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ScienceDirect
Planetary and Space Science 55 (2007) 1069–1092
Planetary and Space Science
www.elsevier.com/locate/pss

Mercury's exosphere origins and relations to its magnetosphere and surface

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Accepted 9 March 2006
Available online 22 January 2007

Abstract

Mariner 10, the only spacecraft that ever passed close to Mercury, revealed several unexpected characteristics: an intrinsic magnetosphere, the highest mean density of any Solar System terrestrial planet and a very thin non-collisional atmosphere. Mercury's atmosphere is very poorly explored since only three atomic elements, H, He and O, were observed during the three flybys of Mariner 10. The measurements done by radio and solar occultations provided upper limits on the neutral and ion densities. These measurements pointed out the close connection between species in Mercury's exosphere and its surface, which is also the case for the Moon. Mariner 10 observations also characterized the vertical distributions and the day to night contrasts of Mercury's exosphere for its lightest components H and He (Broadfoot, A.L., et al., 1976. Mariner 10: Mercury atmosphere. Geophys. Res. Lett. 3, 577–580).

More than a decade later, the first observation from a ground-based observatory of Mercury's sodium (Na) exospheric component was reported (Potter, A.E., Morgan, T.H., 1985. Discovery of sodium in the atmosphere of Mercury. Science 229, 651–653). Since then, potassium and more recently calcium have been identified in Mercury's exosphere. The bright Na resonant scattering emission has been often observed since 1985. This large set of observations is now the best source of information on Mercury's exospheric mechanisms of ejection, dynamics, sources and sinks. In particular, several of these observations provided evidence of prompt and delayed effects, both localized and global, for the very inhomogeneous Mercury's Na exosphere. These inhomogenities have been interpreted as the trace of Mercury's magnetosphere–solar wind interaction and have highlighted some of the main sources of exospheric material. Some of these features have been also interpreted as the trace of a global dayside to night side circulation of Mercury's exosphere and therefore have highlighted also the relation between exospheric production and upper surface composition.

Hopefully, new sets of in situ measurements will be obtained within the next decade thanks to Messenger and Bepi-Colombo missions. Until then, ground-based observations and modelling will remain the only approaches to resolve questions on Mercury's exosphere. Mercury's exospheric composition and structure as they are presently known are described in this paper. The principal models for the main short and long times terms variations and local and global variations of Mercury's exosphere are described. The mechanisms of production and their characteristics are also given. Mercury's exosphere can also be seen as part of the coupled magnetosphere–upper

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0032-0633/$ - see front matter
doi:10.1016/j.pss.2006.11.008

surface–exosphere system and several of the links between these elements are essential to the interpretation of most of the ground-based observations. The relation between Mercury's planet composition and its exospheric composition is also considered, as is the global recycling, sources and sinks of Mercury's exosphere.

Keywords: Mercury; Exosphere; Magnetosphere; Surface; Review

1. Introduction

The atmosphere of Mercury is very tenuous, with a pressure of a fraction of pbar (Broadfoot et al., 1974, 1976). That is, it is an exosphere with Mercury's surface its exobase or, using the name given by Stern (1999) for the Moon's exosphere, it is a surface–boundary–exosphere. It results from a complex interplay of the solar wind, its planetary magnetic field and its rocky surface. It is nearly collisionless, and is highly variable with time and space, characterized by a global asymmetry between dayside and night side and rapid temporal variations, possibly related to varying magnetospheric activity (Killen and Ip, 1999). From Mariner 10 UV measurements, and telescopic optical spectroscopy from Earth, six elements have been identified: Ca, Na, K, H, He and O (Broadfoot et al., 1976; Potter and Morgan, 1985, 1986; Bida et al., 2000). Other species are expected: e.g. H_2, OH, possibly released by impacting bodies onto water ice in craters, and noble gases, both non-radiogenic (Ne) and radiogenic (^{40}Ar, ^{129}Xe). All species representative of the surface composition, directly produced by sputtering from the regolith, should also be present (Hunten et al., 1988). Ions like Si^+, O^+, Al^+ have been observed on the Moon (Hilchenbach et al., 1991, 1993; Cladis et al., 1994; Mall et al., 1998). Volatiles are supplied by solar wind and crustal outgassing, powered by solar UV radiation, particle sputtering and/or meteoritic impact (Madey et al., 1998; Killen et al., 2001). They are lost by thermal and ion escape. Mercury's exosphere is expected to have some features in common with the lunar exosphere, due to similarities between their formation mechanisms (Killen and Ip, 1999; Stern, 1999).

The estimates of the yields for various source processes are made difficult by our ignorance of the bulk composition of the regolith, which is may be volatile-rich with respect to the lunar regolith. Several possible sources of trapped volatiles have to be considered at various time scales. On short time scales (diurnal: a few terrestrial days or weeks), a fraction of atmospheric species is expected to be adsorbed at the surface (mainly during night) and released at sunrise (Sprague et al., 1997a; Hunten and Sprague, 1997, 2002), or in response to local energetic particle precipitation (Potter and Morgan, 1990; Potter et al., 1999). On longer time scales, an important large number of sputtered particles are not directly released to the exosphere, but re-adsorbed in the regolith (Killen and Morgan, 1993a, b; Sprague, 1992, 1993; Yan et al., 2006b). Additionally, the material released by impacting meteorites might be partially retained in the regolith before being delivered to the exosphere. Finally, volatiles continuously diffusing from the deep crust, like radiogenic noble gases, might be present. On geological time scales (a few billion years), solar wind ions and solar energetic particles have been implanted in the regolith, similarly to the lunar case.

Characterizing magnetosphere–exosphere–surface processes on different bodies of the Solar System is required to better understand the Solar System evolution. On Mercury, sputtering, and other volatile production processes, are expected to imprint their signatures on: (i) the composition of the upper layers of the regolith, undergoing selective depletion of elements according to their ejection rates (Leblanc and Johnson, 2003), (ii) the composition and dynamics of the exosphere, which is also the place of a region having complex recycling through adsorption and re-emission at the surface of the regolith (Hunten and Sprague, 2002), (iii) the composition and dynamics of the magnetosphere, where species can irreversibly escape to space, at a rate which is globally proportional to the net extraction rate of species at the surface, and is therefore closely related to the composition of the regolith. Due to the large time and space variability of erosion sources (sputtering, UV flux, meteoritic vapourization, etc.), Mercury is a natural laboratory for the in-depth study of ejection processes from a theoretical, modelling and observational point of view (Madey et al., 1998; Johnson, 2002).

This paper gives an update summary of what is presently known about Mercury's exosphere. The Mariner 10 observations of H and He atoms were the first to detect the presence of an exosphere at Mercury, and are discussed in detail by Hunten et al. (1988). Many puzzles remain, and observations from Messenger and Bepi-Colombo will address them. The present paper concentrates on atoms detected from the ground that were not observed by Mariner 10, and our understanding of which stands to be greatly improved by spacecraft observations. Therefore, this paper should be considered a complement to the three following excellent reviews: Hunten et al. (1988), Hunten and Sprague (1997) and Killen and Ip (1999). It derives from an active collaboration between all of the authors as an answer to the call of opportunity for Bepi-Colombo ESA mission in support to PHEBUS (Probing of Hermean Exosphere By Ultraviolet Spectroscopy: A FUV–EUV spectrometer for the MPO Bepi-Colombo mission, PI: E. Chassefière), the selected UV spectrometer for Mercury Planetary Orbiter in Bepi-Colombo. Section 2 provides some insights on what is presently known on Mercury's exosphere, whereas Section 3 gives elements of the