Mechanism of magnetic hole formation in the magnetosheath

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One-dimensional hybrid simulations are performed to investigate the magnetic hole formation in the shock downstream magnetosheath. In the present model, the interaction between a quasi-perpendicular shock and rotational fluctuations of magnetic field is applied. Simulation results show that intense field-aligned flow generated at the rotational field region makes plasmas isotropic, while the background consists of anisotropic plasmas. At the leading and trailing edges of this flow, strong field gradients are formed which results in the reduction of the magnetic field intensity. The behavior of particles within this field depression is similar to the case of magnetic mirror geometry, where most particles are trapped within the weak field region, leading to a density build-up. Compared with the ordinary mirror instability, the present process forced by external field rotation more efficiently produces such a magnetic field depression.

1. Introduction

Magnetic holes (MHs) are localized structures with depression of the magnetic field intensity found in the solar wind [e.g., Turner et al., 1977; Winterhalter et al., 1994; Fränz et al., 2000]. A simultaneous increase in plasma density and pressure accompanies such a field depression. One remarkable feature of MHs is that the holes are found close to the region with high $\beta$ and temperature anisotropic ($T_{\perp}/T_{\parallel} > 1$) plasma, that is unstable to the mirror mode. Observations by Ulysses spacecraft suggested that MHs dominantly appear in the low latitude interaction regions where large velocity gradients are often formed [Winterhalter et al., 2000]. This may lead to the shock-compressed plasma generation where the conditions for mirror instabilities can efficiently be attained. Therefore, MHs are considered to be remnants of the mirror instability [Winterhalter et al., 1994].

On the other hand, Buti et al. [2001] suggested a model in which large amplitude Alfvén wave packets can lead to MHs formation in the fast solar wind regime. Ulysses observations also indicated the relevance of MHs appearance to such nonlinear Alfvén waves [Tsurutani et al., 2002]. We associate interplanetary MHs with the simultaneous occurrence of anisotropic plasmas and the steepened Alfvén waves. As a suitable generator of such anisotropy, a super-critical quasi-perpendicular shock is taken into account in the present study. We perform one-dimensional hybrid simulations to show how the kinetic process is taking place and how it results in the MHs formation by applying the rotational magnetic field (RF) with Alfvénic fluctuation from upstream onto the shock.

2. Simulation model

A one-dimensional hybrid code is used (the coordinate is taken in a shock-normal direction, $x$-axis). All variables are normalized by the unperturbed upstream parameters: proton number density by $N_p$, magnetic field by $B_0$, velocity by the upstream Alfvén velocity $V_A = |B_0|/\sqrt{\mu_0 m_p N_0}$, time by the inverse proton cyclotron frequency $\Omega_p^{-1} = m_p/eB_0$, spatial scale by the proton inertial length $c/\omega_p$ ($\omega_p$ is the proton plasma frequency), the electric field by $V_A B_0$, and the pressure by $B_0^2/2\mu_0$. The left side is the open boundary $(\partial/\partial x = 0$ at $x = 0$) with continuous injection of particles. The right side boundary ($x = 1000 \ c/\omega_p$) is rigid where particles are reflected as $v_x \rightarrow -v_x$. Shock features are characterized by an upstream Alfvén Mach number $M_A$, a shock normal angle $\theta_n$, and an upstream beta $\beta$; $M_A = 5.13$, $\theta_n = 75^\circ$, and $\beta = 2.0$ in the present study.

The spatial profile of a RF is initially given as follows: the magnetic field $B = (B_0 \cos \theta_n, B_0 \sin \phi(x), B_t \cos \phi(x))$, where $B_t = B_0 \sin \theta_n$ and $\phi(x) = (1 - \tanh((x - x_c)/D))\pi/2$. Here, $x_c$ and $D$ represent the RF initial location and its transition half width ($x_c = 100 \ c/\omega_p$ and $D = 10 \ c/\omega_p$ at present). The RF is carried onto the shock with the background flow. Other parameters are: the spatial grid size $\Delta X = 0.5 \ c/\omega_p$, the time step $\Delta T = 0.01 \Omega_p^{-1}$, and the simulation domain which consists of 2000 cells, each of which contains 500 particles.

![Fig. 1. Time-stacked profiles of (left) the proton density and (right) the magnetic field magnitude.](image-url)
3. Result

Fig. 1 shows the time-stacked profiles of $N_p$ and $|B|$ after the RF hits the shock. We can identify a large structure in the shock downstream spreading spatially with the density enhancement and magnetic field depression around $x \sim 700 \ c/\omega_p$, the development of which starts at $T \sim 180 \ \Omega_p^{-1}$. It is obviously indicated that this MH-associated structure is originated from interplanetary RF.

The snapshots of field and plasma quantities are displayed in the left panels of Fig. 2 at $T = 250 \ \Omega_p^{-1}$. The RF is carried deeply in the downstream, where the magnetic field is depressed with the density increase between $675 < x < 700 \ c/\omega_p$. The proton temperature component parallel to the magnetic field ($T_{p\parallel}$) is largely raised inside this MH structure, which results in the decrease of anisotropy $T_{p\parallel}/T_{p\perp}$ from 10 (in the background) to less than 2.

As can be seen from this profile, the field rotation and the isotropized proton temperature can be considered as the prominent features of MHs. The right panels of Fig. 2 show the detailed proton velocity distributions (A) in the ordinary shock downstream and (B) inside MHs. In the shock downstream, particles gain energy preferentially within the plane perpendicular to $\mathbf{B}$ (here, $x-y$ plane) due to strong gyration, whereas such particle motion firmly tied to the magnetic field is quickly released along the field line when the rotational $B_y$ component is affected.

This release process in particle motion results in the generation of the intense field-aligned flow out of the RF. Alternative view is that the “mirror” force is provided to make this flow: At the leading/trailing edges of this flow, the spatial gradient of magnetic intensity is consequently caused, so that the magnetic depression is formed. Particle accumulation within this depression naturally occurs as an analogy to the kinetic behavior in a normal magnetic mirror. As a result, MHs structure is developed.

Details are more rigorously discussed by Tsubouchi and Matsumoto [2005].

4. Conclusion

The results of the present hybrid simulations are summarized as follows.

The magnetic depression - density pulse structure, magnetic holes (MHs), can be generated in the downstream of a quasi-perpendicular shock where rotational fluctuations in interplanetary magnetic field are imposed. The proton temperature increases to become isotropic inside the MHs, whereas it is strongly anisotropic ($T_{p\perp}/T_{p\parallel} > 1$) in the normal shock downstream. The direct conversion of the kinetic energy $E_{k\perp}$ into $E_{k\parallel}$ due to the enforced change of field direction gives the effective parallel heating which leads to isotropization. As a result, the intense field-aligned flow is triggered, and acts as a mirror force generator leading to formation of the field gradient at its leading/trailing edges. The magnetic depression arises in this way.

Acknowledgments. Computation for this study was performed with the KDK system of the Research Institute for Sustainable Humanoosphere (RISH) at Kyoto University as a collaborative research project.

References


Fig. 2. Left: (from top to bottom) Hybrid simulation results for spatial profiles of the magnetic field intensity, transverse component of the magnetic field ($B_y$ by broken line, $B_z$ by solid line), proton number density, and proton temperature (perpendicular by broken line, parallel by solid line). Every quantity is normalized by the initial upstream parameters, and the spatial unit is the upstream proton inertial length $c/\omega_p$. Right: Proton velocity distributions accumulated in the region of A (600 < $x$ < 620 c/\omega_p) and B (690 < $x$ < 705 c/\omega_p).