Geomagnetic storms driven by Alfvén interior crisis

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Abstract

A numerical study of an interior crisis of a large-amplitude Alfvén wave described by the driven-dissipative derivative nonlinear Schroedinger equation, in the low-dimensional limit, is reported. An example of Alfvén interior crisis is characterized using the unstable periodic orbits and their associated invariant stable and unstable manifolds in the Poincaré plane. We suggest that this type of chaotic transition can be observed in space and laboratory plasmas. In particular, Alfvén intermittency driven by an interior crisis in the solar wind can provide a physical mechanism for exciting geomagnetic storms.

Introduction

Large-amplitude interplanetary Alfvén waves are known to be responsible for the occurrence of geomagnetic storms. In this paper we study the origin of one type of nonlinear manifestation of Alfvén waves known as interior crisis.

Crisis is a global bifurcation caused by the collision of a chaotic attractor with an unstable periodic orbit (UPO) or its associated stable manifold. There are two types of crisis: boundary crisis and interior crisis. A boundary crisis is characterized by the sudden birth/death of a chaotic attractor, whereas an interior crisis is characterized by the sudden expansion/contraction of the size of a chaotic attractor.

The phenomenon of crisis in plasmas is of current interest to improve our understanding of chaotic transitions in space, astrophysical and laboratory plasmas. Chian et al. (1998) developed a model of Alfvén intermittency observed in the solar wind based on crisis-induced intermittency. It was shown that crisis-induced intermittency can appear in a three-wave model of magnetospheric radio emissions (Chian et al., 2002a). High-dimensional interior crisis was found in an extended spatiotemporal plasma system described by the Kuramoto-Sivashinsky equation (Chian et al., 2002b).

In a recent paper, a new chaotic transition mechanism to Alfvén chaos via boundary crisis was reported (Chian et al., 2002c). A double boundary crises generated by the same unstable periodic orbit was identified in a complex plasma region in the presence of a large number of coexisting attractors. The aim of this paper is to characterize an Alfvén interior crisis using the tools of unstable periodic orbits and their corresponding stable and unstable manifolds.

Method

The nonlinear evolution of a large-amplitude Alfvén wave propagating along an ambient magnetic field is described by the driven-dissipative derivative nonlinear Schroedinger equation (DNLS) (Chian et al., 1998). This equation can be used to model Alfvén waves and Alfvén turbulence observed in space plasmas such as planetary magnetospheres and solar wind, astrophysical plasmas such as interstellar and intergalactic media, and in laboratory plasma experiments such as radio wave heating of tokamaks.

We adopt the stationary wave solutions of the driven-dissipative DNLS to analyze the low-dimensional dynamics of an Alfvén system. A bifurcation diagram is constructed by varying the dissipation control parameter while keeping other control parameters fixed. We analyze the dynamics within a periodic window of the bifurcation diagram, and calculate the behavior of the maximum Lyapunov exponent, calculated by the Wolf algorithm.

The interior crisis is characterized by a sudden jump in the value of the maximum Lyapunov exponent. The characterization of Alfvén interior crisis can be carried out using the Poincaré method. Unstable periodic orbit is the key for characterizing the chaotic transitions of a dynamical system such as the interior crisis. On the Poincaré plane, an UPO transforms into a saddle fixed point. We determine the saddle and its associated invariant stable and unstable manifolds from the numerical solutions and demonstrate the homoclinic tangency between the stable and unstable manifolds of the saddle responsible for the onset of Alfvén interior crisis.

Our analysis shows that Alfvén interior crisis is a fundamental feature of the stationary Alfvén waves of the DNLS. This result can be extended to search for high-dimensional Alfvén interior crisis. In fact, Chian et al. (2002b) applied the same nonlinear dynamics techniques adopted in the present paper to characterize high-dimensional interior crisis in the Kuramoto-Sivashinsky equation. Based on these results, it is expected that Alfvén interior crisis should play an important role in the spatiotemporal chaotic transitions in plasmas.

Conclusions

In conclusion, we have extended the dynamical systems techniques developed by Chian et al. (2002c) to characterize an Alfvén interior crisis. Our analysis based on the low-dimensional solutions of the driven-dissipative derivative nonlinear Schroedinger equation demonstrates that chaotic transitions involving either boundary and interior crises are readily encountered in plasmas. We suggest that Alfvén boundary crisis and Alfvén interior crisis play a fundamental role in the dynamics of Alfvén turbulence in space, astrophysical and laboratory plasmas. In particular, Alfvén interior crisis can induce Alfvén intermittency in the temporal fluctuations of the interplanetary magnetic field, which can lead to the onset of geomagnetic storms.

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