

INTERACTION OF THE SOLAR WIND WITH MAGNETIZED ASTEROIDS

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ABSTRACT/RESUME

We use a 2-D hybrid code (fluid electrons, particle ions) to simulate the interaction of the solar wind with a magnetized asteroid. The asteroid field is taken as a dipole with different strengths. For a small magnetic moment a whistler wake is generated. Stronger dipoles generate a magnetosonic perturbation. We compare simulation results with the signatures observed by Galileo near Gaspra and Ida. When the IMF is 90° to the solar wind flow, the wake is downstream from the asteroid, and is formed by whistler and magnetosonic waves. When the IMF is $\approx 45^\circ$ to the flow, part of the wake is upstream. From the discrepancies found between observations and simulations we conclude that signatures near Gaspra and Ida were not generated by the solar wind interaction with magnetized asteroids.

1. INTRODUCTION

It is of much interest to determine if asteroids can possess a global remanent magnetic field. Such a field would place constraints on their composition, origin and thermal evolution. Asteroids are classified according to color and albedo. Low-albedo C-type asteroids, with neutral color in the visible, and high-albedo S-type with reddish color are both generally thought to be primitive and to have undergone little thermal evolution. Alternatively S-type asteroids may be similar to stony meteorites containing silicates and metallic iron. Such asteroids may have undergone differentiation, possibly leading to a metallic core. If asteroids have a remanent magnetic field, with a sufficiently coherent direction of magnetization, their interaction with the solar wind will create a magnetic perturbation in the flow. The nature of this interaction depends on the strength, and orientation of their global magnetic field, and of the solar wind and interplanetary magnetic field (IMF) conditions.

Greenstadt [1] studied the interaction of the solar wind with an asteroid considering two possibilities. If the asteroid field is sufficiently high to form an obstacle (magnetosphere) to the solar wind then the flow is diverted around this obstacle and a shock forms in front of it. If on the other hand, the

asteroid field is not sufficient to form an impenetrable obstacle to the flow, then the interaction would result in a whistler wake downstream of the asteroid. This is due to the small size of asteroids, which is between the electron and ion gyroradius ($\rho_e < r_a < \rho_i$).

Galileo observed magnetic field rotations near S-type asteroids Gaspra and Ida. These rotations have been interpreted as signatures of the solar wind interaction with the asteroids [2, 3, 4]. It was proposed that the standing wave produced is mediated by the whistler mode due to the size of the body, which is between the electron and ion gyroradius. The radius of Gaspra and Ida are 7 and 15 km, while $\rho_i \approx 2000$ km and $\rho_e \approx 1$ km.

A third encounter with an asteroid occurred when Deep Space 1 (DS1) flew by asteroid Braille [5]. In this case, data show substantial levels of magnetization. In contrast to this, and to Galileo observations, NEAR-Shoemaker measurements have established extremely low levels of magnetization for asteroid 433 Eros [6]. The variety of situations found near asteroids indicate that different magnetic properties exist in different type of asteroids. The study of the magnetic signatures observed near asteroids and a clear understanding of how they interact with the solar wind will help us to determine their magnetic characteristics.

Interplanetary magnetic perturbations are commonly found in the solar wind, then to determine if the signatures observed by Galileo are asteroid related and if they match the whistler wake characteristics, the interaction of the solar wind with a small magnetized object requires to be addressed in detail. We use 2-D hybrid simulations (fluid electrons, particle ions) and study the interaction between the solar wind and a magnetized asteroid for different dipolar field strengths. We compare Galileo observations with signatures generated in our simulations. Detailed descriptions of our results are given in [7] and [8].

2. SIMULATION RESULTS

We have performed 2-D hybrid simulations resembling the solar wind and IMF conditions

observed during Galileo encounters with Gaspra and Ida. Simulations are 2-D in space but the electromagnetic fields and velocities are 3-D. The simulation box and the IMF are on the X-Y plane with X along the solar wind velocity. We consider two cases for the IMF direction, 1) 90° to the flow, along Y, 2) 45° to the flow. The simulation box is $40 \times 40 c/\omega_p$ long with 400×400 cells, where c/ω_p is the proton skin depth in the solar wind (≈ 70 - 100 km near 1 AU). The asteroid is represented by a line dipole at the center of the box. The dipole axis is along Y and the asteroid rotation is not included. The use of a line dipole is due to the 2-D nature of the simulation where the field decreases as $1/r^2$ instead of as $1/r^3$. The 2-D nature of the simulation implies some limitations such as the absence of flow divergence in the third dimension which changes the nature of interaction, and in particular can produce some nonphysical reconnection. Nevertheless, the use of a 2-D hybrid simulation gives valuable information about the solar wind interaction with a magnetized asteroid.

The asteroid size is one cell ($0.1 c/\omega_p$) and solar wind is continuously injected from the left with Alfvén Mach number $M_A=8$ along X. The simulation is run until a stationary state is reached. Other boundaries are open for the plasma to leave. The asteroid cell is considered out of the simulation domain and ions entering the cell are lost representing absorption by asteroid. Details on the code and of simulation settings are given in [7, 9]. To study how the strength of the asteroid magnetic field changes the interaction region and compare simulations with Galileo observations near Gaspra and Ida we consider different dipolar moments. The strength of the dipole field in each run is represented in two ways. One is D_p , the distance (in proton inertial lengths) from the asteroid at which solar wind ram pressure is equal to asteroidal magnetic pressure. This is a physical scale useful to understand the change in the nature of the interaction region as the level of magnetization is increased. The other is B_s , the estimated surface magnetic field strength (in nT).

2.1 IMF Perpendicular to Solar Wind

During the Galileo encounter with Gaspra, the IMF was 90° to the solar wind flow. Figure 1 shows B_x and density of the wake wave that forms for different dipolar field strengths. When the dipolar field is weak, $D_p=0.054$ (panels (a)-(b)), the wake is formed downstream of the asteroid by whistler waves with perturbations in B_x and B_z with amplitudes smaller than 10% the IMF. Due to the small size of the obstacle, defined by D_p , no shock is formed. The wave wake is noncompressive with no variation in B_y and B, and in agreement with this, no density perturbation is observed. For a

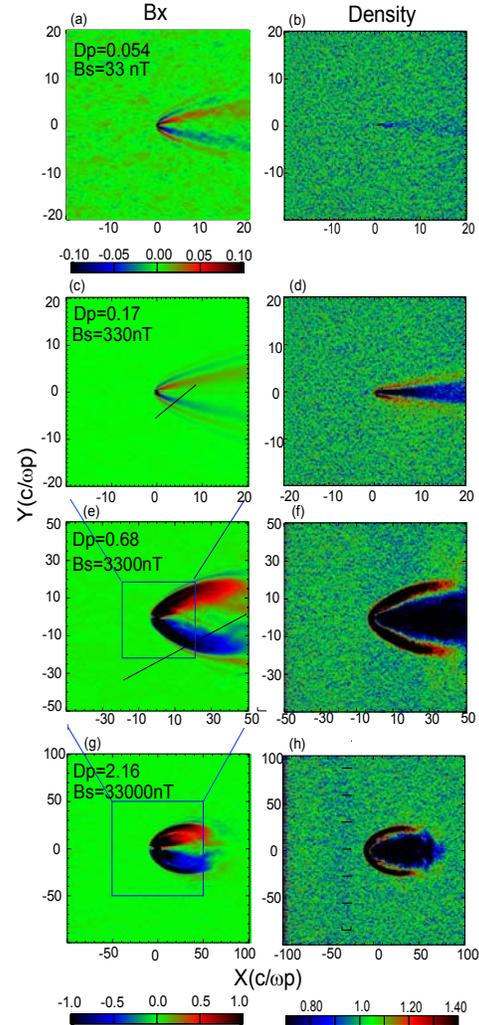


Fig. 1. B_x and density for different values of D_p . Scale is indicated for (a). For the rest of B_x panels, and density the scale is indicated below.

stronger dipolar moment, with $D_p=0.17$ (c, d) the wake wave is downstream of the asteroid and is more complex and extended, with stronger perturbations in B_x and B_z . The outer waves are noncompressional, in agreement with the whistler mode. However, downstream from the whistler wave, and closer to the asteroid there is a region where B_y and B change. There is a plasma tail with density enhancements at its edges and depletion within the tail. The perturbation is noncompressive as appropriate for a whistler wave until the plasma tail edge is reached. Fast and slow magnetosonic (MS) waves are associated with the formation of the tail [5]. The edge of the tail is the transition region from a whistler wake into MS waves. Panels (e)-(f) show the wake that is formed for larger dipolar moment, with $D_p=0.68$ (simulation box is $100 \times 100 c/\omega_p$). The resultant wake is totally different and much more extended. The square in

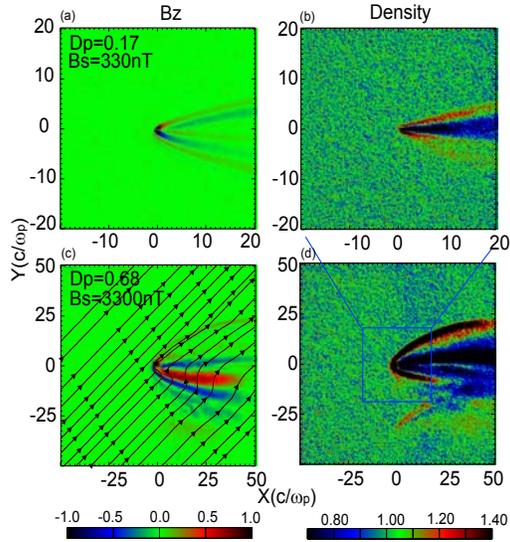


Fig. 2. B_z and density for different values of D_p when the IMF is 45° to the solar wind flow. The projection of the total magnetic field is displayed in (c).

(e) shows the size of the simulation box in (c). B_x , B_y , and B_z change significantly and the wake nose forms slightly upstream. These characteristics plus the density pile up in front of the asteroid indicate that this wake is generated by fast MS waves. Panel (e) shows wave fronts slightly upstream of the MS perturbation. These fronts are transverse and are identified as whistlers. They are in the outer part because they propagate faster than MS waves. When $D_p=2.16$, a fast MS wake forms upstream, and a shock-like structure develops ahead of the asteroid. The wake wave is larger than in the previous case. This series of simulation shows that the density pile up that becomes the magnetosheath for very large obstacles begins when $D_p \approx 1$ i.e. an ion inertial length and grows for larger D_p . Simulations for larger D_p that we do not illustrate here show that at $D_p = 12$ the interaction is dominated by a shock wave, and at $D_p \geq 40$ there is a magnetospheric type interaction. In summary, the nature of the interaction region changes drastically with the level of asteroidal magnetization. Its strength controls both the size of the interaction region and the nature of the waves that affect the deflection of the plasma flow. Our results highlight the importance of using a hybrid code to study this problem, in which kinetic ion effects are important.

2.2 IMF quasi-parallel to solar wind

During the Galileo encounter with Ida, the IMF was quasi-parallel to the solar wind flow. Figure 2 shows B_z and density for wave wakes that form when the IMF is 45° to the solar wind flow. $D_p=0.17$ in panels, (a)-(b), and $D_p=0.68$ in panels (c)-(d). In contrast to the perpendicular case, and in

agreement with previous results [4], for these runs the wave wakes are asymmetric. See [7] for a discussion of what causes the asymmetry. The wake that is generated when $D_p=0.17$ (a, b) has two components, the outer part consists of whistler waves that propagate upstream along the field due to their large phase speeds. Downstream from this region there is a MS component associated with the plasma tail. The whistler waves propagate upstream a distance, $2 c/\omega_p$, and the wave wake is slightly upstream of the asteroid. The type of interaction changes when $D_p=0.68$. The wake is accompanied by density and magnetic field pile up ahead of the obstacle, but in contrast to the perpendicular IMF geometry, the pile up is more extended on the quasi-perpendicular side of the wake. On the quasi-parallel side, density and magnetic field pile up occurs only close to the wake nose. The solar wind is perturbed, and as in the previous run, the wave wake forms at a small distance, $5 c/\omega_p$ upstream of the obstacle. The wake nose is dominated by compressive waves.

3. COMPARISON WITH GALILEO DATA

We compare the signatures observed by Galileo near Gaspra and Ida with simulations to determine if observed rotations were generated by the solar wind interaction with the asteroids. We take cuts along simulation wakes (trajectories in Fig. 1c, e) resembling Galileo trajectories. In the case of Gaspra the observed perturbation was downstream of the asteroid [3, 8], mainly in B_x , with an average value of 50% of the IMF strength. B_y and B_z were less perturbed and B remained almost constant. The upstream IMF was $\approx 90^\circ$ to the flow. When we compare the observed signature with the whistler waves generated when $D_p=0.054$ and $D_p=0.17$ profiles of B_x and B agree with observations, with a significant rotation in B_x and no change in B. However, the amplitude and extent of the simulated wave are small in comparison with observations. In addition, the simulated wave shows a rotation in B_z that was not observed by Galileo. For $D_p=0.68$, simulated profiles show more similarities with Galileo data. The perturbation in B_x is 50% of the IMF strength and covers a large distance. B and n do not change until they reach the plasma tail. The extent of the rotation in B_x along the trajectory in Fig. 1e is $25 c/\omega_p$ which corresponds to 2248-3946 km, for densities between $2\text{-}6 \text{ cm}^{-3}$. This resembles the size of the observed perturbation ≈ 1780 km. The simulated wave is $20 c/\omega_p$ (≈ 1800 km) from the asteroid. This is similar to the distance from Gaspra at which the rotation was observed (1600 km), but there are discrepancies. These include a positive rotation in B_z , the lack of a second rotation in the simulation signature, and the simulated perturbation is further downstream than the observed one.

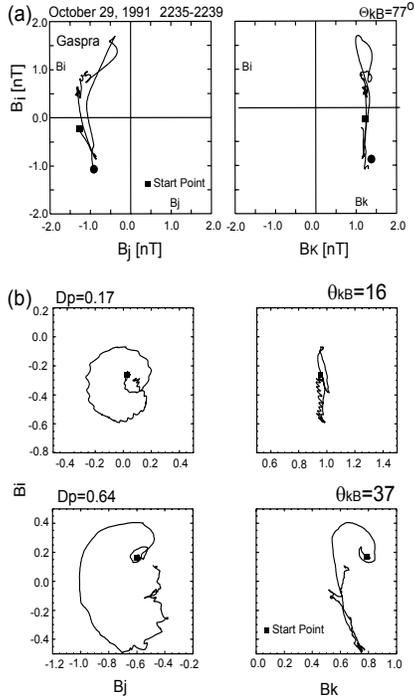


Fig. 3. (a) Minimum variance analysis of the rotation observed near Gaspra. (b) Minimum variance analysis of trajectories shown in Fig. 1(c), (e).

To compare in more detail Galileo observations with simulations we perform minimum variance analysis. Figure 3 shows that the observed perturbation is linearly polarized in contrast to the almost circularly polarized signature of the simulations. Minimum variance analysis for a solar wind magnetic discontinuity observed by Galileo earlier on the day of the Gaspra encounter shows that the perturbation near Galileo has similar polarization properties to this discontinuity [8]. The fact that the perturbation resembles more an interplanetary magnetic discontinuity than the whistler waves in our simulations, plus other discrepancies found in our comparison lead us to conclude that the signature observed by Galileo near Gaspra was not generated by the interaction of the solar wind with the asteroid.

In the case of Ida, the observed rotation was mainly in B_z with an amplitude of $\approx 20\%$ the IMF [3, 8]. There was little change in B_x and B_y , and the initial perturbation was observed at a large distance, ≈ 4000 km upstream of the asteroid. The IMF was at 54° to the flow. We compare Galileo observations with the results of simulations when the IMF is 45° to the solar wind flow. The most significant discrepancy between our simulations and observations is that for the two asteroid dipolar fields used here, the wave wake forms only slightly upstream (≤ 1000 km) of the asteroid in comparison

with the large distance at which the perturbation was observed upstream of Ida. In addition, the observed perturbation was linearly polarized in contrast to the almost circularly polarized signature of the runs. Therefore, we believe that it is unlikely that this perturbation was generated by the interaction of the solar wind with the asteroid.

4. CONCLUSIONS

The region of interaction of the solar wind with a magnetized asteroid changes with asteroidal magnetic field strength. For small D_p the region is dominated by a whistler wake downstream of the body. When D_p approaches c/ω_p the nature of the interaction changes and the wave becomes compressive forming slightly upstream. Larger values of $D_p \gg 1$ result in a shock-like structure ahead of the asteroid. Eventually a magnetosphere forms for sufficiently high D_p . The characteristics of the signatures observed near Gaspra and Ida differ from properties of the signatures in our simulations. We conclude that the observed signatures were not generated by the interaction of the solar wind with magnetized asteroids.

5. REFERENCES

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