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Dynamics of Electrons and Heavy Ions in Mercury's Magnetosphere

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Several basic magnetospheric processes at Mercury have been investigated with simple models. These include the adiabatic acceleration and convection of equatorially mirroring charged particles, the current sheet acceleration effect, and the acceleration of Na^+ and other exospheric ions by the magnetospheric electric and magnetic fields near the planetary surface. The current steady-state treatment of the magnetospheric drift and convection processes suggests that the region of the inner magnetosphere as explored by the Mariner 10 spacecraft during its encounter with Mercury should be largely devoid of energetic (>100 keV) electrons in equatorial mirroring motion. As for ion motion, the large gyroradii of the heavy ions permit surface reimpact as well as loss via intercepting the magnetopause. Because of the kinetic energy gained in the gyromotion, the first effect could lead to sputtering processes and hence generation of secondary ions and neutrals. The second effect could account for the loss of about 50% of Mercury's exospheric ions.

1. INTRODUCTION

Since the discovery of strong atmospheric sodium emission from Mercury (Potter and Morgan 1985, 1986, Tyler *et al.* 1986), much attention has been focused on the issues of source/sink and dynamics of the Na/K exosphere. For example, in the work of Ip (1986) and Smyth (1985, 1986), it has been shown that solar radiation pressure plays a very important role in the ballistic motion and surface transport of the sodium and potassium atoms. One basic feature of the random walk motion across the planetary surface with strong perturbation by the solar radiation pressure is that the sodium (and potassium) atoms would be subject to a systematic acceleration to the antisunward direction and atoms emitted with a speed exceeding 2 km sec^{-1} from the surface could be ejected to the nightside forming an elongated sodium tail. One interesting consequence of the injection and ionization of the Na and K atoms into Mercury's magnetosphere is that the magnetospheric plasma composition should be enriched in Na^+ and K^+ ions and other heavy ions sputtered from the surface (Ip 1986). The possibility exists that plasma–surface interaction could be essential in forming a "metallic" magnetosphere at Mercury. It is thus of interest to examine some of the dynamical properties of the exospheric ions in the magnetospheric environment. Our investigation is divided into two parts. In the first part, we consider the basic configuration of Mercury's magnetosphere as a scaled-down model of the Earth's magnetosphere. In particular, the global electrostatic potential distribution and particle drift pattern will be briefly reviewed from the point of view of comparative study of these two magnetospheric systems. In the second part, the finite gyroradius effect on the trajectories of heavy ions is examined. A few examples are used to illustrate the potential importance of direct electric field acceleration of the Na^+ ions on the loss and recirculation of the exospheric sodium and potassium atoms.

2. GENERAL CONSIDERATION

The Mariner 10 flyby observations of Mercury had shown that Mercury has a

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magnetospheric system with many basic features similar to those of the terrestrial magnetosphere (Ness *et al.* 1974, 1975, Ogilvie *et al.* 1974, 1977, Simpson *et al.* 1974). By combining the magnetic field measurements and plasma data together, Ogilvie *et al.* (1977) showed that the size of the Mercury magnetosphere relative to the planet itself is about a factor of 8 smaller than the corresponding scaling for the Earth. That the distance of the magnetopause is at $L_{MP} = 1.4R_M$ for Mercury ($L_{MP} = 11R_E$ for the Earth) also means that the magnetospheric configuration of Mercury is unfavorable to the stable trapping of a population of ring current particles which is usually found within $8R_E$ in the case of the terrestrial magnetosphere.

Figure 1 offers the simplest explanation for this view as it shows how the tracing of constant magnetic field magnitude profiles should lead to the interception of the equatorially mirroring charged particles by the magnetopause. Nevertheless, Baker *et al.* (1986) has recently invoked the quasi-trapping of energetic electrons ($E > 170$ keV) near Mercury as an explanation for the recurrence of short-termed bursts in major charged particle events as detected by the energetic particle experiment onboard Mariner 10 (Simpson *et al.* 1974). Furthermore, it was suggested by Baker (1986) that besides *in situ* acceleration in Mercury's magnetosphere, interplanetary electrons of Jovian origin could be injected into the inner magnetosphere during episodes of enhanced convection process (see Siscoe *et al.* (1975), Ogilvie *et al.* (1977), and Goldstein *et al.* (1981) for discussions on the substorm-like effect at Mercury). As a result of conservation of magnetic moment ($\mu = mV_\perp^2/2B$), the low-energy Jovian electrons could be energized to megaelectron volt energies by inward convection.

The equatorial trajectories of electrons with three different μ values injected at large distance down the magnetotail are shown in Fig. 2. In order to simulate the effect of enhanced convection, the dawn-to-dusk electric field is assumed to be E = 150 keV/6R_M which is about a factor of 10 larger than the nominal value of 7 keV/6R_M (Ogilvie *et al.* 1977, Siscoe *et al.* 1975).

Because of the slow rotation of the planet, the model computation can be simplified by neglecting the $\mathbf{V} \times \mathbf{B}$ electric field due to the corotation of the planetary magnetic field. Under steady-state conditions,

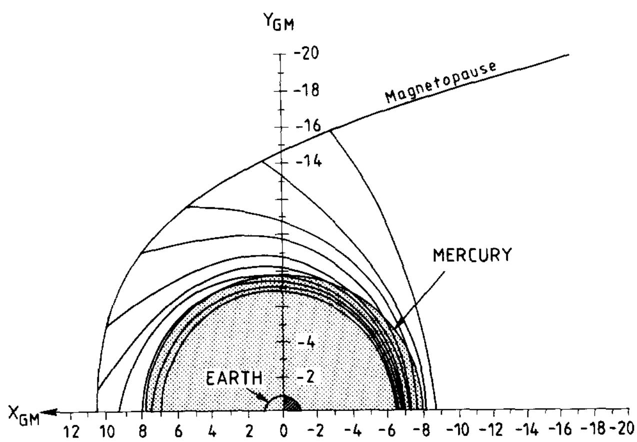

FIG. 1. A comparison of the relative sizes of the magnetospheres of Mercury and the Earth. The contours of equal magnetic field magnitude at the equator (Roederer 1970) are indicated. The distances are marked in units of Earth radii (R_E) and it can be seen that equatorially mirroring charged particles would move in trapped orbits only for radial distances $<8R_E$.

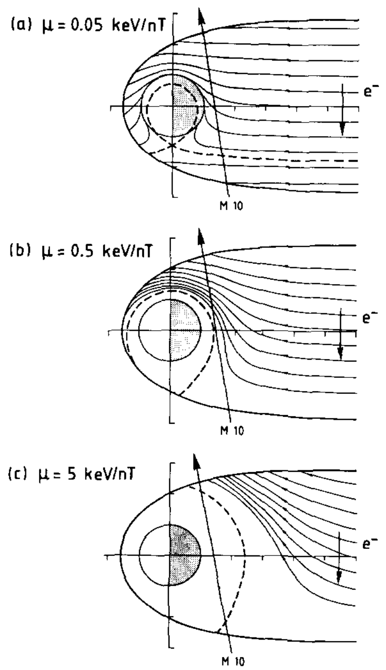

FIG. 2. Drift patterns of equatorially mirroring electrons with three different values of magnetic moment (μ): (a) μ = 0.05 keV/nT; (b) μ = 0.5 keV/nT; and (c) μ = 5 keV/nT. The trajectory of the Mariner 10 spacecraft on March 29, 1974, is also indicated.

the inward drift motion of the equatorially mirroring electrons can be described by using the well-known relation (Alfven and Fälthammar 1963) between the conservation of energy,

$$|e|\Phi = |e|\Phi_0 + eE(x - x_0), \qquad (1)$$

and the invariance of the magnetic moment,

$$\mu = \frac{|e|\Phi_0}{2B_0} = \frac{|e|\Phi}{2B}. \qquad (2)$$

In the above equations, $B(r)$ is the magnetic field strength of a dipole moment situated at the planetary center with $r = (x^2 + y^2)^{1/2}$, B_0 is a uniform field in the z-direction, $|e|\Phi$ is the total energy at (x, y), and $|e|\Phi_0$ is the total energy at the initial position (x_0, y_0).

Because of the gradient B drift effect, the electrons are accelerated to the dawn side of the magnetosphere as they move toward the planet. The dashed curves denote the boundaries of the Alfven layers inside of which convective entry of charged particles with certain μ values are forbidden (Alfven and Fälthammar 1963). It is interesting to note that the drift patterns are quite sensitive to the μ values and hence the maximum particle energy at closest distance to the planetary surface which could be gained by such adiabatic acceleration is also strongly dependent on μ. For example, in the case of μ = 0.05 keV/nT, $|e|\Phi_{max} < 20$ keV (Fig. 2a); and in the case of μ = 5 keV/nT, $|e|\Phi_{max} < 70$ keV (Fig. 2c). That for the more energetic electrons their trajectories should intercept the magnetopause at distances beyond the flight path of Mariner 10 during its first encounter is also of significance, as it shows that the scenario of Jovian electron injection–acceleration—as envisaged by Baker (1986) and Baker *et al.* (1986)—could be a highly complex process.

As we have learned from measurements in the terrestrial magnetosphere, the substorm process is generally accompanied by large changes in the global magnetic and electric field patterns. Furthermore, the drift trajectories of charged particles—not exactly in equatorial mirroring—may deviate from what have been depicted in Figs. 1 and 2; the validity of the scenario by Baker *et al.* (1986) thus should be investigated by taking these effects into account. By the same token, the issue of reinterpreting the Mariner 10 data of the energetic particle measurements (Simpson *et al.* 1974, Armstrong *et al.* 1975, 1979) cannot be clearly resolved at this point. In any event, our present results do suggest that the injection model of energetic (>300 keV) electrons (cf. Baker 1986, Baker *et al.* 1986) has to be carefully reviewed.

During the substorm-like process, ions also will be injected toward the planet. In the idealized situation, the trajectories of equatorially mirroring particles should be assymmetrical with respect to the planet–Sun axis as those of the electrons with the same μ values. Thus protons and other ions will be diverted toward the dusk side as they drift inward.

For nonequatorially mirroring particles, there is another drift motion vertical to the magnetotail: the combined effect of the dawn-to-dusk electric field and the tail-aligned magnetic field is to focus charged particles toward the central current sheet from both lobes (Speiser 1965, Alfven 1968). When the charged particles reach the current sheet, they could be temporarily trapped into gyromotion across the current sheet hence tapping a fraction of the cross-tail electrostatic potential. In the case of the Earth, such steady-state current sheet acceleration has been invoked as the main mechanism responsible for the generation of the energetic ion beams observed at the plasma sheet boundary (Lyons and Speiser 1982, Andrews *et al.* 1981) while the reconnection process at the separatrix can also contribute to such ion beams (Sarris and Axford 1979). As a result of the small size of Mercury's magnetosphere the gyroradii of heavy ions, however, are no longer negligible in the consideration of the drift motion. Some examples for the current sheet drift–acceleration effect of the Na^+ and Fe^+ ions are shown in Fig. 3. The corresponding particle trajectories are calculated assuming a uniform magnetic field configuration (B_t = 30 nT in the two lobes with opposite polarities and a uniform dawn-to-dusk electric field in the $+y$ direction). With an electric field of $E = V_{sw} \times B_{IMF}/10(\sim 10^{-3}$ Vm^{-1}), the Na^+ ions would traverse the whole magnetic tail in a few gyrations and even less for the Fe^+ ions. During conditions of enhanced electric field such that $E \sim V_{sw} \times B_{IMF}$, the cross section of the magnetotail could accommodate no more than one gyration. This shows that the finite gyroradius effect must be taken into account when we investigate the dynamics of the magnetospheric ions of heavy masses.

Another unique feature of the magnetospheric plasma dynamics at Mercury has to do with the fact that the planet occupies a

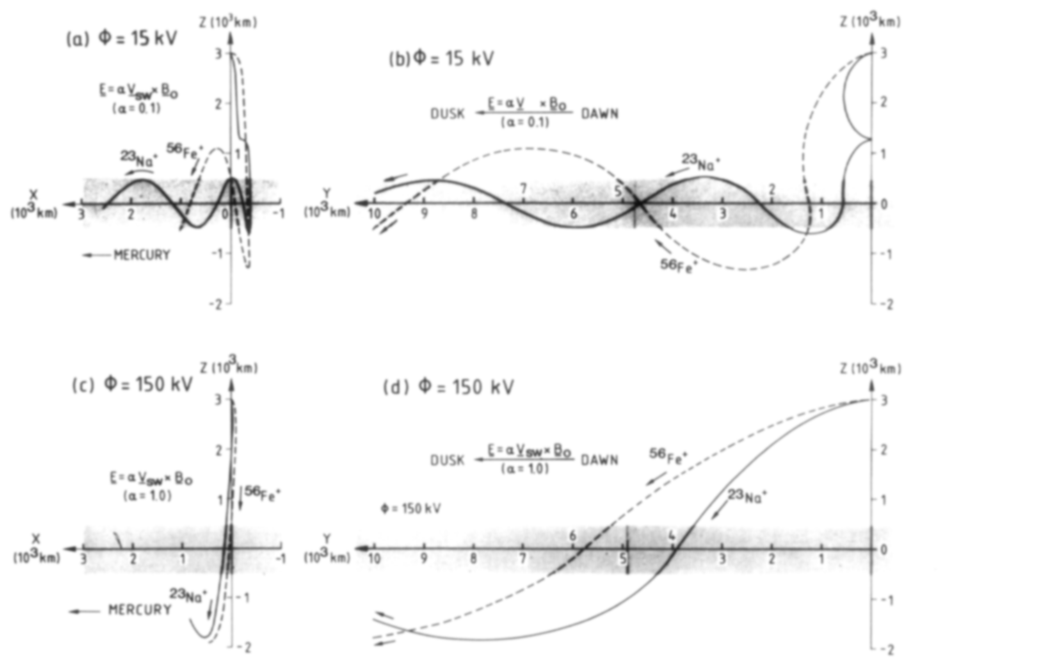

FIG. 3. Examples of **E** × **B** drift and current-sheet interaction of heavy ions in the magnetotail of Mercury. Two cases are considered. The first case is for a nominal cross-tail electric field with (a) representing the particle trajectories in the *XZ*-plane (i.e., the meridian plane) and (b) the *YZ*-plane perpendicular to the magnetotail. The second case (c and d) is for an enhanced cross-tail electric field.

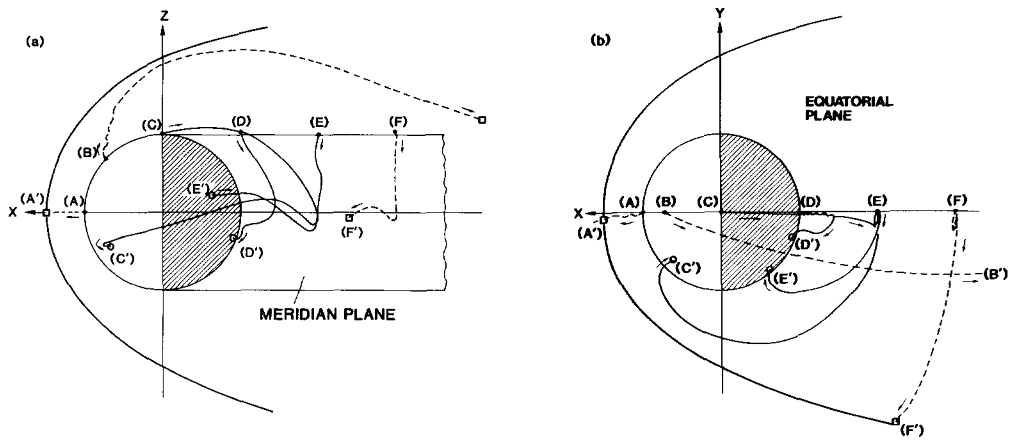

FIG. 4. Examples of gyration motions of Na^+ ions produced at different locations in the meridian (XZ) plane. The dashed lines denote particle trajectories which intercept the magnetopause and the solid lines denote those that reimpact the planetary surface: (a) for projections on the XZ (meridian) plane and (b) for projections on the XY (equatorial) plane.

large volume of the magnetosphere such that the photoions created near the planetary surface would be strongly subject to the influence of the convective electric field. In other words, immediately after ionization the (Na^+, say) ions will be accelerated by the electric field mapped from the magnetotail via the field lines connected to the polar cap regions. The resulting gyromotion coupled with the finite-gyroradius effect could have interesting implications on the escape and surface impact of these exospheric ions. This issue is addressed in the next section.

3. HEAVY ION DYNAMICS

Different from the drift motion in the magnetotail in which case a two-dimensional model for the **E** and **B** fields is sufficient to highlight the major dynamical features, the electrodynamics of heavy ions in the vicinity of Mercury requires a three-dimensional model of the magnetospheric field. That Mercury's magnetosphere is similar to a scaled-down terrestrial magnetosphere provides a useful guide in the construction of a pertinent magnetic field model of which the formulation by Luhmann and Friesen (1979) was adopted here. The basic parameters we have assumed are that the equatorial surface field B_e = 385 nT, a tail field of B_0 = 100 nT, and the half-thickness of the current sheet separating the two lobes of opposite polarities is ΔZ = 500 km. The above values of B_e and B_0 are different from the corresponding ones reported by Beard (1986) and Connerney (1986); the qualitative property of the heavy ion trajectories is not significantly affected by this difference, however. It is also to be noted that the near-surface field at Mercury is expected to be strongly perturbed by the magnetospheric current system induced by its solar wind interaction.

Concerning the electrostatic electric field, we have assumed it to be uniform and pointing in the dawn-to-dusk direction throughout the whole magnetosphere. This is certainly an oversimplification; however, as a first study such simplification still serves to demonstrate several of the basic effects.

Examples of trajectories for Na^+ ions initially positioned at six different points in the meridian (XZ) plane are illustrated in Figs. 4a and 4b. The solid lines denote trajectories which reimpact the planetary surface and the dashed lines denote those intercepting the magnetopause. Two points are immediately clear from these numerical results: (1) the exospheric ions are not bound to the magnetic field but rather tend to be swept away by the convection electric field; (2) besides loss to the magnetopause, a fraction of the photoions could return to the surface with a much larger speed (100–400 km sec^{-1}) hence inducing further sputtering effects.

Because of the dawn-to-dusk pointing of the electrostatic electric field, photoions created on the dawnside hemisphere will be accelerated toward the planetary surface whereas the possibility of free escape exists for those created on the duskside. Furthermore, as the photoionization time scale varies by a factor of 2.3 between perihelion and aphelion, the ionization/transport process illustrated here could have some effect on the surface transport and recycling of the sodium and potassium atoms at Mercury as a function of the orbital phase. Assuming a surface production rate proportional to the cosine of the solar insolation angle on the dayside hemisphere, we have estimated that about half of the photoions will be lost by this acceleration mechanism. Since the total number of sodium atoms in Mercury's exosphere is on the order of $8.1 \times 10^{11} \times \pi R_M^2 \simeq 1.4 \times 10^{29}$ atoms according to the published result by Potter and Morgan (1985), the effective loss rate of the Na^+ ions could be as high as 2×10^{25} ions sec^{-1} with a photoionization rate of 3×10^3 sec. The magnetospheric convection effect is thus potentially a major process in reducing the ionospheric (and exospheric) content of Mercury. Note that the electric field distribution near the planetary surface will be most important in determining the relevant ion trajectories. The surface electric field pattern, however, should be rather complex; more detailed computations for the electric field distribution have to be performed before a better idea on the intercoupling of the loss and source processes can be obtained.

4. DISCUSSION

In this short paper, we have applied several of the basic concepts pertinent to the Earth's magnetosphere to Mercury. Of special interest are the relative size of the planet to the magnetospheric configuration and the convection pattern of the plasma flow. The averaged shape of the magnetosphere should impede the formation of a quasi-trapped population of charged particles surrounding Mercury as well as injection of energetic electrons in the context of a steady-state convection model. On the other hand, the large gyroradii of the heavy ions would allow the direct access of the magnetospheric particles to most parts of the planet. As a result surface sputtering could play a role in injecting secondary ions and neutrals into the magnetospheric environment. With the penetration of the convection electric field to the near-surface of the planet, the stability of the neutral exosphere would be related to the acceleration of the photoions by the global and local **E** and **B** fields. Since the loss rate can be estimated to be very large ($\sim 2 \times 10^{25}$ ions sec^{-1}), there are also very strong implications on the source(s) of the Na and K atmosphere. Much remains to be done in this area as more detailed and precise models of Mercury's magnetospheric fields can be adopted to the numerical computations.

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