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The Mercury Environment: A Literature Survey

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Abstract

A literature survey was conducted focusing primarily on the plasma environment of planet Mercury, and secondarily on its neutral atmosphere and the electrical properties of the planetary surface. An extensive literature list, with narrative comments for selected publications is presented.

Introduction

Planet Mercury is by far the least explored of the Terrestrial planets. The only close-up measurements so far were made by the NASA probe Mariner 10 in 1974-75. Many publications appeared in the later half of the 1970's, after which there was a clear decline for more than a decade. Since the mid-1990's there has been renewed interest in Mercury related to the upcoming NASA mission Messenger scheduled for launch in 2004 and the planned ESA-ISAS mission BepiColombo with a launch foreseen around 2011. The present report surveys the literature on Mercury's environment, primarily its plasma environment and those components of the neutral environment and the planetary surface which are relevant to plasma processes. After a brief introductory summary of the current understanding of Mercury's environment, we present a literature list grouped into topics, where the publications are listed chronologically under each topic. For selected publications, brief narrative comments are given. At the end, we include a list of compilations on Mercury science.

Table 1 summarizes average interplanetary conditions at the Terrestrial planets. Because of Mercury's elliptic orbit around the Sun there is a significant annual variation in the average solar wind conditions at Mercury.

Table 1. Average interplanetary conditions at the Terrestrial planets (after *Slavin and Holzer*, 1981).

Planet	R AU	V_{sw} km s^{-1}	N_P cm^{-3}	$\|\mathbf{B}\|$ nT	T_p eV	T_e eV
Mercury	0.31	430	73	46	17	22
	0.47	430	32	21	13	19
Venus	0.72	430	14	10	10	17
Earth	1.00	430	7	6	8.0	15
Mars	1.52	430	3.0	3.3	6.1	13
Scaling	---	R^0	R^{-2}	$(R^{-2}+1)^{1/2}/R$	$R^{-2/3}$	$R^{-1/3}$

To the surprise of many, Mariner 10 data revealed an intrinsic planetary magnetic field at Mercury, sufficiently strong for a proper magnetosphere to be set up. The equatorial surface magnetic field strength is of the order of a few hundred nT. The magnetosphere set up has an average subsolar stand-off distance of 1.1-1.4 R_M.

The magnetospheric plasma is in many regions tenuous. Plasma densities as low as 0.01 cm^{-3} have been suggested in the lobes. In the inner magnetosphere densities of the order 1 cm^{-3} are expected. Typical electron temperatures are in the range 5-10 eV.

Mercury lacks any significant atmosphere and, thus, also lacks a significant ionosphere. On the dayside there is a thin layer of electrons photoemitted from the surface. Even though the electron density of the layer may be high, the related height-integrated conductivity is likely low because of the small vertical extent of the layer.

Signatures of field-aligned currents have been reported. Whether such currents are persistent is unclear, because of the apparent absence of any obvious closure mechanism at low altitude. Also reported are field line resonances, with ULF waves bouncing between hemispheres.

There are some indications of possible radiation belts at Mercury. If they exist they are likely relatively short-lived and the associated ring current is probably only partial rather than global.

Substorm activity was inferred from Mariner 10 data. Because of the vastly different spatial as well as temporal scales of Mercury's magnetosphere compared to the Terrestrial one, substorms are believed to occur on timescales of minutes rather than hours.

These are but a few of the main characteristics of Mercury's environment. Many more details are available in the literature surveyed in this report.

The Solar Wind at Mercury's Orbit

Broadfoot, A. L., Ultraviolet spectrometry of the inner solar system from Mariner 10, *Rev. Geophys. Space Phys., 14,* 625, 1976.

Kumar, S., and A. L. Broadfoot, Mariner 10 observations of the local interstellar wind, *Bulletin of the American Astronomical Society, 8*, 532, 1976.

Mercury's Magnetosphere

Simpson, J. A., J. H. Eraker, J. E. Lamport, and P. H. Walpole, Electrons and protons accelerated in Mercury's magnetic field, *Science, 185*, 160, 1974.

Armstrong, T. P., S. M. Krimigis, and L. J. Lanzerotti, A reinterpretation of the reported energetic particle fluxes in the vicinity of Mercury, *J. Geophys. Res., 80,* 4015, 1975.

> During the Mercury flyby of Mariner 10, observations of large fluxes of energetic electrons (energies in excess of 0.3 MeV) and protons (energies between 0.53 and 1.9 MeV) were reported (*Simpson et al.*, 1974). It is shown here that the response of the proton detector in the Mariner 10 experiment is most plausibly attributable to the pileup of low-energy electrons rather than the presence of protons. It is concluded that no 'new' acceleration mechanism has been identified at Mercury.

Siscoe, G. L., N. F. Ness, and C. M. Yeates, Substorms on Mercury, *J. Geophys. Res., 80*, 4359, 1975.

> Mariner 10 data show a strong interaction between the solar wind and Mercury. Some of the features observed in the night side magnetosphere suggest time-dependence. Interpreted as temporal events, these features bear striking resemblances to substorm phenomena in the Earth's magnetosphere.

Siscoe, G., and L. Christopher, Variations in the solar wind stand-off distance at Mercury, *Geophys. Res. Lett., 2*, 158, 1975.

> The intrinsic dipole model of the magnetosphere of Mercury is combined with statistics on the solar wind dynamic pressure from Explorers 33 and 35 to obtain histograms of the solar wind stand-off distance for aphelion, perihelion and median distance of Mercury from the Sun. The magnetic field is strong enough to normally stand off the solar wind. Only on rare occasions, direct impact of the solar wind onto the surface will occur.

Fairfield, D. H., and K. W. Behannon, Bow shock and magnetosheath waves at Mercury, *J. Geophys. Res., 81*, 3897, 1976.

Herbert, F., M. Wiskerchen, C. P. Sonett, and J. K. Chao, Solar wind induction in Mercury: Constraints on the formation of a magnetosphere, *Icarus, 28(4),* 489, 1976.

A model is outlined in which the origin of Mercury's magnetic field is attributed to electromagnetic induction from the interplanetary magnetic field. No mechanism is discovered which can account for the magnetospheric features.

Hill, T. W., A. J. Dessler, and R. A. Wolf, Mercury and Mars: the role of ionospheric conductivity in the acceleration of magnetospheric particles, *Geophys. Res. Lett., 3,* 429, 1976.

Mercury's magnetosphere accelerates charged particles, whereas Mars' magnetosphere apparently does not. It is proposed that this difference results from differences in ionospheric conductivity. Mercury, which has no conducting ionosphere and probably an insufficiently conducting surface, can exhibit rapid solar-wind-induced convection and hence particle acceleration in its magnetospheric tail.

Ogilvie, K. W., J. D. Scudder, V. M. Vasiliunas, R. E. Hartle, and G. L. Siscoe, Observations at the planet Mercury by the plasma electron experiment: Mariner 10, *J. Geophys. Res., 82*, 1807, 1977.

Mariner 10 particle observations provide a determination of the dimensions and properties of the magnetosphere, independently of and in general agreement with magnetometer observations.

Whang, Y. C., Magnetospheric magnetic field of Mercury, *J. Geophys. Res. 82*, 1024, 1977.

An alternative model is presented for the magnetospheric magnetic field of Mercury in which the external field is represented by an image dipole and a tail field and the internal field includes a dipole, a quadrupole, and an octupole. The dipole moment estimated by this model is approximately $2.4*10^{22}$ G cm^3, tilted 2.3 degrees from the normal to the planetary orbital plane and having the same directional sense as that of the earth.

Ness, N. F., The magnetosphere of Mercury, *in Solar System Plasma Physics*, edited by Kennel, C. F., L. J. Lanzerotti, and E. N. Parker, North-Holland Publishing Company, 1979.

According to Mariner 10 data on Mercury's magnetosphere, the bow shock and magnetosheath signatures in the magnetic field are entirely consistent with the geometry expected for interaction between a planet-centered magnetic dipole and the solar wind. The geometrically determined distance to the magnetopause stagnation point of solar wind flow was 1.45 ± 0.15 R_M. No evidence for the permanent existence of a trapped charged particle radiation belt. Characteristic time scales for transient phenomena at Mercury should be reduced by a factor of about 20 in comparison with those on Earth, i.e., a few minutes for substorms versus an hour at Earth.

Slavin, J. A., and R. E. Holzer, The effect of erosion on the solar wind stand-off distance at Mercury, *J. Geophys. Res., 84*, 2076, 1979.

Predicts that the mean solar wind stand-off distance for average solar wind dynamic pressure conditions will be 0.2-0.7 R_M inward from its ground state position. A dipole moment of $(6\pm2)*10^{22}$ G cm^3 is calculated from the observed bow shock and magnetopause positions. Finally, the importance of magnetic flux transfer in the solar wind-magnetosphere-atmosphere-surface interaction at Mercury is briefly discussed.

Whang, Y. C., Model magnetosphere of Mercury, *Phys. Earth Planet. Inter., 20*, 218, 1979.

A three-dimensional quantitative model of Mercury's magnetosphere based on Mariner 10 data is presented. The model assumes that the Mercury surface magnetic field consists of a dipole, a quadrupole, and an octupole. In addition, the plasma characteristics and regions of quiet and disturbed signatures observed from Mariner 10 are discussed.

Goldstein, B. E., S. T. Suess, and R. J. Walker, Mercury: Magnetospheric processes and the atmospheric supply and loss rates. *J. Geophys. Res., 86*, 5485, 1981.

Magnetospheric processes at Mercury are investigated to determine how they affect the source and loss rates of the neutral He and H atmosphere. The solar wind impacts the surface only about 6% of the time, and the resulting atmospheric supply rate is negligible. The extent to which magnetospheric convection recycles photoions back to the planetary surface, and to a lesser extent the uncertainty in the number of atoms exposed to sunlight, leads to considerable uncertainty in atmospheric loss estimates.

Russell, C. T., The magnetopause of the Earth and planets, *Adv. Space Res., 1(1)*, 67, 1981.

The intrinsic magnetic fields of Mercury, the Earth, Jupiter and Saturn, all deflect the solar wind well above the planetary surface. The current layer or magnetopause which flows between the magnetized solar wind and magnetospheric plasmas should play an important role in determining the strength of the interaction but had so far only been investigated at the Earth.

Slavin, J. A., R. E. Holzer, Solar wind flow about the terrestrial planets. 1 - Modeling bow shock position and shape, *J. Geophys. Res., 86*, 11401, 1981.

Slavin, J. A., Bow shock studies at Mercury, Venus, Earth, and Mars with applications to the solar-planetary interaction problem, Thesis (Ph.D.), Univ. of California, Los Angeles, 1982.

Whang, Y. C., and K. I. Gringauz, The magnetospheres of Saturn, Mercury, Venus and Mars, *Adv. Space Res., 2(1),* 61, 1982.

The characteristics of the magnetospheres of Saturn, Mercury, Venus and Mars are discussed.

Kirsch, E., and A. K. Richter, Possible detection of low energy ions and electrons from planet Mercury by the HELIOS spacecraft, *Ann. Geophys., 3*, 13, 1985.

The incidence occurring in May 1979 when the Helios-2 spacecraft, located upstream of the magnetosphere of Mercury, was able to detect low energetic ion (greater than 80 keV) and electron (greater than 60 keV) fluxes coming from the direction of the Hermean magnetosphere, and propagating towards the sun, is reported. It is concluded that the observed particles are of direct magnetospheric origin produced by substorm activities or are released from the radiation belts of Mercury. Solar-wind particles reflected from and accelerated at the bow shock of Mercury are excluded. This conclusion was later questioned by *Russell et al.* (1988).

Russell, C. T., and R. J. Walker, Flux transfer events at Mercury, *J. Geophys. Res., 90*, 11067, 1985.

Signatures of FTE events occur both in the magnetosheath and in the magnetosphere. They last about 1 sec and hence have a dimension of about 400 km. The net amount of flux transfer is much less than that at Earth. It is estimated that less than 1 percent of the available solar wind potential drop is applied by FTEs to the magnetosphere of Mercury. Evidence for steady state reconnection is also observed which may apply a potential drop from 5 to 25 kV across the Mercury magnetopause. The magnetopause itself appears to be about 500 km thick.

Slavin, J. A., E. J. Smith, B. E. Goldstein, and S. P. Christon, Magnetotails of the terrestrial planets: A comparative study, *in Lunar and Planetary Inst. Terrest. Planets: Comp. Planetology*, p. 13, 1985.

Baker, D. N., J. A. Simpson, and J. H. Eraker, A model of impulsive acceleration and transport of energetic particles in Mercury's magnetosphere, *J. Geophys. Res., 91,* 8742, 1986.

A qualitative model of substorm processes in the Mercury magnetosphere is presented based on Mariner 10 observations obtained in 1974-1975. The suggestion is supported that energetic particles up to about 500 keV are produced by strong induced electric fields at 3 to about 6 R_M in the Hermean tail in association with substorm neutral line formation.

Ip, W.-H., The sodium exosphere and magnetosphere of Mercury, *Geophys. Res. Lett., 13*, 423, 1986.

Following the recent optical discovery of intense sodium D-line emission from Mercury, the scenario of an extended exosphere of sodium and other metallic atoms is explored.

Baker, D. N., J. E. Borovsky, J. O. Burns, G. R. Gisler, and M. Zeilik, Possible calorimetric effects at Mercury due to solar wind-magnetosphere interactions, *J. Geophys. Res., 92,* 4707, 1987.

As a result of the solar wind interaction with the magnetosphere of Mercury, several effects are expected: (1) direct interaction of the solar wind with the surface of Mercury; (2) substorm-like magnetotail processes and (3) the presence of Jovian electrons may produce transient, very low frequency synchrotron-emitting radiation belts.

Cheng, A. F., R. E. Johnson, S. M. Krimigis, and L. J. Lanzerotti, Magnetosphere, exosphere, and surface of Mercury, *Icarus, 71(3),* 430, 1987.

It is presently suggested in light of the atomic Na exosphere discovered for Mercury that this planet, like the Jupiter moon Io, is capable of maintaining a heavy ion magnetosphere. Since

Mercury's Na supply to the exosphere is primarily internal, it would appear that Mercury is losing its semivolatiles and that this process will proceed by way of photosputtering.

Christon, S. P., J. Feynman, and J. A. Slavin, Dynamic substorm injections - Similar magnetospheric phenomena at Earth and Mercury, *in Magnetotail Physics*, Baltimore, MD, Johns Hopkins University Press, p. 393, 1987.

Several recently discovered correlations between the energetic electrons, plasma electrons, and magnetic fields at Mercury are discussed.

Criston, S. P., A comparison of the Mercury and Earth magnetospheres: Electron measurements and substorm time scales, *Icarus, 71(3),* 448, 1987.

Ip, W.-H., Dynamics of electrons and heavy ions in Mercury's magnetosphere, *Icarus, 71(3),* 441, 1987.

The present investigation of Mercury magnetosphere processes employs simple models for equatorially mirroring charged particles, as well as the current sheet acceleration effect. The large gyroradii of such heavy ions as those of Na allow surface reimpact as well as magnetopause-interception losses to occur.

Vasyliunas, V. M., Heat conduction limits on calorimetric effects at Mercury due to solar wind-magnetosphere interactions, *J. Geophys. Res., 92,* 13658, 1987.

Russell, C. T., D. N. Baker, and J. A. Slavin, The magnetosphere of Mercury, *in Mercury*, edited by Vilas et al., Univ. of Arizona Press, Tucson, p. 514, 1988.

Mariner-10 data on the properties of Mercurian magnetosphere are examined. Many questions regarding the intrinsic magnetic field properties of Mercury remain unanswered, such as the existence of radiation belts, magnetic storms, the size of auroral regions, the mechanism of global magnetospheric convection, and the source of plasma.

Christon, S. P., Plasma and energetic electron flux variations in the Mercury 1 C event: Evidence for a magnetopause boundary layer, *J. Geophys. Res., 94*, 6481, 1989.

Charged-particle and magnetic-field data obtained during the first encounter (on March 29, 1974) of Mariner 10 with the planet Mercury are re-examined. It is shown that Mariner 10 sampled the hot substorm energized magnetospheric plasma sheet for the first 36 sec of the C event and, for the next 48 sec, alternatingly sampled hot (plasma sheet) and cold (boundary-layer magnetosheath-like) plasma regions.

Russell, C. T., ULF waves in the Mercury magnetosphere, *Geophys. Res. Lett., 16*, 1253, 1989.

ULF waves are present in the magnetic records returned by the Mariner 10 spacecraft. Deep in the magnetosphere narrowband waves with 2-second periods are found. These waves may be standing waves on field lines anchored in the core.

Ip, W.-H., On the surface sputtering effects of magnetospheric charged particles at Mercury, *Astrophys. J., 418*, 451, 1993.

Russell, C. T., A study of flux transfer events at different planets, *Adv. Space Res., 16(4),* 159, 1995.

Flux transfer events are disturbances in and near the magnetopause current layer that cause a characteristic signature in the component of the magnetic field parallel to the average boundary normal. Such disturbances have been observed at Mercury, Earth and Jupiter but not at Saturn, Uranus or Neptune. At Earth FTEs last about 1 minute and repeat about every 8 but at Mercury with a much smaller magnetosphere the events last seconds and are tens of seconds apart. Interpretation involves magnetic flux ropes.

Balogh, A., Mercury: the planet and its magnetosphere, *Planet. Space Sci., 45(1),* 1, 1997.

Blomberg, L. G., Mercury's magnetosphere, exosphere and surface: low-frequency field and wave measurements as a diagnostic tool, *Planet. Space Sci., 45*, 143, 1997.

Diagnostics with combined electric and magnetic field measurements at Mercury are reviewed. Fundamental electrodynamics questions which can be answered by means of a Mercury Orbiter are discussed. These include, solar wind-magnetosphere coupling, coupling to low altitude, exospheric or planetary surface conductivity, auroral particle acceleration, and magnetospheric substorms.

Engle, I. M., Mercury's magnetosphere: Another look, *Planet. Space Sci., 45*, 127, 1997.

The measurements made of Mercury's magnetic field during the Mercury I and III flybys have been incorporated into models of the Hermean magnetosphere-magnetotail system. This paper presents results of a study that employs an adaptation of the Beard model but also adopts the assumption that the incident solar wind pressure was different at the times of the two Mercury magnetosphere encounters. The corresponding standoff distances are 1.31 R_M for the Mercury III encounter and 1.08 R_M for the Mercury I encounter.

Glassmeier, K.-H., The Hermean magnetosphere and its ionosphere-magnetosphere coupling, *Planet. Space Sci., 45(1),* 119, 1997.

Grande, M., Investigation of magnetospheric interactions with the Hermean surface, *Adv. Space Res., 19(10),* 1609, 1997.

For Mercury, studies of the surface and the magnetosphere form a single linked problem. Therefore new instrumental approaches are considered. One such instrument would be a neutral atom imager.

Grard, R., Photoemission on the surface of Mercury and related electrical phenomena, *Planet. Space Sci., 45(1),* 67, 1997.

Solar photons interact with the surface of Mercury due to the absence of an atmosphere. Photoemission provides the means of a direct electrical coupling between the planet and its magnetospheric environment and sets a lower limit of the order of 10^{-5} S to the conductance of the surface of a perfectly insulating regolith.

Ip, W.-H., Time-variable phenomena in the magnetosphere and exosphere of Mercury *Adv. Space Res., 19*, 1615, 1997.

Lundin, R., S. Barabash, P. Brandt, L. Eliasson, C. M. C. Nairn, O. Norberg, and I. Sandahl, Ion acceleration processes in the Hermean and terrestrial magnetospheres, *Adv. Space Res. 19(10),* 1593, 1997.

The solar wind interaction with Mercury might be strongly dependent on a tenuous, but yet significant, exoionosphere. The large-scale solar wind energy and mass transfer and the intrinsic plasma acceleration processes near Mercury may have very much in common with plasma processes near Earth. Conclude that the acceleration and outflow processes at Mercury, although present in a more extreme environment compared to the other Earth-like planets, are expected to have many similarities with the acceleration and outflow processes near Earth.

McKenna-Lawlor, S. M. P., Characteristic boundaries of the Hermean magnetosphere and energetic particles close to the planet, *Planet. Space Sci., 45,* 167, 1997.

Roux, A., N. Cornilleau-Wehrlin, A. Meyer, and L. Rezeau, Measurements of a.c. magnetic fields and currents in the Hermean magnetosphere, *Planet. Space Sci., 45*, 163, 1997.

The plasma trapped inside the Hermean magnetosphere is unlikely to corotate. Unlike other magnetized planets, a large convection electric field should prevail close to Mercury. Small-scale fluctuating currents involving Alfvén waves are expected to develop and to exert a control on the magnetospheric dynamics.

Slavin, J. A., J. C. J. Owen, J. E. P. Connerney, and S. P. Christon, Mariner 10 observations of field-aligned currents at Mercury, *Planet. Space Sci., 45*, 133, 1997.

Clear evidence of substorm activity was obtained in the form of intense energetic particle injections similar to those observed in the near-tail region at Earth. In this study the Mariner 10 magnetic field measurements taken during the two nightside flybys are re-examined for evidence of field-aligned currents (FACs). FAC coupling to the weak ionosphere and/or planetary surface might be expected to be low in intensity and short-lived. However, compelling evidence is found for intense FACs following a substorm-type energetic particle injection. The implications of these FAC observations for the height integrated electrical conductivity at low altitudes, for the electrodynamics of this magnetosphere, and for the planning of future Mercury missions are discussed.

Torkar, K., M. Fehringer, F. Rüdenauer, R. J. L. Grard, and W. Riedler, Necessity and feasibility of spacecraft potential control in the Hermean magnetosphere, *Planet. Space Sci., 45(1),* 149, 1997.

This paper formulates the scientific and technical requirements on a spacecraft potential control system in the space environment of Mercury.

Luhmann, J. G., C. T. Russell, and N. A. Tsyganenko, Disturbances in Mercury's magnetosphere: Are the Mariner 10 "substorms" simply driven?, *J. Geophys. Res., 103(A5)*, 9113, 1998.

In addition to providing the first in situ evidence of a magnetosphere at Mercury, the first flyby by Mariner 10 inspired reports of Earth-like substorms. In this paper the authors demonstrate that the "disturbed" structure observed outbound from closest approach during the first Mariner 10 flyby can alternatively be explained as a consequence of a typical period of rotating IMF. The results also remind the authors that driven reconfigurations must always be considered in studies of transients in the Terrestrial magnetosphere.

Grard, R., H. Laakso, and T. I. Pulkkinen, The role of photoemission in the coupling of the Mercury surface and magnetosphere, *Planet. Space Sci., 47(12),* 1459, 1999.

The role of photoemission in closing field-aligned currents and in balancing the flow of magnetospheric electrons which precipitate to the surface is investigated. Shown that the loss cone angle is always larger than 30-40° on the dayside. Concluded that the closure of field-aligned current is unlikely.

Othmer, C., K.-H. Glassmeier, and R. Cramm, Concerning field line resonances in Mercury's magnetosphere, *J. Geophys. Res., 104(A5),* 10369, 1999.

Kabin, K., T. I. Gombosi, D. L. DeZeeuw, and K. G. Powell, Interaction of Mercury with the solar wind, *Icarus, 143*, 397, 2000.

The structure of the Hermean magnetosphere obtained by a global three-dimensional MHD simulation is presented. The Hermean magnetosphere is studied for the typical solar wind parameters at perihelion and the nominal Parker spiral IMF. Although the magnetosphere of Mercury is qualitatively similar to Earth's magnetosphere, it's much smaller size results in many quantitative differences. For example, the magnetic field lines of Mercury are closed only for latitudes less than 50°, while for Earth the similar latitude will be 75°. One conclusion is that direct interaction of Mercury with the solar wind is a rare phenomenon.

Barabash, S., A. V. Lukyanov, P. C:son Brandt, and R. Lundin, Energetic neutral atom imaging of Mercury's magnetosphere 3. Simulated images and instrument requirements, *Planet. Space Sci., 49(14-15),* 1685, 2001.

The paper presents simulations of the energetic neutral atom (ENA) production in the Mercury magnetosphere and the obtained ENA images for the equatorial and polar vantage points. Concludes that ENA imaging of the Mercury magnetosphere is feasible.

Burlaga, L. F., Magnetic fields and plasmas in the inner heliosphere: Helios results, *Planet. Space Sci., 49(14-15),* 1619, 2001.

This paper reviews the plasma and magnetic field observations from Helios that provide a general basis for interpreting the observations of Mercury that will be made by orbiting spacecraft. The solar wind interaction with Mercury will be much stronger than the interaction with Earth. Moreover, the solar wind at Mercury is probably more variable than that at Earth. Need for measurements of the solar wind while spacecraft are in orbit around Mercury.

Giampieri, G., and A. Balogh, Modeling of magnetic field measurements at Mercury, *Planet. Space Sci., 49(14-15),* 1637, 2001.

Mapping Mercury's internal magnetic field with a magnetometer in closed orbit around the planet will provide valuable information about its internal structure. They try to quantify these expectations by analyzing simulated data in order to estimate the measurement errors due to the limited spatial sampling. Finally, the main limitation of the model, due to the presence of time-varying external magnetospheric currents, is addressed.

Killen, R. M., A. E. Potter, P. Reiff, M. Sarantos, B. V. Jackson, P. Hick, and B. Giles, Evidence for space weather at Mercury, *J. Geophys. Res., 106(E9),* 20509, 2001.

Lukyanov, A. V., O. Umnova, and S. Barabash, Energetic neutral atom imaging of Mercury's magnetosphere 1. Distribution of neutral particles in an axially symmetrical exosphere, *Planet. Space Sci., 49(14-15),* 1669, 2001.

A simple analytical model to obtain density distributions of neutral particles in an axially symmetrical exosphere is presented. As examples, density profiles of helium and oxygen in Mercury's exosphere were calculated.

Lukyanov, A. V., S. Barabash, R. Lundin, P. C:son Brandt, Energetic neutral atom imaging of Mercury's magnetosphere 2. Distribution of energetic charged particles in a compact magnetosphere, Planet. Space Sci., 49(14-15), 1677, 2001.

Investigate the feasibility of energetic neutral atom (ENA) imaging of Mercury's magnetosphere interacting with the tenuous exosphere. Developed a simple model simulating dynamics of hot proton plasma near Mercury.

Orsini, S., A. Milillo, E. De Angelis, A. M. Di Lellis, V. Zanza, and S. Livi, Remote sensing of Mercury's magnetospheric plasma environment via energetic neutral atoms imaging, *Planet. Space Sci., 49(14-15),* 1659, 2001.

Exploring the plasma dynamical behavior of Mercury via energetic neutral atom (ENA) analysis is briefly discussed. The analysis of the Hermean ENA would clarify issues like the existence of radiation belts. Feasibility of ENA imaging in the Hermean environment is demonstrated.

Sarantos, M., P. H. Reiff, T. W. Hill, R. M. Killen, and A. L. Urquhart, A B_x-interconnected magnetosphere model for Mercury, *Planet. Space Sci., 49*, 1629, 2001.

The access of solar wind plasma to the surface of Mercury depends on the magnetic fields in the vicinity of the planet. Open regions for the access of incident particles to the surface as a function of the IMF are calculated. The results are compared with existing sodium data. Conclude that increased ion-sputtering due to solar wind-magnetosphere interactions may explain the temporal and spatial variations of the sodium exosphere seen at Mercury. Predict B_x dependence.

Wurz, P., and L. G. Blomberg, Particle populations in Mercury's magnetosphere, *Planet. Space Sci., 49*, 1643, 2001.

Delcourt, D. C., T. E. Moore, S. Orsini, A. Millilo, and J.-A. Sauvaud, Centrifugal acceleration of ions near Mercury, *Geophys. Res. Lett., 29(A12),* 2002.

Ip, W.-H., and A. Kopp, MHD simulations of the solar wind interaction with Mercury, *J. Geophys. Res., 107(A11),* 1348, 2002.

A numerical MHD code is used to simulate the dynamical responses of Mercury's magnetosphere to different orientations of the interplanetary magnetic field (IMF) and values of the solar wind dynamical pressure. It is found that the IMF orientation is very effective in changing the size of the polar cap.

Blomberg, L. G., and J. A. Cumnock, On Electromagnetic Phenomena in Mercury's Magnetosphere, *Adv. Space Res., in press*, 2003.

Some similarities and differences between Mercury's and Earth's magnetospheres are discussed. In particular how electric and magnetic field measurements can be used as a diagnostic tool to understand the dynamics of Mercury's magnetosphere.

Mercury's Atmosphere

Belton, M. J. S., D. M. Hunten, and M. B. McElroy, A search for an atmosphere on Mercury, *Astrophys. J., 150,* 1111, 1967.

Broadfoot, A. L., D. E. Shemansky, and S. Kumar, Mariner 10 - Mercury atmosphere, *Geophys. Res. Lett., 3,* 577, 1976.

Identification of helium and hydrogen as atmospheric constituents. Subsolar point densities are estimated at 4500 cm^{-3} for He and 8 cm^{-3} for the thermal component of H. Non-thermal component in H with a scale height of approximately 70 km has been observed near the limb off the subsolar point, providing a total apparent number density of 90 cm^{-3}.

Kumar, S., Mercury's atmosphere - A perspective after Mariner 10, *Icarus, 28,* 579, 1976.

The Mariner 10 data indicate that Mercury's atmosphere is apparently similar to that on the moon. Helium could be supplied to the atmosphere either by the radioactive decay of uranium and thorium in the planetary crust or by accretion of a small fraction of the solar-wind flux.

Killen, R. M., A. E. Potter, and T. H. Morgan, Spatial distribution of sodium vapor in the atmosphere of Mercury, *Icarus, 85(1)*, 145, 1990.

The density and shape of the sodium exosphere of Mercury can give clues to the interactions of cosmic dust, the solar wind, and the radiation field with the planetary surface and magnetosphere. The subsolar column abundance of sodium varied from $3.8*10^{11}$ atoms/cm^2 on

April 3, 1988, to $2.8*10^{11}$ atoms/cm^2 on April 6, 1988. Suggested that these anomalies may be related to the interaction of the photoionized sodium atoms with the magnestosphere.

Potter, A. E., and T. H. Morgan, Evidence for magnetospheric events on the sodium atmosphere of Mercury, *Science, 248*, 835, 1990.

Sputtering of surface minerals could produce sodium vapor in polar regions during magnetic substorms when magnetospheric ions directly impact the surface. Another important process may be the transport of sodium ions along magnetic field lines toward polar regions, where they impact directly on the surface of Mercury and are neutralized to regenerate neutral sodium atoms.

Lammer, H., and S. J. Bauer, Mercury's exosphere: Origin of surface sputtering and implications, *Planet. Space Sci., 45(1),* 73, 1997.

The existence of gaseous species H, He, O, Na and K, established by EUV spectroscopic observations on Mariner 10 for the first three and ground-based observations for the last two species with column contents of the order of 10^{12} cm^{-2} or less, qualify the gaseous envelope of Mercury as an exosphere (column content per definition $<10^{14}$ cm^{-2}). H and He seem to have its origin in the direct supply from the solar wind. The heavier constituents can arise from particle and photon interactions with surface materials. Mercury's exosphere is a low attenuation medium for solar EUV radiation which therefore can penetrate to its surface. Under these circumstances no ionospheric “layer” can be formed. The ionization of exospheric species leads to electron-ion pair formation which is balanced by chemical loss and transport processes. The densities of the ionized exospheric component do not exceed a few electrons/ions cm^{-3}, and thus yield an extremely low height-integrated Pedersen conductivity.

Morgan, T. H., and R. M. Killen, A non-stoichiometric model of the composition of the atmospheres of Mercury and the Moon, *Planet. Space Sci., 45(1),* 81, 1997.

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Potter, A. E., and T. H. Morgan, Sodium and potassium atmospheres of Mercury, *Planet. Space Sci., 45(1),* 95, 1997.

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Slater, D. C., T. H. Morgan, and S. A. Stern, Modern lightweight UV spectrographs for in situ studies of the exosphere and photo-ion population about Mercury, *Planet. Space Sci., 45(1),* 101, 1997.

Potter, A. E., R. M. Killen, and T. H. Morgan, Rapid changes in the atmosphere of Mercury, *Planet. Space Sci., 47*, 1441, 1999.

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Mercury's Surface Properties

Ip, W.-H., Electrostatic charging and dust transport at Mercury's surface, *Geophys. Res. Lett., 13,* 1133, 1986.

Tentatively concluded that the nightside hemisphere could be occasionally charged to a surface potential of a few kilovolts. Ions impinging on the planetary surface could result in characteristic and observable X-ray emission. X-ray emission could also be detected from protons and heavy ions generated in the magnetotail region.

Ip, W.-H., On the surface sputtering effects of magnetospheric charged particles at Mercury, *Astrophys. J., 418*, 451, 1993.

Grard, R., Photoemission on the surface of Mercury and related electrical phenomena, *Planet. Space Sci., 45(1),* 67, 1997.

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Ness, N. F., et al., The magnetic field of Mercury Part I, *J. Geophys. Res., 80*, 2708, 1975.

Magnetic field observations obtained during the Mariner 10 encounter with Mercury on March 29, 1974 presented. Concludes that an internal planetary field exists with dipole moment approximately $5.1*10^{22}$ G cm^3. The magnetic field observations reveal the formation of a magnetic tail and neutral sheet. The origin of the magnetic field is discussed.

Ness, N. F., K. W. Behannon, R. P. Lepping, and Y. C. Whang, Magnetic field of Mercury confirmed, *Nature, 255,* 204, 1975.

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Ness, N. F., K. W. Behannon, R. P. Lepping, and Y. C. Whang, Observations of Mercury's magnetic field, *Icarus, 28(4)*, 478, 1976.

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Sharpe, H. N., and D. W. Strangeway, The magnetic field of Mercury and modes of thermal evolution, *Geophys. Res. Lett., 3*, 285, 1976.

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Jackson, D. J., and D. B. Beard, The magnetic field of Mercury, *J. Geophys. Res., 82*, 2828, 1977.

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The Mercury Environment: A Literature Survey

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Abstract. A literature survey was conducted focusing primarily on the plasma environment of planet Mercury, and secondarily on its neutral atmosphere and the electrical properties of the planetary surface. An extensive literature list, with narrative comments for selected publications is presented.

23 pages.

Keywords: Mercury, magnetosphere, atmosphere, planetary magnetic field, literature survey