TYPE II SOLAR RADIO BURSTS: THEORY AND SPACE WEATHER IMPLICATIONS

IVER H. CAIRNS*, S. A. KNOCK, P. A. ROBINSON and Z. KUNCIC
School of Physics, University of Sydney, Sydney, NSW 2006, Australia
*(*author for correspondence, e-mail; cairns@physics.usyd.edu.au)*

Abstract. Recent data and theory for type II solar radio bursts are reviewed, focusing on a recent analytic quantitative theory for interplanetary type II bursts. The theory addresses electron reflection and acceleration at the type II shock, formation of electron beams in the foreshock, and generation of Langmuir waves and the type II radiation there. The theory's predictions as functions of the shock and plasma parameters are summarized and discussed in terms of space weather events. The theory is consistent with available data, has explanations for radio-loud/quiet coronal mass ejections (CMEs) and why type IIs are bursty, and can account for empirical correlations between type IIs, CMEs, and interplanetary disturbances.

Key words: coronal mass esjections, electron reflection, plasma waves, radiation, shocks, solar radio emission, type II bursts

1. Introduction

Type II solar radio bursts were discovered in dynamic spectra as slowly drifting bands, often in pairs differing in frequency by a factor ≈ 2 (Wild *et al.*, 1954). They were quickly interpreted in terms of a coronal shock wave accelerating electrons, driving Langmuir waves near the electron plasma frequency f_p, and producing radio emission near f_p and $2f_p$ (Wild *et al.*, 1954, Nelson and Melrose, 1985). Interplanetary type II bursts were discovered in spacecraft data (Cane *et al.*, 1982) and definitively associated with coronal mass ejections (CMEs), traveling shock waves, and radiation near f_p and $2f_p$ (Cane and Stone, 1984; Lengyel-Frey, 1992; Reiner *et al.*, 1998a). The basic model for coronal type IIs is strongly supported by *in situ* observations of an interplanetary type II source: Bale *et al.* (1999) observed the shock wave, reflected electrons, Langmuir waves, and radiation generated near the local f_p and $2f_p$.

The primary purpose of this paper is to summarize and review our recent theory for type II bursts (Knock *et al.*, 2001, 2003) and related work (Kuncic *et al.*, 2002a, 2002b). Earlier, qualitative theories are reviewed elsewhere (Nelson and Melrose, 1985; Robinson and Cairns, 2000). The secondary purpose is to relate the theory to space weather physics, resulting in explanations for known empirical connections between type IIs and space weather events like CMEs, as well as new predictions. The theory is an analytic, quantitative description of type IIs with four stages:

Space Science Reviews **107:** 27–34, 2003.

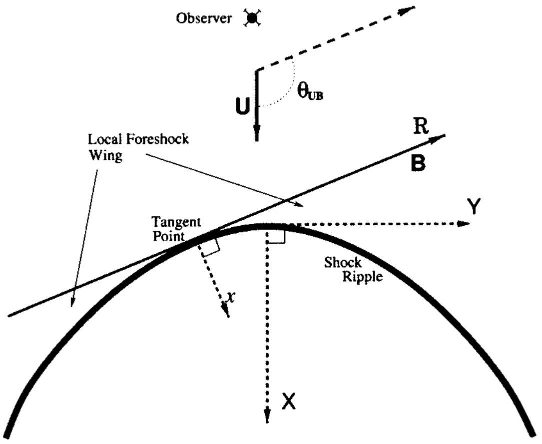

Figure 1. Foreshock geometry, shock and plasma variables, and coordinate systems.

(i) electron reflection and acceleration at the shock, including the shock's magnetic mirror and electrostatic cross-shock potential (Kuncic *et al.*, 2002a), (ii) formation of electron beams in the upstream foreshock region by time-of-flight effects (Filbert and Kellogg, 1979; Cairns, 1986), (iii) energy flow into Langmuir waves from electron beams, and (iv) specific nonlinear Langmuir processes for f_p and $2f_p$ radiation (Robinson and Cairns, 2000). Section 2 summarizes the basic physics and results while Section 3 contains predicted trends for type II emission. Comparisons between observation and theory, connections to space weather events, and future work are discussed in Section 4.

2. Basic Theory

Consider the global shock or a localized ripple thereon (cf. Bale *et al.*, 1999). Important shock/ripple parameters are (Figure 1): $U = |\mathbf{V}_{sh} - \mathbf{v}_{sw}|$ is the shock's speed relative to the plasma, where $\mathbf{V}_{sh}$ and $\mathbf{v}_{sw}$ are the (aligned) shock velocity and solar wind velocity, respectively, $\mathbf{B}_1$ is the upstream magnetic field vector, θ_{bu} the angle between $\mathbf{V}_{sh}$ and $\mathbf{B}_1$, and b is the shock's curvature parameter defined by $X = bY^2$. Then $b = R_c^{-1}$, where R_c is the radius of curvature at the shock's nose. The important plasma properties are the electron and ion temperatures T_e and T_i and the parameter κ of the incoming, gyrotropic, generalized-Lorentzian electron distribution, defined by

$$f_\kappa(v_\parallel, v_\perp) = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa)}\pi^{-3/2}V_e^{-3}\left(1 + \frac{v_\parallel^2 + v_\perp^2}{V_e^2}\right)^{-(\kappa+1)} \tag{1}$$

where $V_e = \sqrt{k_B T_e/m_e}$ is the electron thermal speed. The reduced distribution $F_\kappa(v_\parallel)$ formed by integrating (1) over $v_\perp$ varies asymptotically as $v_\parallel^{-2(\kappa+1)}$: lower κ corresponds to more high-velocity particles.

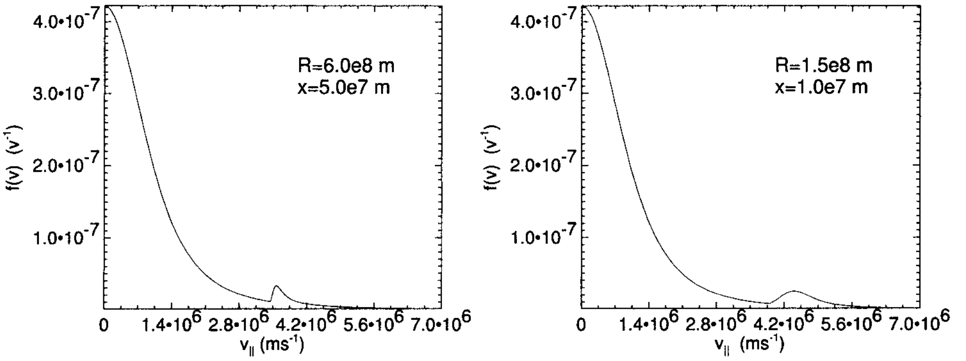

Figure 2. Beams in $F_\kappa(v_\parallel)$ at two foreshock locations (Knock *et al.*, 2001).

Electron reflection is best described in the de Hoffman-Teller frame, where the convection electric field vanishes, due to conservation of magnetic moment and energy, the latter subject to the electrostatic cross-shock potential ϕ_{cs}. The magnetic mirror ratio B_2/B_1 is predicted by the Rankine-Hugoniot conditions, which depend on the plasma's normal flow speed relative to the shock $\mathrm{U}_n = (\mathbf{V}_{sh} - \mathbf{v}_{sw})_n$, the angle θ_{Bn} between $\mathbf{B}_1$ and the local normal, the Alfven speed V_A and the sound speed c_S. Similar dependences exist for ϕ_{cs}, predictable analytically (Kuncic *et al.*, 2002a), which modifies the shock's loss cone at low $v_\parallel$ and makes it more difficult to reflect low $v_\parallel$ electrons. Reflection by the shock's magnetic mirror leads to shock-drift acceleration (SDA) in the plasma rest frame, similar to a ping-pong bat accelerating a ball: the reflected particle speed $v_\parallel^r$ is related to the initial speed $v_\parallel^i$ by

$$v_\parallel^r \approx 2v_d \, \tan\theta_{Bn} - v_\parallel^i \, , \tag{2}$$

where v_d is the component of $\mathbf{U}$ perpendicular to $\mathbf{B}_1$.

Liouville's Theorem is used to predict the reduced distribution $F_\kappa(v_\parallel)$ throughout the foreshock, by tracing particle paths back to the shock (with B_2/B_1 and ϕ_{cs} varying with position), unfolding the effects of SDA taking into account (2), equating $f(v_\parallel^r, v_\perp)$ to $f_\kappa(v_\parallel^i, v_\perp)$, and then integrating over $v_\perp$. Figure 2 shows that a beam develops by time-of-flight effects (Cairns, 1986; Knock *et al.*, 2001), as for Earth's bow shock (Filbert and Kellogg, 1979; Cairns, 1987; Fitzenreiter *et al.*, 1990). This beam is unstable to growth of Langmuir waves, with the available free energy varying with position (Knock *et al.*, 2001). Quasilinear relaxation relates the wave energy density at saturation to the available free energy. At marginal stability, as predicted by stochastic growth theory, the power flow into Langmuir waves equals the total time derivative of the available free energy, yielding (in steady-state)

$$\frac{d}{dt}W_L = \mathbf{v}.\frac{\partial}{\partial \mathbf{r}}\left(\frac{N_b v_b \Delta v_b}{3}\right) , \tag{3}$$

where N_b, v_b, and Δv_b are the number density, average speed, and spread in speed of the beam after quasilinear flattening. The term $\mathbf{v}.\partial/\partial\mathbf{r}$ is now approximated by v_b/l, where l is the distance from the shock to the observer location along the trajectory for $v_\parallel = v_b$.

Standard analytic nonlinear plasma theory yields the efficiencies with which energy is converted from the beam-driven Langmuir waves L into: (1) backscattered Langmuir waves L', $\phi_{L'}$, via the electrostatic decay $L \longrightarrow L' + S$, where S denotes an ion acoustic wave; (2) radiation near f_p, ϕ_F, via the electromagnetic decay $L \longrightarrow T(f_p) + S'$ where T represents a radio photon; and (3) $2f_p$ radiation, ϕ_H, via the coalescence $L + L' \longrightarrow T(2f_p)$. Functional forms are stated elsewhere (Knock *et al.*, 2001); although they depend on v_b, Δv_b, V_e, and the ion acoustic speed V_S, characteristic values are $\phi_{L'} \approx 10^{-3}$ and $\phi_F \approx \phi_H \approx 10^{-6}$. Combined with (3), these efficiencies yield the volume emissivities of radiation (power output per unit volume and solid angle) throughout the foreshock, with

$$j_M = \frac{\phi_M}{\Delta\Omega_M} \frac{N_b m_e v_b^3}{3l} \frac{\Delta v_b}{v_b} , \tag{4}$$

where $M = F$ or H, and $\Delta\Omega_F \approx 2\pi$ and $\Delta\Omega_H \approx 4\pi$ are the solid angles into which the radiation is produced.

Figure 3 shows j_F and j_H as functions of foreshock position (Knock *et al.*, 2001) for parameters appropriate to Bale *et al.*'s (1999) type II shock: $U = 744$ km s^{-1}, $\kappa = 2.5$, $b = 10^{-9}$ m^{-1}, $T_e = 3T_i = 1.5 \times 10^5$ K, $N_e = 7 \times 10^6$ m^{-3}, and $B_1 = 6$ nT. Fundamental radiation is predominantly produced where v_b is large, near the tangent field line, due to strong dependences of ϕ_F on v_b. Harmonic radiation, however, is produced over a greater area but with smaller peak magnitude. The peak values and characteristic ranges of j_F and j_H are comparable to those observed and predicted (Robinson and Cairns, 2000) for interplanetary type III bursts near 1 AU. Integrating the volume emissivities over the foreshock yields the flux $\int j_M/D^2\, d^3V$ of radiation, where D is the distance between the 3-D source element and observer.

3. Theoretical Trends for type II Emission

Figure 4 shows the fluxes of f_p and $2f_p$ radiation predicted as functions of U and κ for an observer at $(X, Y) = (-10^9$ m, 0) upstream of a single 3-D ripple (Knock *et al.*, 2003). Other parameters are as for Figure 3. The fluxes increase with increasing U and decreasing κ. Below ≈ 200 km s^{-1}, decreasing U at constant κ causes a rapid, approximately logarithmic drop-off in the fluxes. Similarly, increasing κ by 1 at constant U causes the harmonic flux to decrease by about 1 order of magnitude, while the fundamental flux varies by closer to 2 orders of magnitude between $\kappa = 2$ and 3. Accordingly, relatively small changes in U near 150 km s^{-1} and κ near 3 can change the predicted flux by orders of magnitude, thereby appearing to turn the emission on and off.

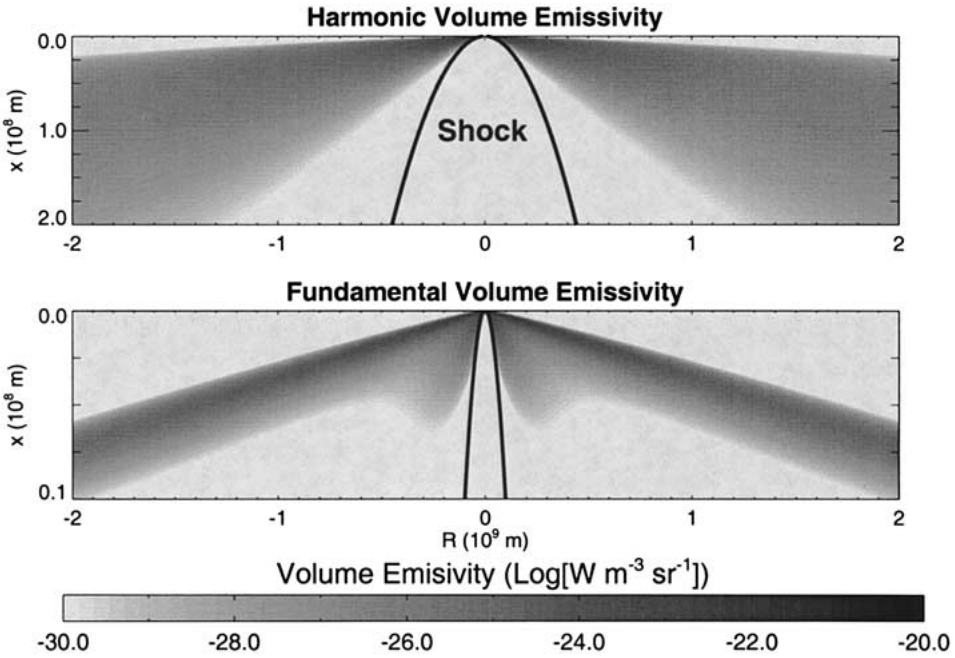

Figure 3. Volume emissivities j_F and j_H in the foreshock (cf., Knock *et al.*, 2001) for the shock and plasma parameters described in the text.

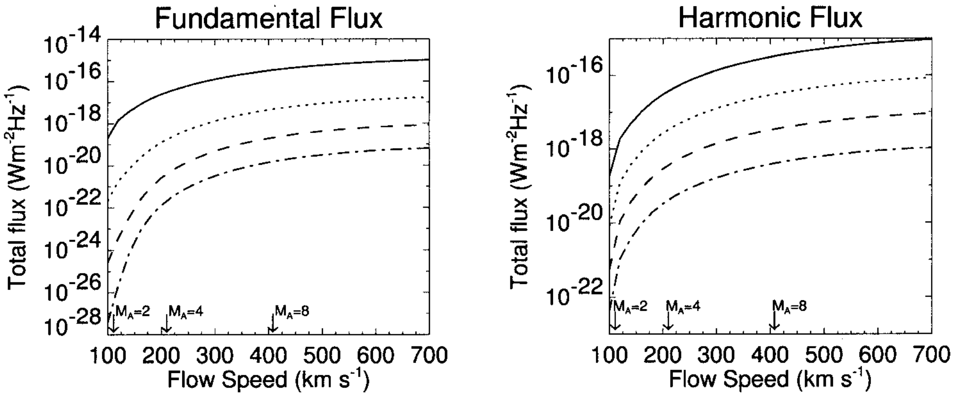

Figure 4. Variations of the predicted fundamental and harmonic flux with U and κ (Knock *et al.*, 2003): κ decreases from 2 to 5 from the top to bottom curve.

Figure 4 predicts that radio-loud shocks should be faster and move through solar wind regions with smaller v_{sw} and κ. The dependence on U follows from (i) SDA producing more fast electrons via (2), (ii) the shock's increased mirror ratio, and (iii) the increased foreshock volume at large $v_{\|}$. These effects increase the number or speeds of fast electrons, as does decreasing κ, leading to increased emission. Other trends as functions of b, T_e, θ_{UB}, N_e and B_1 exist (Knock *et al.*, 2003):

qualitatively, more intense radiation is predicted for smaller b (larger R_c), higher T_e and N_e, θ_{UB} closer to 90 deg, and lower B_1 and T_i. Since shock properties vary in the inhomogeneous solar wind, these dependences suggest type II bursts should be bursty and time-varying.

Preliminary comparisons with the fluxes $\approx 10^{-18}$ W m^{-2} Hz^{-1} observed for Bale *et al.*'s (1999) type II are encouraging (Knock *et al.*, 2001) given uncertainties in the shock and plasma parameters, with Figure 4 predicting fundamental and harmonic fluxes $\approx 10^{-17}$ W m^{-2} Hz^{-1}. A similar theory for Earth's foreshock radiation typically yields fluxes within a factor of 2 of those observed (Kuncic *et al.*, 2002b).

4. Relationships to Space Weather Events

The preceding theory predicts that radio-loud type II's should be associated with faster and larger (higher U and R_c) shocks and coronal mass ejections (CMEs). This is consistent with known space weather correlations (Cane and Stone, 1984; Gopalswamy *et al.*, 2001a). Since it is U and κ rather than V_{sh} alone that are relevant, the scatter in correlations of radio-loud or radio-quiet shocks with V_{sh} may be due to variations in v_{sw}, κ, and b. Radio-quiet CMEs are expected to have low U, large b and κ, quasi-radial $\mathbf{B}_1$, and small T_e and N_e.

The theory predicts 'hot spots' or localized bursts of type II radiation when the shock moves into solar wind regions with more high-v particles (lower κ), higher N_e or higher T_e. Examples are corotating interaction regions (CIRs), which increase the number of high-v electrons, and prominences. The theory is thus consistent with Reiner *et al.*'s (1998b) observations of hot spots associated with a CIR and prominence material. A more global example is of a fast CME shock overtaking an earlier CME, encountering the enhanced fast particles and heated, denser plasma associated with the slower CME's shock. Qualitatively one expects the second CME to produce a stronger type II burst than the first CME (if upstream parameters are otherwise identical), sometimes with neither CME being radio-loud until the second shock interacts with the first's downstream plasma. These expectations appear consistent with 'colliding CME' events recently seen (Gopalswamy *et al.*, 2001b).

These results point to the theory having significant future potential as a predictor of space weather. Predictions for multiple ripples, dynamic spectra, and coronal type IIs are still being developed. These indicate that IMF direction is important, with possible space weather implications, and that simulations of rippled shocks from the corona to 1 AU are necessary. Finally, we caution that the flux, shock, and plasma parameters of interplanetary type IIs remain poorly known and that detailed data-theory comparisons must still be performed.

5. Conclusions

An analytic, quantitative theory for type II solar radio bursts now exists (Knock *et al.*, 2001, 2003), treating electron energization at the shock, formation of electron beams, and transfer of electron energy into Langmuir waves and radio emission in a 3-D source volume. Predictions suitable for observational testing exist and preliminary comparisons are encouraging. Theory predicts that the radio flux depends sensitively on properties of the shock and solar wind plasma, so that type IIs should often be bursty and irregular. Radio-loud shocks and CMEs are predicted to be faster, larger, and to move through plasmas with lower v_{sw} and κ, with the first two dependences being consistent with known correlations and the others as yet untested. Explanations exist, and are qualitatively consistent with observations, for intensifications of type IIs associated with CIRs, prominences and colliding CMEs. While the theory has significant potential for space weather prediction, it must first be applied to coronal type IIs and tested in detail.

References

Bale, S. D., Reiner, M. J., Bougeret, J. L., Kaiser, M. L., Krucker, S., Larson, D. E. and Lin, R. P.: 1999, 'The Source Region of an Interplanetary Type II Radio Burst', *Geophys. Res. Lett.* **26**, 1573–1576.

Cairns, I. H.: 1986, 'Source of Free Energy for Type II Solar Radio Bursts', *Proc. Astron. Soc. Austr.* **6**, 444–446.

Cairns, I. H.: 1987, 'The Electron Distribution Function Upstream from the Earth's Bow Shock', *J. Geophys. Res.* **92**, 2315–2327.

Cane, H. V., Stone, R. G., Fainberg, J., Steinberg, J. -L. and Hoang, S.: 1982, 'Type II Solar Radio Events Observed in the Interplanetary Medium. 1 General Characteristics', *Solar Phys.* **78**, 187 –198.

Cane, H. V. and Stone, R. G.: 1984, 'Type II Solar Radio Bursts, Interplanetary Shocks, and Energetic Particle Events', *Astrophys. J.* **282**, 339–344.

Filbert, P. C. and Kellogg, P. J.: 1979, 'Electrostatic Noise at the Plasma Frequency Beyond the Earth's Bow Shock', *J. Geophys. Res.* **84**, 1369–1381.

Fitzenreiter, R. J., Klimas, A. J. and Scudder, J. D.: 1990, 'Three-Dimensional Model for the Spatial Variation of the Foreshock Electron Distribution: Systematics and Comparison with Data', *J. Geophys. Res.* **95**, 4155–4173.

Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A. and Bougeret, J. -L.: 2001a, 'Characteristics of Coronal Mass Ejectrions Associated with Long-Wavelength Type II Radio Bursts', *J. Geophys. Res.* **106**, 29219–29229.

Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A. and Bougeret, J. -L.: 2001b, 'Radio Signatures of Coronal Mass Ejection Interaction: Coronal Mass Ejection Cannibalism?', *Astrophys. J.* **548**, L91–94.

Knock, S. A., Cairns, I. H., Robinson, P. A. and Kuncic, Z.: 2001, 'Theory of Type II Radio Emission from the Foreshock of an Interplanetary Shock', *J. Geophys. Res.* **106**, 25041–25051.

Knock, S. A., Cairns, I. H., Robinson, P. A. and Kuncic, Z.: 2003, 'Theoretically predicted properties of Type II radio Emission from an Interplanetary Foreshock', *J. Geophys. Res.* **108**, 1126–1137.

Kuncic, Z., Cairns, I. H. and Knock, S. A.: 2000a, 'Analytic Model for the Electrostatic Potential Jump Across Collisionless Shocks, with Application to Earth's Bow Shock', *J. Geophys. Res.* **107**(A8), 10.1029/2001JA000250.

Kuncic, Z., Cairns, I. H. and Knock, S. A.: 2000b, 'Earth's Foreshock Radio Emission', *Geophys. Res. Lett.* **29**(8), 47(1)–47(4).

Lengyel-Frey, D.: 1992, 'Location of the Radio Emitting Regions of Interplanetary Shocks', *J. Geophys. Res.* **97**, 1609–1617.

Nelson, G. S. and Melrose, D. B.: 1985, 'Type II Bursts', in N. Labrum and D. J. McLean (eds.), *Solar Radiophysics*, Cambridge, Cambridge University Press, pp. 333–359.

Reiner, M. J., Kaiser, M. L., Fainberg, J. and Stone, R. G.: 1998a, 'A New Method for Studying Remote Type II Radio Emissions from Coronal Mass Ejection-Driven Shocks', *J. Geophys. Res.* **103**, 29651–29664.

Reiner, M. J., Kaiser, M. L., Fainberg, J., Bougeret, J. -L. and Stone, R. G.: 1998b, 'On the Origin of Radio Emission Associated with the January 6–11, 1997, CME', *Geophys. Res. Lett.* **25**, 2493–2496.

Robinson, P. A. and Cairns, I. H.: 2000, 'Theory of Type III and Type II Solar Radio Emissions, in R. G. Stone *et al.*(eds), *Radio Astronomy at Long Wavelengths*, American Geophysical Union, Washington, pp. 37–45.

Wild, J. P., Murray, J. D. and Rowe, W. C.: 1954, 'Harmonics in Spectra of Solar Radio Disturbances', *Austr. J. Sci. Res.* **A7**, 439–459.