere during the transit of 8 November 2006. We used both the Main Spectrograph of the McMath–Pierce Solar Telescope at the Kitt Peak National Observatory, Arizona and the Interferometric BIdimensional Spectrometer (IBIS), a dual Fabry–Perot interferometer, at the Dunn Solar Telescope, Sunspot, New Mexico. IBIS is a tunable narrowband filter whose main components are two, air-spaced, 50 mm diameter Fabry–Perot interferometers (Cavallini, 2006; Cavallini and Reardon, 2006; Reardon and Cavallini, 2008; Righini et al., 2010). While spectra from the McMath–Pierce Main Spectrograph clearly showed absorption around the shadow of Mercury against the Sun, the data from the IBIS instrument were very superior, mostly due to the instrument's capability for short exposure times and high spectral resolution. Consequently, we report only the IBIS observations in this report.

Important scientific questions concerning the Mercury sodium exosphere can be addressed by observation of the transit. The surface density, zenith column density and temperature of exospheric sodium can be determined from measurements of the tangent absorption of sodium atoms above the Mercury surface during the transit. There is no other Earth-based method available to infer these fundamental properties of the sodium exosphere. Models of the sodium exosphere predict that the latitudinal variation of

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sodium along the terminator should differ between the dawn and dusk terminator (Leblanc and Johnson, 2010). The transit observation is the best way to test directly this prediction, since the entire terminator circumference is observed simultaneously. The temperature of the exosphere can be mapped in terms of line width, and used to test models for source processes. Solar radiation pressure accelerates sodium atoms in the antisunward direction, directly towards Earth during a transit. The predicted velocity achieved by the atoms is uncertain, since it depends on skip distances, energy of interaction with the surface, and so on. However, it can be measured directly during a transit, providing a real number against which to test theoretical models of the interaction of the sodium exosphere with solar radiation pressure and the surface.

2. Data acquisition and processing

2.1. Data acquisition

The IBIS instrument was operated during the transit to collect images of sodium D_2 absorption around the Mercury silhouette during the period 19:26:27 UT to 20:18:33 UT on November 8, 2006 at the Dunn Solar Telescope at the National Solar Observatory at Sunspot, New Mexico. A total of 46 scans were obtained during this interval. The adaptive optics (AO) system (Rimmele, 2004) was utilized during all the observations, with the disk of Mercury itself serving as the reference target. The AO system and tip-tilt mirror kept Mercury fixed in the field of view, while the solar scene scrolled behind.

The observed spectral range from 5888.24 to 5891.13 Å was sampled with a total of 159 spectral steps. In a 0.3 Å range covering the red wing of the line profile where the absorption feature from Mercury was expected, the line was incrementally scanned in wavelength steps of 0.0087 Å, while in most of the rest of the line, the sampling was in 0.030 Å steps (the finer sampling was also used around the 5888.7 Å telluric line). The sampling is illustrated in Fig. 1.

It took approximately 46 s to perform a single scan of the full line profile, during which time the disk of Mercury was moving at a rate of 0.085 arcsec/s relative to the surface of the Sun, shifting 4 arcsec against the background solar features. A total of 45 full spectral scans were obtained. Each raw image was 1024 × 512 pixels, with a spatial scale of 0.083 arcsec per pixel.

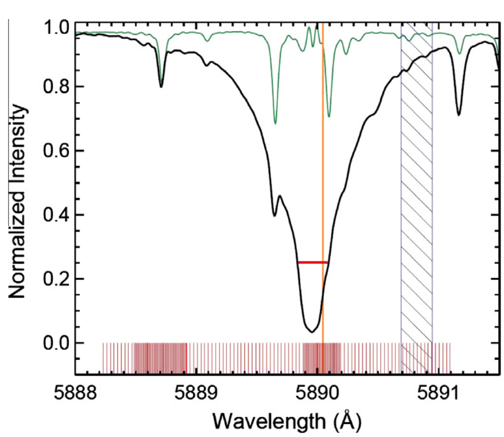

Fig. 1. This plot shows the spectral scan positions (red ticks along the bottom). The red bisector is the position where the line width was measured and corrected, the blue band is the interval that was used as the reference for the line depth normalization, and the orange line is the nominal position of the sodium absorption feature from the exosphere. The green spectrum at the top is the atmospheric absorption spectrum from the Kitt Peak atlas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Data processing

Residual distortions produced by the terrestrial atmosphere were removed by destretching each image with the subsequent image in the spectral scan to align the solar structures on 2.5 × 2.5 arcsec subfields (after removing the drift of the solar structures caused by the telescope tracking of Mercury). To improve the correction near the dark disk of Mercury, a radial gradient filter was calculated for each image, taking into account the fact that the observed planetary disk was not perfectly circular due to the distortions produced by the terrestrial atmosphere. The destretch vectors were calculated based on these radially filtered images and then applied directly to the original, unfiltered images. The spectral profile at each position in the field of view was then interpolated onto a common wavelength grid with 0.0087 Å steps. As part of this interpolation, the radial instrumental blue shift was also removed. Because the disk of Mercury overlapped the optical center of the image, the blue shift was small near the limb (~1 mÅ) of Mercury. The images were then trimmed spatially to produce an x,y,λ data cube with dimensions of [800, 512, 329] pixels.

We selected the 26 spectral scans that showed the best seeing conditions in the wavelengths expected for the exosphere absorption signature. These spectral data cubes were summed to produce a single spectral scan with the magnitude of the intensity fluctuations due to solar structures greatly reduced. However there were still systematic variations in the depth, width, and intensity of the solar sodium D_2 line at different points in the field due to the nature of the solar structures sampled at each position. In order to isolate the absorption feature produced by the Hermean exosphere, it was necessary to remove these variations. This is especially critical because during the transit the absorption feature from the exosphere is shifted approximately 0.1 Å to the red of the solar line core due to Mercury's motion relative to the Sun. This shift places the feature at approximately the wavelength where the intensity crosstalk produced by inherent Doppler-shifts or line width variations in the solar line profile will be greatest.

For all points in the field of view the total line depth (between the line core minimum intensity and the mean intensity in the red wing of the profile in the range +0.75 to 1.0 Å), the line core position, and the line width at 25% of the continuum intensity (approximately ±0.12 Å from the line core) were measured. This intensity level was chosen for the bisector measurement in order to minimize disturbances from telluric lines present in both the red and blue wings of the line profile. The normalization to the nearby red wing intensity also provided a correction for the intensity changes at points near the limb of Mercury as points were covered or uncovered during the 20 s it took to scan in wavelength between the core and red wing.

A reference profile was generated by averaging the line profiles in an annulus between 4 and 16 arcsec (1960 and 7820 km) above the limb of Mercury. Prior to averaging, each individual profile was shifted to align the line position (measured in both the wing and core) with the average position, the total line depth normalized to unity, and scaled to have line width equal to the average across all the profiles. This gave an average profile that was not broadened by line shifts or width variations.

Then for the spectrum observed at each point in the field of view, this average profile was shifted in wavelength, and scaled in intensity and line width to match each observed spectrum. The observed profile was then divided by the scaled reference profile to remove the solar absorption and derive the profile of the relative absorption, if present.