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CORONAL TRANSIENT WAVES AND CORONAL SHOCK WAVES

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ABSTRACT

Coronal transient (or EIT) waves have been discovered by the EIT instrument aboard the SOHO spacecraft as a global wave phenomenon in the low corona. Most of them are associated with solar type II radio bursts appearing predominatly in the radio frequency range 40-100 MHz. Such type II radio bursts are signatures of shock waves travelling outwards in the upper corona. Since the mean EIT wave velocity of 270 km/s is well above the sound speed in the corona, these waves are considered as fast magnetosonic waves propagating nearly perpendicular to the ambient magnetic field in the low corona. On the other hand, the shock waves related to type II bursts have a mean velocity of 740 km/s, which must be well above the local Alfven speed. Considering both phenomena to be caused by the same initial energy release (flare), these waves can be used as diagnostic tools for the magnetic field in the solar corona. Thus, a magnetic field strength of 1.9 G is deduced from the EIT wave speeds at 0.08 solar radii above the photosphere. Such values are well expected above nonactive regions in the low corona. Then, a typical magnetic field strength of 1 G is calculated at 0.8 solar radii above the photosphere leading to a typical Alfven speed of 300-500 km/s in the upper corona. This value is well below the type II burst related shock velocities.

Key words: EIT waves, shock waves, coronal magnetic field.

1. INTRODUCTION

The observations of the **E**xtreme ultraviolet **I**maging **T**elescope (**EIT**) instrument (Delaboudiniere et al. 1995) aboard the SOHO spacecraft revealed the so-called coronal transient waves (Moses et al. 1997, Thompson et al. 1998). These waves appear as a bright rim (sometimes niceley circularly) expanding around the flaring active region in the EIT pictures (see Figure 1). Although the EIT waves remind of the Moreton waves (Moreton & Ramsey 1960), they are visible in EUV spectral lines (e. g. 195 Å of Fe XII) emitting by a $1.6 \cdot 10^6$ K hot coronal plasma, while the Moreton waves are seen in the 10^4 K hot chromosphere. The velocities of Moreton waves (> 400 km/s) exceed well those of EIT waves (150-350 km/s). Moreton waves are accompanied by solar type II radio bursts (Kai 1970). Solar type II radio bursts (see Figure 1) are signatures of shock waves propagating through the corona (Nelson & Melrose 1985). Uchida (1968) considered Moreton waves and the type II burst related shock waves to be caused by the same origin (flare). While the relationship between the Moreton waves and the solar type II radio bursts is well accepted (cf. Svestka (1976)), Klassen et al. (1999) presented a statistical analysis revealing the close relationship between the EIT waves and the type II burst associated shock waves.

A special example of a EIT wave occuring during the event on May 12, 1997 and its relation to a solar type II radio burst (see Figure 1) is presented in Section 2. Furthermore, the results of the statistical analysis by Klassen et al. (1999) are summarized in this Section. The interpretation of the relationship between the EIT waves and solar type II radio bursts and its consequences are discussed in Section 3.

2. OBSERVATIONS

Figure 1 shows the EIT images and the corresponding dynamic radio spectrum of the event on May 12, 1997. At the top sequences of running difference images at 195 Å made by the EIT instrument (Delaboudiniere et al. 1995) aboard the SOHO spacecraft reveal as a coronal disturbance initially generated at a relative small area on the Sun between 04:17-04:35 UT is propagating globally like a circular wave on the solar hemisphere at least until 05:07 UT. This global wave phenomenon 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. 1999). The corresponding active region was located at N21° W08°. At the bottom the dynamic spectrum of the solar radio radiation is presented in the frequency range 40-400 MHz. It was recorded by the new radiospectralpolarimeter (Mann et al. 1992) of the Astrophysikalisches Institut Potsdam. The associated solar radio activity in terms of type III and type IV bursts occurred on 04:44 UT (see Figure 1). A solar type II radio burst started about 90 MHz on 04:54 UT (see Figure 1). It appears as enhanced emission stripes slowly drifting

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from high to low frequencies in dynamic radio spectra (Nelson & Melrose 1985). Most of them show a fundamental-harmonic structure as this example too (see Figure 1). The measured drift rate D_f = -0.06 MHz/s at 28 MHz is transformed with respect to the fundamental band (Klassen et al. 1999). The temporal relationship between the EIT wave and the solar type II is evidently seen in this special example (see Figure 1).

Table 1. The velocities of the EIT waves and the corresponding solar type II radio burst sources

#	date	start time (UT)	$V_{\rm EIT}$ (km/s)	$V_{\rm typeII}$ (km/s)
1	April 1, 1997	08:01	234	885
2	April 1, 1997	10:32	226	803
3	April 1, 1997	13:49	240	782
4	April 2, 1997	05:36	256	639
5	April 2, 1997	09:27	278	727
6	April 7, 1997	13:58	340	786
7	April 15, 1997	14:15	307	798
8	May 12, 1997	04:54	292	1029
9	May 25, 1997	14:25	300	267
10	May 28, 1997	12:29	-	649
11	July 24, 1997	13:08	-	572
12	September 17, 1997	11:43	239	671
13	September 24, 1997	11:03	275	739
14	September 25, 1997	11:46	-	-
15	September 28, 1997	14:17	246	462
16	October 7, 1997	12:47	-	543
17	October 9, 1997	11:57	-	504
18	November 3, 1997	09:09	276	1224
19	November 3, 1997	10:28	200	1059
20	November 6, 1997	11:55	465	-
21	November 27, 1997	13:15	157	911

Klassen et al. (1999) investigated a sample of 21 EIT waves and revealed their relation to solar type II radio bursts. The results of this study are summarized in Table 1. The EIT wave velocities $V_{\rm EIT}$ (fourth column in Table 1) are immediately deduced from the running-difference images at 195 Å. The source velocity of the type II bursts are found from their drift rates $D_{\rm f}$ in the dynamic radio spectra. The radio emission takes place near the local electron plasma frequency $f_{\rm pe} = (e^2 N_{\rm e}/\pi m_{\rm e})^{1/2}$ ($m_{\rm e}$, electron mass) for the fundamental band of the type II burst. Then, a relationship between the drift rate $D_{\rm f}$ measured at the frequency f ($\approx f_{\rm pe}$) and the radio source velocity $V_{\rm typeII}$ along the density gradient $N_{\rm e}^{-1} \cdot dN_{\rm e}/ds$ is found to be

$$D_{\rm f} = \frac{f}{2} \cdot \frac{1}{N_{\rm e}} \frac{dN_{\rm e}}{ds} \cdot V_{\rm typeII} \qquad (1)$$

The (onefold) Newkirk (1961) model

$$N_{\rm e}(r) = N_0 \cdot 10^{4.32 R_{\rm S}/r} \qquad (2)$$

(N_0 = 4.2 · 10^4 cm^3; $R_{\rm S}$, solar radius) has been used as a radial density model of the solar corona for calculating the type II burst source velocites $V_{\rm typeII}$ (fifth column in Table 1) from the drift rates $D_{\rm f}$. Note that the Newkirk (1961) model corresponds to a barometric height formula with a temperature of $1.4 \cdot 10^6$ K (Mann et al. 1999). Such a model agrees very well with the white light scattering measurements by Koutchmy (1994) at equatorial regions of the solar corona. Figure 2 presents histogramms of the distribution of the EIT wave ($V_{\rm EIT}$, bottom) and type II burst source velocities ($V_{\rm typeII}$, top) according to Table 1. It is seen evidently, that the type II burst source velocities exceed well those of the EIT waves. Thus, mean values of 271 km/s and 739 km/s are found for the velocities of the EIT waves and the associated solar type II radio burst sources, respectively.

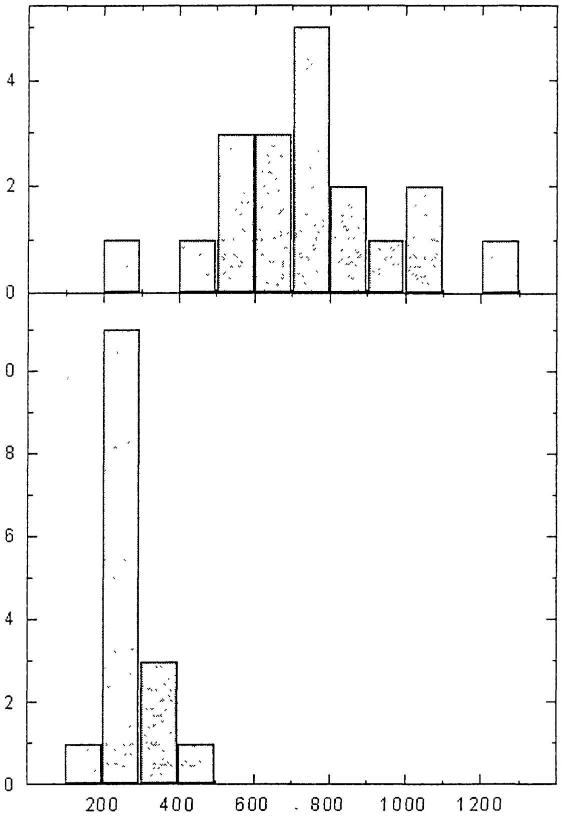

Figure 2. The Figure shows the distribution of the velocities of the solar type II radio burst sources (top) and the EIT waves (bottom) according to Table 1.

3. DISCUSSION

As seen in Figure 1 coronal transient (or EIT) waves are globally travelling on a hemisphere of the Sun. Therefore, they are mainly propagating in quiet solar regions, i. e. outside active regions, although they are initially excited by a sudden energy release (flare) above active regions. Assuming a temperature $T = 1.4 \cdot 10^6$ K as a typical value in the quiet solar corona a sound speed $c_{\rm s} = (\gamma k_{\rm B} T/\mu m_{\rm p})^{1/2}$ = 179 km/s ($\gamma = 5/3$, ratio of specific heats; $k_{\rm B}$, Boltzmann's constant; μ, mean molecular weight; $m_{\rm p}$, proton mass) is obtained. Here, a value of 0.6 has been

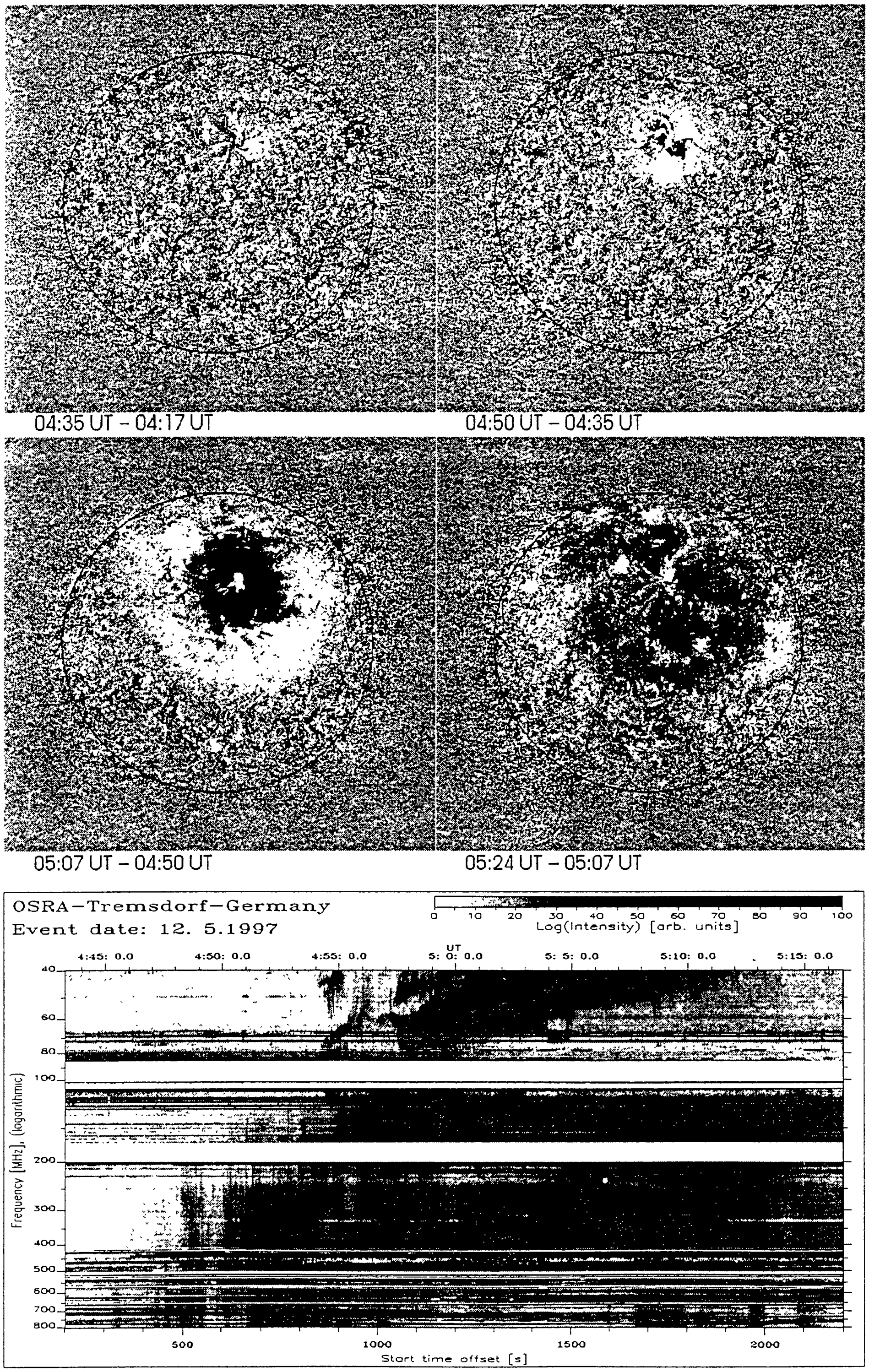

Figure 1. The Figure shows the event on May 12, 1997. Running-difference images of the EIT instrument are presented at the top. The coronal transient (or EIT) wave is seen evidently. The corresponding dynamic radio spectrum is shown in the range 40-800 MHz at the bottom.

1999ESASP.446..477M

used for μ. Since the mean EIT wave velocity V_{EIT} = 279 km/s exceeds well this value of the sound speed, coronal transient waves are considered as fast magnetosonic waves propagating nearly perpendicular to the ambient magnetic field in quiet coronal regions. Here, the magnetic field is assumed to be radially directed outside active regions. Then, the EIT wave velocity is related to the sound speed c_{s} and the Alfven speed v_{A} according to $V_{\mathrm{EIT}} = (v_{\mathrm{A}}^2 + c_{\mathrm{s}}^2)^{1/2}$ (cf. Priest (1982)) providing a mean value of 203 km/s for the Alfven speed. The EIT waves are regarded to be generated in the low corona at about $0.08R_{\mathrm{S}}$ = 56000 km above the photosphere. An electron number density of $4.22 \cdot 10^8$ cm^{-3} is expected at this height level according to the Newkirk (1961) model (cf. Eq. (2)). Then, the magnetic field strength B can be calculated by

$$B = v_{\mathrm{A}} \cdot \sqrt{4\pi\mu m_{\mathrm{p}} N} \tag{3}$$

Here, N denotes the full particle number density, which is related to the electron number density N_{e} by $N_{\mathrm{e}} = 0.52N$ for $\mu = 0.6$. Doing this a magnetic field strength of 1.9 G is obtained at $0.08R_{\mathrm{S}}$. According to the magnetic flux conservation, i. e. $Br^2 = const$, a magnetic field strength B_{S} = 2.2 G is found at the photosphere. Such a value is really expected in quiet photospheric regions (Priest 1982). Using the conservation of the magnetic flux the magnetic field can be continued to arbitrary radial distances r from the Sun by

$$B(r) = B_{\mathrm{S}} \cdot \left(\frac{R_{\mathrm{S}}}{r}\right)^2 \tag{4}$$

where a magnetic field strength of 4.8 nT is obtained at 1 AU. This value agrees well with the measured ones at 1 AU (Mariani & Neubauer 1990).

In Table 2 the electron number density N_{e}, the magnetic field strength B, and the Alfven speed v_{A} are calculated according to the Eqs. (2), (4), and (3) for different height levels in the corona, respectively. Note that the values of the plasma parameters given here, especially in Table 2, are not exact values but they should be considered as rough estimations, since the corona is strongly inhomogeneous. In the outer corona, i. e. beyond $2R_{\mathrm{S}}$, the (onefold) Newkirk (1961) model is no longer sufficient to describe the real density behaviour. Therefore the Newkirk model is adapted to the density model by Mann et al. (1999) at 1.8-2.0R_{S}. Using this the radial behaviour of the Alfven speed v_{A} is displayed in Figure 3, where the magnetic field strength are taken from Eq. (4). A local maximum of 800 km/s appears for the Alfven speed at 3.8R_{S}.

Table 2. The electron plasma frequency, the electron particle number density, the magnetic field strength, and the Alfven speed at different radial distances in the solar corona

f_{pe} (MHz)	r/R_{S}	N_{e} (cm^{-3})	B (G)	v_{A} (km/s)
170	1.10	$3.59 \cdot 10^8$	1.8	193
100	1.25	$1.24 \cdot 10^8$	1.4	255
70	1.37	$6.08 \cdot 10^7$	1.2	312
40	1.62	$1.98 \cdot 10^7$	0.8	365
20	2.10	$4.96 \cdot 10^6$	0.5	456

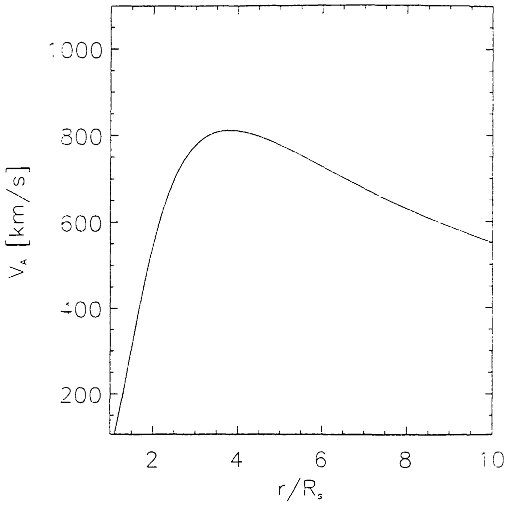

Figure 3. Radial behaviour of the Alfven speed

Solar type II radio bursts are signatures of shock waves travelling outwards in the corona (Nelson & Melrose 1985, Mann, 1994). These shocks accelerate electrons to suprathermal velocities. The energetic electrons excite Langmuir waves which are converted into radio waves escaping the corona. In order to generate suprathermal electrons the shock wave must have an Alfven-Mach number M_{A} exceeding a critical one. i. e., $M_{\mathrm{A}} \geq 1.6$ under coronal circumstances (Mann et al. 1994).

During the individual events both the coronal transient (EIT) wave and the solar type II radio bursts are considered to be generated by the same initial energy release (flare). The sudden energy release of a flare produces locally a huge disturbance above active regions in the corona. These disturbance is propagating as a compressional magnetohydrodynamic wave through the whole corona leading to the EIT waves in the low corona and after.a wave steepening to a shock wave in the higher corona. This shock wave causes a type II radio burst due to electron acceleration if its Alfven-Mach number M_{A} fulfills the relation $1.6 \leq M_{\mathrm{A}}$ (Mann et al. 1994). The solar type II radio bursts studied by Klassen et al. (1999) in association to EIT waves appear usually below 100 MHz. Therefore the velocity of the shocks related to type II bursts must be greater than 408 km/s (see Table 2). The mean velocity of solar type II radio burst sources is 739 km/s, i.e. well above the local Alfven speed (see Table 2) as required. This value was found from the drift rates of solar type II radio bursts measured typically about 70 MHz. At the 70 MHz level in the corona the Alfven speed has a value of 312 km/s (cf. Table 2). This shows, that the shock waves associated with type II bursts have a mean Alfven-Mach number of 2.4. Note that the shock velocities deduced from the drift rates are radial velocities and, consequently, lower limits of the real ones. Because of the maximum of the Alfven speed (see Figure 3), a coronal shock wave must have a velocity exceeding 800 km/s in order to penetrate into the interplanetary space.

In summary, coronal transient waves and coronal shock waves associated with solar type II radio bursts can be used as a diagnostic tool for the magnetic field in the solar corona, as demonstrated in this paper.

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REFERENCES

Delaboudiniere, J.-P., Artzner. G.E., Brunaud, J., and 25 co-authors 1995, Solar Phys., 162, 291

Kai, K. 1970, Solar Phys., 11, 310

Klassen, A., Aurass, H., Mann, G., and Thompson, B.J. 1999, A&A, in press

Koutchmy, S. 1994, Adv. Space Res., 14(4), 29

Mann, G., Aurass, H., Voigt, W., and Paschke, J. 1992, ESA-Journal, SP-348, 129

Mann, G., Classen, T., and Aurass, H. 1994, A&A, 295, 775

Mann, G., Jansen, F., MacDowall, R.J., Kaiser, M.L., and Stone, R.G. 1999, A&A, in press

Mariani, F. and Neubauer, F.M. 1990, in Physics of the Inner Heliosphere (ed. by R. Schwenn and E. Marsch), Springer-Verlag, Berlin, Heidelberg, p. 183

Moreton, G. E. and Ramsey, H.E. 1960, Publ. Astron. Soc. Pacific, 72, 357

Moses, D., Clette, F., Delabouniniere, J.-P., and 32 co-authors 1997, Solar Phys., 175, 571

Nelson, G.S. and Melrose, D. 1985, in Solar Radiophysics (ed. by D.J. McLean and N.R. Labrum), Cambridge University Press, Cambridge, p. 333

Newkirk, G.A. 1961, ApJ, 133, 983

Priest, E.R. 1982, Solar Magnetohydrodynamics, Reidel, Dordrecht

Svestka, Z. 1976, Solar Flares, Reidel, Dordrecht

Thompson, B.J., Plunkett, S.P., Gurman, J.B., Newmark, J.S., Cyr, O.C.St., and Michels, D.J. 1998, Geophys. Res. Lett., 25, N 14, 2465

Uchida, Y. 1968, Solar Phys., 4, 30