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THE SODIUM EXOSPHERE AND MAGNETOSPHERE OF MERCURY

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Abstract. Following the recent optical discovery of intense sodium D-line emission from Mercury, we explore the scenario of an extended exosphere of sodium and other metallic atoms. It is shown that the strong effect of solar radiation pressure acceleration would permit the escape of Na atoms from Mercury's surface even if they are ejected at velocity less than the surface escape velocity. Fast photoionization of the Na atoms is effective in limiting the tailward extension of the sodium exosphere, however. The subsequent loss of the photoions to the magnetosphere could be a significant source of the magnetospheric plasma. The recirculation of the magnetospheric charged particles to the planetary surface could also play an important role in maintaining an extended sodium exosphere as well as a magnetosphere of sputtered metallic ions.

Introduction

Among planetary objects, Mercury is unique in the sense that its atmosphere is extremely tenuous and at the same time it has a magnetic field sizable enough to stand off the solar wind with the magnetopause distance at about 1.6 R_M (Ness et al., 1974). The Mariner 10 spacecraft encounters with Mercury have also shown that many energetic charged particle events occurred in a burst-like manner (Ogilvie et al., 1974; Simpson et al., 1974) indicating a very dynamic magnetospheric system therein. The time scale of the observed bursts of energetic (>0.3 MeV) electrons and (>0.5 MeV) protons are consistent with the theoretical consideration that at Mercury the substorm process triggering transient particle acceleration should occur in a time interval of minutes (Siscoe et al., 1975).

Direct scaling of the magnetospheric phenomenology from the Earth to Mercury should be somewhat modified however, because of the very different atmospheric and ionospheric structures of these two planets. As the Mariner 10 UV airglow spectrometer measurements (Broadfoot et al., 1974) have set very low values for the surface densities of hydrogen atoms ($n(H) = 8$ cm^{-3}) and of helium atoms ($n(He) = 4.5\times10^3$ cm^{-3}) on the dayside of Mercury, and the upper limit of the dayside surface gas density was determined to be 10^6 particles cm^{-3} by the radio occultation experiment (Fjeldbo et al., 1976), it was usually suggested that there should be very little interaction between the magnetosphere and the planetary atmosphere. (For a rather thorough discussion on the magnetosphere - surface process involving He atoms and the consequence of radiogenic outgassing from the planetary interior, see Goldstein et al., 1981.) However, the recent discovery of strong sodium D-line emission from Mercury (Potter and Morgan, 1985; Schneider et al., 1985) could mean that several new aspects should be added to the scenario of atmosphere-magnetosphere coupling at Mercury. In the following, the issue of an extended sodium exosphere and its magnetospheric interaction will be pursued. Areas of uncertainties will be pointed out to facilitate further theoretical and observational investigations.

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A Sodium Exospheric Model

The observed value of an average column density of 8×10^{11} Na atoms cm^{-2} had been used to infer a surface density at the subsolar point of 1.5×10^5 cm^{-3} on the basis of a scale height ($H \simeq 50$ km) as determined by the surface temperature of 500 K (Potter and Morgan, 1985). Since at surface impact, unlike the H and He atoms, the sodium atoms should stick to the ground via physiosorption (Lichtman, 1979), the vertical distribution of the Na atoms might not be governed by the thermal velocity dictated by the surface temperature; instead it should depend on the ejection process. For several viable mechanisms of surface ejection of Na atoms (i.e., meteoroid impact and charged particle sputtering which has been preliminarily explored by McGrath-Kinnally and Johnson, 1985), the initial kinetic energy of the ejected particles could be $\simeq$ 1-2 eV (Grün and Reinhard, 1981; Carter and Colligon, 1968); the possibility thus exists that the Na atoms could be flung into ballistic orbits with altitudes much larger than 50 km. Under this condition, by virtue of the large solar radiation pressure acceleration and fast photoionization effect of the sodium atoms, a number of interesting consequences would result.

For example, in Figure 1 are shown the ballistic trajectories of Na atoms emitted at three different initial velocities (V_o) but with the same direction from the planetary surface. The first case with $V_o = 2$ km s^{-1} indicates that after reaching the maximum altitude the Na atoms will be returned to the surface because of the gravitational force of the planet (Mercury's surface escape velocity $V_{escape} = 4.3$ km s^{-1}). However, because of the strong action of the solar radiation pressure ($a_r = 173$ cm s^{-2}), the Na atoms could be accelerated in the antisunward direction gaining enough energy to escape from the planet altogether even if V_o = 3-4 km s^{-1} (see also Smyth, 1985 for similar consideration). A tail of sodium atoms could thus form this way. In other words, the observed morphology of sodium emission behind the planet may be used to infer the ejection condition - as in the similar case of Io's sodium cloud (Smyth and McElroy, 1978).

To investigate further the possible structure of the sodium exosphere, a Monte Carlo model tracing the orbital history of individual particles under the effects of solar radiation pres-

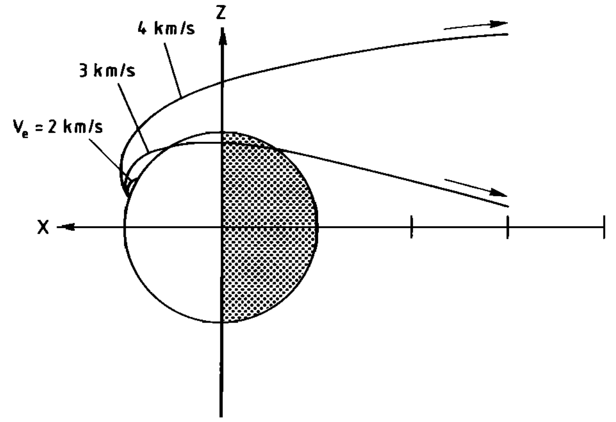

Fig. 1. Examples of ballistic trajectories of sodium atoms ejected from Mercury's surface with three different initial velocities: V_{ej}= 2 km s^{-1}; 3 km s^{-1}; and 4 km s^{-1}.

sure acceleration and photoionization loss has been constructed. In the calculation, particles are assumed to be emitted from the planetary surface with a fixed velocity (V_{ej}) but with the initial direction randomly oriented. Under steady state condition, a number (=5000) of particle streams are traced with the relative number density at each time step (t_k) reduced by a factor $\exp(-t_k/t_i)$ where t_i = 3.3×10^3 sec is the photoionization time of the Na atoms at r = 0.35 AU. Angular symmetry with respect to the sun-Mercury axis was further assumed and the numerical results for a variation of the source strength per unit area as a cosine of the solar insolation angle (θ) are shown in Figure 2.

The illustrated brightness or column density distributions with a grid size of 0.1 R_M × 0.1 R_M are calculated by assuming the line-of-sight is perpendicular to the sun-Mercury axis. The first case (Figure 2.a) is for V_{ej}= 2 km s^{-1} and the second case (Figure 2.b) is for V_{ej}= 3 km s^{-1}. In computation of the optical emission, the shadow effect of the planetary disk has been taken into consideration.

As expected, the high velocity ejection leads to a rather extended distribution of the sodium atoms with maximum altitude reaching 0.4 R_M at the subsolar point and a stretched out tail formation is seen in the antisunward direction (Figure 2.b). When the ejection velocity is reduced to 2 km s^{-1} (Figure 2.a) the sodium optical emission pattern will be concentrated much more on the sunlit hemisphere reflecting the cos θ dependence of initial surface ejection considerably better.

The Na^+ ions produced in the exosphere via photoionization will be either returned to the planetary surface or ejected into the solar wind or the magnetosphere. The first route should be followed by the photoions created on the dayside region threaded by closed magnetic field lines. The storage of the Na^+ ions in the flux tube by means of magnetic mirroring or electrostatic reflection from a positively charged surface may contribute significantly to the formation of a dayside ionosphere. As for the ions created in the field lines connecting to the magnetotail, they would be a source for the plasma mantle as well as the plasma sheet. From the present numerical calculations it could be found that the relative amount of sodium atoms contained in the volume accessible to the magnetospheric tail is about 2.5% of the total exospheric sodium population in the case (a) of V_{ej}= 2 km s^{-1} and about 14% in the case (b) of V_{ej}= 3 km s^{-1}.

Since the total number of sodium atoms in Mercury's exosphere can be approximated from the observations of Potter and Morgan (1985) by using the following expression:

$$N_{pm} \simeq 8.1\times10^{11} \times \pi R_M^2 \simeq 1.4\times10^{29} \text{ atoms} \quad (1)$$

the Na^+ ion production rate in Mercury's magnetosphere can be written as

$$\dot{N}_i(a) \simeq 0.025 f N_{pm}/t_i \quad (2)$$

and

$$\dot{N}_i(b) \simeq 0.14 f N_{pm}/t_i \quad (3)$$

where f (≤ 1) is a ratio of the content of the extended exosphere to the value derived from the observation of Potter and Morgan. In other words, if all sodium emission observed is due to sodium atoms concentrated on the surface, then f = 0;

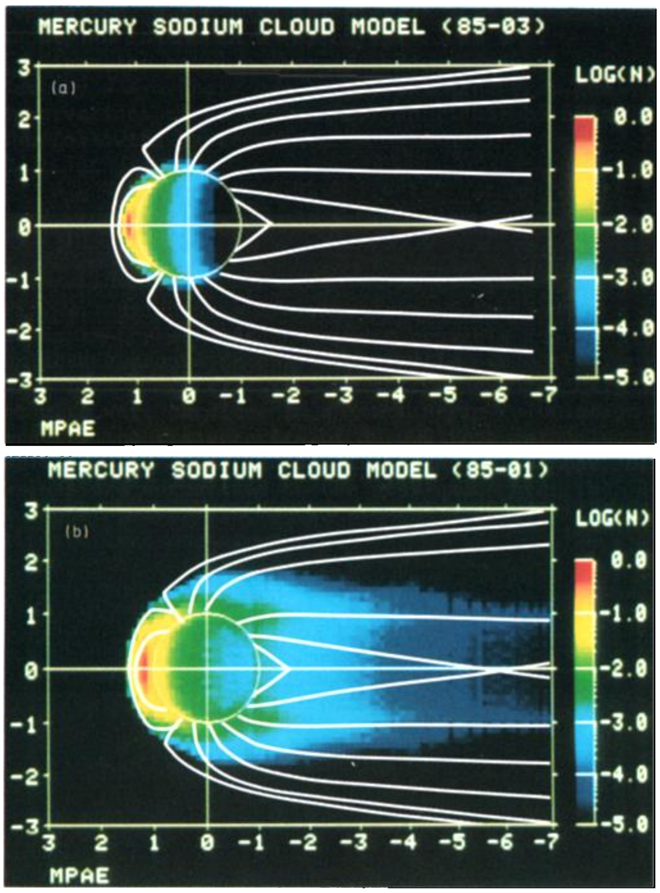

Fig. 2. Brightness distributions of the sodium atoms in the extended exosphere possibly in existence around Mercury: (a) initial velocity V_{ej}= 2 km s^{-1}; (b) V_{ej}= 3 km s^{-1}. The numerical results were obtained in a Monte Carlo calculation tracing the trajectories of 90,000 test particles emitted with a cos θ dependence. The brightness values are normalized to the peak value near the subsolar point. Also shown are the magnetic field lines of the magnetosphere.

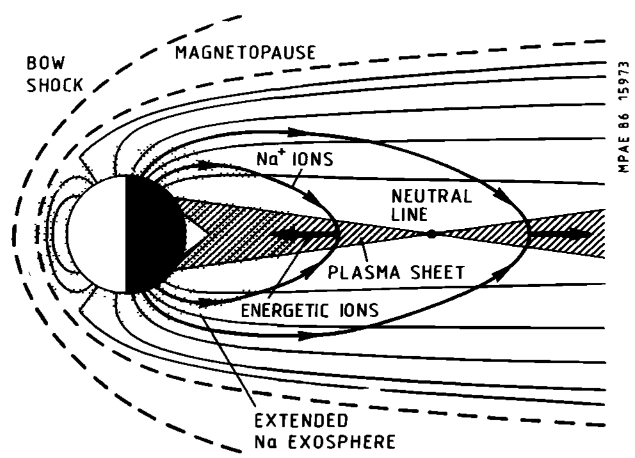

Fig. 3. A hypothetical scenario of how the magnetosphere of Mercury may generate its mass supply by a cycle of surface, sputtering, ionization, and plasma sheet acceleration.

and if all sodium atoms are distributed in an extended envelope with the particles leaving the surface at an initial speed of 2-3 km s^{-1}, then f = 1.

For the sake of comparison, setting f $\simeq$ 0.1 we have $\dot{N}_i(a) \simeq 1.2 \times 10^{23}$ Na^+ ions s^{-1} and $\dot{N}_i(b) \simeq 6.5 \times 10^{23}$ Na^+ ions s^{-1}. The corresponding solar wind entry rate into Mercury's magnetosphere would be on the order of $2{\times}10^{24}$ protons s^{-1} adopting an entry coefficient of 10^{-3}. The potential contribution of the sodium exosphere to the magnetospheric mass budget therefore could be quite appreciable if the extended exosphere has a content of $\geq$ 10% of the sodium cloud detected in optical emission.

The Sodium Magnetospheric Supply

A very simple approach has been employed here to explore the possible effects of a sodium exosphere of Mercury. It is seen that for an ejection velocity sufficiently large (V_{ej} > 2 km s^{-1}), a tail of neutral Na atoms will form in alignment with the magnetotail. This also brings up the issue so far untouched upon which concerns the exact ejection process of the Na atoms. With a ballistic transit time of 1000 s the required surface production rate would be about $\dot{N}_{pm} \simeq 1.4{\times}10^{26}$ s^{-1}. This amount exceeds the sputtering yield from the solar wind protons entering the magnetosphere with a sputtering coefficient of 1-10 atoms/ion (Carter and Colligon, 1968). If the mixing ratio (X_{Na}) is taken into consideration, the solar wind sputtering effect would be even less important. Hypervelocity meteoroid impact should be able to generate impact vapour on the order of 10^{25} X_{Na} atoms s^{-1}; but it is also not sufficient to account for the estimated production rate of $\dot{N}_{pm}$.

Another possibility would be photosputtering. According to Madey and Stockbauer (1983) the effective cross section of photon-stimulated desorption (PSD) of atoms from surface varies between 10^{-18} cm^2 and 10^{-24} cm^2 depending on the material in question. Thus, in the idealized situation of a monolayer of pure sodium atoms (i.e., 10^{15} atoms cm^{-2}) and a solar UV flux of $3{\times}10^{11}$ photons cm^{-2} s^{-1}, PSD provides at best $5{\times}10^{25}$ Na atoms s^{-1} in total. Without a more detailed look of the photosputtering and processing of the surface material of Mercury, it would seem that there is an apparent difficulty in interpreting the observed Na emission as the result of solar radiation if the PSD rate is not extremely large. In any event, the above consideration indicates that all these effects combined together should permit the formation of a tenuous exosphere of sputtered atoms including Na, Al, Mg, Si, Fe, ...

It should be noted that the assumed ejection profile with a cos θ dependence (hence simulating the PSD effect) has the property of minimizing the loss of the Na^+ ions to the magnetosphere. For other distributions, such as a uniform ejection law, the injection rate of Na^+ ions should be correspondingly larger. One other sputtering effect not directly connected with the dayside sodium optical emission is bombardment by the magnetospheric charged particles at the nightside hemisphere. For exospheric ions drifting into the plasma sheet, they will be accelerated by the cross-tail electrostatic field to an average kinetic energy of about 7 keV (Siscoe et al., 1975). Subsequent convection/injection of these accelerated ions towards the planet will be terminated by surface impact. The neutrals and secondary heavy ions (positive and negative) will be recirculated into the magnetosphere. It is therefore possible that Mercury derives its magnetospheric plasma largely from such plasma-surface interaction. It also remains to be seen whether an appreciable fraction of the photoions created in the dayside ionosphere could be accelerated to an energy of a few hundred eV by parallel electric field or other effects so that an extended exosphere could be substained by sputtering effect of the ionospheric particles. The general picture of Mercury's surface/exosphere/magnetosphere interaction is summarized in Figure 3.

Discussion

In this brief report, we have considered two possible ideas related to the atmospheric and plasma environment of Mercury, namely (1) the possible existence of an extended exosphere of sodium (and other metallic) atoms resulting from different types of surface sputtering processes (i.e., meteoroid impact, photodesorption, solar wind bombardment, etc.); (2) the very probable formation of a magnetosphere of heavy ions via recirculation, acceleration, and surface sputtering effect of the energetic charged particles.

The first item can be investigated in more detail by ground-based observations of the optical sodium emission and theoretical modeling as outlined here. Important information on the velocity distribution, emission geometry, and spatial distribution could be gleaned from fine-resolution spectroscopic observations as well as filtered imagery. The detection of a tail-like extension of the sodium emission will be most interesting in this respect.

Somewhat independent but still related to the formation of an extended exosphere is the build-up of a magnetosphere of sodium and metallic ions partly from the effect of magnetospheric plasma-surface interaction. In the case of the magnetospheres of Jupiter and Saturn, solid surface sputtering by energetic charged particles as a means to provide plasma source is a known process (see Cheng et al., 1985). However, for Mercury, it is the planetary surface which is directly subject to sputtering effect. It is thus expected that in situ plasma measurements at Mercury should reveal a large flux of heavy ions (Na^+, Al^+, Fe^+, Ca^+, etc.) reflecting the surface composition of the planet.

One source mechanism not touched upon here concerns the radiogenic outgassing process as probably observed on the lunar surface (Hodges, 1977). Besides radiogenic He, ^{40}Ar will be produced via the decay of ^{40}K. Thus the measurement of ^{40}Ar in the magnetospheric composition will be a direct tracer of the radioactive decay in the interior of Mercury. However, the generation of Na atoms must be of a different nature if it is related to surface outgassing.

Since a large portion of the magnetotail will be shielded from solar radiation, the magnetospheric ions (i.e., Ca^+) will not be conveniently monitored by optical methods. In any event, if the surface sputtering rate by energetic charged particles is modulated by the solar wind condition, some characteristic temporal variation (i.e., a periodicity of 25 days) may appear in the optical emission of the sodium atoms. It is therefore still possible to investigate some aspects of the magnetospheric dynamics of Mercury by ground-based observations. Research efforts in this direction should also path the way for magnetospheric studies in an orbiter mission.

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