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Recurrent Modulation of Jovian Electron intensities: Ulysses KET measurements

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Abstract: Corotating Interaction Regions (CIRs) are regions in the heliosphere that are formed at the leading edges of high-speed solar wind streams originating in coronal holes. Here we concentrate on the modulation of Jovian electrons by CIRs observed with the Kiel Electron Telescope onboard Ulysses. After its launch on Oct. 6, 1990 Ulysses followed an in-ecliptic path towards Jupiter (green curve). The closest approach occurred on Feb. 8, 1992, when Ulysses began its out-of-ecliptic dive. During that period the flux of 2-10 MeV electrons, originating from Jupiter, were modulated by Corotating Interaction Regions until the spacecraft (s/c) reached a latitude of $\sim 30^\circ$. Due to the orbital periods of Jupiter and Ulysses, the s/c came again close to the planet in 2004. As in 1992 and 1993 the MeV electron fluxes were modulated by CIRs in 2005. In 2006 this modulation stopped again, when the s/c was above 30 degree latitude. In order to understand this decay we present a detailed analysis of a series of recurrent Jovian electron decreases and its relation to the solar wind plasma parameters.

Introduction

Intensities of 3-20 MeV electrons have been measured in the inner heliosphere from 1990 to 2007 by the Kiel Electron Telescope (KET) on board Ulysses. Beside solar and galactic cosmic ray electrons, observations by Pioneer 10 showed that Jupiter is a source of MeV electrons in the solar system [1, 2]. Teegarden *et al.* [1] further identified Jupiter as the source of "quiet time" electron increases previously observed at 1 AU [3, 4]. It was successfully proposed that electrons are continuously released from the Jovian magnetosphere and that their variability is mainly caused by varying heliospheric conditions [5].

Ulysses Trajectory and Instrumentation

After its launch on Oct. 6, 1990 Ulysses followed an in-ecliptic path towards Jupiter. The closest approach to the giant planet occurred on Feb. 8, 1992, when Ulysses began its out-of-ecliptic dive. Fig. 1 left displays the Ulysses trajectory from launch in 1990 to 1994 (blue curve) and from 2003 to 2005 (red curve) in a reference frame where the Sun and Jupiter are fixed, and a standard Parker magnetic field line for a solar wind speed of 400 km/s "passing through" Jupiter. This allows a direct eyeball estimate of the magnetic connection between Ulysses and Jupiter for a typical solar wind speed. Because the s/c's orbital period is 6.2 years, compared to 11.9 years for Jupiter, Ulysses was again close to Jupiter in February 2004. Furthermore, Jupiter's orbital period of 11.9 years is comparable with the solar cycle length, so that heliospheric conditions are similar to the 1992 - 1993 time period. In this study we used the solar wind speed and composition, the magnetic field strength, the count rates of $\sim$1 MeV protons and $\sim$7 MeV electrons as measured by the Solar Wind Observations Over the Poles of the Sun (SWOOPS) [6], the Solar Wind Ion Composition Experiment (SWICS) [7], the magnetic field investigation (VHM/FGM) [8], the Low Energy Telescope (LET) and the Kiel Electron Telescope (KET) on the Ulysses Cosmic Ray and Solar Particle Investigation (COSPIN) onboard Ulysses [9] in order to investigate the influence of Corotating Interaction Regions on the 2.5-7 MeV electron flux.

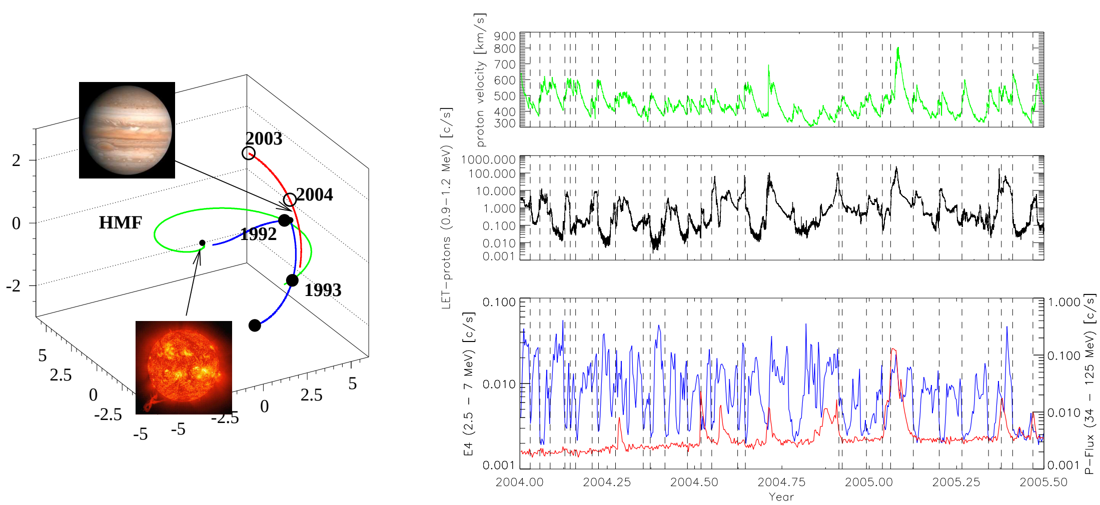

Figure 1: Left: Sections of the Ulysses trajectory from launch to 1994 (blue curve) and from 2003 to 2005 (red curve) in a coordinate system where the positions of Jupiter and Sun are fixed. A Parker magnetic field line in Jupiter's orbital plane is shown for a solar wind speed of 400 km/s. Circles are plotted at the beginning of each year. The right panel displays from top to bottom: hourly averaged solar wind speed, daily averaged count rate of 0.8-1.2 MeV proton, 2.5-7 MeV electrons (blue), and 38-125 MeV protons (red). The dashed lines give the times where the SIs/discontinuities of the CIRs were observed.

Observations

Fig. 1 right displays from top to bottom the hourly averaged solar wind speed, the count rate of 0.9-1.2 MeV and 38-125 MeV protons and 2.5-7 MeV electrons. While increases in the 38-125 MeV protons indicate time periods of solar energetic particle events, recurrent variation of the 0.9-1.2 MeV and daily averaged 2.5-7 MeV electrons as well as in the solar wind speed and magnetic field are obvious. In 2004 and 2005 Ulysses was "upstream" from the planet and successive Corotating Interaction Regions (CIRs) have been observed [10]. CIRs are long-lasting large-scale plasma structures, generated in low and middle latitude regions of the heliosphere by the interaction of a stable fast solar wind stream from a coronal hole with the surrounding slow solar wind. At a distance typically beyond one AU a Forward Shock (FS), which is moving into the slow wind ahead is formed. Typical signatures are a step like increase of the solar wind speed, density, magnetic field strength. The FS is followed by one or more Stream Interfaces (SIs) or discontinuities. A SI is a surface that separates the slow and the fast stream. Typical signatures for SIs are a decrease in density and an increase in kinetic temperature by a factor of 2 and a small speed increase [11]. If those signatures are unclear, we speak of discontinuities. The Reverse Shock (RS) is moving backward into the fast stream. Typical signature are step like increase of the solar wind velocity and decrease of magnetic field strength. In 2004 and 2005, when the solar wind experiments and the magnetometer observed typical recurrent structures, Ulysses was located in such a way that a CIR swept past Ulysses before it reached the Jovian magnetosphere. For the time period from 2004 to 2005, several CIRs have been identified by applying the analysis described in Wimmer-Schweingruber *et al.* [11]. Interestingly, most CIRs do not exhibit clear SI as defined by both kinetic and compositional signatures, i.e., SIs are very hard to identify. SOHO images show not yet fully developed polar coronal holes, but small equatorial coronal holes which differ from the slow wind less compositionwise than the large polar coronal holes. However, apparent forward and reverse shocks or pressure/compression waves were identified for all CIRs studied in this paper. In what follows we investigate the influence of these CIRs on the propagation of 2.5-7 MeV electrons coming from Jupiter.

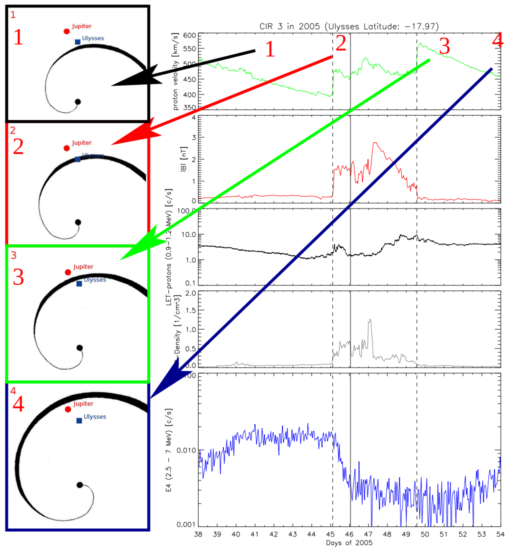

Figure 2: (1) to (4) sketch of different position of a corotating interaction regions (CIRs) with respect to the position of Jupiter and Ulysses; adapted from Conlon and Simpson [12]. On the right side hourly averaged solar wind speed, magnetic field strength, 0.9-1.2 MeV protons, solar wind density and 2.5-7 MeV electrons.

Analysis

Fig. 2 shows a typical time profile observed during Feb. 2005 with better temporal resolution. Shown in this figure are from top to bottom the solar wind speed, magnetic field strength, the intensity of 0.9-1.2 MeV protons, solar wind density and the count rate of 2.5-7 MeV electrons. At the time period 1) the CIR has not reached Ulysses nor Jupiter, and the intensity of the MeV protons and electrons are at their quiet time values. When the CIR forward shock passes Ulysses (dashed line), the solar wind speed and density and the magnetic field strength are increasing. Since the forward shock is able to accelerate low energy particles, the intensity of 0.9-1.2 MeV protons is increasing. In contrast the count rate of 2.5-7 MeV electrons is decreasing indicating that the propagation conditions to Jupiter have been changed. A day later the SI has been identified by its compositional changes (solid line). It is important to note that the proton intensity shows a local minimum during the passage of the SI. This is in agreement with the analysis of Pioneer 10 and Ulysses data by Intriligator et al. [13]. The 0.9-1.2 MeV proton intensities are increasing again until about 4 days later when the reverse shock passes Ulysses (dashed line). The electron intensity, however, is not affected by the passage of the RS. The electron count rate stays low for the next three days and then starts to increase again. This increase is not accompanied by any changes in the local plasma parameters. Therefore it has been suggested by Conlon and Simpson [12] that the electron time profile is correlated with the CIR geometry. As illustrated in panel 4) of Fig. 2 the increase occurred when the CIR had passed Jupiter. In agreement with this model the Ulysses measurements indicate that MeV-electrons can not propagate through the CIR. Therefore, CIRs act as a barrier for relativistic electrons propagating between the Jovian magnetosphere and Ulysses (see panel 3 of Fig. 2 and Ferrando et al. [5]). The electron time profile shown in Fig. 2 is typical for 90% of 44 identified CIRs. The other four electron decreases do not occur when the FS passed Ulysses, but at the SI. Fig. 3 displays in its four panels the same parameters as Fig. 2 for the time period around August 12, 2004 (doy 227). The dashed lines indicate the passage of the FS and RS, respectively. The solid line represents the time of the SI crossing. Obviously the FS has no influence on the electron time profile. This is a surprise because the magnetic connectivity to Jupiter is changed due to the FS. In all of the four exceptions the intensity is rising several hours before the passage of the SI and drops at the SI by an order of magnitude within two hours. Thus the SI acts as a very efficient diffusion barrier. The pitch angle distribution shows an anisotropy during a few hours before the SI, which is consistent with these SI acting as “snow plows”. A preliminary analysis of these SIs shows also pronounced compositional signatures.

Summary

In this paper we analysed 44 corotating Jovian electron decreases seen by Ulysses during 2004 to 2005. The SI has been determined by its compositional signatures. In agreement with previous studies we find that the CIR is acting as a diffusive barrier for Jovian electron propagation. Our detailed analysis yields that in 40 of 44 cases the electron

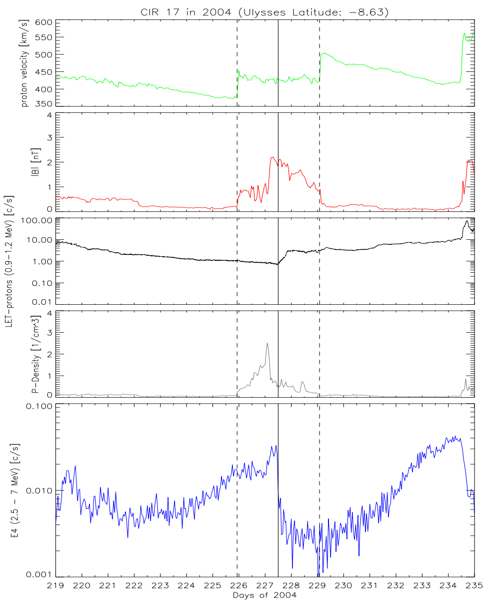

Figure 3: Same parameters as in Fig. 2 but for the time period around doy 227 in 2004.

intensity decreases gradually after the passage of the FS. During the other 4 events a sudden drop-out is measured during the SI crossing. In all cases the electron increase after the event can be correlated with the passage of the CIR past Jupiter.

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