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Generation Mechanism for Magnetic Holes in the Solar Wind

B. Buti, B.T. Tsurutani, M. Neugebauer and B.E. Goldstein

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

Abstract. A new mechanism for generation of magnetic holes in the solar wind is presented. In the high speed solar wind, large-amplitude right-hand polarized Alfvénic wave packets propagating at large angles to the ambient magnetic field are shown to generate magnetic holes (MHs). Characteristics of these holes crucially depend on plasma β (β being the ratio of kinetic pressure to magnetic pressure) and the ratio of electron temperature T_e to proton temperature T_i. Proton temperature anisotropy is found to be favorable but not essential for the development of MHs. From our simulations we observe MHs with microstructures bounded by sharp gradients (magnetic decreases) in some cases. The holes generated by this process have thicknesses of hundreds of ion Larmor radii, typical of many of the solar wind hole observations, the depths of the holes are also comparable. The theory can explain the presence of MHs seen in the solar wind for those cases when anisotropies are not favorable for the development of the mirror mode instability.

Introduction

The study of magnetic holes (depressions in the magnitude of the magnetic field) in the solar wind is attracting a lot of attention as more observations have recently been reported by a number of authors using Ulysses data (Smith and Marsden, 1995). Linear magnetic holes (MHs) in the interplanetary medium were reported by Turner et al.(1977). These are isolated structures embedded in uniform magnetic fields and have widths typically $\sim 2 \times 10^4$ km. These were found in regions of high proton β with very small changes in the direction of the magnetic field. Mirror mode depressions have been reported in magnetosheaths of Earth, Jupiter and Saturn (Tsurutani et al., 1982) and also in the environment of comets (Russell et al., 1987).

Ulysses high resolution magnetic field and plasma data recently stimulated further investigations. Winterhalter et al.(1994) found a large number of linear magnetic holes in the solar wind; their latitudinal distribution has recently been reported by Winterhalter et al.(2000). In the polar solar wind at Ulysses distances ($\sim 2AU$) magnetic depressions (MDs), apparent holes bounded by discontinuities, with scale sizes of $25 - 70$ proton gyroradii have been reported by Tsurutani et al.(1999). These depressions are solitary structures that are often bounded by discontinuities. From Ulysses data, similar conclusions about the association of tangential discontinuities with MHs have been drawn by Fränz et al.(2000).

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The observed linear magnetic holes have been interpreted as mirror modes by Winterhalter et al. (1994). They claim that within the holes the anisotropies and plasma β are large enough to satisfy the threshold for the mirror mode instability. According to Fränz et al.(2000) the proton anisotropy within the holes is not always higher than that outside the holes and the mirror mode instability criterion is satisfied only in $\sim$ 50% of all cases. In such cases mirror mode is debatable as the source for MHs, so one should look for an alternative explanation. Baumgärtel (1999) has suggested that these holes are dark soliton solutions of the Derivative Nonlinear Schrödinger (DNLS) equation (Kennel et al., 1988; Hada et al., 1989; Buti, 1990) governing AW propagating at large angles to the ambient magnetic field. From simulation studies of the interaction of two propagating dark solitons, Baumgärtel claimed that, unlike the bright solitons, the dark solitons are stable. Since in the derivation of the DNLS (cf. Kennel et al. 1988) only linear density perturbations ($\delta\rho$) are retained, his simulation can not account for the evolution of ($\delta\rho$) at all. Consequently Baumgärtel's results do not guarantee a real stability. Inclusion of density fluctuations could drastically change the stability properties. We would like to stress that one should exercise great caution in accepting Baumgärtel's claim that MHs are DNLS dark solitons for the simple reason that the DNLS equation is strictly valid only for parallel / quasi parallel propagation (Kennel et al., 1988). Baumgärtel wrongly claims that Kennel et al.(1988) had shown its validity for propagation at very large angles. We have done hybrid simulations to investigate the evolution of dark as well as bright solitons appropriately incorporating nonlinear density fluctuations as well as kinetic effects. We find that in both cases even a single soliton, let alone two interacting solitons, is not stable. Bright solitons propagating at large angles are found to evolve into MHs. Since the present paper deals with MHs, discussion of stability of dark solitons is out of place here; results for dark solitons will be reported in a separate publication.

In this paper, we present an alternative model for the generation of MHs. Taking clues from Ulysses observations showing the continuous existence of very large amplitude ($\delta B/B \sim 1-2$) Alfvén waves (Smith et al., 1995) accompanying the fast solar wind, we decided to explore the possibility of these waves as a potential source for the observed MHs. In principle large amplitude Alfvén waves should evolve into solitary waves (Buti et al., 1999) but curiously enough according to our knowledge such solitary Alfvénic structures have not been observed in the solar wind. From the dispersive MHD simulations, Buti et al.(1998) have shown that these structures get disrupted due to coupling of δB and $\delta\rho$. This coupling plays a very significant role in plasmas with large $\beta(\sim 1)$. In fact, the neglect of this coupling by

Table 1. Properties of Magnetic Holes from evolution at t = 800 gyroperiods.

β	$\beta_i \beta_e$	$B_p B_0$	A	Depth (B_0)	Width (R_L)	$\|\Delta\phi\|$ deg
4	3	2	2	0.70	200	2.7
4	3	2	1	0.25	70	3.7
4	1	2	2	0.35	100	2.7
4	3	0.8	2	0.55	215	5.6
4	3	0.8	1	0.40	175	1.6
2.4	3	0.8	2	0.35	260	0.1
2.4	2	0.8	1.4	0.30	160	0.7

Baumgärtel (1999) is the reason for the misleading conclusion drawn by him. Inhomogeneities can also destroy these solitary structures (Buti et al., 1999). In the solar wind, plasma kinetic effects play a very important role. Buti et al.,(2000; 2001) have incorporated the latter effects in hybrid simulations of Alfvénic wave packets (AWP) and found interesting new features like collapse of left hand polarized wave packets and generation of ion density holes. All these investigations were restricted to parallel propagation of AWPs in isotropic plasmas. Here we have extended our high resolution hybrid simulations to investigate the evolution of right-hand polarized (RHP) AWP propagating at very large angles ($\sim 80^\circ$) in anisotropic plasmas similar to the high speed solar wind (large β, $T_e < T_i$ and $T_{i\perp} \neq T_{i\parallel}$). These wave packets introduce localized inhomogeneities in an otherwise homogeneous plasma. For plasma parameters consistent with regions where MHs have been observed our simulations show that these packets evolve into MHs with characteristics similar to those observed in the polar solar wind. Propagation at large angles is a pertinent condition for the generation of MHs. However proton thermal anisotropy is not a must and it can be relaxed.

Simulation Model

We use a one-dimensional hybrid code (Winske and Leroy, 1985) to study the nonlinear dynamical evolution of large-amplitude AWP propagating along the x-axis at an angle θ to the ambient magnetic field $\mathbf{B}_0 = (B_0 cos\theta, B_0 sin\theta, 0)$. In our simulations, electrons are treated as an isothermal fluid whereas the protons are treated as particles having an initial biMaxwellian distribution modified by localized density inhomogeneity. Although there is only one spatial coordinate ($\partial/\partial y = \partial/\partial z = 0$), all three components of all the fields are retained in our simulations. For the high-resolution studies, we take the simulation box length as 860 ion - inertial lengths ($L_i \equiv V_A/\Omega_i$) with 2048 grid points and 200 particles in each cell. Simulations are carried out using periodic boundary conditions. For the initial condition, we take an AWP with,

$$B\ (x,\ t=0)\ =\ \frac{(2^{1/2}-1)^{1/2}\ B_p\ e^{i\phi\ (x)}}{\sqrt{(2^{1/2}\ \cosh\ (2\ V_p\ x)-1)}}, \qquad (1)$$

where $B = B_y + iB_z$, B_p is the amplitude of the wave packet, ϕ is the phase given by,

$$\phi\ (x)\ =\ V_p\ x\ -\ \frac{3}{8(1\ -\ \beta)}\ \int_{-\infty}^{2x} \mid B \mid^2 dx' \qquad (2)$$

and V_p is the speed in the wave frame of reference and is defined by,

$$V_p = (2^{1/2}-1)\ B_p^2\ /\ [8\ (\beta-1)]. \qquad (3)$$

Throughout, we use the normalized variables e.g., $\mathbf{B}$ is normalized to B_0, ρ to ρ_0, $\mathbf{v}$ to $V_A = B_0/(4\pi\rho_0)^{1/2}$ (V_A being the Alfvén velocity), t to inverse of Ω_i, the ion cyclotron frequency and l to L_i. The subscript '0' refers to the equilibrium quantities. Note that Eq. (1) is an RHP super-Alfvénic soliton solution of the DNLS (for parallel propagating AW) in the wave frame of reference (Verheest and Buti, 1992). β appearing in Eqs.(2) and (3) is the plasma β i.e., $\beta = \beta_e + \beta_i$ with T_i defined as $T_i = (T_{i\parallel} + 2T_{i\perp})/3$. Specific reasons for selecting soliton solution as initial condition are elaborated in Buti et al. (1999). Eq.(1) represents a localized magnetic field pulse in an otherwise homogeneous plasma. Correspondingly the initial transverse magnetic field $\mathbf{b} = (b_y, b_z)$

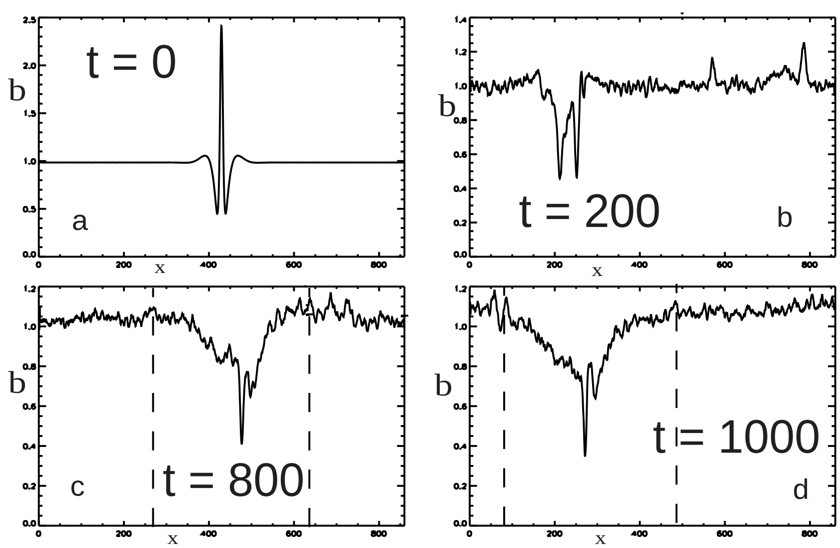

Figure 1. shows spatio-temporal evolution of magnitude of the magnetic field (b) of an RHP wave packet for $\beta = 4$, $B_p = 2$, $A = 2$, $\theta = 80^\circ$ and $\beta_i/\beta_e = 3$ at $t = 0, 100, 800$ and 1000 ion-gyroperiods.

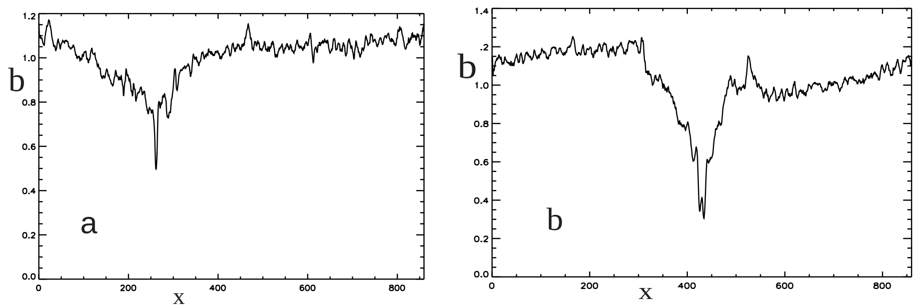

Figure 2. shows evolution of b at $t = 1000$. a) shows MH similar to the one in Fig. 1d but with zero initial density fluctuations; b) same as Fig. 1d but with initial density given by Eq.(8).

is given by,

$$b_y(x, t = 0) = B_0 sin\theta + \mid B \mid cos\phi, \tag{4}$$

$$b_z(x, t = 0) = \mid B \mid sin\phi. \tag{5}$$

For strong pulses with $\mid B \mid \geq 1$ density perturbations, driven by the pondermotive force (PF) of magnetic field fluctuations ($\delta\rho \propto |B|^2$), become very significant. To incorporate them appropriately, for the initial density we have considered the following three different cases:

$$\rho(x, t = 0) = 1, \tag{6}$$

$$\rho(x, t = 0) = 1 + \frac{1}{2(\beta - 1)} \mid B(x, t = 0) \mid^2, \tag{7}$$

$$\rho(x, t = 0) = 1 + \frac{1}{(1 + \beta_e/\beta_i)} \mid B(x, t = 0) \mid^2 . \tag{8}$$

It may be noted that the sign of second term on the right hand side of Eq.(7) is compatible with kinetic derivation of the DNLS whereas Eq.(8) represents the density corresponding to the drift kinetic treatment (Inhester, 1990). Even when we initially take uniform plasma i.e., Eq.(6), density perturbations are generated by the PF during the evolution (see Fig.3b). For the initial velocities we use the appropriate relations governing AW namely $v_{y,z} = -B_{y,z}$. The code of Winske and Leroy (1985) has been modified to impose correct periodic boundary conditions in the presence of the localized inhomogeneities introduced by our initial conditions.

Simulation Results

Recently Buti et al.,(2000 a, b) had looked into the spatio-temporal evolution of large amplitude AWPs propagating parallel to $\mathbf{B_0}$ in isotropic plasmas. In our present simulations, we instead take the localized AWP propagating at $\theta \sim 75^\circ - 80^\circ$. Simulation parameters used are compatible with the regions where MHs are observed (Winterhalter et al., 1994; Fränz et al., 2000). The spatio-temporal evolution of the transverse magnetic field b ($= (b_y^2 + b_z^2)^{1/2}$) for $\beta = 4$, $T_i/T_e = 3$, $A \equiv T_{i\perp}/T_{i\parallel} = 2$, $B_p = 2$ and $\theta = 80^\circ$ are shown in Fig.1. Note that the average value of A in polar solar wind is ~ 1 but just outside (pre event) an MH, A can be ≥ 2 (Neugebauer et al., 2001). For Figs.1 and 2, thermal noise in the simulation data is removed by averaging over $10L_i$. However for Table 1. no averaging has been done. We see a quick conversion of the compressive wave packet into an MD bounded by sharp gradients (see Fig.1b). Later on, around $t = 800$ ion gyroperiods (see Fig.1c), this MD evolves into a deep magnetic hole with depth ($= b_{max} - b_{min}$) ~ 0.6 (0.7) B_0 and width (shown by dotted lines) $\sim 350\ L_i$ i.e., $200R_L$ (= ion gyroradii). From Fig.1d we see that at $t = 1000$ the hole attains depth of ~ 0.65 (0.8) B_0 and width $\sim 400\ L_i$. The numbers in parenthesis for depths correspond to data with no averaging. In the solar wind for proton density (N_P) = 0.5, $L_i \sim 360$ kms. The change in the direction of magnetic field across the hole in this case is only 2.7°. The holes reported here are solitary structures like the 'linear holes' but have microstructures in some cases. The corresponding density fluctuations (N) (see Fig.3a)) are always compressive i.e., b and N are anticorrelated as in the case of observed MHs (see Fig.6 of Fränz et al., 2000). Fig.3b shows the evolution of N for the case $N(t = 0) = 0$. Fig.3 clearly shows the effect of nonlinear forces due to magnetic field fluctuations on the particle dynamics. The coupling of N with B provides a source of perturbation that allows overlapping of dark and bright soliton solutions of the DNLS (cf. Buti, 1990) and hence the conversion of a compressive AWP to a MH.

Table 1 shows how the properties of MHs change with β, B_P and A. From the results shown in this table, we infer that the holes do form even in an isotropic plasma unlike the mirror mode model for MHs. However the sizes of the holes (depth and width) are smaller in an isotropic case. Similar results hold good for $B_p = 2$ as well as 0.8 but the decreases in depth and width are much larger for the latter case. For all the cases shown in the Table, the angle of propagation is 80°. It is worth noting that the change in magnetic field direction across the hole in all the cases is $\leq 6^\circ$. The depth of MH decreases but the width increases when plasma β is changed from 4 to 2.4 whereas both depth and width decrease with a decrease in T_i/T_e.

We repeated the simulations for other large angles of propagation ($70^\circ < \theta < 80^\circ$); the results (not shown here) were qualitatively the same but showed slight quantitative differences. However, for parallel propagation no holes whatsoever were observed. Instead only turbulence/noise was observed. In all the cases discussed so far, the initial density profile used was according to Eq. (7). In order to make sure that the MH formation was not due to this specific initial condition, we repeated the calculations using Eq.(6) ; the results are shown in Fig.2a. Similar results for the density profile given by Eq.(8) are shown in Fig.2b. On comparing Figs.2a and 2b with Fig.1d showing the evolution at $t = 1000$, we see some quantitative but no qualitative differences in the properties of the MHs generated. This confirms that the source of MHs in our model is the localized AWP rather than any specific *initial* localized density profile. We would like to emphasize however that the coupling of N generated during the evolution (see Fig.3) with the magnetic field fluctuations plays a crucial role in the development of MHs. If this coupling was absent there would be no evolution of the density fluctuations whatsoever.

Discussion and Conclusions

Localized inhomogeneities introduced by large amplitude AWPs lead to MHs in the fast solar wind. We would like to stress that the initial magnetic pulse given by Eq.(1) is very different from the dark soliton solutions of the DNLS studied by Baumgärtel. As pointed out by Kennel et al. (1988), validity of DNLS equation for propagation of Alfvén waves at large angles is questionable. Unfortunately Baumgärtel had misinterpreted our results (Kennel et al., 1988) to justify his use of DNLS equation for large angle propagation. Moreover in his stability analysis of two counterstreaming dark solitons, density *evolution* has been ignored whereas in the present paper we have shown the crucial role played by *evolving* density perturbations in the nonlinear evolution of AWP. In summary the mechanism proposed here is altogether different from Baumgärtel's model. In the initial stages of the evolution, we observe MDs bounded by sharp gradients (see Fig.1b) and later on these MDs evolve into MHs with thicknesses of hundreds of Larmor radii. Most of the holes produced in our model seem to be solitary in nature and have shapes resembling either 'V' or 'W'. For generation of these holes, propagation at very large angles is found to be essential whereas the restriction on proton temperature anisotropy can be relaxed. Consequently our model can also explain the presence of observed MHs in the solar wind for the cases when anisotropies are not favorable for the development of the mirror mode instability. The initial localized density inhomogeneities are favourable but not a must for the generation mechanism outlined in the present paper. However this does not mean that the evolution of the density can be ignored. As shown in Fig.3b, density perturbations are generated during the evolution even for the case of zero initial density perturbation. Properties of MHs e.g., depth, width etc. depend on plasma β, ion-temperature anisotropy and the amplitude of the wave packet (see Table 1).

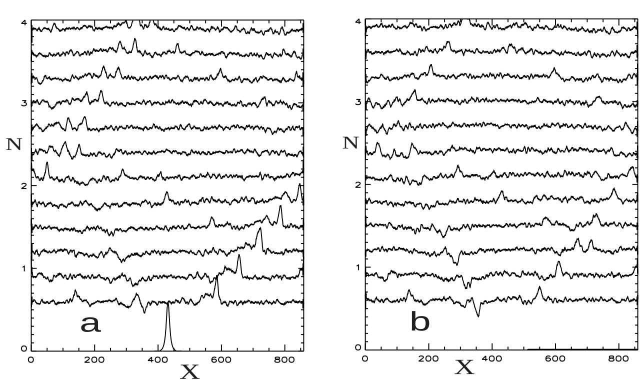

Figure 3. Stack plots for density fluctuations (N) for $\beta = 4$, $B_p = 2$, $A = 2$, $\theta = 80°$ and $\beta_i/\beta_e = 3$ at $t = 0, 80$ and $(80 + \Delta t)$ with $\Delta t = 40$ ion-gyroperiods. Initial density profiles used for Figs.3a and 3b respectively are given by Eqs. (7) and (6).

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References

Baumgärtel, K., Soliton Approach to Magnetic Holes, *J. Geophys. Res., 104*, 28295, 1999.

Buti, B., Nonlinear and Chaotic Alfvén Waves in *Solar and Planetary Plasma Physics, Ed. B. Buti, World Scientific, Singapore*, 92, 1990.

Buti, B., V. Jayanti, et al., Nonlinear Evolution of Alfvénic Wave Packets, *Geophys. Res. Letts., 25*, 2377, 1998.

Buti, B., V.L. Galinski, et al., Evolution of Nonlinear Alfvén Waves in Streaming Inhomogeneous Plasmas, *Astrophys. Jou., 523*, 849, 1999.

Buti, B., M. Velli, et al., Hybrid Simulations of Collapse of Alfvénic Wave Packets, *Phys. Plasmas, 7*, 3998, 2000.

Buti, B., B.E. Goldstein, et al., Ion Holes in the Solar Wind : Hybrid Simulations, *Geophys. Res. Letts. 28*, 91, 2001.

Fränz, M., D. Burgess, et al., Magnetic Field Depressions in Solar Wind, *J. Geophys. Res., 105*, 12725, 2000.

Hada, T., C.F. Kennel and B. Buti, Stationary Nonlinear Alfvén Waves and Solitons,*J. Geophys. Res., 94*, 65, 1989.

Inhester, B., A Drift-Kinetic Treatment of the Parametric decay of large- Amplitude Alfvén Waves, *J. Geophys. Res., 95*, 10525, 1990.

Kennel, C.F., B. Buti, et al., Nonlinear, Dispersive, Elliptically Polarized Alfvén Waves,*Phys. Fluids, 31*,1949, 1988.

Neugebauer, M., B.E. Goldstein, et al., Ion Distributions in Large Magnetic Holes in the Fast Solar Wind, *J. Geophys. Res.,* in press, 2001.

Russel, C.T., W. Riedler, et al., Mirror Instability in the Magnetosphere of Comet Halley, *Geophys. Res. Lett., 14*, 644, 1987.

Smith, E.J., A. Balogh, et al., Ulysses Observations of Alfvén Waves in the Southern and Northern Hemispheres,*Geophys. Res. Lett., 22*, 3381 (1995).

Smith, E.J. and R.G. Marsden, Ulysses Observations from Pole-To-Pole: An Introduction, *Geophys. Res. Lett., 22*, 3297 (1995).

Tsurutani, B.T., E.J. Smith, et al., Lion Roars and Nonoscillatory Drift Mirror Waves in the Magnetsheath, *J. Geophys. Res., 87*, 6060, 1982.

Tsurutani, B.T., G.S. Lakhina, et al., Energetic Particle cross-field diffusion: interactions with Magnetic Decreases (MDs), *Nonlinear Processes Geophys.,6*, 235, 1999.

Turner, J.M., L.F. Burlaga, et al., Magnetic Holes in the Solar Wind, *J. Geophys. Res., 82* , 1921, 1977.

Verheest,F. and B. Buti, Parallel Solitary Alfvén Waves in Warm Multispecies Beam-Plasma Systems *J. Plasma Phys., 47*, 15, 1992.

Winske, D. and M.M. Leroy, Hybrid Simulation Techniques applied to the Earth's Bow Shock in *Computer Simulations of Space Plasmas* , Eds. H. Matsumoto and T. Sato (D. Reidel, Hingham, Mass., 1985), p. 25.

Winterhalter, D., M. Neugebauer, et al., Ulysses Field and Plasma Observations of Magnetic Holes in the Solar Wind and their Relation to Mirror Mode Structures, *J. Geophys. Res., 99* , 23371, 1994.

Winterhalter, D., E.J. Smith, et al., The Latitudinal Distribution of Solar Wind Magnetic Holes,*Geophys. Res. Lett., 27*, 1615, 2000.

B. Buti, B.T. Tsurutani, M. Neugebauer and B.E. Goldstein, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

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