EIT WAVES, CORONAL SHOCK WAVES, AND SOLAR ENERGETIC PARTICLE EVENTS

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Abstract

EIT waves are often associated with Solar type II radio bursts as recently revealed by Klassen et al. [2000]. It is well–known that Solar type II radio bursts are generated by shock waves traveling through the corona of the Sun. Since both phenomena are causally connected with each other, they can be used as a diagnostic tool of the magnetic field in the corona. Thus, a magnetic field of 2.2 G and 0.5 G is deduced to be at the photosphere and at a distance of 2 Solar radii above quiet Solar regions, respectively. Such a behaviour of the magnetic field leads to a local maximum of the Alfvén speed of about 740 km/s at a distance of 3.8 Solar radii. The occurrence of such a maximum has important consequences for the formation and development of shock waves in the Solar corona and the near–sun interplanetary space and their ability to accelerate particles leading to Solar energetic particle events.

1 Introduction

The observations of the Extreme ultraviolet Imaging Telescope (EIT) [Delaboudiniere et al., 1995] aboard the SOHO spacecraft revealed a new wave phenomenon, the so–called coronal transient (or EIT) waves [Moses et al., 1997; Thompson et al., 1998]. These waves appear as bright rims (sometimes circularly) propagating over a hemisphere of the Sun in the EUV light. Although the EIT waves remind of the Moreton waves [Moreton and Ramsey, 1960] they appear in an EUV spectral line of 195 Å emitted by a 1.6×10^6 K hot corona, whereas the Moreton waves are seen in the 10^4 K chromosphere. Furthermore, the velocities of Moreton waves ($>$ 400 km/s) exceed well those of EIT waves (150–350 km/s). The relationship between Moreton waves and Solar type II radio bursts is well accepted in the literature [Svestka, 1976], and a close relationship between EIT waves and Solar type II radio bursts was reported by Klassen et al. [2000]. It is well–known, that type

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II radio bursts represent signatures of shock waves traveling through the Solar corona [Nelson and Melrose, 1985].

Now, a particular Solar event on May 12, 1997 is presented to illustrate the relation between EIT waves and Solar type II radio bursts. Figure 1 shows the EIT images and the corresponding dynamic radio spectrum of this event. At the top a sequence of running difference images at 195 Å recorded by the EIT instrument [Delaboudiniere et al., 1995] aboard the SOHO spacecraft. A coronal disturbance initially generated by a flare in a small area on the Sun on 04:17–04:35 UT is propagating like a circular wave over a hemisphere of the Sun. Such a wave is called coronal transient (or EIT) wave [Moses et al., 1997; Thompson et al., 1998]. The EIT wave has a velocity of 289–294 km/s [Klassen et al., 2000]. At the bottom the dynamic radio spectrum of the same event is presented in the frequency range 40–800 MHz. It was recorded by the radiospectralpolarimeter of the Astrophysikalisches Institut Potsdam [Mann et al., 1992]. Solar type III and IV radio bursts appeared already on 04:44 UT. A Solar type II radio burst started at 90 MHz on 04:54 UT . It occurs as stripes of enhanced radio intensity slowly drifting from high to low frequencies [Nelson and Melrose, 1985]. A radial velocity of the type II radio burst source of 1029 km/s is deduced from the drift rate of −0.06 MHz/s at 28 MHz [Klassen et al., 2000]. The close relationship between the EIT wave and the Solar type II radio burst is evidently seen in this particular event. At the same event a coronal mass ejection (CME) rose from the Sun on 05:15 UT and drove an interplanetary shock wave ahead itself which was seen as an IP type II burst by the WAVES instrument [Bougeret et al., 1995] aboard the WIND spacecraft. A jump of the local plasma line recorded at 01:00 UT on May 15, 1997 by the WAVES instrument indicates the arrival of the IP shock resulting in a mean shock velocity of 615 km/s from the Sun up to 1 AU. The COSTEP instrument [Müller–Mellin et al., 1995] aboard the SOHO spacecraft measured the on–set of enhanced fluxes of energetic electrons (0.25–0.7 MeV) and protons (4.3–7.8 MeV) at 1 AU on 05:12 UT and 07:40 UT during the same event, respectively.

Klassen et al. [2000] studied a sample of 21 EIT waves and revealed their close relationship to Solar type II radio bursts. The velocity V_{EIT} of EIT waves is immediately determined from the running–difference images of the EIT instrument at 195 Å. Their velocities are in the range 157 km/s $\leq V_{EIT} \leq$ 465 km/s with the mean value of 271 km/s. The source velocity of type II radio bursts is derived from their drift rates D_f in the dynamic radio spectra. Generally, it is assumed that the radio emission takes place near the local electron plasma frequency $f_{pe} = (e^2 N_e / \pi m_e)^{1/2}$ (e, elementary charge; N_e, electron number density; m_e, electron mass) [Melrose, 1980]. Then, the relation

$$D_f = \frac{f}{2} \cdot \frac{1}{N_e} \cdot \frac{dN_e}{ds} \cdot V_r \qquad (1)$$

between the drift rate D_f measured at the frequency f ($\approx f_{pe}$) and the radial velocity V_r of the radio source can be derived. The onefold Newkirk [1961] model

$$N_e = N_0 \cdot 10^{4.32 R_S / r} \qquad (2)$$

($N_0 = 4.2 \cdot 10^4$ cm^{-3}; R_S, Solar radius) has been adopted as a radial electron density model of the Solar corona for determining the source velocities of the type II bursts (c.f.

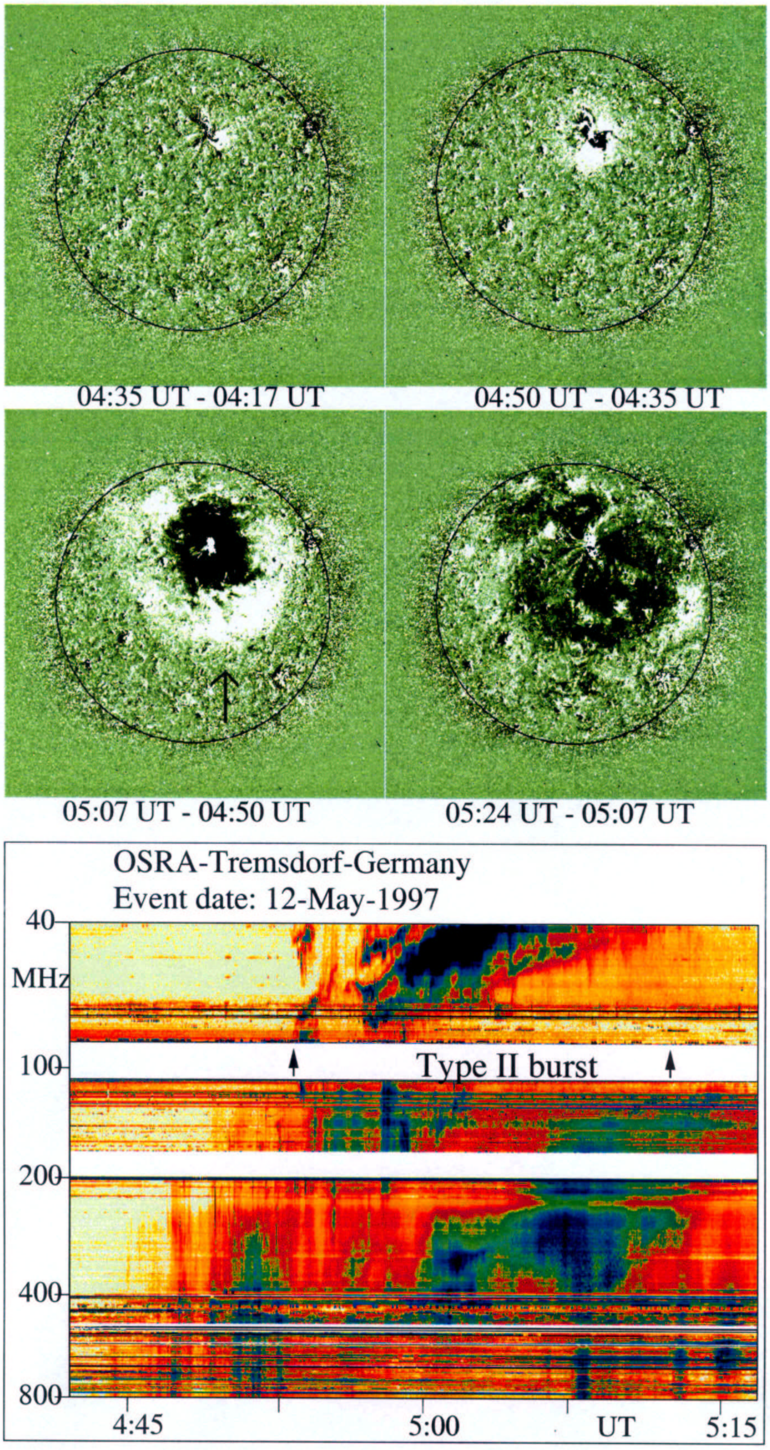

Figure 1: Running–difference images of the EIT instrument of the Solar event on May 12, 1997 (top) and the corresponding dynamic radio spectrum in the range 40–800 MHz (bottom).

Equation (1)). Note that the Newkirk [1961] model corresponds to a barometric height formula with respect to a temperature of $1.4 \cdot 10^6$ K [Mann et al., 1999a]. Even that is the temperature at which the 195 Å line is emitted. Furthermore, the onefold Newkirk [1961] model agrees very well with the white light scattering observations by Koutchmy [1994] above quiet equatorial regions of the corona. According to Equation (1) the radial source velocities of the type II radio bursts are in the range 267–1224 km/s with a mean value of 739 km/s in the case of the sample considered.

2 Interpretation

Since the EIT waves are a globally traveling wave phenomena, they are mainly propagating in quiet Solar regions, i. e. outside active regions. Therefore, they are moving nearly perpendicular to the ambient magnetic field, which is regarded to be radially directed in quiet coronal regions. Adopting a typical temperature $T = 1.4 \cdot 10^6$ K in the quiet Solar corona, a sound speed $c_s = (\gamma k_B T/\mu m_p)^{1/2} = 179$ km/s ($\gamma = 5/3$, ratio of specific heats; k_B, Boltzmann's constant; $\mu = 0.6$, mean molecular weight of the coronal plasma; m_p, proton mass) is obtained. Since the mean velocity of EIT waves (279 km/s) exceeds well the value of the sound speed, coronal transient waves should be considered as being fast magnetosonic waves propagating nearly perpendicular to the magnetic field. Then, the velocity V_{EIT} of EIT waves is related to the sound speed c_s and the Alfvén speed v_A by $V_{EIT} = (c_s^2 + v_A^2)^{1/2}$ (see for instance Priest [1982]). Thus, an Alfvén speed of 203 km/s is deduced at the level where the EIT line is generated. The 195 Å line seen with enhanced intensities at the EIT waves are emitted in the low corona at about 0.08 R_S above the photosphere. According to the Newkirk [1961] model (c.f. Equation (2)) an electron number density of $4.22 \cdot 10^8$ cm^{-3} is expected there. Then the magnetic field B can be calculated by

$$B = v_A \cdot \sqrt{4\pi\mu m_p N}, \tag{3}$$

where the full particle number density N is related to the electron number density by $N = 1.92 N_e$ if $\mu = 0.6$. Thus, a magnetic field of 1.9 G is deduced at a level of 0.08 R_S. Assuming the conservation of the magnetic flux, the magnetic field can be continued by

$$B(r) = B_S \cdot \left(\frac{R_S}{r}\right)^2 \tag{4}$$

to arbitrary distances r from the center of the Sun . Thus, a magnetic field of $B_S = 2.2$ G and 4.8 nT (1 $nT = 10^{-5}$ G) is obtained at the photosphere and in the heliosphere at 1 AU, respectively [Mann et al., 1999b]. Both values agree well with the measured ones [Priest, 1982; Mariani and Neubauer, 1990].

It is well–known, that the onefold Newkirk [1961] model (c.f. Equation (2)) is only appropriate to describe the radial density behaviour in the corona above quiet Solar regions [Koutchmy, 1994], whereas the density model by Mann et al. [1999a] describes very well the radial density behaviour in the heliosphere [c.f. Leblanc et al. 1998]. It bases on a special solution of Parker's wind equation [Parker, 1958]. Consequently, the onefold Newkirk [1961] (c.f. Equation (2)) and the density model by Mann et al. [1999a]

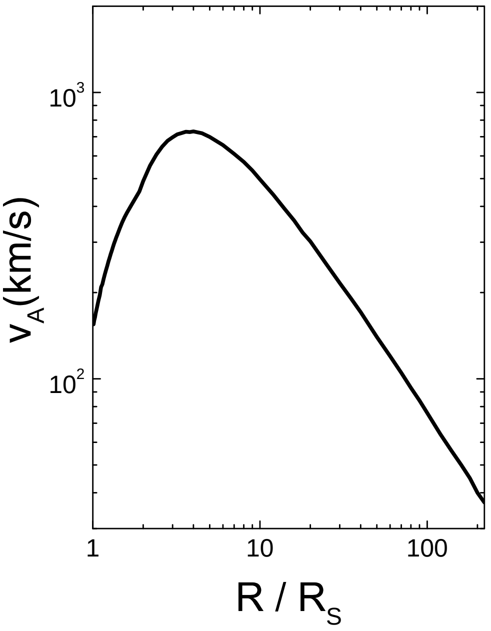

Figure 2: Radial behaviour of the Alfvén speed from the Solar corona up to the interplanetary space at 1 AU.

are adopted in the range $r \leq 1.8\ R_S$ and $1.8\ R_S \leq r$, respectively. Now, the radial density behaviour of the local Alfvén speed can be calculated by employing the aforementioned density model and the magnetic field model of Equation (4) as displayed in Figure 2. As seen in Figure 2, the Alfvén speed takes a local maximum of 740 km/s at a radial distance of 3.8 R_S from the center of the Sun.

The study by Klassen et al. [2000] reveals a causal relationship between the EIT waves and Solar type II radio bursts. Mann et al. [1999b] offered the following scenario for this phenomenon: The sudden energy release of a flare produces a huge disturbance above active regions in the Solar corona. This is the source of a compressional magnetohydrodynamic wave propagating through the whole corona. This wave occurs as the EIT wave in the low corona. In the upper corona it forms a shock wave after wave steepening due to the decreasing density and magnetic field. This shock wave appears as a Solar type II radio burst in a dynamic radio spectrum.

3 Conclusions

The occurrence of a local maximum of the Alfvén speed at 3.8 R_S has the consequence, that only shock waves with a velocity exceeding 740 km/s are able to propagate from the corona into the interplanetary space. Furthermore, coronal disturbances like CMEs with velocities below 740 km/s are able to drive a shock wave ahead themselves just beyond a distance of 3.8 R_S. As well–known IP shocks driven by CMEs are the source of gradual Solar energetic proton events [Kahler, 1994; Reames et al., 1996]. If such shocks are formed just beyond a certain distance from the Sun in the near–Sun interplanetary space, the place of formation has consequences in the on–set time of Solar energetic particle events (SEPs). For instance, the IP shock associated with the Solar event on May 12, 1997 has a velocity of 615 km/s. Such a disturbance becomes super–Alfvénic at a distance of 7 R_S, i. e., the IP shock is formed after 6830 s of the associated flare. Then, it can accelerate protons. 5.8 MeV protons have a velocity of 33163 km/s and need consequently a time of 4375 s to travel from the place of generation, i. e. at 7 R_S, up to 1 AU, where they can be detected by the COSTEP instrument [Müller–Mellin et al., 1995] aboard the SOHO spacecraft. Thus, the on–set of the energetic proton event in the range 4.3–7.8 MeV is 11205 s ($\approx$ 187 min) after the initial energy release, which was about 04:26 UT during this particular event, i. e., the on–set of enhanced fluxes of protons with energies in the range 4.3–7.8 MeV is expected on 07:33 UT, which was really observed by the COSTEP instrument.

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