Magnetic structures in the heliosheath

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[1] We propose a solitary wave model for small scale magnetic structures observed in the solar wind and more recently in the Voyager 1 observations of the heliosheath. The model is based on the recent, fully nonlinear theory of solitary waves by McKenzie et al. (2001, 2004). Our solutions i.e., magnetic holes, humps, trains of holes and humps, are strongly nonlinear (70 to 80% change in the magnetic field at the centre), propagate at large angles (>60°) to the mean magnetic field and are well approximated by Gaussians. The structures are almost pressure balanced with an anti-correlation between the magnetic field and the plasma density, and no change in the magnetic vector across the structure. These features are consistent with observations of magnetic structures in the heliosheath. **Citation:** Avinash, K., and G. P. Zank (2007), Magnetic structures in the heliosheath, *Geophys. Res. Lett.*, *34*, L05106, doi:10.1029/2006GL028582.

1. Introduction

[2] A Magnetic Hole [MH] is a stationary stable structure with a small scale depression of the magnetic field in the centre. Such structures were first observed in the interplanetary magnetic field by *Turner et al.* [1977]. Later, similar structures were observed in the magnetosheath of Saturn [*Tsurutani et al.*, 1982; *Violante et al.*, 1995], Jupiter [*Erdős and Balogh*, 1996], Earth [*Kaufmann et al.*, 1970; *Tsurutani et al.*, 1982], and Comet Halley [*Russell et al.*, 1987]. In fact they have been shown to exist over the full range of heliocentric distances and latitudes [*Winterhalter et al.*, 2000; *Sperveslage et al.*, 2000; *Tsurutani et al.*, 2002]. Magnetic holes have a width which is usually a few tens of pick up proton (∼5 eV) gyroradii, though sometimes wider structures, bounded on both sides by sharp discontinuities called magnetic decreases [MD], have also been observed [*Tsurutani et al.*, 2005]. Voyager 1 has reached the heliospheric termination shock (HTS) and is currently in the heliosheath. The magnetometer data from Voyager 1 has returned interesting yet puzzling observations of magnetic fields in the heliosheath. In particular, it has revealed the presence of a rich class of stationary magnetic structures e.g. magnetic holes, sinusoids etc [*Burlaga et al.*, 2006]. Interestingly, the data also shows the presence of magnetic 'humps' with magnetic field maxima in the centre, trains of several holes and humps, and sequences of merged holes and humps (L. F. Burlaga et al., private communication, 2006). Such structures have not yet been observed in the solar wind or planetary magnetosheaths. The typical characteristics of the structures seen in the interplanetary magnetic field and the heliosheath can be summarized as (i) strongly nonlinear with a large decrease/increase of the magnetic field in the centre of the structure; (ii) an anti-correlation between the magnetic field and the plasma density/temperature, resulting in an almost pressure -balanced structure; this feature has been observed in planetary magnetic field but yet to be observed in the heliosheath (iii) a width of a few tens of pick up proton (∼5 eV) gyro-radii; (iv) nearly perpendicular propagation to the mean magnetic field; as is evident from large angles between the field vector and the minimum variance direction [*Burlaga et al.*, 2006] (v) occurrence in a high β plasma (β is the ratio of plasma and magnetic pressure); (vi) and the magnetic field changes mostly in magnitude with very little or no change in the direction of the magnetic field (linear holes).

[3] Since the first observation in 1977, there has been considerable progress in understanding the physics of magnetic holes, although still incomplete. Initially, because of the observed temperature anisotropy, these structures were explained as due to the mirror instability [*Winterhalter et al.*, 1994; *Tsurutani et al.*, 1982, 1992]. *Kivelson and Southwood* [1996] and *Pantellini* [1998] developed nonlinear theories that identified holes with the nonlinear saturated states of the mirror instability. Later, it was shown that the threshold for the mirror instability ($T_\perp/T_\parallel > 1$) is not met in most of the cases [*Fränz et al.*, 2000; *Tsurutani et al.*, 2005]. A recent 1D hybrid simulation [*Baumgärtel et al.*, 2003] shows that magnetic holes are not the saturated states of the mirror instability. Other theories for the formation of magnetic holes include a sheet model based on the solutions of the Vlasov-Maxwell equations [*Burlaga and Lemaire*, 1978], a model based on magnetic reconnection [*Zurbuchen and Jokipii*, 2002], a model based on wave – wave interaction [*Vasquez and Hollweg*, 1999], and beam micro-instabilities [*Neugebauer et al.*, 2001]. *Tsurutani et al.* [2005] have emphasized the role of the phase steepened Alfven waves and the concomitant ion heating due to the pondermotive force in the formation of magnetic holes. *Baumgärtel* [1999] has identified magnetic holes in terms of the dark soliton solutions of the derivative nonlinear Schrodinger (DNLS) equation [*Kennel et al.*, 1988; *Buti et al.*, 2001a]. In particular, he has shown that the dark soliton is stable under Hall-MHD dynamics. A dark (bright) soliton is a magnetically rarefactive (compressive), hole (hump) like structure with a magnetic field minima (maxima) in the centre. However, this approach has been criticized on the grounds that the DNLS equation is valid only for parallel or at most quasi-parallel propagation, while magnetic holes have been observed to propagate nearly perpendicular to the mean magnetic field.

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Furthermore, the derivation of the DNLS is based on a perturbative expansion that assumes $\Delta B/B \ll$ and hence is inadequate for holes where $\Delta B/B \leq 1$.

[4] In this paper, we propose a solitary wave model for magnetic holes and humps which is based on the recent work of *McKenzie et al.* [2001, 2004] suitably modified to take into account the effect of interstellar neutrals. This theory is fully nonlinear and utilizes the conservation laws of the underlying MHD physics in order to construct bright as well as dark soliton solutions of arbitrary amplitude, traveling at arbitrary angles to the magnetic field. Our model consequently avoids all the aforementioned controversies regarding the validity of DNLS. We show that using this model, one can construct a rich class of stationary structures e.g. holes, humps, sequences of holes/humps, very similar to those seen recently in the Voyager 1 magnetic field observations.

2. Model

[5] Our model closely follows the model of *McKenzie et al.* [2001, 2004]. However it takes into account the effect of interstellar neutrals. These, through charge exchange, provide extra sources of momentum and energy and modify the ion dynamics of McKenzie et al.

[6] In the heliosheath, the shock compressed, high β solar wind protons interact with an oncoming flow of neutral hydrogen atoms via charge exchange. This interaction leaves the total number of each species unchanged. The charge exchange interaction between low energy interstellar neutral hydrogen atoms and high energy solar wind protons produces a new non-thermal population of energetic neutrals that are distinct from the interstellar neutrals. Following *Pauls et al.* [1995], *Liewer et al.* [1996] and *Khabibrakhmanov et al.* [1996], this component of energetic neutrals is neglected. This is justified because both the density and their interaction with the plasma is lower than those of interstellar neutrals, hence their effects is expected to be weak. The hot heliosheath plasma is taken to be another fluid. We thus consider a two fluid model of plasma and neutrals. In the solar wind as well as in the heliosheath, on account of charge exchange effects, pick up ion physics and relatively high ion beta, the proton dynamics is different from that of electrons. Such systems are adequately described by the Hall-MHD set of equations where Hall inertia effects are retained while the magnetic field is frozen in the electron fluid. In this limit the proton dynamics is governed by the continuity and momentum equations given by

$$\frac{\partial n_p}{\partial t} + \nabla \cdot n_p \vec{u}_p = 0; \tag{1}$$

$$m_p \frac{\partial n_p \vec{u}_p}{\partial t} + m_p \nabla \cdot n_p \vec{u}_p \vec{u}_p + \nabla p_p = q n_p \vec{E} + q n_p \vec{u}_p \times \vec{B} - m_p \sigma U^* N \left(\vec{u}_p - \vec{V}\right) n_p, \tag{2}$$

where n_p, u_p, p_p are the proton number density, fluid velocity and the kinetic pressure respectively while σ, U^*, N, $\vec{V}$ represent the charge exchange cross-section, characteristic interaction speed, neutral number density and the velocity respectively. The variables E and B denote the electric and magnetic fields. The last term on the right hand side of (2) represents the momentum input due to charge exchange. The equation of state for protons, which relates proton pressure to the density, is also modified due to the energy input from charge exchange, and is given by [*Florinski et al.*, 2005]

$$\frac{d}{dt}\left(\frac{p_p}{n_p^\gamma}\right) = \frac{\sigma U^* N n_p}{n_p^\gamma}\left[\frac{(\gamma-1)\left(\vec{u}_p - \vec{V}\right)^2}{2} + \frac{kT_p}{m_p} - \frac{p_p}{2n_p}\right], \tag{3}$$

where T_p is the plasma temperature. In the absence of the charge exchange (σ = 0), it reduces to the usual adiabatic equation of state $p_p \propto n_p^\gamma$. The neutral dynamics is described by following equations,

$$\frac{\partial \vec{N}}{\partial t} + \nabla \cdot N\vec{V} = 0; \tag{4}$$

$$\frac{\partial N\vec{V}}{\partial t} + \nabla \cdot N\vec{V}\vec{V} = \sigma U^* N\left(\vec{u}_p - \vec{V}\right) n_p, \tag{5}$$

where we have neglected the neutral pressure. The motion of the neutrals is assumed to be along the x direction i.e. $\vec{V} = V\hat{x}$. The electrons in the Hall MHD limit are mass less and are governed by

$$(\nabla p_e)/q n_e + \vec{E} + u_e \times \vec{B} = 0, \tag{6}$$

where u_e is the electron velocity and p_e is the electron pressure which satisfies the equation of state $p_e \propto n_e^\gamma$, and n_e is the electron number density. Equations (1) to (6) are supplemented by Maxwell's equations

$$\nabla \times \vec{B} = \mu_0 \vec{J}; \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}; \quad \vec{J} = q\left(n_p \vec{u}_p - n_e \vec{u}_e\right). \tag{7}$$

To construct 1D stationary state structures moving along x, we set $\partial/\partial t = 0$, $\nabla = \partial/\partial x$ in (1) to (6). At $x = -\infty$, protons are assumed to be moving along $\hat{x}$ with a velocity u_0 while the neutrals are assumed to be moving with a velocity V_0 in a direction opposite to that of protons. This velocity, typically is a fraction of u_0. The magnetic field at this location is given by $\vec{B}_0 = B_x\hat{x} + B_{z0}\hat{z}$, where θ is assumed to be the angle between $\hat{x}$ and $\vec{B}_0$. Because $\partial/\partial t = 0$, $\nabla = \partial/\partial x$, B_x = const., we have E_y = const., E_z = const and $J_x = 0$. Using (6), we set $E_y = u_0 B_{z0}$ and $E_z = 0$. Due to quasi-neutrality $n_p \approx n_e$, and $J_x = q(n_p u_{px} - n_e u_{ex}) = 0$ implies $u_{px} \approx u_{ex}$. The equation of continuity for protons and neutrals gives

$$m_p n_p u_{px} = m_p n_{p0} u_0 = M_p, \tag{8}$$

$$m_N N V = m_N N_0 V_0 = M_N. \tag{9}$$

Adding the electron, ion, and neutral equation of motion and integrating from $x = -\infty$ to x yields

$$M_p u_{px} + M_N V + p - p_0 = M_p u_0 + M_N V_0 - \frac{\left(B_y^2 + B_z^2\right)}{2\mu_0} + \frac{B_{z0}^2}{2\mu_0}, \tag{10}$$

where $p = p_e + p_i$, $p_0 = p_{p0} + p_{e0}$ and p_{p0}, p_{e0} are proton and electron pressure at $x = -\infty$. On dividing this equation by $M_p u_0$ and defining, $M_\perp^2 = u_0^2/V_\perp^2$, $M_\parallel^2 = u_0^2/V_\parallel^2$, $c_s^2 = \gamma p_0/m_p n_{p0}$, $M_s^2 = u_0^2/c_s^2$, $u_{px}/u_0 = u$, $\overline{V} = V/u_0$, $b_y = B_y/B_{z0}$, $b_z = B_z/B_{z0}$, ($V_\perp$, ($V_\perp$, $V_\parallel$) = (B_x, B_{zo})/$\sqrt{\mu_0 m_p n_{p0}}$ we derive

$$u - 1 + \frac{M_N}{M_p}\left(\overline{V} - \overline{V}_0\right) = -\frac{1}{\gamma M_s^2}\left(\frac{p}{p_0} - 1\right) - \frac{1}{2M_\perp^2} \cdot \left\{1 - \left(b_y^2 + b_z^2\right)\right\}, \tag{11}$$

where we have used the same adiabatic index for electrons and protons. The other two components of the equation of motions are

$$M_p u_{py} = \frac{B_x B_y}{\mu_0}; \tag{12}$$

$$M_p u_{pz} = \frac{B_x}{\mu_0}\left(B_z - B_{z0}\right). \tag{13}$$

The stationary form of the equation of motion for protons is

$$\left(\overrightarrow{u}_p \cdot \nabla\right)\overrightarrow{u}_p = \frac{q}{m_p}\left(\overrightarrow{E} + \overrightarrow{u}_p \times \overrightarrow{B}\right). \tag{14}$$

Taking the y and z components, using (12) and (13) to eliminate $u_{py.}$, u_{pz} in terms of b_y, b_z, we obtain following coupled differential equations for b_y and b_z

$$u\frac{db_y}{dx} = \frac{1}{L}\left[1 - M_\parallel^{-2} - b_z\left(u - M_\parallel^{-2}\right)\right]; \tag{15}$$

$$u\frac{db_z}{dx} = \frac{b_y}{L}\left(u - M_\parallel^{-2}\right), \tag{16}$$

where $L = M_\parallel(\Omega/V_\perp)$, $\Omega = qB_0/m_p$. Since $M_\parallel \approx 1$ and $V_\perp \approx u_0$, L is approximately equal to the proton gyro radius ρ_i. Equation (11) relates b_y, b_z, u, p with $\overline{V}$. An additional relation between these variables can be obtained from the modified equation of state given in (3). *Khabibrakhmanov et al.* [1996], and *Florinski et al.* [2005] have argued that in the heliosheath, the first two terms on the right hand side of (3) are smaller than the third. It is largest on the solar side as well as interstellar side of the heliopause because usually in these regions, the plasma thermal speed is greater than the thermal speed of neutrals and the relative speed of the fluids. Thus, retaining the third term, using $n_p \propto u_{px}^{-1}$ from (8), and using the normalized variables defined earlier, we obtain

$$u\frac{d}{dx}\left(p_p u^\gamma\right) = \frac{-1}{L^*\overline{V}}\left(p_p u^\gamma\right), \tag{17}$$

where $(L^*)^{-1} = (\sigma U^* N_0 \overline{V}_0)/2u_0$ is the scale length associated with charge exchange. The final equation between u and $\overline{V}$ is given by the equation of motion for neutral hydrogen in (5), given in normalized variables as

$$u\frac{d\overline{V}}{dx} = \frac{2}{L^*}\left(\frac{u}{\overline{V}} - 1\right)\frac{n_{p0}u_0}{N_0 V_0}. \tag{18}$$

The set of equations (11) along with (15)–(18) constitute a set of five equations which can be solved to obtain five unknowns b_y, b_z, u, p and $\overline{V}$ as functions of x. The initial data for these variables at $x = -\infty$ is $b_y = 0$, $b_z = 1$, $u = 1$, $p = 1$ and $\overline{V}_0 = V_0/u_0 = -\alpha$ where α is a fraction less than unity. However, in general these equations do not guarantee the existence of solitary wave solutions. The necessary and sufficient conditions for the existence of these solutions have been discussed by *McKenzie et al.* [2001, 2004]. These conditions are (i) in the neighborhood of the initial data only exponential growing eigenvalues should exist; (ii) solitary wave solutions contain a maxima/ or minima in variables like b or u. The sonic point where the sound speed matches the local flow velocity i.e., $u = (1/M_s^{2/\gamma+1})$ should not be located between the initial point and the maxima/minima (otherwise the flow would be choked). In the next section, we construct some solitary wave solutions appropriate to the conditions of the heliosheath.

3. Solutions

[7] Solitary wave structures may be constructed for given values of $M_\perp$, $M_\parallel$ and M_s (besides the values for L, L^* etc.). The angle of propagation θ is given by $\tan\theta = M_\perp/M_\parallel$. In the shock compressed heliosheath, the plasma β is high. The mean magnetic field is ~ 0.1 nT (nanotesla), while the proton density and temperature are $n_p \approx 10^{-3}$ cm^{-3}, $T_p \approx 10^6$ K. For these values $\beta = 4$, $c_s \approx 100$ km/sec $V_A \approx 70$ km/sec (V_A is the Alfven velocity using the mean magnetic field). Since the heliosheath is subsonic, we choose $M_s = 0.5$, $u_0 \approx 50$ km/sec. The neutral density and the flow velocity are $N_0 \approx 0.2$ cm^{-3}, $V_0 \approx -20$ km/sec, thus $\alpha = -0.4$ The charge exchange cross-section $\sigma \approx 3 \times 10^{-15}$ cm^2 while a typical value of U^* is about $\sim$300 km/sec. For these parameters $L^* \approx 10^{10}$ km while L is approximately equal to proton gyro-radius which is about $\sim$150,000 km in the heliosheath [*Burlaga et al.*, 2006]. For these parameters the right hand side in (17) and (18) is small. In Figure 1 we show a dark solitary wave structure for $M_\parallel = 0.96$, $M_\perp = 0.58$ and $M_s = 0.5$. The mean magnetic field was chosen to be $\sim$0.11 nT and in the solution the minimum magnetic field at the centre is 0.03 nT. The structure is $\sim 8\ \rho_i$ wide and is traveling at an angle of 60° with respect to the mean magnetic field. This is similar to the isolated magnetic hole observed by *Burlaga et al.* [2006] with a mean magnetic field $\sim$0.11 nT, minimum magnetic field at the centre $\sim$0.03 nT, is about 10 proton gyro radii wide and is traveling at angle $\sim$70° with respect to the mean magnetic field. Further, *Burlaga et al.* [2006] have shown that holes and humps are well approximated by Gaussians. As shown in Figure 1, our solution is also well approximated by Gaussians except that it has somewhat longer tail which indicates the presence of higher moments. The magnetic

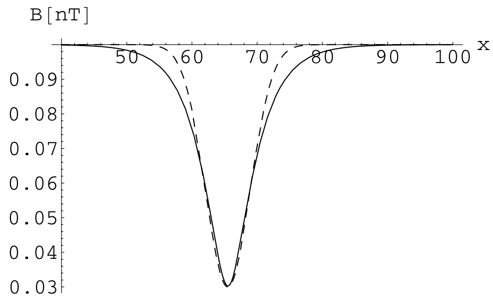

Figure 1. Dark solitary wave structure for $M_{\parallel} = 0.96$, $M_{\perp} = 0.58$ and $M_s = 0.5$. The distance is normalized with proton gyro-radius ρ_i. The mean magnetic field is ~0.11 nT. In the centre of the structure the minimum magnetic field is 0.03 nT. The structure is 8 ρ_i wide and is traveling at an angle of 60° with respect to the mean magnetic field. The dashed line shows the Gaussian fit.

vector does a full rotation around the direction of propagation before recovering its direction across the structure. In this sense, our solution corresponds to a linear hole. In the literature there is some discussion whether magnetic holes are pressure balanced. Our solution here is not pressure balanced in the strictest sense. There is considerable flow; but the thermal pressure almost balances the magnetic pressure. As expected, the magnetic hodograph for this solution is 'cigar' shaped [*Baumgärtel*, 1999]. In Figure 2 we show a solution containing a train of magnetic holes while in Figure 3 we show a train of magnetic humps. Such structures have also been seen recently in Voyager 1 observations (L. F. Burlaga et al., private communication, 2006). These solutions were constructed by choosing an initial condition which was slightly different i.e. the initial value of b_y was not zero but was small and finite. We have verified that the characteristics of our solutions do not depend on this value. Our solutions presented here thus reproduce all the features of the magnetic holes mentioned earlier and are consistent with the recent Voyager 1 observations.

4. Summary and Discussion

[8] To summarize, based on the theory of *McKenzie et al.* [2001, 2004], we propose a solitary wave model for the magnetic structures observed in the planetary magnetosheath and more recently in Voyager 1 heliosheath observations. The solutions are strongly non-linear with a 70 to

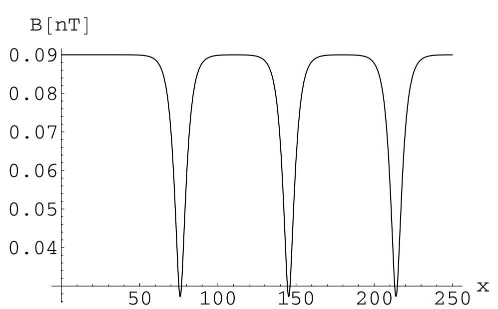

Figure 2. Train of magnetic holes. The solution is constructed by choosing small but finite b_y. The solution however is independent of this choice.

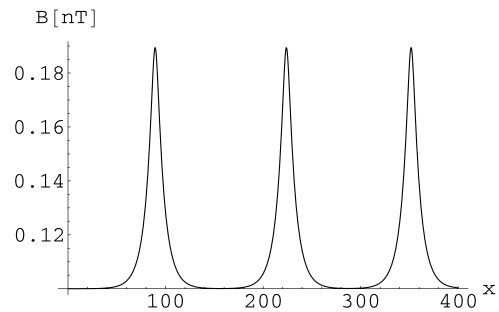

Figure 3. Train of magnetic humps.

80% change in the magnetic field in the centre of the structure and travel nearly perpendicularly to the magnetic field with a velocity that is a fraction of the local Alfven velocity. The magnetic field and density are anti-correlated with no change in the direction of the magnetic vector. Since the McKenzie et al. theory is time independent, it does not address the stability of the solutions. In the context of the DNLS equation, the stability of the soliton solution has been addressed by *Buti et al.* [2001b], *Baumgärtel* [1999] and *Baumgärtel et al.* [2003]. In these investigations the temporal evolution of either a single pulse or the interaction of two solitons was studied numerically via a 1D hybrid code. The results of these investigations are somewhat at variance with each other and inconclusive. *Buti et al.* [2001b] find that dark as well as bright DNLS solitons are unstable. These results are inconsistent with the observations of Voyager 1 which show the presence of long lived, robust magnetic holes as well as humps [*Burlaga et al.*, 2006]. On the other hand, the results of Baumgärtel et al. show that the dark soliton is stable while the bright ones are not. These results are partially consistent with the Voyager 1 observations, which as stated above, show the presence of long lived magnetic holes as well as humps. Thus, the stability of the DNLS solution as well as the fully nonlinear solutions presented here should be examined afresh. In our model, the neutrals and plasma were considered as two fluids. Due to their substantial contribution to the pressure, pick up ions can mediate small scale structures in the solar wind such as shocks and magnetic holes [*Burlaga et al.*, 1994; *Whang and Burlaga*, 1993; *Zank and Pauls*, 1997]. While this is captured in the overall pressure in our 1-fluid model, the pressure is not separated into the pickup ion and solar wind plasma components. Following, for example, *Isenberg* [1986], the pickup ions can be modeled as a hot fluid co-moving with a cold solar wind plasma. We propose to take up this issue as well as that of stability of the solitary wave structures presented here in a future investigation.

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