Testing a theory for type II radio bursts from the Sun to near 0.5 AU

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Abstract. Type II solar radio bursts have resisted detailed explanation for over 60 years despite being the archetype for collective radio emission associated with shocks. Type II bursts are important because they involve fundamental physics and because most large space weather events at Earth are associated with large, fast, coronal mass ejections (CMEs) and so with type II bursts. Here we present strong evidence for the accurate and quantitative simulation of a type II burst from the deep corona (near 3 solar radii) to near 0.5 AU. The event was observed by the widely separated STEREO A and B spacecraft between 29 November and 1 December 2013. To do so we combine data-driven three-dimensional magnetohydrodynamic simulations (the BATS-R-US code) for the CME and plasma background with an analytic quantitative kinetic model for electron reflection at the shock, transfer of electron energy into Langmuir waves and radio emission, and propagation of radiation to an arbitrary observer. The intensities and frequencies of the radio emissions vary by factors $\approx 10^4$ and $\approx 10^2$, respectively. The theory predicts the intensities, frequencies, and timings of the multiple islands of type II emission very well, with the theory typically in error by less than a factor of 10, 20%, and less than an hour, respectively, for both STEREO A and B. This agreement is strong evidence for the type II theory itself and for accurate prediction by BATS-R-US, when carefully initialised with available data, of the background plasma and magnetic field configurations and of the CME’s properties and motion.

1. Introduction
Type II solar and interplanetary radio bursts are bands of emission, often occurring in pairs that differ in frequency by a factor close to 2.0, that drift from frequencies of order 1-200 MHz to 30 kHz and below as their sources move over several days from the corona through the solar wind to Earth and beyond [1, 3, 2, 4, 5]. They are the second most intense class of solar radio bursts, differing in time scale and exciter from the more intense type III radio bursts which typically last about 1 hour.

Type II bursts are the archetype for coherent radio emission produced upstream of shocks: electrons accelerated at the shock form beams in velocity space, which
drive high levels of Langmuir waves near the electron plasma frequency $f_p$, which then couple nonlinearly to produce radio emission near $f_p$ and $2f_p$ (so-called fundamental and harmonic “plasma emission”, respectively). The shocks are produced upstream of fast coronal mass ejections (CMEs). Type II bursts thus address fundamental science, since shocks and the electron beam - Langmuir wave systems are two of the most fundamental and important classes of phenomena in plasma physics, space physics, and astrophysics. In addition, the plasma emission mechanism is one of only 4 known coherent radio emission mechanisms.

Despite being discovered over 60 years ago a widely accepted quantitative theory for type II bursts, their fine structures, and their associations with other solar and interplanetary phenomena does not exist [2, 6, 5]. However, we have made great progress recently by combining a kinetic radiation theory [7, 8, 9, 10, 6, 11, 12] with event-specific 3D MHD simulations of CME evolution using the BATS-R-US code [13, 14]. These works demonstrate good agreement for type II emission in the high corona at 1 - 14 MHz for several events with no interplanetary extension [15, 16, 17]. The present paper is a first step towards demonstrating that this theory/simulation capability can accurately predict type II emission from the deep corona to 1 AU. It is the first interplanetary type II burst detected in situ (with associated Langmuir waves and energised electrons) by one of the two STEREO spacecraft (STEREO A, specifically), with both STEREO A and B observing the remote type II emission and the CME itself. The event occurred 29 November - 1 December 2013, with S.D. Bale first noticing the event and [18] first publishing the detailed Langmuir wave observations. Figure 1(left) and 1(right) show snapshots of the radio event and the associated CME, respectively, derived from NASA’s CDAWeb facility courtesy of N. Gopalswamy and colleagues. As discussed more below, the figure shows that the type II is produced only after the CME passes about 10 solar radii ($R_S$).

The advent of a combined kinetic radio - MHD CME simulation capability is potentially vital for predicting space weather at Earth. The reasons are that over 90 per cent of large space weather events at Earth are driven by large and fast CMEs [19, 20] and that type IIIs are preferentially produced by large and fast CMEs [2, 21, 5]. Thus, if we can accurately simulate specific type II bursts from the Sun to 1 AU, with radio data-theory comparisons establishing confidence in both the radio theory and the MHD simulation code, then prediction of whether the CME will hit the Earth’s magnetosphere and what the $B_z$ profile is will ideally allow quantitative prediction of the CME’s space weather effects, if any, with adequate lead-time for mitigation.

This paper proceeds by summarizing the radio theory and initialisation of the MHD simulation (Section 2) and presenting the radio predictions and observations in Section 3, restricted to the range $10^{-0.1}$ MHz. Section 4 contains the discussion and a summary.

2. Radio theory and MHD simulation

The radiation theory [7, 8, 9, 6, 11] involves 4 main physical steps, all of which are described quantitatively with analytic theory. The spatially varying shock location, shock normal, and upstream magnetic field and plasma parameters required to predict the radio emission are taken from the underlying MHD simulation, here the BATS-R-US code [13, 14, 22, 23, 24, 25, 26]. A more detailed description of the physics is elsewhere.
First, some superthermal ambient electrons are reflected back upstream of the shock by the shock’s magnetic mirror, resulting in energy gains, a loss cone, and an electron beam. The corresponding acceleration process is shock-drift acceleration, sometimes known in this context as magnetic mirror reflection since the electron gyroradii are typically small compared with the spatial scale of the shock’s ramp [27]. The energy gain depends on the angle $\theta_{bn}$ between the (local) shock normal and the (local) upstream magnetic field vector $\mathbf{B}$, with energy gains up to a factor $\approx 10$ for large $\theta_{bn} \approx 90$ deg and strong shocks with magnetic jumps $\approx 4$. Conservation of magnetic moment and energy in the de Hoffman - Teller frame are used to relate the initial and final electron velocities.

Second, a superthermal electron beam develops upstream of the shock because electrons require a minimum speed $v_e$ parallel to $\mathbf{B}$ in order to escape upstream of
the shock [28, 7, 29]. In the plasma rest frame this “cutoff” or “escape” speed is

\[ v_c = V_{sh} \sec \theta_{bn} \, , \]  

where \( V_{sh} \) is the shock speed normal to the shock surface. The electron beam speed is \( \approx v_c \). Liouville’s theorem is used to predict analytically the distribution function of electrons everywhere upstream of the 3D shock, assuming superposition of electrons reflected from the shock’s magnetic mirror and ambient electrons with a kappa distribution (in velocity)[11]. Interestingly, the escape speed mechanism corrects the physics compared with the earlier time-of-flight mechanism [28] but yields very similar \( v_s [7, 29] \).

Third, if fast enough, dense enough, and cold enough, the electron beam will drive Langmuir waves with frequencies just above \( f_p \) via the standard electron beam or “bump-on-tail” instability [28, 2, 7, 29]. As the waves grow, they take energy from the beam electrons, relaxing the distribution function towards a so-called “quasilinear plateau” for which the electron distribution function is locally flat and the resonant Langmuir waves have zero growth or damping. The energy flux into the Langmuir waves can be estimated using quasilinear theory as [8]

\[ \frac{dW_L}{dt} = m_e n_b v_b^2 \Delta v_b^3 \frac{2}{3l} \]  

The righthand side corresponds to an energy density multiplied by a fraction with the unit of inverse time. Here \( n_b, v_b, \) and \( \Delta v_b \) are the beam’s number density, speed, and spread in speed, respectively, at a specified location a distance \( l \) from the shock, all calculable analytically for \( \kappa \) electron distributions [11]. Clearly regions with large \( n_b, \) large \( v_b \) (corresponding to \( \theta_{bn} \approx 90 \, \text{deg} \) and large \( V_{sh} \) from Eq. 1) and small \( l \) are favoured for large energy fluxes into (and so usually large electric fields for) Langmuir waves.

The fourth step is to convert some Langmuir wave energy into radio emission [2, 8, 5]. Sufficiently intense Langmuir waves undergo electrostatic decay \( L \rightarrow L' + S \) of beam-driven Langmuir waves \( L \) into backscattered Langmuir waves \( L' \) and ion acoustic waves. Stimulated by these \( S \) waves, the electromagnetic decay \( L \rightarrow T(f_p) + S' \) of beam-driven \( L \) waves generates fundamental radio emission \( T(f_p) \) near \( f_p \) and ion acoustic waves \( S' \). Coalescence \( L + L' \rightarrow T(2f_p) \) of the \( L \) and \( L' \) waves produces harmonic radio emission \( T(2f_p) \) near \( 2f_p \). Known conversion efficiencies for these processes [30, 8, 5] are then combined with the calculated power flux into the Langmuir waves and the simulated electron beam and plasma parameters to analytically calculate the radiated power per unit volume into \( f_p \) and \( 2f_p \) radiation as functions of frequency, time, and location upstream of the shock [8, 11, 12]. Summing the emission from all active foreshock sources and taking into account the inverse square dependence of the flux on the distance between each cell and the observer, straight-line propagation from each cell to the observer (but with propagation blocked when the path includes locations with higher \( f_p \) than the radiation frequency \( f \)), and simple propagation time-delays (assuming \( f \gg f_p \)), leads to the predicted dynamic spectrum \( I(f, t) \). The conversion efficiencies for \( f_p \) and \( 2f_p \) radiation depend differently on the beam and plasma parameters [30, 8, 11], so that not all source regions on the shock will produce both observable \( f_p \) and \( 2f_p \) radiation.
Figure 2 shows the relative locations of STEREO A and B, the Sun, and Earth for the type II burst of 29 November - 1 December 2013. STEREO A and B are both on the backside of the Sun. Together, Figures 1 and 2 are consistent with the CME being directed primarily towards STEREO A. (Consistent with this STEREO A observed the CME-driven shock but STEREO B and near-Earth spacecraft did not.) Accordingly, and since STEREO A and B are almost 1 AU apart and the radio flux from a source depends on the inverse distance squared to the observer, we expect that STEREO A and B will measure significantly different dynamic spectra and so provide two independent tests of our type II theory/simulation capability.

![Figure 2](image)

**Figure 2.** Relative locations of STEREO A and B, the Sun, and Earth on 29 November 2013.

We use the 3D MHD code BATS-R-US code, developed at the University of Michigan [13, 14], to develop a realistic, event-specific, 3D model for the observed CME and to predict the evolution of the CME and its driven shock as they propagate through a realistic, event-specific, 3D plasma and magnetic field model for the background corona and solar wind. BATS-R-US solves the resistive MHD equations with a block-adaptive Riemann solver scheme.

The standard setup routines within BATS-R-US are used very carefully to develop the required models for the background corona and solar wind and for the CME. Magnetic fields in the background corona and solar wind are reconstructed using a potential field solar surface extrapolation from the Wilcox Observatory’s photospheric magnetograms for this specific solar rotation [22, 23]. The plasma is simulated using the standard BATS-R-US setup [24, 25, 26] with a refined Wang-Sheeley-Arge model driven by this solar rotation’s ACE spacecraft density data, plus spatially-varying polytropic indices for the solar wind acceleration and empirical heating functions for compression regions. A short run with these initial conditions allows an MHD-stable background to develop. The electron and proton plasma densities, temperatures, and flow velocities are assumed to equal the corresponding MHD quantities.
The initial CME is an analytic Titov and Demoulin [31] flux rope that is dimensioned using STEREO coronagraph data and has field directions given by the magnetogram data (not shown). The flux rope is superposed on the MHD background, with a short run yielding an MHD-stable background.

The CME release is via a standard current pulse method, whose characteristics are tailored iteratively using multiple short simulation runs) so that the predicted and observed CME height-time diagrams match below 5 solar radii. After CME release the existence and location of the CME-driven shock is established by looking for the surfaces with maximum entropy gradients. Rankine-Hugoniot analyses are then used to determine the shock normals, shock velocity, and plasma and magnetic field parameters upstream and downstream of the shock. Crucially, we emphasise that with the characteristics of the plasma and shock determined in position and time from the MHD simulation, and a value of $\kappa = 2.5$ [32] chosen for the ambient electrons, there are no free parameters in the predictions for the radio emission (or the shock and CME).

3. Radio results for 0.1 - 10 MHz: STEREO A and B event of 29 November to 1 December 2013

Figure 3 compares the theoretical predictions with the observations for both STEREO A and B in the domain 0.1 – 10 MHz. (The results below 0.1 MHz, including the local radio onset, Langmuir waves, shock crossing, and CME characteristics observed at STEREO A are discussed elsewhere [18, 33]. Figure 3’s top and middle panels show the dynamic spectra predicted for STEREO A and B (left and right, respectively) without and with the instrumental background, respectively. The type II is predicted to consist of multiple islands of emission, both fundamental (lower frequency, more intense emissions) and harmonic, with intensities that vary by a factors of over $10^6$ without background and of over $10^4$. For this event the dominant emission is predicted to be fundamental in this frequency range, with the harmonic being essentially at or below the instrumental background. (Although not shown here, harmonic emission is predicted and observed to dominate radio emission just before the CME-driven shock crosses STEREO A.) It is clear that the dynamic spectra predicted for STEREO A and B are recognisably different, with multiple islands of emission being detectable only for STEREO A and almost all islands more intense for STEREO A. This is expected for a source closer to STEREO A than B, as expected based on the Figure 2 and the CME and its shock crossing STEREO A but not STEREO B.

The bottom panels in Figure 3 superpose the envelopes of the predicted radio signals from the middle panels (with white borders) over the STEREO wave data. All six panels use the same absolute colour bars. It is evident that the theoretical predictions agree very well with the observations, since the white envelopes are very close in frequency and time to the observations. Moreover, the islands agree very closely in colour and so intensity. For instance the first island of fundamental emission is almost precisely predicted in frequency ($\approx 1.3 - 2.0$ MHz), time ($\approx 2200 - 2230$ UT), and intensity ($\approx 10^{-18}$ W m$^{-2}$ Hz$^{-1}$) and the second island is displaced upwards by $\approx 10 - 20\%$ but has the correct colour. The predictions and observations are also consistent for the remaining islands, although interference from type III bursts complicates detailed comparisons. A very weak signal near 3 MHz and time 2220 UT may be harmonic emission just above
the instrumental background, rather than just below the background as predicted. It is appropriate to conclude that the theory predicts the observed radiation well, being within a factor of 10 in intensity over range of at least a factor of $10^4$, within 20% in frequency, and within better than an hour in time.

An important point to make, in addition, is that significant emission is not predicted where it is not observed. Specifically, the theory does not predict a metric type II burst.
or emission above about 4 MHz and none is observed.

4. Discussion and Summary
It is important to understand the island structure of the observed radio emissions, the absence of emission above about 4 MHz, and where the shock develops. Figure 4(Left) presents the ratio of the simulated magnetic field strengths just downstream and upstream of the shock as a function of radial distance $r$ (and so of time) along the direction determined by the velocity vector of the CME’s centroid, corresponding to the shock’s nose location (or maximum distance from the Sun). This ratio $B_2/B_1$ must exceed 1 for a shock to exist. Since $B_2/B_1 > 2$ for $r > 2R_S$, Figure 4(Left) shows that a moderately strong shock forms below $2R_S$ and that the shock only strengthens by about 40% with increasing $r$ and $t$. With Figure 1 showing that no type II emission is observable until the CME reaches about $10R_S$ and Figure 4(Left)’s showing that the shock evolves low in the corona and remains moderately strong from early times, it is clear that this event’s type II emission does not turn on quickly after the shock forms or strengthens suddenly. Accordingly the start of type II emission cannot be interpreted routinely as the time of the shock’s formation or as a time when the shock suddenly strengthens.

![Figure 4](image.png)

**Figure 4.** (Left) The ratio $B_2/B_1$ of the magnetic field downstream and upstream of the nose of the simulated shock (corresponding to the Rankine-Hugoniot prediction for the shock) as a function of heliocentric distance $r$. (Right) The value of $\theta_{bn}$ at the shock’s nose as function of $r$.

Figure 4(Right) shows $\theta_{bn}$ as a function of $r$ along the velocity vector of the CME’s centroid. Crucially, $\theta_{bn}$ remains small compared with 85 deg until $r \geq 11R_S$ and Figure 1 shows that the radio emission starts when the shock nears $11R_S$. Thus, Figures 1, 3, and 4 provide strong evidence that the first island of radio emission starts when the shock’s nose reaches a spatial region where the magnetic field orientation is close to perpendicular to the shock normal (almost parallel to the local shock surface). This is where the theory in Section 2 (cf. also [34, 2, 7, 5]) predicts that mirror reflection can
produce fast electrons and a large energy flow into the Langmuir waves should occur. Put another way, the radio emission starts when sufficiently large regions of the shock reach regions where $\theta_{bn} \approx 85 - 90\,\text{deg}$. Similar results were found in our earlier work on purely decametric type II bursts [15, 16, 17]. The simulation results are therefore internally self-consistent and consistent with the theory. Furthermore, the very good agreement between the observations and the predictions provides strong evidence that the theory and simulation account very well for the observations and so represent a viable solution for the “type II problem”.

It is emphasized that the agreements in frequency, timing, and intensity of the islands of observed and predicted type II emission in Figure 3 are amazingly good. This demonstrates not only that the kinetic radio theory is performing extremely well but also that the predicted time-varying 3D shock location, velocities, and jump conditions and also the predicted 3D magnetic fields (both their orientations and magnitudes) and density structures are predicted very well by our data-driven BATS-R-US simulation.

It is typical in works on solar and interplanetary radio bursts to regard the density at any given location to vary by a factor of 10 up or down with time (e.g., from day to day), corresponding to factors of 3 in $f_p$ and 3 to 6 in the radiation frequency (the latter for $2f_p$ radiation). Similar comments follow for the density as a function of solar latitude and longitude and $r$. Thus to correctly predict the frequency of the radiation to within $\approx 20\%$ and whether the radiation is produced near $f_p$ or $2f_p$ are major theoretical feats. Similarly, the predicted electron beam, Langmuir wave, and radio emission parameters depend sensitively on $\theta_{bn}$ upstream of the 3D shock, as shown in Section 2 and the papers quoted therein, so to accurately predict the observed islands of emission within a factor of 10 in intensity, $20\%$ in frequency, and fractions of an hour in time requires very accurate prediction of the 3D CME and plasma properties by the data-driven BATS-R-US simulation. To be blunt, for these reasons the authors expected to only obtain qualitative agreement between observations and predictions when they started this work. Since they have found similarly good semi-quantitative agreement for their 3 published events [15, 16, 17] and the current event, the agreement found does not appear to be chance but instead to show that carefully initialised, data-driven, BATS-R-US simulation runs appear to be a very fruitful approach to modelling CMEs and related triggering of space weather events. Indeed, although not shown here, the current run predicts very well the time-varying $B_z$ field and the shock’s arrival time (within about 1 hour) at STEREO A [33]. Thus, the agreement found can be regarded as strong evidence that BATS-R-US when properly initialised is surprisingly accurate.

The current analyses have multiple limitations. One is that we assumed that the background corona and solar wind remained constant over a solar rotation when setting up the simulation. This ignores time variations during the event-centered solar rotation. Others are the multiple, but standard, assumptions made in the BATS-R-US setup for the corona and solar wind [22, 23, 24, 25, 26]. Another is that a simple Titov and Demoulin [31] model is assumed for the flux rope, with parameters inferred from coronagraph images and by comparing the predicted and observed CME height-time variations. Nevertheless, the very good agreement found between the predicted and observed radio emissions (and the shock arrival time and $B_z(t)$ variations at STEREO A [33]) suggests that these limitations are not severe.
Multiple avenues for further work are apparent. One is to directly predict the time-varying locations of the active radio sources and to compare these with STEREO and other observations. Another is to model one or more metric type II bursts, as well as other type IIs that extend into the interplanetary medium. Another is to refine the theory, for instance along the lines in Ref [5]. Another, perhaps more important, one is to couple the radio code with the output from other 3D MHD codes for the current event and other events.

In summary, this paper presents strong evidence for the accurate and quantitative simulation of a type II burst from the deep corona (near 3 solar radii) to near 0.5 AU. The analysis combines data-driven and event-specific 3D MHD simulations with the BATS-R-US code for the CME, shock, and plasma background with an analytic quantitative kinetic model for electron reflection at the shock, transfer of electron energy into Langmuir waves and radio emission, and propagation of radiation to an arbitrary observer. The intensities, frequencies, and timings of the islands of radio emission are predicted very well by the simulation, with errors typically by less than a factor of 10 (over a range of \( \approx 10^4 \)), 20% (over a range of 100), and less than an hour, respectively, for both STEREO A and B. The radio source turns on when sufficiently large regions of the shock enter plasma domains where \( \theta_{bn} \geq 80 \text{ deg} \), as expected theoretically, and not when the shock first develops. In this case the type II emission is predicted and observed to start when the shock nose is near \( 11R_S \) whereas the shock forms below \( 2R_S \). Together with previous results for three decametric type IIs, the very good agreement between the predictions and observations provides strong evidence for the type II theory itself and for the accurate prediction by BATS-R-US (when carefully initialised, at least) of the CME’s 3D properties and motion and of 3D plasma and magnetic field environment through which the CME-driven shock moves.

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