# GENERATION OF HIGHLY ENERGETIC ELECTRONS AT THE RECONNECTION OUTFLOW SHOCK DURING SOLAR FLARES

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**Abstract**

In the solar corona stored magnetic field energy is suddenly released by magnetic reconnection during flares. Hot jets appear in the outflow region of the reconnection site. If these jets penetrate into the surrounding plasma, standing shocks are established. There, electrons can be accelerated by shock drift acceleration up to high energies. This mechanism is treated in a fully relativistic manner. If the highly energetic electrons travel along the magnetic field lines towards the denser chromosphere, they can emit hard X-ray radiation via bremsstrahlung. The theoretically obtained results are compared with the radio and hard X-ray data of the solar event on October 28, 2003, since signatures of highly relativistic electrons have been observed during this event.

## 1 Introduction

In the declining phase of the present solar cycle huge events occurred in the period October/November 2003. Especially, the event on October 28, 2003 showed a strong enhancement of the hard X- and $\gamma$-ray radiation as observed by the INTEGRAL spacecraft [Gros et al., 2004]. The appearance of hard X- and $\gamma$-ray radiation implies the existence of highly energetic electrons. The energetic electrons generated during a solar flare travel along the magnetic field lines from the corona towards the denser chromsphere, where they emit electromagnetic tadiation up to the $\gamma$-ray range via *bremsstrahlung* [Brown, 1971]. During the solar event on October 28, 2003 a strong enhancement of the photon fluxes was observed in the intial (impulsive) phase 11:02−11:06 UT. The photon flux in the range 7.5-10 MeV was only enhanced in the initial phase for 1 minute (11:02:30−11:03:30 UT) (see Fig. 6 in Gros et al. [2004]). That indicates the production of highly energetic electrons with energies of at least 8 MeV during this event. A mechanism which allows to generate such relativistic electrons will be offered in the present communication.

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During solar flares stored magnetic energy is suddenly released by magnetic reconnection. Initially, a prominence is destabilized and rises up in the corona. Then, the underlying magnetic field lines are stretched leading to the formation of a current sheet. If the electric current is exceeding a critical value there, the local resistivity is strongly enhanced due to the excitation of plasma waves in the so-called *diffusion region* (DR) finally leading to magnetic reconnection [Treumann and Baumjohann, 1997]. Due to the strong curvature of the magnetic field lines at the reconnection site the incoming plasma flow is shooting away as hot plasma jets (J). If the velocity of these jets is super-Alfvénic, a fast magnetosonic shock wave, also called *termination shock* (TS), can be established due to the deceleration of the jet (see Fig. 1), e. g. by the encounter with a underlying loop. The appearance of such shocks was prediced in the numerical simulations by Forbes [1986] and Shibata et al. [1995]. Tsuneta and Naito [1998] proposed that these shocks are the source of energetic electrons needed of the hard X-ray radiation.

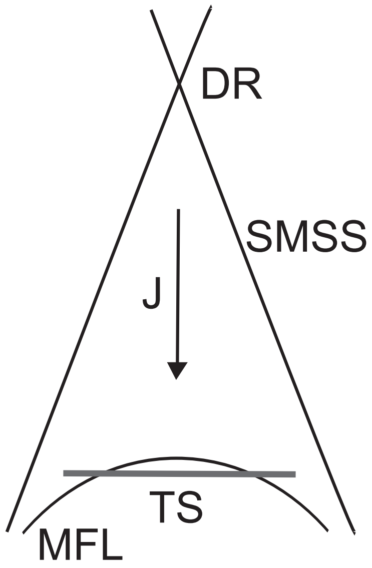

*Figure 1: Sketch of the reconnection outflow region enclosed by the slow mode standing shocks (SMSS). (DR, diffusion region; TS, termination shock; MFL, magnetic field lines)*

In the solar radio radiation shock waves occur as so-called *type II radio bursts* [Nelson and Melrose, 1985; Mann, 1995]. In dynamic radio spectra they appear as stripes of enhanced radio emission slowly drifting from high to low frequencies (Fig. 2). Generally, it is assumed that the radio emission takes place near the local electron plasma frequency, i. e. $f_{obs} \approx f_{pe}$ with $f_{pe} = (e^2 N_e / \pi m_e)^{1/2}$ (e, elementary charge; $N_e$, electron number density; $m_e$, electron mass) and/or its harmonics [Melrose, 1985]. Then, the high and low frequencies are emitted in the low and high corona, respectively. Consequently, a relationship

$$D_f = \frac{f_{obs}}{2} \cdot \frac{1}{N_e} \cdot \frac{dN}{ds} \cdot V_{source} \tag{1}$$

can be derived between the drift rate $D_f$ and the velocity $V_{source}$ of the radio source. Here, $dN_e/ds$ is the density gradient along the propagation path. Generally, the spectral features

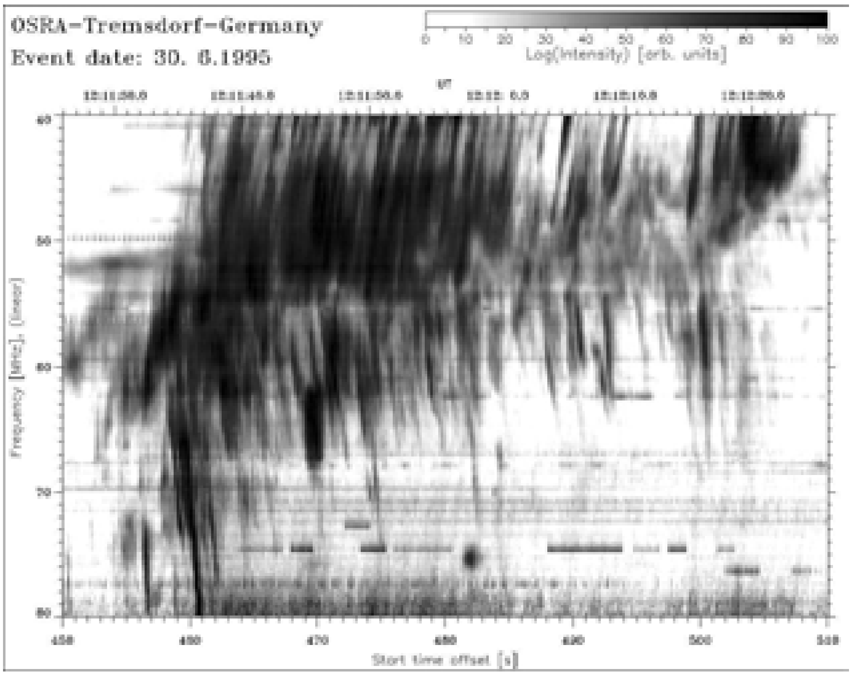

*Figure 2: An example of a solar type II radio bursts. The "backbone"is slowly drifting from 60 to 42 MHz. The rapidly drifting "herringbones" are nicely seen during the whole event.*

of solar type II radio bursts consist of two components, the so-called "backbone" and "herringbones". The "backbone" is the aforementioned slowly drifting emission stripe. It is related with the shock wave travelling outwards through the corona. The "herringbones" are rapidly drifting emission stripes shooting up from the "backbone" to high and low frequencies. They are regarded as electron beams accelerated by the associated shock wave [Mann, 1995]. All these features are impressively seen in the example shown in Figure 2.

In contrast to shock waves associated with the type II radio burst the termination shocks are not travelling but standing shocks. Thus, they should appear as a nearly non-drifting type II radio burst feature in dynamic radio spectra. Aurass et al. [2002] and Aurass and Mann [2004] firstly reported on radio signatures of such shocks.

Figure 3 shows the dynamic radio spectrum of the initial phase of the event on October 28, 2003. It shows similar features as the usual type II radio bursts, i. e. a non-drifting "backbone" around 300 MHz and the "herringbones". That evidently indicates that it is really a signature of a "standing" shock. It simultaneously appears with the strong enhancement of the photon fluxes up to an energy of 10 MeV as observed by INTEGRAL (see Fig. 6 in Gros et al. [2004]), revealing a close relationship between this shock and the generation of highly energetic electrons.

In the present communication the suggestion of Tsuneta & Naito is adopted for explaining the generation of highly energetic electrons at the intial phase during the event on October 28, 2003. The "standing" shock is assumed to be the termination shock at which electrons are accelerated by *shock drift accleration* (see Sect. 2) up to high energy of about 10 MeV

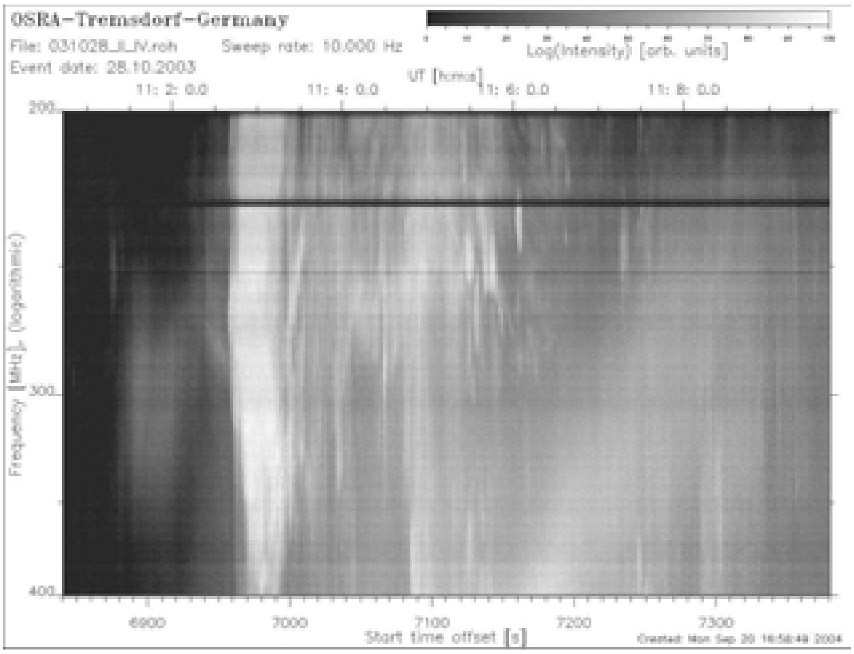

*Figure 3: Dynamic radio spectrum in the frequency range 200−400 MHz during the initial phase 11:02−11:08 UT*

under coronal circumstances as discussed in Section 3.

## 2 Shock Drift Acceleration

It is well-known that fast magnetosonic shock waves are acompanied with a compression of both the density and the magnetic field (see e. g. Treumann & Baumjohann [1997]). Thus, a shock wave is a moving magnetic mirror at which charged particles can be reflected and, subsequently, accelerated. This process is usually called *shock drift acceleration*. Since it is intended to explain the generation of highly energetic electrons with energies up to 10 MeV, the shock drift accleration must be treated in a fully relativistic manner.

The shock wave is located in the z-y plane and moves with a speed $\mathrm{v}_s$ along the x-axis. At first a Lorentzian transformation along the x-axis is done in order to have the shock wave at rest. Subsequently, another Lorentzian transformation is performed along the y axis so that the inflowing plasma velocity is directed along the upstream magnetic field. Then, the motional electric field is removed in this special frame, which is called *de Hoffmann-Teller frame*. Here, the upstream magnetic field is put into the x-z plane and takes an angle $\theta$ towards the x axis. Consequently, the shock speed is $\mathrm{v}_s \cdot \sec\theta$ in the de Hoffmann-Teller frame (see e. g. Ball & Melrose [2001] for the non-relativistic approach).

According to the addition theorem of relativistic velocities, the particle velocities in the de Hoffmann-Teller frame can be expressed by the initial ones

$$\beta_{i,HT,\|} = \frac{\beta_{i,\|} - \beta_s}{1 - \beta_{i,\|}\beta_s} \tag{2}$$

and

$$\beta_{i,HT,\perp} = \frac{\beta_{i,\perp}}{1 - \beta_{i,\|}\beta_s} \cdot \sqrt{1 - \beta_s^2} \tag{3}$$

with $\beta_{i,\|} = V_{i,\|}/c$, $\beta_{i,\perp} = V_{i,\perp}/c$, and $\beta_s = v_s \sec\theta/c$. The reflection takes place under the conservation of the kinetic energy, i. e. $\beta_{HT,\|}^2 + \beta_{HT,\perp}^2 =$ const, and the magnetic moment $\beta_{HT,\perp}^2/B =$ const, since the motional electric field is already removed. The influence of the electrostatic cross-shock potential [Goddrich & Scudder, 1984; Kunic et al., 2002] can be neglected if highly energetic particles are considered, since it is of the order of a few $k_B$T ($k_B$, Boltzmann's constant; T, temperature). Finally, the reflection process can be performed by $\beta_{r,HT,\|} = -\beta_{i,HT,\|}$ and $\beta_{r,HT,\perp} = \beta_{i,HT,\perp}$. Here, the indices "i" and "r" denote the state before and after the reflection, respectively. After performing this reflection process the Lorentzian transformations from the de Hoffmann-Teller frame back to the initial one, a relationship between the particle velocities after the reflection and the initial ones is found to be

$$\beta_{r,\|} = \frac{2\beta_s - \beta_{i,\|}(1 + \beta_s^2)}{1 - 2\beta_{i,\|}\beta_s + \beta_s^2} \tag{4}$$

and

$$\beta_{r,\perp} = \frac{(1 - \beta_s^2)}{1 - 2\beta_{i,\|}\beta_s + \beta_s^2} \cdot \beta_{i,\perp} \tag{5}$$

Additionally, the reflection condition

$$\beta_{i,\perp} \geq \frac{\tan\alpha_{lc}}{\sqrt{1 - \beta_s^2}} \cdot (\beta_s - \beta_{i,\|}) \tag{6}$$

must be satisfied by the initial particles in order to be accelerated. The loss-cone angle is ususally defined by $\alpha_{lc} = \arcsin[(B_{up}/B_{down})^{1/2}]$, Here, $B_{up}$ and $B_{down}$ denote the magnitude of the magnetic field in the up- and down-stream region of the shock, respectively (see Mann et al. [2005] for further details of the relativisitc generalization of shock drift acceleration).

Shock drift acceleration basically represents a transformation in the $\beta_\perp - \beta_\|$ plane. In Figure 4, this transformation is illustrated for two shock speeds $\beta_s = 0.1$ and 0.9. Here, the particles initially located in the sector left from the dashed lines are tranformed into the sector to the right of them. This process is connected with a gain of energy. It should be emphasized that there is a critical shock speed $\beta_s^*$. For shock waves with a speed $\beta_s > \beta_s^*$, only particles with the initial velocity $\beta_{i,\|} > 0$ are accelerated, whereas the other ones are totally transmitted into the downstream region.

## 3 Discussion

Since the radio signatures of TS are observed around 300 MHz at the harmonic emission the plasma parameters usually found at the 150 MHz level in the corona are chosen as the basic parameters for the further discussion. The 150 MHz level is connected with an electron number density $N_0 = 2.8 \cdot 10^8$ cm$^{-3}$ and expected at a height of 160 Mm above

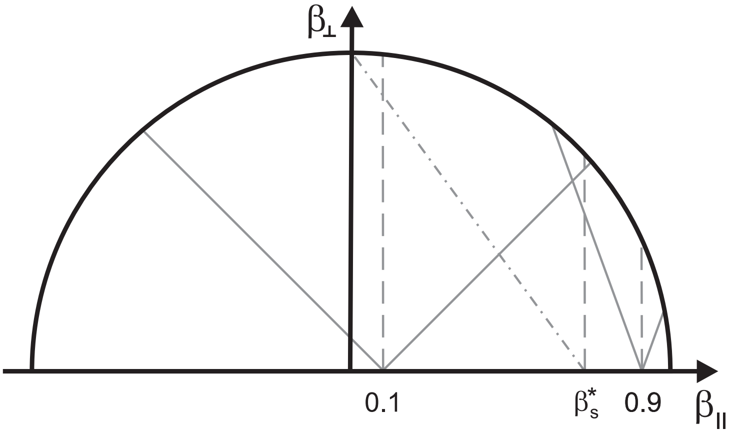

*Figure 4: Illustration of shock drift acceleration in the $\beta_\perp - \beta_\parallel$ plane. $\beta_s^*$ is given for $v_s$ = 1500 km/s and $\alpha_{lc}$ = 45°.*

the photosphere according to a twofold Newkirk [1961] coronal density model. There, a magnetic field strength of 5 G can be expected above active regions [Dulk and McLean, 1978] resulting in an Alfvén speed $v_A$ = 610 km/s. For the TS a jump of the density $N_{down}/N_{up}$ = 2 is assumed according to the bandwidth of the type II burst associated with the TS (Fig. 3). That leads to a compression of the magnetic field $B_{down}/B_{up}$ = 2 across the TS and an Alfvén-Mach number $M_A$ = 2.3, i. e. the shock speed is $v_s$ = 1500 km/s, according to the Rankine-Hugoniot relationships. Furthermore, a typical flare temperature of $10^7$ K related to a thermal electron velocity $v_{th,e}$ = 12300 km/s is assumed for the discussion.

In order to determine the phase space density of the accelerated electrons, a velocity distribution function in the upstream region of the TS has to be introduced. Here, a so-called *kappa distribution* defined by

$$f = C_\kappa \cdot \left[1 + \frac{E}{\kappa E_\kappa}\right]^{-\kappa-1} \tag{7}$$

($E = m_0c^2[(1-\beta^2)^{-1/2}-1]$ with $\kappa$ =10 is considered as the appropriate one in the corona [Maksimovich et al., 1997; Pierrard et al., 1999]. The constant $C_\kappa$ is fixed by normalizing the distribution function to unity. According to the kinetic definition of the temperature, i. e. $\bar{E} = 3N_0k_BT/2$, the parameter $E_\kappa$ is related to the temperature T by $E_\kappa = k_BT \cdot (\kappa\text{-}3/2)/\kappa$. Then, the number of electrons dN in the range $[\epsilon + d\epsilon, \epsilon]$ and $[\vartheta + d\vartheta, \vartheta]$ is found from Eq. (7) to be given by

$$\frac{1}{N_0} \cdot \frac{dN}{d\vartheta d\epsilon} = 2\pi C_\kappa c^3 \sin\vartheta \cdot \frac{\sqrt{\epsilon(2+\epsilon)}}{(1+\epsilon)^4} \cdot \left[1 + \frac{\epsilon}{\kappa\epsilon_\kappa}\right]^{-\kappa-1} \tag{8}$$

with $\epsilon = E/m_0c^2$ and $\epsilon_\kappa = E_\kappa/m_0c^2$. The pitch angle $\vartheta$ is usually defined by $\beta_\parallel = \beta \cdot \cos\vartheta$.

Since an enhanced photon flux up to the range 7.5−10 MeV was observed during the event on October 28, 2003, the production of 8.5 MeV electrons by the proposed mechanism is demonstrated for example. An electron with the initial energy of 2.57 MeV and an inital pitch angle of $6.74^o$, i. e. $\beta_{i,\|} = 0.9793$ and $\beta_{i,\perp} = 0.1157$ is accelerated by a shock wave with a speed of 1500 km/s and an angle $\theta = 89.71^o$, i. e. $\beta_s = 0.993$, to a final state with $\beta_{r,\|} = 0.998$ and $\beta_{r,\perp} = 0.0393$, i. e. with a final energy of 8.54 MeV and a final pitch angle of $2.25^o$, via shock drift acceleration. The number of electrons with an energy of 8.54 MeV and a pitch angle of $2.25^o$ is found to be $N_0^{-1} \cdot dN/d\vartheta d\epsilon = 2.4 \cdot 10^{-34}$ (see Eq. (8)). They are produced from such ones with an initial energy of 2.57 MeV and an initial pitch angle of $6.74^o$. Their number is $N_0^{-1} \cdot dN/d\vartheta d\epsilon = 3.6 \cdot 10^{-28}$ according to Eq. (8). Thus, the proposed acceleration mechanism enhances the number of 8.5 MeV electrons by a factor of $1.5 \cdot 10^6$ in comparison to the state without any acceleration.

After the acceleration of the electrons at the TS, they will encounter the TS once more because of the curvature of the magnetic field lines in the outflow region of the reconnection site. Since the shock speed $\beta_s = 0.993 > \beta_s^* = 0.707$ ($\alpha_{lc} = 45^o$ because of $B_{down}/B_{up} = 2$), all energized electrons are able to penetrate into the downstream region at the second encounter as already explained in Section 2. Then, they propagate along the magnetic field lines towards the denser chromosphere, where they can emit hard X- and $\gamma$-ray radiation via bremsstrahlung.

Highly energetic electrons can be produced at the TS as the source of non-thermal hard X- and $\gamma$-ray radiation in the chromospheric footpoints as well as at the loop-top areas. The proposed mechanism is able to explain the generation of relativistic electrons up to energies of 10 MeV. Such electrons are needed for the enhanced photon fluxes as observed by the INTEGRAL spacecraft during the solar event on October 28, 2003.

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## References

Aurass, H and G. Mann, Radio Observations of Electron Acceleration at Solar Flare Reconnection Outflow Termination Shocks, *ApJ*, **615**, 526–530, 2004.

Aurass, H, B. Vršnak, and G. Mann, Shock-excited Radio Bursts from Reconnection Outflow Jets, *A&A*, **384**, 273–281, 2002.

Ball, L. and D. B. Melrose, Shock Drift Acceleration of Electrons, *Publ. Astron. Soc. Austr.*, **18**, 361–372, 2001.

Brown, J. C., The Deduction of Energy Spectra of the Non-thermal Electrons in Flares, from the Observed Dynamic Spectra of Hard X-Ray Bursts, *Solar Phys.* **18**, 489–502, 1971.

Dulk, G. A., and D. J. McLean, Coronal Magnetic Fields, *Solar Phys.*, **57**, 279–295, 1978.

Forbes, T. G., Fast-Shock Formation in the Line-Tied Magnetic Reconnection Models of Solar Flares, *ApJ*, **305**, 553–564, 1986.

Goddrich, C. C. and J. Scudder, The Adiabatic Energy Change of Plasma Electrons and the Frame Dependence of the Cross-Shock Potential at Collisionless Magnetosonic Shock Waves, *J. Geophys. Res.*, **107**, 10,029–10,045, 2002.

Gros M., V. Tatischeff, J. Kiener, B. Cordier, C. Chapuis, G. Weidenspointner, G. Vedrenne, A. von Kienlin, R. Diehl, A. Bykov, M. NMéndez, INTEGRAL/SPI Observation of the 2003 Oct. 28 Solar Flare, *Proc. 5th INTEGRAL Workshop*, 25–33, 2004.

Kunic, Z., I. H. Cairns, and S. A. Knock, Analytic Model for the Electrostatic Potential Jump Across Collisionless Shocks with Application to Earth's Bow Shock, *J. Geophys. Res.*, **89**, 6654–6672, 1984.

Maksimovic, M., V. Pierrard, and J. Lemaire, A Kinetic Model of the Solar Wind with Kappa Distribution Functions in the Corona, *A&A*, **324**, 725–734, 1997.

Mann, G., Theory and Observations of Coronal Shock Waves, in *Coronal Magnetic energy Releases*, edited by A. O. Benz and A. Krüger, Lecture Notes in Physics **LNP 444**, Springer, Heidelberg, 183–200, 1995.

Mann, G., H. Aurass,and A. Warmuth, Electron Acceleration at the Solar Flare Reconnection Outflow Shock, *A&A*, accepted, 2005.

Melrose, D. B., Plasma Emission Mechanisms, in *Solar Radiophysics*, edited by D. J. McLean and N. R. Labrum, Cambridge University Press, Cambridge, 177–210, 1985.

Nelson, G. S. and D. B. Melrose, Type II Bursts, in *Solar Radiophysics*, edited by D. J. McLean and N. R. Labrum, Cambridge University Press, Cambridge, 333–360, 1985.

Newkirk, G. A., The Solar Corona in Active Regions and the Thermal Origin of the Slowly Varying Component of Solar Radio Radiation., *ApJ*, **133**, 983–1013, 1961.

Pierrard, V., M. Maksimovic, and J. Lemaire, Electron Velocity Distribution Function from the Solar Wind to the Corona, *J. Geophys. Res.*, **104**, 17,021–17,031, 1999.

Shibata, K., S. Masuda, M. Shimojo, H. Hara, T. Yokoyama, S. Tsuneta, T. Kosugi, Y. Ogawara, Hot-Plasma Ejections Associated with Compact-Loop Solar Flares, *ApJ*, **451** L83–L87, 1995.

Tsuneta, S. and T. Naito, Fermi Acceleration at the Fast Shock in a Solar Flare and the Impulsive Loop-Top Hard X-Ray Source, *ApJ*, **495** L67–L71, 1998.

Treumann, R. A. and W. Baumjohann, *Advanced Space Plasma Physics*, Imperial College Press, London, 317–375, 1997.