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Trapped fast MHD waves in dayside magnetosphere

A. Voshchepynets[*], *O. Agapitov*

Taras Shevchenko National University of Kyiv, Glushkova ave., 4, 03127, Kyiv, Ukraine

We studied the dynamics of the magnetosphere response to the solar wind parameters changes using the Alfvén velocity distribution in the Earth's magnetosphere obtained from the IGRF and T89 Earth's magnetic field models and plasma density diffusive equilibrium model. We used the solution of the eigenvalue problem for trapped waves in the dayside magnetosphere cavity as the initial condition for simulation. Numerical simulation of the fast MHD wave packet propagation in 3D magnetosphere cavity shows the occurrence of two global quasi-periodic modes of the dayside magnetosphere: cavity modes at the sub-solar region and waveguide modes at the magnetosphere flanks. The periods obtained in the numerical simulation are consistent with the theoretical predictions and the THEMIS measurements.

Key words: magnetospheric configuration and dynamics, MHD waves and instabilities, Solar wind – magnetosphere interactions

INTRODUCTION

Periodic disturbances of the geomagnetic field were observed since 1886. Dungey [5] first suggested that observed geomagnetic pulsations were standing Alfvén waves on dipolar magnetic field lines (toroidal modes). He also identified poloidal compressional waves, which should propagate across the background magnetic field, and subsequently completed the first decoupled studies of their modes. Southwood [12] and Chen & Hasegava [4] presented the theoretical model of the coupled pulsation problems. They proposed that the solar wind, falling upon the magnetospheric cavity and driving the magnetosheath flow, could excite a travelling Kelvin-Helmholtz surface wave upon the magnetopause (MP). Having an evanescent structure within the magnetosphere, this wave mode could tunnel to excite resonant field line oscillations deep within the magnetosphere. These models however, often require excessive magnetosheath velocity to explain the observed pulsation [6].

Later treatments suggest that global fast modes could be exited inside the entire magnetospheric cavity in response to sudden impulse in the solar wind [8, 9]. In this model, standing waves would be set up between the large Alfvén velocity gradient at outer boundary (often assumed to be the magnetopause) and turning point within the magnetosphere. Frequencies of the cavity mode harmonics were estimated numerically and theoretically [3, 7, 10, 11, 17].

In the recent papers Wright [16], Rickard and Wright [13] have considered the propagation of compressional modes in the magnetosphere waveguide. The waveguide models an open magnetospheric cavity where energy can propagate tailward. Authors concluded that compressional waves with a low azimuthal wavenumber k_y, will propagate slowly tailward, while high k_y modes propagate quickly tailward. These low k_y modes will thus be able to act as long-lived and coherent drivers for Alfvén resonance, and hence cavity models, using a small k_y prescription may still provide a good approximation for modelling of coupled pulsation phenomena even when the cavity is open. After all, a waveguide solution may be synthesized from a sum over cavity solutions with suitable k_y values. Further studies considered that the Kelvin-Helmholtz and the cavity/waveguide mechanisms may be responsible for transformation of the solar wind energy into ULF pulsation, the dominant one at any time probably depending upon the solar wind and magnetosheath conditions.

OBSERVATIONS

The analysis of the THEMIS data captured during multiply crossing of the MP in 2007 makes it possible to conclude that observed quasi-periodic displacement of the MP surface are the manifestation of the same event in different regions of the magnetosphere [1]. The displacement of MP surface is associated with natural oscillations of the day-side magnetosphere - cavity modes and waveguide modes. Period of the oscillations of the cavity modes are esti-

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[*] woschep@gmail.com

mated to be in a range of 6 minutes, which is close to the periods of the observed MP displacement. Cavity modes and waveguide modes lead to the appearance of two different types of the equatorial magnetopause surface displacement: the one-dimensional motion (flapping) and the movement of the running surface perturbation on the magnetosphere flanks (waving), respectively. Data from THEMIS spacecraft allows the observation of these two types of MP's motion (Fig. 1).

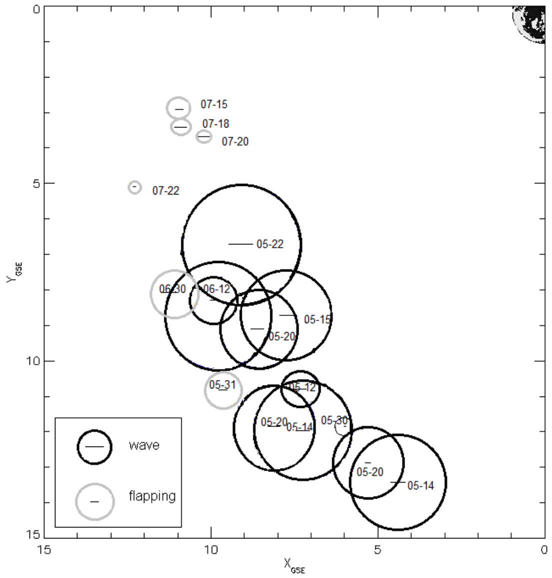

Fig. 1: The results of the MP motion analysis [2]. Fixed MP are multi crossings shown with circles. The circles show the character of motion: black for the MP waving and grey for the MP flapping. The size of circles indicates maximum velocity fixed during the event. The circles size on the legend corresponds to 50 km/s. The amplitudes of the MP displacement in R_E (Earth's radius) are shown with black horizontal lines inside the circles.

NUMERICAL SIMULATION

For the numerical simulation we assume a global perturbation of the magnetosphere magnetic field by a set of wave packets. Theory suggests that these waves are fast MHD waves, which are responsible for energy transport from the solar wind to the ionosphere. We use ray-tracing technique to calculate propagation of the fast MHD waves [15]. It allows us to obtain the system of the first order differential equations from the dispersion equation. Dispersion equation of the fast MHD wave has been taken as a source equation. We used 4th order Runge-Kutta method for numerical solution of differential equation.

Local Alfvén velocity value is the parameter of the medium which is included to the system of equations. It is necessary to have knowledge about the value of magnetic field and plasma density over the magnetosphere to obtain the spatial profile of the velocity distribution. We obtained the magnetosphere magnetic field from the IGRF (International Geomagnetic Reference Field) model and T89 [14] model. We used the diffusive equilibrium model to calculate the plasma density. One of the disadvantages of this model is that it cannot describe changes of density at the magnetopause. For this reason the reflection of the waves from MP should be done artificially. Wave vector changes its direction to opposite and the wave amplitude changes its sign. The resulting spatial distribution of the Alfvén velocity value is shown in Fig. 2.

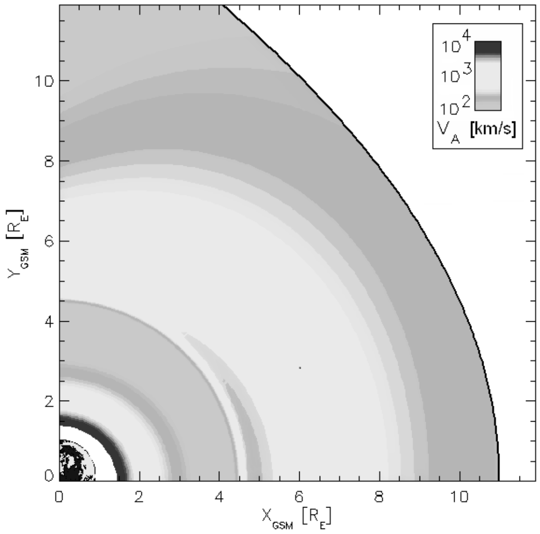

Fig. 2: Spatial distribution of the Alfvén velocity in the XY plane of the GSM coordinate system.

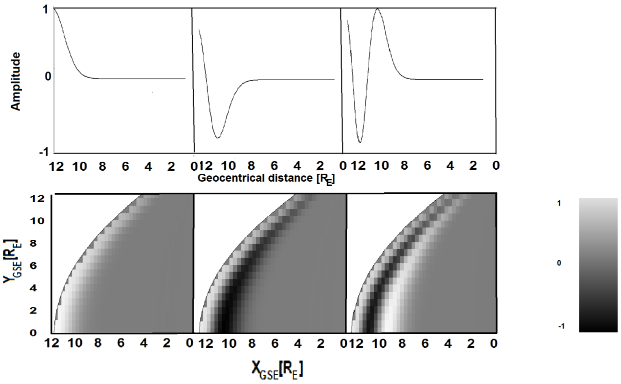

Fig. 3: The initial perturbations of the magnetosphere magnetic field. Top panel shows dependence of the global disturbance on the geocentric distance (cut along the X axis of the GSM coordinate system). Displayed in arbitrary units. Bottom panel represents appropriate disturbance from the top panel in 2D case. The distribution of global disturbances is presented in the equatorial plane of the GSM coordinate system. Colour indicates the amplitude of the wave in relative terms: white colour correspond to 1, black – to -1.

We solved numerically the eigenvalue problem for 1D wave equation for magnetic field with non-uniform spatial distribution of the wave velocity. One boundary was free (corresponding to magnetopause) and other one was locked (corresponding to plasmapause). Spatial distribution of the velocity was similar to the distribution represented in Fig. 2. First three eigenmodes are presented in Fig. 3. We provide amplitude of the waves in arbitrary units. Amplitude of the disturbance of the magnetic field observed by satellites can be up to 10 nT. Result of modulation does not depend on the wave amplitude.

RESULTS

Dynamics of magnetosphere magnetic field disturbances for the several initial conditions, has been curried out. For the first harmonic (see Fig. 3 left), we obtained the oscillation of the magnetic field in the dayside magnetosphere. Obtained oscillations are damped cavity modes with period of 300 seconds. Amplitudes of periodic displacement of the MP position (flapping) coursed by presence of the magnetic field disturbance reached up to 1–2 R_E. The result is qualitatively different in the case of simulation with the initial disturbance with higher harmonic (see Fig. 3, right panel). Results of modelling of the third harmonic are presented in Fig. 4. Fig. 4 shows sequential conditions of the magnetic field in the Earth's magnetosphere with time interval of 10 s. Fig. 4(a) shows conditions which occurs after 170 seconds from the appearance of disturbances. We calculated 10^5 ray trajectories of fast MHD waves evenly distributed in the magnetosphere. Amplitude and wave vector of the waves depend on the initial position (see Fig. 3, the right panel, bottom). We divided the magnetosphere into the cells with the size 0.3×0.3 R_E to obtain the global disturbance by averaging over the amplitudes of the waves in it.

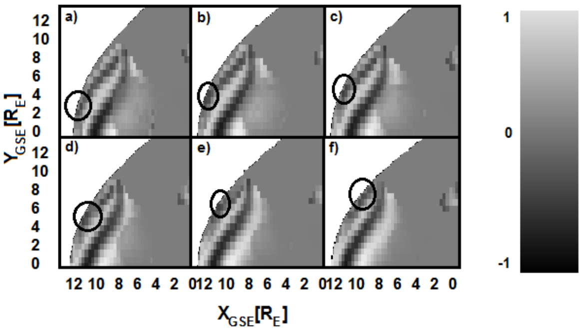

Fig. 4: Temporal changes of the global perturbation of the magnetic field in the magnetosphere in the plane of the geomagnetic equator. Colour indicates amplitude (in arbitrary units) The time delay between images -10 s.

One can see in Fig. 4 on the flanks of the magnetosphere a group of the waves that propagates to the tail region. Perturbation of the magnetic field in magnetosphere changes balance of pressure on the MP. It leads to the changes of magnetopause's configuration. Wavelike structures appear on the surface of MP (waving). The amplitude of the displacement varies with time and reaches the maximum value of 1 R_E. This type of MP motion is associated with waveguide modes in the magnetosphere. Our numerical model does not takes into account the displacement of MP caused by perturbation of the magnetic field in the magnetosphere. Presence of wavelike structures on the MP surface will lead to additional scattering of the wave packets during reflection on MP.

CONCLUSIONS

Numerical simulation of the fast MHD wave propagation processes in the dayside magnetosphere represents two characteristic types of the magnetospheric eigenmodes – the cavity modes in the subsolar region and the waveguide modes on the flanks of magnetosphere. The cavity modes manifest themselves as quasi-periodic oscillations of magnetic field that are often observed in the dayside magnetosphere. The openness of the magnetospheric cavity leads to decreasing of intensity of the oscillations. The obtained periods for the cavity modes are consistent with the results of the spacecraft observation and the theoretical prediction. Arbitrary configuration of the surfaces in the system magnetopause-plasmapause defines region where cavity modes can be trapped. Realistic configuration of the magnetopause should be used for better modelling of these phenomena. The generation of the wavelike structures on the magnetosphere flanks is possible only in a case of generation of the higher harmonic of global disturbance. Modulation shows that the existence of such processes on the flanks of magnetosphere can lead to formation of the wavelike structures on the magnetopause.

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