Phase-steepened Alfvén waves, proton perpendicular energization and the creation of magnetic holes and magnetic decreases: The ponderomotive force

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Received 11 June 2002; revised 31 October 2002; accepted 25 November 2002; published 28 December 2002.

[1] Solar wind protons detected within Magnetic Holes (MHs) and Magnetic Decreases (MDs) are found to be preferentially heated perpendicular to $\vec{\mathbf{B}}_0$. The MHs/MDs are associated with the phase-steepened edges of nonlinear Alfvén waves. The proton anisotropies can lead to the proton cyclotron and mirror mode plasma instabilities. We examine the Ponderomotive Force (PF), a phenomenon due to wave pressure gradients, and show that for this plasma regime and for phase-steepened Alfvén waves, the PF proton acceleration/energization will primarily be orthogonal to $\mathbf{B}_0$. It is suggested that accelerated ions create the MHs/MDs by a diamagnetic effect. *INDEX TERMS:* 2134 Interplanetary Physics: Interplanetary magnetic fields; 2169 Interplanetary Physics: Sources of the solar wind; 2164 Interplanetary Physics: Solar wind plasma; 2109 Interplanetary Physics: Discontinuities. **Citation:** Tsurutani, B. T., B. Dasgupta, C. Galvan, M. Neugebauer, G. S. Lakhina, J. K. Arballo, D. Winterhalter, B. E. Goldstein, and B. Buti, Phase-steepened Alfvén waves, proton perpendicular energization and the creation of magnetic holes and magnetic decreases: The ponderomotive force, *Geophys. Res. Lett.*, *29*(24), 2233, doi:10.1029/2002GL015652, 2002.

1. Introduction

[2] Magnetic holes (MHs) [*Turner et al.*, 1977; *Winterhalter et al.*, 1994, 2000; *Fränz et al.*, 2000] and magnetic decreases (MDs) [*Tsurutani and Ho*, 1999; *Tsurutani et al.*, 1999; *Neugebauer et al.*, 2001] are decreases in the magnitude of the interplanetary magnetic field that can be relatively short (seconds) or can last as long as tens of minutes or even hours in duration. It has recently been shown by *Tsurutani et al.* [2002] that MHs and MDs are presumably the same phenomenon (with MDs longer and with discontinuities bounding an edge), and that they often occur at the edges of phase steepened Alfvén waves.

[3] It is the purpose of this paper to study differences in solar wind proton temperatures within and just outside the MDs to identify evolutionary changes that may be taking place, and hence the nature of these structures. To avoid stream-stream contamination effects, we will study only Alfvén waves/MDs detected within high-speed streams at near-polar latitudes (see *McComas et al.*, 2002). Nine days (208–216) of the 1995 north polar pass (80.2° latitude, 2.0 AU) and nine days (280–288) of the solar maximum 2001 north polar pass (80.2° latitudes 2.0 AU) will be used.

2. Instruments and Data Analyses

[4] The data used for this study were from the magnetometer instrument onboard Ulysses (described in *Balogh et al.*, 1992) and from the plasma instrument described in *Bame et al.* [1992]. We will use the 1995 MD data for the statistical analyses of proton energization (MHs were typically too small to obtain proton measurements within the structures). The plasma instrument made one 3-dimensional measurement every 4 mins. The 2001 data are used for examples of instabilities.

3. Results

[5] Figure 1 illustrates a MH/MD in the first Ulysses north polar pass. The field decrease occurs from 1946:20 UT until 1946:42 UT. The magnetic field magnitude decreases from ~1.6 nT to a minimum of ~0.2 nT and recovers to ~1.7 nT.

[6] In the top four panels, the field is displayed in a RTN coordinate system where **R** is the direction from the sun. There are large magnetic field directional changes that are present within the MD. From 1946:20 UT to 1946:42 UT, the B_R component rotates from −1.1 nT to ~+0.5 nT and the B_N component rotates from ~1.0 nT to ~−1.8 nT.

[7] This discontinuity is ~22 s in duration (the discontinuity is convected past the spacecraft by the radially flowing solar wind). Minimum variance analyses place the $\mathbf{k} \cdot \mathbf{R}$ component at 0.51. With a solar wind speed of ~760 km s^{-1}, the thickness of the discontinuity in the plasma frame is ~8500 km. For a temperature of ~1.2×10^5 K, the local proton gyroradius (assuming $B_0 \cong 0.5$ nT) is ~1050 km. Thus, the scale size of the discontinuity is ~8 ρ_p, where ρ_p is the proton gyroradius.

[8] As previously noted, the MH/MD occurs at the edge of an Alfvén wave. From the minimum variance analyses [*Sonnerup and Cahill*, 1967] taken for data between the dashed vertical lines, the wave is found to be circularly/elliptically polarized ($\lambda_1/\lambda_2 > 3.2$), is planar ($\lambda_2/\lambda_3 = 4.6$), and is propagating at a highly oblique angle (~80°) relative to the ambient magnetic field.

[9] To study the proton evolution, 104 MD events during the 1995 interval were first identified. All 32 cases where proton measurements within these MDs were available are used.

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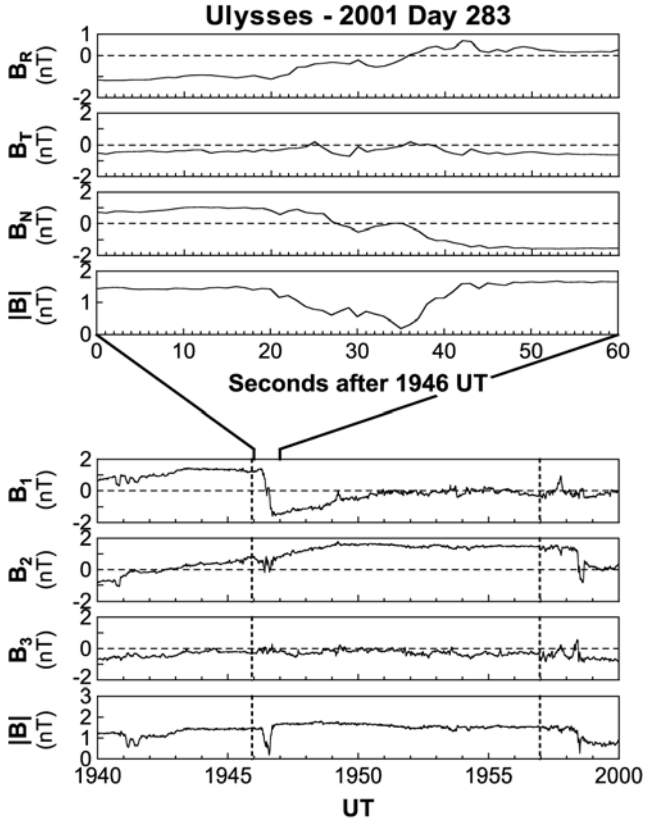

Figure 1. A MH/MD at the edge of an Alfvén wave. The top 4 panels are the discontinuity magnetic field in the RTN coordinate system, and the next 4 panels the Alfvén wave field in minimum variance coordinates.

[10] The ratio of the temperature inside the MD to that outside the MD is shown in Figure 2. For purposes of trying to understand possible energization processes, the temperatures (calculated from the second moments of the parallel and perpendicular proton distributions) are examined.

[11] The top panel shows that the proton perpendicular temperature is almost always higher inside the MD than outside. There are only 4 cases where the temperature was lower. The bottom panel shows that the proton parallel temperature is essentially the same inside the MD as outside the MD.

[12] The statistics of the $T_\perp/T_\parallel$ temperature anisotropies were calculated for the same 32 events. Inside the MD, the anisotropy value is larger than outside. However, it was noted that only 9 out of 32 events had $T_\perp/T_\parallel$ values >1.0 (these results were not shown to save space).

[13] Proton temperature anisotropy analyses on MDs have previously been performed. *Fränz et al.* [2000] found that $T_\perp/T_\parallel$ was higher in 32 of 49 events and lower for 10 events. *Neugebauer et al.* [2001] examined 6 MD events and found that $T_\perp$ increased in the MD events.

4. Perpendicular Energization of Protons

[14] We consider the Ponderomotive Force (PF) as a mechanism for the perpendicular energization of protons. The PF is due to radiation pressure from an inhomogeneous wave field [*Landau and Lifschitz*, 1960; *Lee and Parks*, 1983; *Li and Temerin*, 1993]. Previous work (e.g., *Li and Temerin*, 1993) have focused on parallel (to the ambient magnetic field) acceleration/energization. Here, for a different plasma regime (solar wind), and for high frequency component wave fields, we will show that the PF accelerates/energizes protons primarily perpendicular to the magnetic field.

[15] The Ponderomotive Force (PF) on the solar wind plasma due to obliquely propagating Alfvén waves is the gradient of the ponderomotive potential $-\nabla\Phi_{PM}$, which can be written as:

$$F_p = -\nabla\Phi_{PM} = \frac{e^2}{4m}\nabla\left(\frac{1}{\Omega^2-\omega^2}E_\perp^2 - \frac{1}{\omega^2}E_\parallel^2\right) \tag{1}$$

where $\Omega = eB_0/m$ is the cyclotron frequency. Also $\nabla E_\perp^2$ and $\nabla E_\parallel^2$ are the gradients of the wave perpendicular and parallel electric field components. From the above equation, it is clear that the PF will be strongest in the regions of sharp electric field gradients. We can consider Φ_{PM} as the sum of the average energy gain in the perpendicular ($W_\perp$) and parallel ($W_\parallel$) directions. The expressions for the perpendicular and parallel potentials for protons (the maximum energy gain when the particles are near the sharp wave

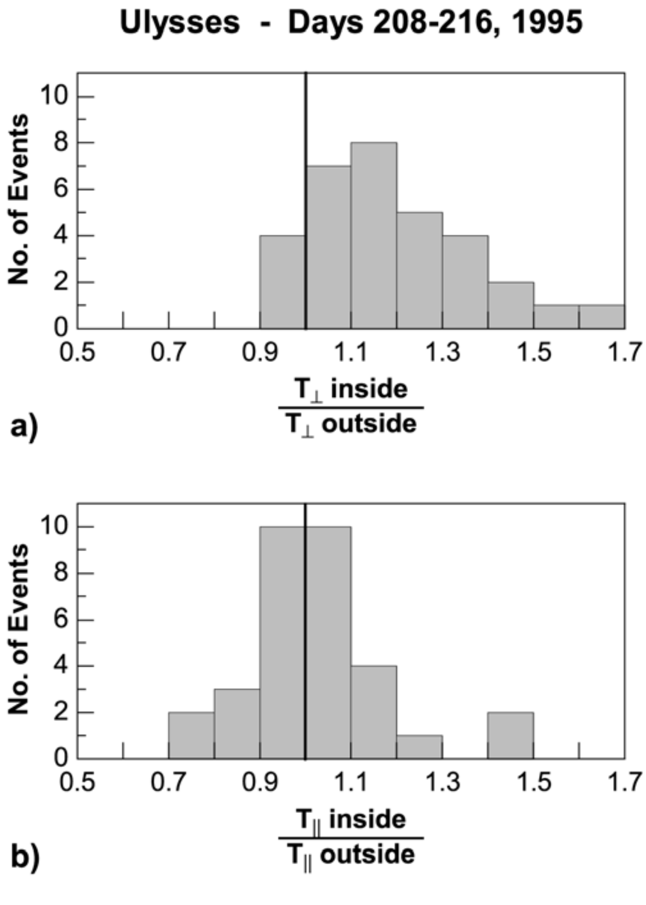

Figure 2. The ratio of proton temperatures within the MD (inside) to that outside the MD. The top panel gives ratios of the perpendicular temperatures and the bottom panel gives the ratios of the parallel temperatures.

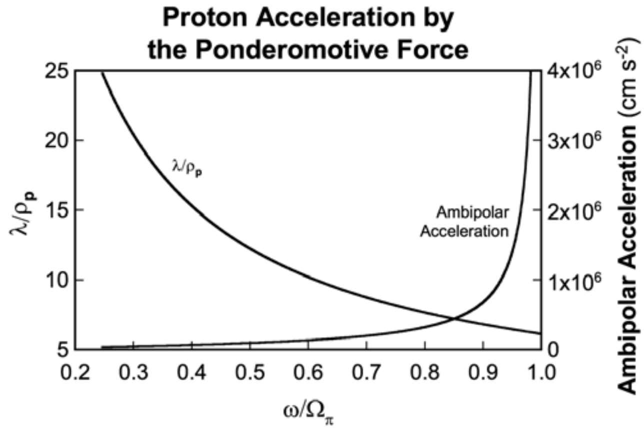

Figure 3. Ambipolar acceleration of protons by the Ponderomotive Force. The plasma parameters used are those from the examples in Figure 1.

gradients) are (see also *Pottelette et al.*, 1993 for lower hybrid wave application):

$$W_\perp = \frac{e^2}{4m_p}\frac{1}{\Omega_p^2 - \omega^2}|E_\perp|^2; \; W_\parallel = \frac{e^2}{4m_p}\frac{1}{\omega^2}|E_\parallel|^2 \tag{2}$$

[16] For model calculations, we will use the case of Figure 1, where B_0 = 1.5 nT and N_P = 0.6 cm^{-3}. Thus the Alfvén speed is ~41 km s^{-1}. From minimum variance analyses, the Alfvén wave is determined to be propagating at ~80° relative to $\mathbf{B}_0$. The phase steepened wave amplitude is ~1.5 nT (Figure 1) and the wave "frequency" is ~1/8 Ω_p.

[17] From Faraday's Law, E = $-V_A \times B$, and **E** is ~0.06 mV m^{-1}. The parallel electric field component can be determined from the wave polarization relationship [*Stasciewicz et al.*, 2001]:

$$\frac{E_\parallel}{E_\perp} = -\frac{k_\parallel k_\perp \rho_s^2}{1 + k_\perp^2 \rho_p^2} \tag{3}$$

where $k_\perp$ = k sin 80° and $\rho_s = C_s/\Omega_p$ where C_s is the ion sound speed.

[18] For the above plasma conditions and the assumption that $\nabla \sim k^{-1}$, it is found that $W_\perp/W_\parallel \sim 3$, e.g., the protons are energized predominantly in the perpendicular to the magnetic field direction. After energization, the protons of course may be thermalized by scattering through interactions with the Alfvén waves or by waves associated with plasma instabilities.

[19] Figure 3 shows the ambipolar acceleration of a proton as a function of wave frequency (see *Li and Temerin* [1993] for more details). As the wave frequency approaches the proton gyrofrequency, the particle perpendicular acceleration increases dramatically. For the scale size of the phase-steepened Alfvén wave edge (~8 ρ_p), the perpendicular acceleration is substantial.

5. Discussion

[20] We have shown that protons are energized in the direction perpendicular to the magnetic field and this can be accomplished by the Ponderomotive Force associated with phase-steepened interplanetary Alfvén waves. In our scenario, the energized protons, via diamagnetic effects, create the field depressions (MHs/MDs).

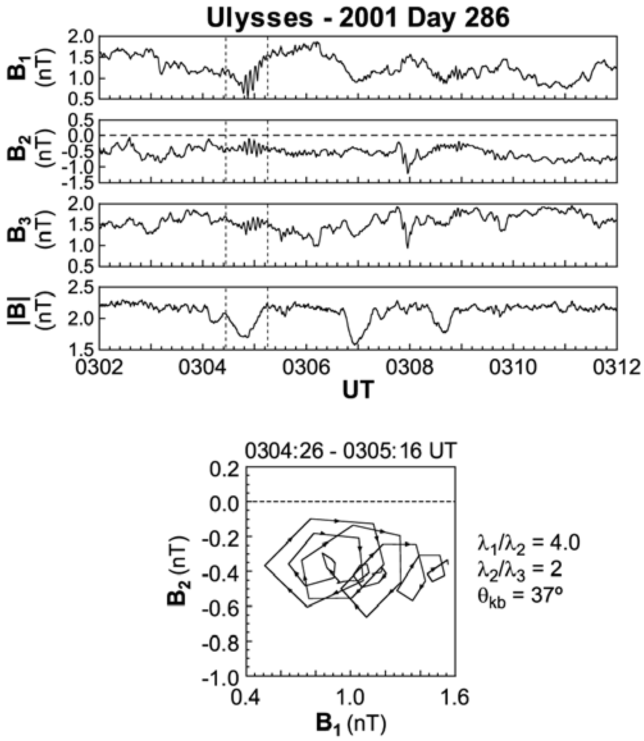

Figure 4. Proton cyclotron waves inside a small amplitude MD (note the |B| scale does not start at 0 nT). The waves are left-hand polarized in the spacecraft frame and are propagating at an angle of 32° relative to $\mathbf{B}_0$. Assuming that the waves are propagating in the solar wind direction, it is estimated that $f_w \sim 0.6 f_p$.

[21] Although the proton perpendicular acceleration does not always lead to $T_\perp/T_\parallel > 1$, one might expect plasma instabilities to develop occasionally. Two instabilities which can be generated by such $T_\perp/T_\parallel$ anisotropies are: the mirror instability [*Southwood and Kivelson*, 1993] and the proton cyclotron (loss-cone) instability [*Anderson*, 1995]. Figures 4 and 5 show examples of both instabilities occurring within

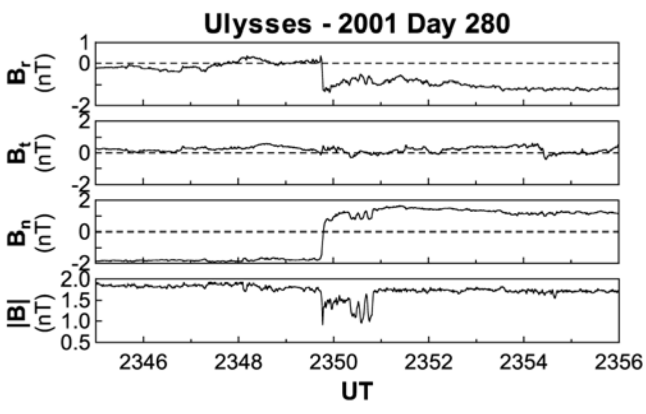

Figure 5. Mirror mode oscillations inside a MD. The scale size is $\lambda \sim 38$ $\mathbf{r_p}$, comparable to mirror mode structures previously detected in planetary magnetosheaths.

MDs. In Figure 4, the circularly polarized waves at 0305 UT in the spacecraft frame are left-handed and have a frequency of f $\sim$ 0.19 Hz. Minimum variance analyses have been performed on the waves. They are found to be propagating at 37° relative to $\mathbf{B}_0$ and 65° relative to **R**. Assuming that the waves are propagating in the solar wind direction (preserving their left-hand polarization), a solar wind speed of ~760 km s^{-1} and a V_A of 43 km s^{-1}, the wave frequency in the plasma frame is calculated to be ~0.02 Hz. This compares well with the local proton cyclotron frequency of 0.03 Hz, giving f $\sim$ 0.6 f_p.

[22] Figure 5 shows a MH/MD with multiple oscillations from ~2350:40 UT to ~2351:00 UT. We take these to be mirror mode structures generated by the proton temperature anisotropy. The structures have a **k** direction 80° relative to $\mathbf{B}_0$. With a local proton temperature of 2.1 $\times$ 10^5 K, the scale size of these structures are ~38 ρ_p, comparable to the mirror mode scale sizes found in the magnetosheath of the Earth, Jupiter and Saturn [*Tsurutani et al.*, 1982].

6. Final Comments

[23] As Alfvén waves propagate outward from the sun, the lowering of the intrinsic phase speed and the conservation of action leads to wave phase steepening. Presumably it is the wave phase steepening (creation of a high-frequency component) that leads to proton perpendicular energization and the $T_\perp/T_\parallel > 1$ anisotropies in high-speed streams previously noted by *Bame et al.* [1975] and *Marsch et al.* [1982]. The Ponderomotive Force accelerates ions in the perpendicular direction, extracting energy from the ever-present Alfvén waves in the solar wind. When the phase-steepening becomes extreme, the proton acceleration intensifies and plasma diamagnetic cavities are formed. This same physical process may be taking place in other regions of the heliosphere such as close to the sun (the solar corona), and in the Earth's auroral ionosphere/magnetosphere.

[24] Our suggested mechanism for creating MHs/MDs by the Ponderomotive Force associated with phase-steepened Alfvén waves does not rule out other possibilities, such as creation by the mirror mode instability [*Winterhalter et al.*, 2000] or by nonlinear evolution of Alfvén waves [*Baumgärtel*, 1999; *Buti et al.*, 2001]. As one example, a gentle proton energization by the PF may lead to mirror instability without the formation of deep diamagnetic cavities. We also have not addressed the issue of the eventual fate of the MH/MD. Does the MH/MD absorb all of the phase-steepened Alfvén wave energy and become a "dead" object convected by the solar wind, or will subsequent impingement of other Alfvén waves lead to subsequent proton energization and evolution? Numerical modeling will be necessary to answer some of these questions.

[25] A reexamination of the proton distribution shown in Figure 3b of *Neugebauer et al.* [2001] has indicated that the perpendicular distribution function is not Maxwellian. The protons with energies between 50 and 200 eV have elevated fluxes, pointing to a small energy range of acceleration. This will be addressed in a subsequent work.

[26] Finally, we would like to mention that other interplanetary particle species can also be energized by the Ponderomotive Force: helium (and heavier) ions, and electrons. This is a more complicated picture, and this discussion will be delayed for subsequent works.

[27] **Acknowledgments.** Portions of this research were carried out at the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

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