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ScienceDirect
Planetary and Space Science 56 (2008) 913–916
Planetary and Space Science
www.elsevier.com/locate/pss

A Hall MHD model to study energetic charged particle events produced during fluctuations in the interplanetary magnetic field intensity

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Received 9 May 2007; received in revised form 28 December 2007; accepted 29 December 2007
Available online 4 January 2008

Abstract

Energetic charged particles, which are often observed in solar active regions, may be also produced in interplanetary space due to the decoupling of ions and electrons in plasma. The Hall term in general Ohm's law is generally thought to be responsible for the decoupling of electrons and ions in plasma during magnetic reconnection. In this paper, a Hall MHD model is developed to study energetic charged particle events produced during fluctuations in the interplanetary magnetic field intensity. Two energetic charged particle events are used to test this model. It is concluded that the Hall effect does not only play the important role in the process of magnetic reconnection, but also in energetic charged particle events produced during fluctuations in the interplanetary magnetic field intensity.

Keywords: Energetic charged particle events; Interplanetary magnetic field; Hall effect; Fluctuations in the magnetic field intensity

1. Introduction

Energetic charged particle events are often observed by spacecraft, usually accompanied by coronal mass ejections (CME), magnetic clouds, interplanetary shocks, etc. (Hu et al., 2003; Lepping et al., 2001; Riley et al., 2004; Wang et al., 2003; Lin, 1998). They are one part of the important events for space science. For example, on 14 July 2000, a full halo-CME was observed by the spacecraft SOHO/LASCO and EIT. At the same time, the energetic charged particle events had been detected by another spacecraft during days 14–16 July 2000. The plasma characteristics of the 'Bastille Day' interplanetary shocks and magnetic clouds which occurred at 1 AU during these days have been previously described and studied (Lepping et al., 2001).

Besides the energetic charged particle events accompanied by interplanetary shocks, they are also often observed by spacecraft during traveling compression regions (Owen and Slavin, 1992; Owen et al., 2005; Kallenrode, 2003). The unidirectional ~1 keV electrons had been observed when spacecraft travel compression regions (Owen et al., 2005), and energetic ion events associated with traveling compression regions can be also observed by spacecraft (Owen and Slavin, 1992). It is very clear that these kinds of energetic charged particles (about several keV) are produced during fluctuations in the interplanetary magnetic field intensity, and different from the solar energetic particles (SEP), which are produced in the solar source. The interplanetary compressed structures had been proved to be important for solar wind storms by the method of statistical analysis (Wang et al., 2003).

In these energetic charged particle events, it can be found that they are often closely related to the fluctuations in the interplanetary magnetic field intensity, whose time scale and space scale can be comparable to the ion inertial scale (about 160 km in the magnetotail). In the present, energetic charged particles accelerated during magnetic reconnection have been observed by spacecraft, and had been detected in laboratory experiments (Lin, 1998). The Hall effect is suggested to be responsible for the decoupling of electrons and ions in plasma during magnetic reconnection, and it plays the key role in the fast magnetic reconnection process

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doi:10.1016/j.pss.2007.12.015

(Ma and Bhattacharjee, 2001; Huang et al., 2007). The Hall current had been observed by spacecraft during magnetic reconnection (Ma and Bhattacharjee, 2001; Nagai et al., 2003). However, the role of the Hall effect in energetic charged particle events has been paid little attention, due to the complexity of Hall dynamics in this region. The observation data for the Hall effect in energetic charged particle events have not be obtained in the corona or interplanetary space far from the Earth's magnetosphere, due to the limit of technique. A question arises: Does the Hall effect act in energetic charged particle events? In this paper, a model is developed to study the Hall effect in energetic charged particle events produced during fluctuations in the interplanetary magnetic field intensity.

2. Hall MHD model

General Ohm's law, which includes the Hall term, can be written as

$$\mathbf{E} = \eta\mathbf{J} - \mathbf{u}\times\mathbf{B} + \mathbf{J}\times\mathbf{B}/(ne), \tag{1}$$

where n is the density of electrons, and e is the unit charge of an electron. The third term on the right-hand side of Eq. (1) is called the Hall term, which leads to the decoupling of ions and electrons in plasma during magnetic reconnection. By analyzing the structure characteristic of the Hall electric field $\mathbf{J}\times\mathbf{B}/(ne)$, we can obtain the approximate distribution of energetic charged particles brought about by the Hall effect in plasma during magnetic reconnection (Huang et al., 2006).

In the coordinate system fixed on the magnetic line, let $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$ denote the unit vectors in the tangential direction, the principal normal direction, and the binormal direction of the magnetic line, respectively, where $\mathbf{e}_3 = \mathbf{e}_1\times\mathbf{e}_2$. The corresponding coordinate variables are x_1, x_2, and x_3, respectively. According to Maxwell's equation $\mathbf{J} = \frac{1}{\mu_0}\nabla\times\mathbf{B}$, the third term on the right-hand side of Eq. (1) can be expressed as (Huang et al., 2006):

$$\mathbf{J}\times\mathbf{B}/(ne) = -\frac{1}{ne}\left(\mathbf{e}_2\frac{\partial}{\partial x_2} + \mathbf{e}_3\frac{\partial}{\partial x_3}\right)\frac{B^2}{2\mu_0} + \mathbf{e}_2\frac{B^2}{ne\mu_0 r}, \tag{2}$$

where r is the curvature radius of the magnetic line at the given point, and μ_0 is the vacuum permeability.

On the right-hand side of Eq. (2), the first term is closely related to the magnetic gradient. When it plays the important role in solar wind, Eq. (2) can be simplified into

$$\mathbf{J}\times\mathbf{B}/(ne) = -\frac{1}{ne}\left(\mathbf{e}_2\frac{\partial}{\partial x_2} + \mathbf{e}_3\frac{\partial}{\partial x_3}\right)\frac{B^2}{2\mu_0}. \tag{3}$$

Based on Eq. (3), it can be concluded that the vector of the Hall electric field is perpendicular to the magnetic field line, and points to the site where the magnetic field is weaker from the site where the magnetic field is stronger. It should be noted that this conclusion is obtained in the case of great fluctuation of the magnetic field strength, no taking the flexure of magnetic field lines into consideration.

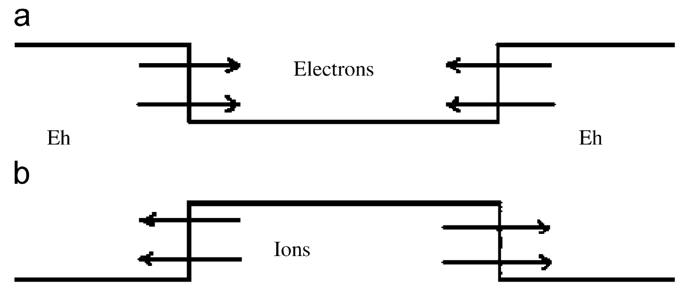

Fig. 1. The sketch for the model to study the Hall effect in energetic charged particle events during the fluctuations of magnetic field intensity. In this sketch, the symbol E_h means the Hall electric field, namely the Hall term $\mathbf{J}\times\mathbf{B}/(ne)$ in general Ohm's law.

In this condition, the first term is more important than the second term on the right-hand side of Eq. (2).

Ions decouple with electrons in plasma due to the Hall effect during fluctuations in the interplanetary magnetic field intensity, and energetic charged particles can be redistributed after the decoupling of ions and electrons in plasma. Two conditions of fluctuations of the interplanetary magnetic field have been sketched in Fig. 1. One is the case that the interplanetary magnetic field strength decreases (see Fig. 1(a)) and the other is the case that the interplanetary magnetic field strength increases (see Fig. 1(b)). Using Gauss's law, it can be inferred that energetic charged particles can be brought about in the regions where the interplanetary magnetic field fluctuates. In the region where the interplanetary magnetic field strength decreases, electrons can be piled up (see Fig. 1(a)). In the region where the interplanetary magnetic field strength increases, ions can be piled up (see Fig. 1(b)).

At the inertial scale of ion (c/ω_i, c is the light speed, and ω_i is the ion frequency), namely about several thousand km, the Hall term in general Ohm's law will play the important role. This conclusion has been confirmed in the spacecraft observation results of the Hall current system, which occurs during magnetic reconnection. This model can be used to study the Hall effect in energetic charged particle events during fluctuations in the interplanetary magnetic field intensity.

3. Event study

3.1. Evidence one

The great 'Bastille Day' shocks which happened during days 14–16 July 2000 provides us a good opportunity to study the Hall effect in energetic charged particle events produced during fluctuations in the interplanetary magnetic field intensity. On 11 July 2000, a halo-CME was observed at 13:27 UT by the LASCO spacecraft. And then the interplanetary shock (called S1) associated with this CME was observed at 15:29 UT on 14 July. The strong shock (called S2) was also observed by WIND at 14:35 UT, on 15 July 2000. The multiple magnetic cloud structures can be also found in the spacecraft observation results. At