

Classes of the solar wind interactions in the solar system

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This short note classifies the interactions between different objects in the solar system and their environments with the solar wind or magnetospheric plasma. The classification is performed using a simple but physically justified M - B diagram, where M is the total mass of the neutral gas around the object and B is the magnetic field (either intrinsic or external) at the object. The solar system objects form groups within the diagram that correspond to the following general classes: magnetospheres, mini-magnetospheres, induced magnetospheres, cometary and Moon-like interactions. The Martian magnetic anomalies are unique objects. We also identify a class termed as combined magnetospheres, which does not contain any objects that meet the present conditions.

Key words: Planetary science, solar wind interactions, comparative magnetospheres.

1. Interaction with the Solar Wind

All of the bodies within the solar system, i.e., the planets, satellites, asteroids, comets and dust particles, are immersed in a supersonic (250–800 km/s) flow of a sparse (<few tens of particles/cm³) solar wind plasma that is composed mainly of protons and carries a frozen-in magnetic field. These bodies produce a disturbance of the plasma flow, i.e., they interact with the solar wind plasma. The satellites of the planets are often located within the interaction regions and interact with the plasma present there. The study of these interactions is an interdisciplinary subject dealing with the plasma physics of the process and the impact of the interactions on the central body's atmosphere or surface. There are numerous reviews at different levels on the subject and we only mention a few general ones. Luhmann (1995) focused on non-magnetized bodies and comets, Coates (1999) the Earth and comets, Cravens (1999) mostly on the terrestrial magnetosphere.

The underlying plasma physics defines the class of the interaction, which differs significantly through the solar system. The nature of the interaction depends on whether the body has a magnetic field and/or an atmosphere. If a body possesses a magnetic field, i.e., it is magnetized, then the body's magnetic field acts via the Lorentz force on the charged particles in the solar wind to change the particle trajectories. If a body lacks a magnetic field and is conductive, then the moving magnetic field of the solar wind flowing over the conductive body generates inductive currents (Faraday law). The magnetic field associated with these currents affects the solar wind-charged particles. The conductivity of rock is low and may only support very low induced currents. If an object has an atmosphere, then its uppermost layer is ionized by the solar extreme ultraviolet

(EUV) radiation and becomes conductive. Normally, the conductivity is proportional to the electron density because the gyrofrequency is much higher than the collisional frequency in magnetized plasmas. Therefore, the magnitude of the induced currents and how much a non-magnetic object would affect the solar wind will depend on the density of its ionosphere. The ionospheric density depends on the neutral atmosphere and the solar EUV intensity. For icy satellites (e.g., Europa and Callisto), the conductivity of the undersurface oceans also affects the interaction process but it is too low in comparison with the ionospheric conductivities to support induced strong currents. To simplify this consideration, we organized the classes of the interactions with the solar wind or the magnetospheric plasmas by considering only two parameters, the magnetic field at the body and the total neutral gas mass.

2. Parameter Estimations

For the objects with an intrinsic magnetic field we use the magnetic field at the equator. For Mercury we use the latest measurements by MESSENGER (Anderson *et al.*, 2011). For ancient Mars we use estimations by Kallio and Barabash (2012). For Callisto and Titan we use the averaged Jovian and Saturnian field in the moon location respectively. Due to the large angle between the magnetic moment and the rotation axis for Uranus and Neptune we use the average field between the poles and the equator. For the objects without intrinsic dipoles we use the interplanetary fields from Russell *et al.* (1988). For comets, the distance $R = 1$ AU is used. For the lunar magnetic anomalies we use a typical field of 300 nT. For the Martian anomalies, a magnetic field of 1500 nT is used.

For the objects with atmospheres (Titan and all of the planets except Mercury) we estimate the total neutral gas mass, M , as

$$M = \frac{4\pi R^2 p}{g},$$

where R is the object radius, p is the atmospheric pressure

Table 1. Typical values for the neutral gas mass M and magnetic field B at different objects.

Object	B , nT	M , kg	Comment on neutral gas mass
<i>Global interactions</i>			
Mercury	195	$6.6 \cdot 10^3$	$N = 4.4 \cdot 10^4 \text{ O/cm}^{-3}$ (Wurz and Lammer, 2003)
Venus	10	$4.8 \cdot 10^{20}$	
Earth	$3.08 \cdot 10^4$	$5.3 \cdot 10^{18}$	
Moon	7	$2.7 \cdot 10^4$	
Mars	3.4	$2.5 \cdot 10^{16}$	
Ancient Mars	60	$2.0 \cdot 10^{18}$	0.5 bar surface pressure
Phobos	3.4	$2.7 \cdot 10^3$	$Q = 10^{23} \text{ s}^{-1}$ (upper limit, Ip and Banaszkiwicz, 1990)
Jupiter	$4.25 \cdot 10^5$	$2.6 \cdot 10^{20}$	M from 1 bar level
Ganymede	770	$1.8 \cdot 10^5$	
Callisto	23	$1.2 \cdot 10^7$	
Saturn	$2.0 \cdot 10^4$	$4.3 \cdot 10^{20}$	M from 1 bar level
Titan	5	$9.0 \cdot 10^{18}$	
Uranus	$2.3 \cdot 10^4$	$9.5 \cdot 10^{19}$	M from 1 bar level
Neptune	$1.4 \cdot 10^4$	$6.9 \cdot 10^{19}$	M from 1 bar level
Comet Hale-Bopp	7	$2.7 \cdot 10^{11}$	$Q = 1.0 \cdot 10^{31} \text{ s}^{-1}$ (Biver <i>et al.</i> , 1997)
Comet 26P/Grigg-Skjellerup	7	$1.3 \cdot 10^8$	$Q = 7.5 \cdot 10^{27} \text{ s}^{-1}$ (Johnstone <i>et al.</i> , 1993)
<i>Small scale interactions</i>			
Lunar magnetic anomalies	300	$2.7 \cdot 10^4$	M same as for the Moon
Mars magnetic anomalies	1500	$2.5 \cdot 10^{16}$	M same as for Mars

at the surface, and g is the equatorial surface gravity.

For the objects with exospheres (Mercury, the Moon, Ganymede, and Callisto) we estimate the total neutral gas mass as

$$M = 4\pi R^2 \cdot H \cdot N \cdot m,$$

where H is the typical scale height of the exosphere, N is the typical surface density, and m is the molecular mass of the main constituent.

For the objects with negligible gravity (comets and Phobos) we estimate the total neutral gas mass as

$$M = Q \cdot \tau \cdot m,$$

where Q is the outgassing rate, and $\tau = 10^6 \text{ s}$ is the typical ionization time at distances of 1–1.5 AU. For simplicity, we chose two representative comets, a strong one and a weak one, the comets Hale-Bopp and 26P/Grigg-Skjellerup, respectively. Typical values for the neutral gas mass M and magnetic field B at different objects are given in Table 1.

3. Classes of Interaction

All objects from Table 1 are plotted on the $\log(M)$ - $\log(B)$ diagram (Fig. 1). Surprisingly, they form well distinguished clusters that reflects the respective classes of the interactions. We identify magnetospheres, mini-magnetospheres, induced magnetospheres, and cometary and Moon-like interactions. In the magnetosphere class, we do not distinguish corotating magnetospheres of the giant planets and icy giants from the terrestrial magnetosphere because this division is related to the size of the region where the corotating electric field dominates over the convective field. We consider these objects as belonging to different types within

the magnetosphere class. Similarly, Ganymede's magnetosphere formed inside the Jovian magnetosphere is considered a different type of mini-magnetosphere.

The diagram is useful for comparative studies because it immediately reveals the members of the same family. This approach works for interactions on the planetary scale and also for smaller objects. We illustrate this point by placing the Martian and lunar magnetic anomalies on the diagram, marked by different symbols. The parameter ranges are given in Table 1. There is nothing similar to the Martian magnetic anomalies although this object does not directly interact with the solar wind. It is immersed in the Martian induced magnetosphere. The lunar magnetic anomalies are directly exposed to the solar wind and are placed surprisingly close to Mercury and Ganymede. This observation emphasizes the importance of the Moon for Mercury studies.

The comets and non-magnetized atmospheric bodies are clearly separated on the diagram although these objects have certain similarities in the physics of the interaction. Indeed, it is the pick-up and mass-loading processes at comets that define the interaction whereas the induced currents determined the interaction physics in induced magnetospheres.

Another observation is that the region of the diagram corresponding to the relatively weak magnetic field (10–300 nT) but substantial neutral gas mass 10^{18} – 10^{23} kg is empty. This region corresponds to a combined magnetosphere class that was first introduced by Dubinin *et al.* (1980) to explain earlier observations at Mars when it was assumed that Mars might have a weak dipole field. Kallio and Barabash (2012) also studied this object with regards to ancient Mars. The interesting question arises here as to why

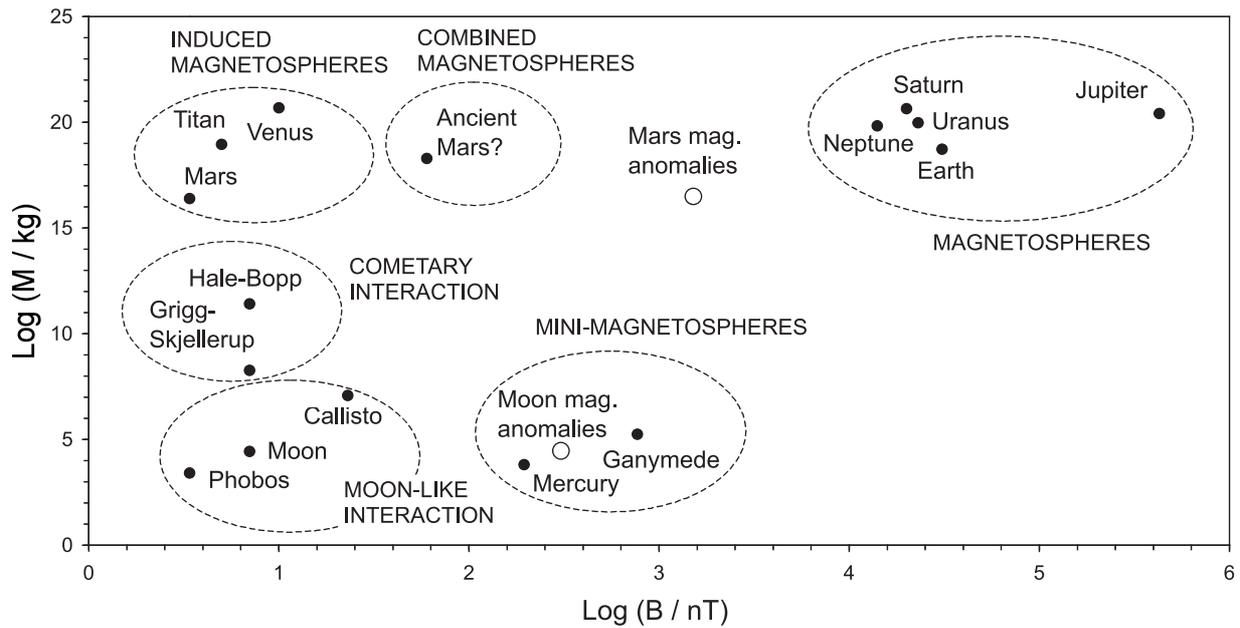


Fig. 1. Classes of the interaction with the solar wind organized by the total neutral gas mass at the object and the ambient magnetic field. The global interactions are shown by solid circles and the small scale interactions are represented by open circles.

this class does not contain any objects for the present conditions. Additionally, why are there not any atmospheric bodies with a weak dipole in the solar system? Are there fundamental physical reasons for this or it just happened to be so in our solar system? Although a classification cannot answer such questions, the classification may help to formulate the correct questions.

The region of strong magnetic fields ($>10^4$ nT) and low atmospheric masses is not populated either. To generate a strong intrinsic field a body should have a large core and/or mantle convection. Such a massive body should be capable of gravitationally trapping a sufficient amount of neutral gases to form an atmosphere.

4. Notes on Terminology

We prefer the term mini-magnetospheres for Ganymede, Mercury, and the Moon magnetic anomalies instead of small magnetospheres because the typical magnetic fields for these objects are indeed 2–3 orders of magnitude weaker than in the magnetosphere class. We also prefer the term induced magnetospheres for non-magnetized atmospheric bodies, such as Mars, Venus, and Titan (when it is in the solar wind). This term emphasizes the commonality with magnetospheres and mini-magnetospheres in the sense that a solar wind void is created in all of these cases. Also, the term induced magnetospheres directly reflects the physics of the obstacle created by the magnetic fields from the induced currents in the conductive ionosphere.

5. Conclusions

The classes of the interactions between the solar wind and the different objects in the solar system are surprisingly well organized on the M - B diagram. The classes are magnetospheres, mini-magnetospheres, induced mag-

netospheres, cometary, and Moon-like interactions, and the unique class of Martian magnetic anomalies. The M - B diagram gives an illustrative but physically justified overview of the possible interactions in the solar system, and it provides a useful guide for comparative magnetospheric studies.

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