How to make a ma

Abstract

On its journey from the Sun, the solar wind encounters bodies with various magnetic field strengths. The stronger planetary magnetic fields create a cavity or magnetosphere in the solar wind that greatly exceeds the scale lengths of the gyrating ions and exhibits self-similar behaviour. The weaker magnetic fields, associated with smaller bodies, create a spectrum of disturbances that differ from the planetary magnetospheres and in which ion scales are important. Global numerical simulations that resolve the ion motion enable us to examine the evolution of these disturbances from simple wakes to complex systems with features very similar to planetary magnetospheres. Examining this hierarchy provides insight into the formation of planetary magnetospheres, including the origin of such features as the magnetotail, plasma sheet, magnetopause, magnetosheath, bow shock and trapped radiation belts.

The solar wind is a supersonic plasma that originates from the Sun and expands radially into the interplanetary space. As it encounters the various bodies in the solar system it creates a variety of disturbances depending on the effective size of the obstacle. Two measures are important: the gyroradius, \( \rho_i \), is the radius of the particle orbit around the magnetic field \( B \) due to the Lorentz force, and is given by \( \rho = v_\text{th} / \Omega = v_\text{th} m / qB \), where \( v_\text{th} \) is the thermal velocity, \( \Omega \) is the gyro (cyclotron) frequency, and \( m \) and \( q \) are the particle mass and charge. The ion inertial length, \( \lambda_i = c / v_\text{th} \) (with \( c \) the speed of light), is related to the displacement that ions suffer when the plasma oscillates at the ion plasma frequency \( \omega_p = (nq^2 / \epsilon_o m) \) (where \( n \) is the density). When the system scale is large compared to the ion gyroradius and the inertial length, the microphysics of the interaction are often ignored and a fluid approach is used. This is in particular true in the solar wind–Earth interaction where kinetic simulations are not feasible (Lyon 2000, Raeder 2003). However, there are situations where obstacle size is much smaller, due to weaker magnetization (such as Mercury and the asteroids) and fluid assumptions are strongly violated. In such cases, global modelling of the interaction region needs to include ion gyration/kinetic effects. Even when dealing with large-scale systems, many critical aspects of the interaction such as energy dissipation and conversion are governed by ion dynamics. As a result, global kinetic simulations of large systems are also highly desirable.

To study the effects of the kinetic or microphysical processes on the global structure of the interaction region, it is best to begin with small-scale disturbances associated with very weak magnetization, increasing the strength of the dipole magnetic field until a magnetosphere is produced. We used computer simulations that solve the motion of the plasma and the electromagnetic fields in a self-consistent manner. These simulations are “hybrid”, in that ion dynamics are treated kinetically, while electrons are modelled as a fluid. These results came from simulations with two spatial dimensions and three velocity components. We use this 2.5-D approach because 3-D hybrid simulations require considerably more computational resources. We begin with weak fields and a weakly magnetized asteroid such as was reportedly detected by Galileo (Kivelson et al. 1993). We increase the magnetic dipole strength until a magnetosphere forms. All bodies in the simulation have no atmosphere or ionosphere and are not electrically conducting.

The simulation box and the interplanetary magnetic field IMF are in the X–Y plane with X along the solar wind velocity \( V_{\text{sw}} \). The IMF is 90° (northward) to \( V_{\text{sw}} \). We use simulation boxes of different sizes, starting at 40 × 40 \( \lambda_i \), up to 600 × 600 \( \lambda_i \). The magnetized body is represented by a line dipole (Ogino 1993) of fixed orientation along the Y axis and \( D_{\text{p}} \), the distance of closest approach. The Alfvén Mach number \( M_{\text{A}} \) is defined as the ratio of the speed of an Alfvén wave, given by \( B / (\mu_0 \rho) \) where...
$B$ and $\rho$ are the upstream undisturbed magnetic field strength in teslas and the mass density in kg m$^{-3}$ and $\mu_o$ is the permeability of free space $4\pi \times 10^{-7}$. The MA values that we use are representative of solar wind conditions at 1 AU. The remaining boundaries are open for the plasma to leave. The simulation is run until a stationary state is reached. Steady state in the simulations is reached by introducing a resistivity with scale length of about 0.03 ion inertial length. Details of the simulation method are given elsewhere (Omidi et al. 2002, Winske and Omidi 1996).

The 2-D nature of the simulation implies limitations such as the absence of flow divergence in the third dimension (Omidi et al. 2002). Nevertheless, 2-D hybrid simulations provide insight into the physics of the solar wind interaction with a magnetized body.

We can compare the different members of our hierarchy of interaction regions using the parameter $D_p$, the distance (in ion inertial lengths, $\lambda_i$) from the dipole at which solar wind dynamic and dipole magnetic pressures are equal. $D_p$ can be interpreted as the effective size of the obstacle. As $D_p$ increases we find that there are four different types of solar wind interaction with a magnetized body. The table summarizes the important features of each type of interaction as described below. When $D_p$ is

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**Table: Characteristics of the solar wind interaction region with magnetized bodies as a function of $D_p$**

<table>
<thead>
<tr>
<th>$D_p$</th>
<th>Upstream plasma changes</th>
<th>Waves</th>
<th>Magnetospheric features</th>
<th>Applicable objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;&lt; \lambda_i$</td>
<td>None</td>
<td>Whistler wake</td>
<td>None</td>
<td>Magnetized asteroid</td>
</tr>
<tr>
<td>$&lt; \lambda_i$</td>
<td>Some flow deflection: Density $n$ increases, and velocity $v$ decreases at $r &gt; D_p$</td>
<td>Whistler wake; Fast &amp; slow magnetosonic waves at wake edges</td>
<td>Precursor of a plasma tail</td>
<td>Magnetized asteroid</td>
</tr>
<tr>
<td>$\geq \lambda_i$</td>
<td>Pile-up at $r - D_p$: Flow deflection $n$, temperature $T$ and $B$ increase; $v$ decreases</td>
<td>Fast mode bow wave; Upstream Slow mode wake</td>
<td>Particle acceleration at dipole; (Particle trapping at belts) Tail with hot plasma</td>
<td>Magnetized planets, starting with Mercury and Earth, with $D_p = 65$ and $640\lambda_i$ respectively</td>
</tr>
<tr>
<td>$&gt;&gt; \lambda_i$</td>
<td>Flow modified and deflected at bow shock, $r &gt;&gt; D_p$: $n$, $T$, $B$ increase; $v$ decreases Magnetosheath</td>
<td>Bow shock</td>
<td>Magnetopause; Cusp; Tail with plasma sheet; Radiation belts; Reconnection, ion acceleration and magnetic islands</td>
<td>Magneto atmospheres with $D_p = 65$ and $640\lambda_i$ respectively</td>
</tr>
</tbody>
</table>

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2: Density and $B_x$ contours of the wake when $D_p < \lambda_i$. See caption of figure 1.
smaller than the ion scales ($D_p << \lambda_i$) the plasma is not modified and a whistler wake is formed. A whistler wave is an electromagnetic wave in which the perturbed electric and magnetic field rotate about the background magnetic field in the direction of motion of the gyrating electrons. Larger values of $D_p < \lambda_i$ lead to some plasma modification near the obstacle, and to the generation of three separate wakes corresponding to whistler, fast and slow magnetosonic modes. (A magnetosonic wave has a longer wavelength than a whistler mode wave, is compressional and ions and electrons are similarly affected.) When $D_p \approx \lambda_i$, the interaction region changes dramatically, the plasma is perturbed, a shock-like structure develops ahead of the dipole, and a hot plasma sheet appears in the tail. A magnetosphere like Earth’s is formed when $D_p > 20 \lambda_i$. The characteristics of the interaction depend on the size of $D_p$ relative to ion scales. The size and complexity of the interaction region increase with $D_p$.

**Onset of the whistler wake, $D_p << \lambda_i$**

The solar wind interaction with a weakly magnetized, non-outgasing body, whose effective size is much smaller than the ion scales ($D_p = 0.05 \lambda_i$), does not affect the plasma density or temperature and only a magnetic signature is generated (figure 1). The magnetic field is so weak that it does not constitute an impenetrable obstacle to the solar wind, which reaches the surface and is absorbed. There is no deflection of solar wind ions and no density or temperature changes occur. As a result, the perturbation consists only of a noncompressive whistler wake downstream of the body with small $B_x$ and $B_y$ fluctuations, and no changes in field magnitude.

**Transition to a magnetosonic wake, $D_p < \lambda_i$**

For stronger magnetization and $D_p = 0.2 \lambda_i$, the wake still forms downstream (figure 2) of the obstacle. In contrast to the previous case, the plasma is modified close to the nose of the obstacle. The density increases ahead of the dipole, and decreases in the tail behind. There is no pile-up region in front of the dipole because the flow velocity never goes to zero, but some flow deflection occurs. The density and velocity change over a region upstream slightly larger than $D_p$. In the tail the temperature and velocity are perturbed. The wake is formed by whistler and magnetosonic (MS) fast and slow waves. Non-compressional whistler waves arise in front of the region where the density increases (figure 2). Closer to the dipole, where the density is enhanced, MS waves can compress the flow form. More characteristics of the whistler and whistler/magnetosonic wakes are given elsewhere (Blanco-Cano et al. 2003). Whistler and whistler/MS wakes such as these are expected to be observed near asteroids if they have a remanent magnetic field. Magnetic signatures near asteroids Gaspra and Ida were interpreted as whistler wakes (Kivelson et al. 1993). But recent analysis shows that the observed signatures do not have the characteristics of a whistler wave (Blanco-Cano et al. 2003).

**Appearance of a magnetosonic bow wave, $D_p = \lambda_i$**

When the obstacle size is comparable to ion scales the interaction changes dramatically. The density increases, where $V_x = 0$, and pile-up occurs at distances $r = D_i$ ahead of the dipole. An MS wave forms upstream, compressing, slowing, heating and diverting the flow around the obstacle (figure 3). The MS wave resembles a fast shock, but spatial scales associated with the wave are comparable to ion gyroradii and therefore different dissipation processes operate. Ion reflection at the bow wave and their subsequent acceleration leads to asymmetries in the wave structure. The MS wave, with plasma and field compression, results from density pile-up. The plasma is heated by particle acceleration at the dipole. This becomes stronger as magnetization increases, and can be interpreted as a precursor of the acceleration that trapped particles suffer at higher dipolar strength, where belts with energetic particles form. Downstream, a region of lower magnetic field identified as a slow mode appears. This separates a slower, cooler plasma from a faster and hotter one in the central tail region. Test particle runs show that this fast and hot plasma results from acceleration in the dipole region. That density pile-up starts to be important when $D_p = \lambda_i$, clearly illustrates that ion gyration has a deep influence on the structure of the interaction region, and on the way that the plasma is modified. In contrast to a planetary magnetopause, pile-up occurs inside dipolar field lines. This, plus the fact that the region is small compared to ion scales, indicate that the interaction still does not meet the criteria for the formation of a magnetosphere (Greenstadt 1971).

**Transition to a magnetosphere, $D_p >> \lambda_i$**

The interaction generates an Earth-like magnetosphere when $D_p > 20 \lambda_i$, i.e. the magnetized obstacle is much larger than the ion scales. In this case the planetary field is strong enough that a magnetosphere, magnetosheath, and bow shock system are produced (figure 4). Plasma parameters show that there is not a pile-up region within a distance $r = D_i$ from the planet as before. The interaction is mediated by a shock wave at a large distance upstream ($= 100 \lambda_i$), where the solar wind is compressed, heated and...
diverted. This results in a magnetosheath where the density, temperature and field are enhanced, and the flow is decelerated. The shock leads to ion reflection, which in turn can modify the plasma. The magnetosphere extends ∼30λi upstream, and a much larger distance downstream. Solar wind density drops at the distance to which closed dipolar field lines extend, so that the field is an impenetrable obstacle to the flow, and a magnetopause current layer is formed. A thin magnetopause current layer, separating solar wind from magnetospheric plasma, is possible when the ion gyroradius becomes much smaller than the magnetopause thickness.

The simulated magnetosphere shows the basic features observed at Earth: a cusp, a tail with a plasma sheet bounded by boundary layers, and the existence of energetic ions at the dipolar, magnetopause and central tail regions (figure 4). The most energetic ions, with energies ∼40 keV are accelerated at the dipole where field lines provide efficient magnetic mirrors in which to trap particles, eventually leading to the formation of radiation belts. Evidence of magnetic reconnection, in which IMF lines link up with magnetospheric lines (Dungey 1961), is provided by the magnetic islands, or plasmoids, in the high-latitude magnetosphere and in the central tail region. Reconnection processes can contribute to ion acceleration in the magnetopause and tail as suggested by the energetic ions at the plasmoids.

**In summary**

Our models show that the solar wind interaction with magnetized bodies can occur in many different ways. It is clear that the system size in relation to ion scales strongly affects the nature of the interaction region and the characteristics of the waves that affect the deflection and modify the plasma. For weak magnetization the flow is not modified because obstacle size is small compared to ion scales, and only a magnetic whistler wake is formed. When the field is not so weak, a whistler/MS wake is generated. These signatures are expected near asteroids if they have a significant remanent magnetic field. The interaction changes dramatically and the plasma starts to be modified ahead of the dipole when obstacle size is similar to ion scales (Dp ∼λi). The formation of a magnetosphere requires that the dipolar field is strong enough for the obstacle effective size to be larger (Dp >20λi) than ion scales. In this case a bow shock, magnetosheath, magnetospheric system is driven, and the flow is modified far upstream. The magnetospheres of all planets in the solar system have Dp > 20λi, (e.g. 85 for Mercury, 640 for Earth and 5800 at Jupiter), so they share the same basic features: a cusp, a tail with a plasma sheet, and energetic ion populations. The simulations reveal that reconnection, the process that couples plasma circulation in planetary magnetospheres to the solar wind flow, is an end member of a series of micro-scale processes that evolve with the scale size of the interaction. At Earth reconnection is important in energizing the magnetosphere. In magnetospheres with smaller Dp, such as Mercury, reconnection with the solar wind magnetic field may be relatively more important than on Earth; at Jupiter, less important. Our results show that even kinetic processes, which involve small-scale phenomena, are very important to the global structure of the solar wind interaction with a magnetized body. In practice these processes are tailored by features of each planet, such as the presence or absence of moons and atmospheres, creating a rich phenomenological environment.

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**References**


