Advances in Geosciences
Vol. 19: Planetary Science (2008)
Ed. Anil Bhardwaj

A COMPARISON OF THE EXOSPHERES OF MERCURY AND THE MOON

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Ground-based optical studies of the similarities and dissimilarities of the sodium emissions of Mercury and the Moon have provided a lot of important information on the basic structures and dynamics of these two surface-bound exospheric systems. There are a number of key issues to be clarified. These include the relative importance of ion sputtering in producing sodium atoms (and hence other gas species) comparison to meteoroid impact and photo-desoption effect, and the potential importance of magnetic anomalies (if exist) in modifying the space weathering effect of Mercury's surface. The new observations from the MESSENGER spacecraft at Mercury and the several lunar orbiters including Kaguya of Japan, Chang'e-1 of China and Chandrayaan-1 of India are expected to bring us answers and, certainly, far more questions to these two atmospheres of unique importance in comparative planetology.

1. Introduction

After so many years of waiting in line, the study of the exospheres of Mercury and the Moon has finally been ushered into the limelight. The new generation of plasma instruments onboard the Kaguya lunar orbiter of JAXA and the MESSENGER spacecraft of NASA have already yielded a wealth of information on the dynamics and compositions of the pickup ions created by surface interactions. For example, Zurbuchen *et al.*[1] reported that in Mercury's magnetosphere traversed by the MESSENGER spacecraft, the ions with mass-to-charge (m/q) ratio between 3.8 and 42 are dominated by metallic ions (i.e. Na^+, Mg^+, S^+, Si^+, K^+, Ca^+, etc) ejected from the planetary surface. Preliminary reports of plasma measurements on the Kaguya lunar orbiter showed the presence of pickup ions of similar chemical composition.[2]

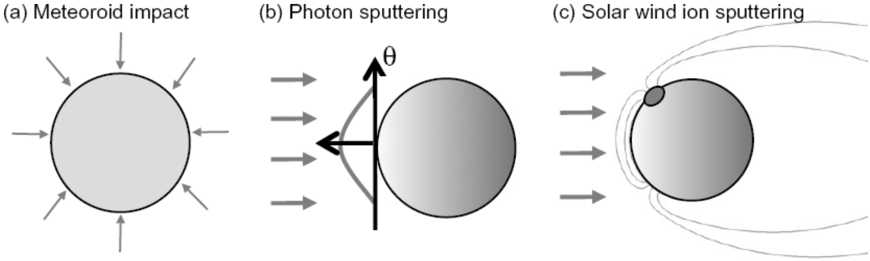

Fig. 1. A summary of the three major source mechanisms of the sodium atoms on Mercury: (a) the production process with the meteoroid impact is uniformly distributed; (b) the production process with the photon sputtering is distributed as $\cos^n\theta$ centered around the sub-solar point; (c) the production process with the solar wind ion sputtering is confined in a finite ara a high latitude. Note that the whole sunward hemisphere will be source region in the case of the Moon. (After Wang and Ip[4])

Figure 1 illustrates the three main source mechanisms which are believed to be responsible for the production of the surface-bound exospheres of both Mercury and the Moon.[3,4] As depicted, the photon-stimulated desorption effect has strong dependence on the zenith angle of the Sun. On the other hand, the meteoroid impact mechanism is generally assumed to be uniform across the planetary surface. The ion sputtering process could have strong asymmetry if solar wind particles are the main agent in ejecting neutral atoms from the surface material. In effect, both Mercury and the Moon are subject to strong surface interaction with planetary magnetospheric plasma. The only difference is that Mercury has its own intrinsic magnetic field while the Moon would go in and out of Earth's magnetosphere. It is also important to note that meteoroid impact could bring in volatile molecules like H_2O and CO_2 from outside. There are major uncertainties in the relative importance of the various source mechanisms. The situation is particularly murky in the case of Mercury.

Because of its exceptional brightness, the optical D-line emissions of the sodium atoms at 5890 A and 5896 A have been used as a tracer for planetary and satellitary atmospheres. An excellent example is the sodium cloud of the Jovian moon, Io.[5] The sodium emissions from Mercury and the Moon have played the same role and much useful information on the nature of their atmospheres has been obtained by ground-based observations. A number of excellent reviews on Mercury's exosphere have been produced just prior to the first encounter of the MESSENGER spacecraft on January 7, 2008.[6,7] Note that it is common to consider the lunar atmosphere to be just a copy of Mercury's (or vice versa). This is likely a misconception because there are probably many important differences ranging from the physical properties of the surface materials of both planetary bodies to the interaction of their dust and regolith layers with the corresponding plasma and thermal environments. On the other hand, these two exospheric systems do share some major similarities in their origin and dynamics. It is therefore timely to compare the similarities and dissimilarities of these two surface-bound exospheres so that the basic questions to be addressed can be highlighted. We will focus on three issues here, namely, (1) the formation of the extended atomic sodium comas and tail structures; (2) the time variability, and (3) the existence of surface magnetic anomalies.

2. Extended Sodium Comas and Tails

Immediately after the first report of the discovery of Mercury's strong optical D-line emission of the sodium atoms by Potter and Morgan,[8] Ip[9] and Smyth[10] produced theoretical models to show the possible formation of an extended sodium coma and tail because of the action of the solar radiation pressure force. To achieve this, the initial emission speed of the sodium atoms has to exceed a threshold value of about $2\,\mathrm{km\,s^{-1}}$. It was only recently that the presence of such a sodium tail was reported by Potter *et al.*,[11] Potter and Killen,[12] Kameda *et al.*[13] and Baumgardner *et al.*[14] The wide-field imaging observations of Baumgardner *et al.*[14] showed that the length of the sodium tail could be as long as 1,600 R_M (1 R_M = one Mercury's radius).

The formation of an extended sodium coma surrounding the Moon was also predicted[15] subsequent to its discovery.[16] Once again, the full size of the lunar sodium exosphere was revealed by the wide-field imaging observations of the Boston group.[17] The images taken during lunar eclipses (in order to reduce the glare of the lunar disk) indicated that the radius of the exospheric halo could be as large as 12 lunar radii. This means that the Moon should also possess a tail made up of Na atoms.[15] To produce escaping Na atoms from Mercury requires the production of exospheric atoms at emission speed exceeding $2\,\mathrm{km\,s^{-1}}$ and somewhat less for the Moon.[9,10] Therefore ion sputtering must play an important role since both photon-stimulated desorption and meteoroid impact evaporation would only create atoms of emission speed mostly at $0.9\,\mathrm{km\,s^{-1}}$ and $1.4\,\mathrm{km\,s^{-1}}$, respectively, according to Bruno *et al.*[18] As a result, we should expect the production rate of the extended sodium halo/tail to be controlled by solar wind activity or the interplanetary condition. From this point of view, it is interesting to note that Smith *et al.*[19] and Wilson *et al.*[20] reported the detection of a distant lunar sodium tail associated with the surface impact bombardment of the Leonid meteor shower on the Moon in 1998. In these narrow-band imaging measurements, the peak sodium atom production rate increased by a factor of about 4 from 7×10^{21} atoms s^{-1} to 2.5×10^{22} atoms s^{-1}. In addition, the ejection velocity was estimated to be above $2.1\,\mathrm{km\,s^{-1}}$ which was considerably larger than the Bruno *et al.* value of $0.9\,\mathrm{km\,s^{-1}}$ and $1.4\,\mathrm{km\,s^{-1}}$. There are thus still many uncertainties in the surface emission mechanisms of the lunar sodium atoms.

3. Time Variability

One noteworthy feature of the sodium emission from Mercury's disk has to do with its night-to-night brightness variation sometimes observed.[21,22] In addition, the brightness enhancement tended to appear in the high-altitude region, especially in the polar area.[11] Similar pattern of polar enhancement was reported in the imaging observations of Baumgardner *et al.*[14] This effect gives the impression that magnetospheric dynamics must be the controlling factor. That is, the cusp regions of the polar magnetosphere tend to provide open access of the solar wind particles to the planetary surface (see Fig. 1c). As for the persistent north-south asymmetry, we believe that it might be the result of an anomaly of the surface magnetic field which allows more charged particle to precipitate in the north (with weaker field). Certainly, this hypothesis will be tested by the MESSENGER observations in near future. Space measurements will also permit the examination of the dependence of the sodium production rate on the photosputtering effect. At Mercury, a major source mechanism of the Na atoms is due to the irradiation of the solar ultraviolet photons.[18,23] It is therefore quite likely that the production rate of the Na atoms will suddenly increase following a solar flare. A coordinated observation program to monitor the variability of sodium brightness of the planetary disk and the sodium tail and their correlation with solar activity and interplanetary condition near Mercury will provide definitive answer to these basic questions.

It is important to point out that the three source mechanisms depicted in Fig. 1, namely, ion sputtering, photon-stimulated desorption, and meteoroid impact, can be coupled via magnetospheric process. This is because the exospheric neutrals supplied by these mechanisms will be partly ionized and be fed into Mercury's magnetosphere. Trapping and acceleration of the Na^+, Mg^+, S^+, Si^+, K^+, Ca^+ pickup ions might lead to re-impact of these energetic ions on the planetary surface thus producing yet another population of exospheric neutrals.[24,25] This sequence of events is both complex and highly interrelated and we have no clues yet on how it would work at Mercury. But ground-based observations of the lunar corona of sodium atoms have given us a glimpse of what might happen as far as the basic process is concerned. In their detailed investigation of the behavior of the Moon's extended sodium atmosphere during lunar eclipses, Mendillo *et al.*[16] suggested that solar wind sputtering is not an important source of the sodium atoms because the halo did not subside after the Moon entered Earth's magnetospheric tail where the solar wind flux is highly reduced. On the basis of this unique set of observations, these authors concluded that photon-stimulated desorption should provide about 85% of the exospheric sodium atoms while the rest (about 15%) should come from meteoroid impact evaporation. This result is consistent with the theoretical calculation of Wurz *et al.*[23] But in a subsequent re-analysis of the full-moon observational data, Wilson *et al.*[26] found that the brightness of the lunar sodium exosphere has good correlation with the Moon's passage through the Earth's plasma sheet in the magnetotail. They therefore suggested that surface interaction with the plasma sheet ions could lead to a higher level of photo-desorption. On the other hand, it is to be investigated whether the higher flux of energetic charged particles in the magnetospheric plasma sheet could lead to enhanced surface sputtering rate of the sodium atoms. This problem can be best attacked by coordinated observations combining ground-based observations and spacecraft in-situ measurements by the lunar orbiters.

Sarantos *et al.*[27] re-examined an event of lunar passage of the magnetospheric plasma sheet based on the spectroscopic measurements of the sodium line emission above the equator from 100 to 4,000 km attitudes by the McMath-Pierce Solar Telescope.[28] They concluded that the observed short-term decrease of the sodium emission which was accompanied by an increase of the exospheric temperature from 1,200 K to 3,000 K could not be explained by the chancy impact of a 0.5-m radius meteoroid on the lunar surface. The above discussion demonstrated clearly the complexity of the exospheric origins and the uncertainties still remain in our understanding of the Moon (and Mercury by implication) with its space environment and the interplanetary meteoroid complex. The joint in-situ measurements by Kaguya, Chang'e-1, Chandrayaan-1 and any other future lunar missions (such as LADEE of NASA), supported by ground-based observations will

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bring new insights to the origin and temporal evolution of the lunar atmosphere.

4. Magnetic Anomalies

The MESSENGER spacecraft, after its Mercury Orbit Insertion (MOI), will begin the phase of detailed mapping of the planetary surface and its magnetic environment. From the point of view of comparative planetology, it would be of interest to infer possible magnetic features based on the lunar magnetic field measurements from previous missions like Apollo 16 and Lunar Prospector. A case in point is about the existence of magnetic anomalies (i.e. high field regions on the Moon which appear to be correlated with antipodal young lunar basins like Imbrium, Orientale, Serenitatis, and Crisium.[29–32] The theory developed by Hide[31] and subsequently by Hood,[34] Hood and Huang[33] and Hood and Avtemieva[36] is based on the idea that the convergence of shock wave of the dust clouds and plasma from a

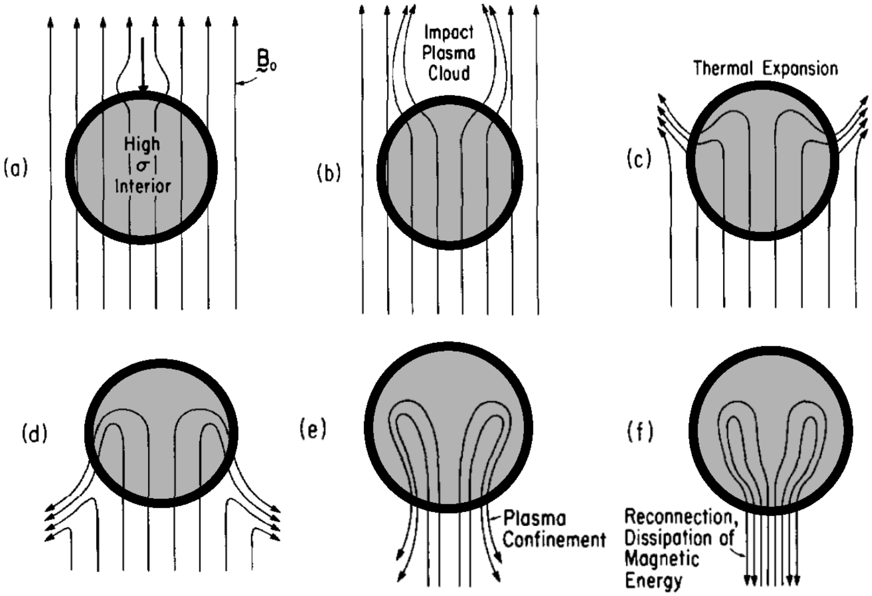

Fig. 2. A schematic illustration of the possible existence and origin of magnetic anomalies from the basin-forming impact of the Caloris basin on Mercury. The expansion and convergence of the impact plasma cloud would carry the ambient magnetic field of the interplanetary medium and/or the intrinsic planetary magnetic field to the antipodal pint resulting in a strong field region. (After Lin *et al.*[31])

basin-forming impact on the antipodal region will lead to an enhancement of the surface magnetic field. These magnetic anomalies have important effects on shielding some local areas from solar wind protons thus modifying the surface weathering process.[37] It is likely that the trapping and escaping of the exospheric pickup ions are also influenced by the magnetic anomalies. In this context, Mercury could serve as a testing ground of the antipodal impact shock theory.[33,34] That is, the antipodal region of the Caloris impact basin would be expected to be characterized by high surface field strength.

5. Summary and Discussion

In this review, we have made a brief description of the structures and time variability of the sodium exospheres of Mercury and the Moon as observed from ground-based telescope facilities. Even though we seem to have some ideas on the cause and effect of the dynamics and highly complex behaviors of these two surface-bound exospheres, the essential information is still missing and no definitive conclusion can be drawn. The next few years will be remembered as the break-through years of the studies of the lunar and Hermean atmospheres analogous to the revolutionary impact of the Giotto encounter with comet Halley on cometary research. On the other hand, it is tempting to speculate that if the surface magnetic anomalies of the Moon can be explained by the basin-forming impact theory, we probably will find similar magnetic anomalies on the antipodal side of the Caloris basin.

Acknowledgments

I thank Dr. Drew Potter, Dr. Rosemary Killen and the two anonymous reviewers for useful comments on the manuscript. This work was partially supported by NSC 97-2112-M-008-011-MY3 and NSC 97-2111-M-008-018-MY3 and a grant of NCU 5500 Top University Program.

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