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Energy transfer in the solar wind–magnetosphere: Long-term fluctuations and intermittency

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Abstract

In this paper, we investigate the transfer of energy from the solar wind to the terrestrial magnetosphere. We make a selected brief review of the links between long-term fluctuations of the solar wind variables (velocity, magnetic field) and several multiscale magnetospheric processes. We emphasize those aspects that describe the non-linear magnetospheric response to solar wind changes. The variations of the flux of relativistic electrons with solar wind velocity over a solar cycle are discussed. Experimental evaluation of the substorm energy budget at solar maximum and minimum is also reviewed. The paper provides also a brief review on the intermittent fluctuations observed in the solar wind and the magnetosphere. The solar wind intermittency may be viewed as the hallmark of a turbulent process that sometimes departs from the traditional fluid or MHD turbulence. Recent analysis of geomagnetic indices and their correlation with the solar wind show that large amplitude, intermittent fluctuations have probabilities larger than for a Gaussian distribution, at smaller temporal scales. In the magnetosphere, particularly in the plasma sheet and the cusp the magnetic field fluctuations also show signs of intermittency that could be associated to a multifractal structure of the energy transfer. The dynamical aspects reviewed in this paper contribute to a picture of the magnetosphere as a non-linear system, driven out of equilibrium and responding to solar forcing on a broad range of spatio-temporal scales.

Keywords: Long term variations in the magnetosphere; Non-linear processes in the magnetosphere; Solar cycle; Turbulence; Intermittency; Solar wind; Radiation belts; Substorms; Plasma sheet; Cusp

1. Introduction

The solar wind continuously conveys solar plasma and energy at the interface with the terrestrial plasma and electromagnetic field. At 1 AU the energy deposited by the solar wind is orders of magnitude smaller than the solar electromagnetic radiation. However, the solar wind is the most important factor in shaping the large scale plasma environment of the Earth. One legitimate question is how the energy transfer takes place? How can one describe the energy cascade from large/driving scales to small/dissipation scales?

In this paper, we briefly review our understanding of the multiscale transfer of energy in the magnetosphere. The interaction between the solar wind and the Earth's magnetosphere has been investigated theoretically and experimentally at a wide range of spatial and temporal scales. In situ measurements demonstrate the high variability in space and time of the magnetosphere and solar wind. The variation of the Sun's activity over the solar cycle drives large scale and long-term magnetospheric variations. Localized, intermittent fluctuations also play an important role for the processes that govern the transfer of energy from the solar wind driver to the magnetosphere and upper ionized atmosphere.

On the one hand, the effects of long-term variations in the Sun on the magnetospheric and atmospheric state are receiving increased attention, particularly due to their possible link with the terrestrial climate. On the other

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hand, the analysis of the energy transfer at medium and microscales are providing information regarding the physics of the fundamental processes that govern the transfer of energy, thus contributing to a better understanding of the system as a whole. In order to describe the global properties of the solar wind–magnetosphere interaction we have selected several examples of magnetospheric processes, well documented in the literature, for which the transfer of energy from the solar wind to the magnetosphere takes place over a broad range of time scales, from the solar cycle to much smaller time intervals, on the order of seconds.

Intermittency is related to the sudden occurrence, in space or time, of ''extreme events'' or large amplitude variations of plasma variables like, for instance, the bulk velocity or magnetic field intensity. Intermittency is investigated with statistical methods of analysis. It has been evidenced in the solar wind as well as in various magnetospheric regions. The emerging picture is that of a turbulent interaction with localized (in space and in time) spikes of energy transfer and dissipation.

In the next section, we will review the main characteristics of some selected magnetospheric processes and will emphasize the effects of the long-term fluctuations. In the third section, we discuss the statistical properties of fluctuations in the solar wind and the magnetosphere and illustrate the presence of intermittency. The paper concludes with a discussion on the contemporary models of the non-linear dynamics of the magnetosphere supported by experimental data of the type discussed in this work.

2. Magnetospheric processes: examples of long-term variations

The energy input and the characteristics of the solar wind at 1 AU vary significantly during the solar cycle. At solar maximum the important solar wind perturbations are produced by coronal mass ejections that carry a high density plasma with moderate velocity in the proximity of the Earth's magnetosphere. At solar minimum the observations show frequent high speed streams and/or corotating interaction regions with a relatively lower density but enhanced velocity or magnetic field. Depending on the geoefficiency of the solar wind parameters (Crooker, 2000), long-term fluctuations are observed in the magnetosphere. The importance of the solar wind forcing versus magnetospheric internal mechanisms is still an open question. In the following we emphasize the effects of the Sun's activity during the solar cycle on some selected magnetospheric processes.

2.1. Electron Van Allen belts

The radiation belts are extremely dynamic regions, where particle acceleration and transport take place. The global response of the electron belts to solar wind variations is complex and not yet fully understood. Enhanced electron fluxes over a broad range of L-shells are linked to the increase of the solar wind speed, notably during the passage of high speed streams (Paulikas and Blake, 1979; Baker et al., 1990a). The correlation of relativistic electron flux (of the order of several MeV) with the solar wind velocity is higher than with the IMF B_z (and any other solar wind parameter), suggesting the existence of energy transfer processes that are not directly linked to reconnection (Vassiliadis et al., 2002). One possible candidate is the ULF waves excited by the Kelvin–Helmholtz instability at the magnetopause (Rostoker et al., 1998).

In situ data analyzed by Vassiliadis et al. (2002, 2003, 2005) over one solar cycle, revealed the spatio-temporal structure of the electron belt responding to changes in the solar wind velocity. Closer to the Earth, the inner belt regions ($L < 4$) show a rather rapid ''hydrodynamic-like'' coupling with the variations of the solar wind ram pressure, of the order or less than one day. The enhancement of relativistic electrons at $L < 4$ is most likely associated to storm-time injections following the impact of solar wind magnetic clouds (Baker et al., 1998). Over a solar cycle this region maintains its radial extent and has the tendency to be localized at slightly larger L during solar minimum (Vassiliadis et al., 2003).

The region where the flux of relativistic electrons is the most intense is localized between $L = 4.1$ and 7.5. Its response to solar wind input has a delay of approximately 2 days and is the most effective for solar wind structures like high speed streams and shocks. The radial extent of this region decreases during the ascending part of the solar cycle (Vassiliadis et al., 2003) when the solar wind forcing compresses more and more the magnetosphere, thus modifying the spatial structure of the electron belts. The physical mechanism responsible for the enhancement of relativistic electron fluxes is probably linked to ULF waves activation and resonant absorption by low-energy electrons (Elkington et al., 2003). Johnson and Wing (2005) have found a two day timescale for the non-linear magnetospheric response in the K_p index, that has also been associated to high speed streams and energization of electrons in the outer radiation belt.

A lower flux of relativistic electrons is measured at larger radial distances ($L > 7.5$). A significant reduction of its radial extent is observed during the ascending part of the solar cycle. An analysis of the precursors of enhanced relativistic fluxes at higher L-shells shows that the outer belt region responds differently than the lower L-shells; the solar wind parameters associated to increase of the outer relativistic electron fluxes are an increased solar wind density and low speed as well as a positive IMF B_z (Vassiliadis et al., 2003, 2005).

The dynamics of the electron radiation belts over the solar cycle illustrates that the magnetosphere is a nonlinear system responding at various spatio-temporal scales to spatio-temporal variations of the solar wind forcing.