Estimation of CME shock wave speed out of type II bursts

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Introduction

The Sun is an active star that produces large-scale energetic events, such as solar flares and coronal mass ejections (CMEs). These phenomena are observable across the electromagnetic spectrum, from gamma rays with energies of hundreds of MeV to radio waves with wavelengths of tens of meters. Solar flares and CMEs can excite plasma oscillations which can emit radiation at metric and decametric wavelengths. These bursts are classified in five main types. Type I bursts are short-duration narrowband features that are associated with active regions.

Type II bursts (see figures 3 and 4 below) are thought to be excited by magneto-hydrodynamic (MHD) shockwaves. They frequently occur as two relatively slow drifting emission bands [fundamental (f) and harmonic (h)] with a frequency ratio of approximately 1:2. The frequency drift from high to low frequencies (typically about 0.5 MHz/s) results from the decrease of electron density (*Ne*) with radial distance (r) in the solar atmosphere. The observed drift rate can be converted into a velocity (v) if the dependence of *Ne* on *r* is known.

Type III bursts result from energetic particles escaping along open magnetic field lines. Type IV bursts show broad continuum emission with rapidly-varying fine structures. The smooth short-lived continuum following a Type III burst is called a Type V.

In this document we concentrate on type II bursts mostly connected to CMEs and we will demonstrate how to derive the shock wave speed in interplanetary space.

In the solar corona energetic electrons are released e.g. during solar flares and travel along magnetic field lines either toward or away from the Sun. While they propagate through the plasma background they excite Langmuir waves via beam-plasma-instability. The energy of Langmuir waves is partly converted into electromagnetic radiation with a frequency close to the electron plasma frequency, f, and/or its harmonics such that

Corona: The outermost layer of the Sun is the corona. Only visible during eclipses, it is a low density cloud of plasma with higher transparency than the inner layers. The white corona is a million times less bright than the inner layers of the Sun, but is many times larger. The corona is hotter than some of the inner layers. Its average temperature is 1 million K but in some places it can reach 3 million K. Temperatures steadily decrease as we move farther away from the core, but after the photosphere they begin to rise again. There are several theories that explain this, but none have been proven.

Langmuir waves: Plasma oscillations, also known as "Langmuir waves" (after Irving Langmuir), are rapid oscillations of the electron density in conducting media such as plasmas or metals. The oscillations can be described as an instability in the dielectric function of a free electron gas. The frequency only depends weakly on the wavelength. The quasiparticle resulting from the quantization of these oscillations is the plasmon. Langmuir waves were discovered by American physicists Irving Langmuir and Lewi Tonks in the 1920s.

$$\omega = 2\pi f = \sqrt{\frac{e^2\,Ne}{\varepsilon\,me}} = 2\pi\,8.977\,10^3\,\sqrt{Ne} \qquad (1)$$

$$f = 8.977\,\sqrt{Ne} \quad [\text{Hz, m}^{-3}] \qquad (2a)$$
$$f = 8.977\,10^{+3}\,\sqrt{Ne} \quad [\text{Hz, cm}^{-3}] \qquad (2b)$$
$$f = 8.977\,10^{-3}\,\sqrt{Ne} \quad [\text{MHz, cm}^{-3}] \qquad (2c)$$
$$f = 8.977\,10^{-6}\,\sqrt{Ne} \quad [\text{MHz, m}^{-3}] \qquad (2d)$$

where ε, e, m_e and N_e denote to the dielectric constant of vacuum, the elementary charge, the mass of an electron and the electron number density, respectively. For equation (1) as a graph, see figure 1.

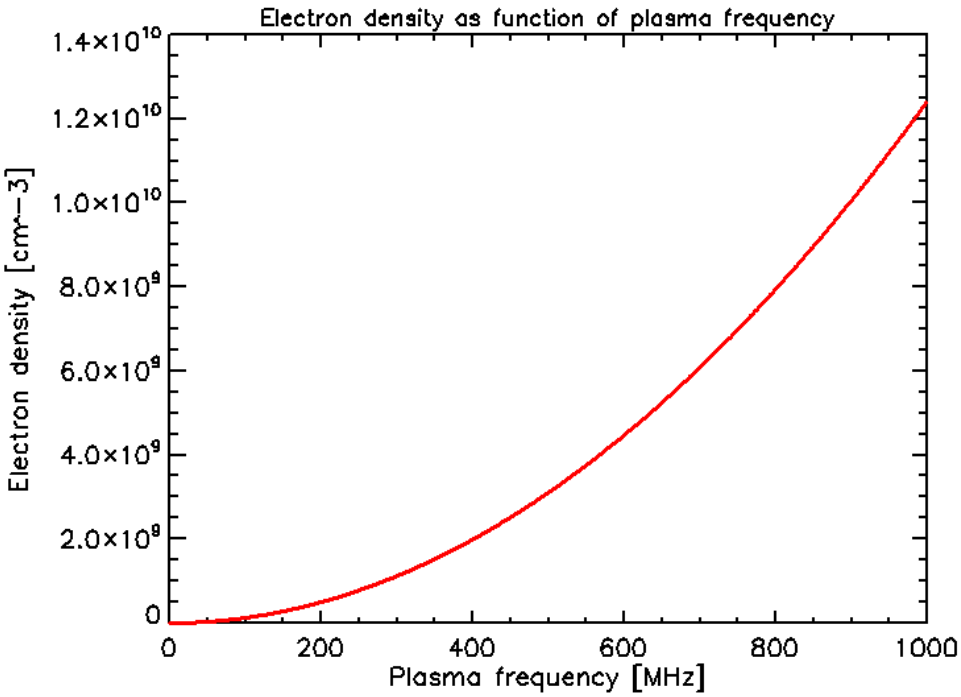

Figure 1: Electron density as function of plasma frequency (MHD) in solar corona.

If those electrons have sufficient energy, and the plasma background is dense enough, they can emit non-thermal X-ray radiation via bremsstrahlung, which can be detected by spacecrafts such as Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) or by the Spectrometer Telescope for Imaging X-rays (STIX) which is one of 10 instruments on board of Solar Orbiter, (launch ~ 2017).

On the other hand electrons moving toward the interplanetary medium up to distance of 1 AU can be observed in-situ by spacecrafts such as WIND.

All type II bursts in this paper were observed with Callisto spectrometers which are part of the worldwide e-Callisto network (http://www.e-callisto.org/). In the text below we will develop a step by step procedure to estimate the shock wave speed of CME which are closely related to type II bursts.

WIND is a spin stabilized spacecraft launched in November 1, 1994 and placed in a halo orbit around the L1 Lagrange point, more than 200 Re upstream of Earth to observe the unperturbed solar wind that is about to impact the magnetosphere of Earth.

Step-by-step procedure to derive shock speed from type II bursts

- Define and measure at least two frequencies f(t) at opposite times t of observation, see figure 3.
- Determine the electron density scale height in the ambient corona medium to get the shock speed at different times (t). Several theories about density exist based on different assumptions about the degree of solar activity. Density scale height need the density variation in the corona as a function of distance r from the Sun center. Newkirk [Newkirk 1961] developed a theory in 1961 which is still valid nowadays, shown graphically in figure 2, although today there are newer but more complex models available, e.g. Gottfried Mann [Mann 2011].

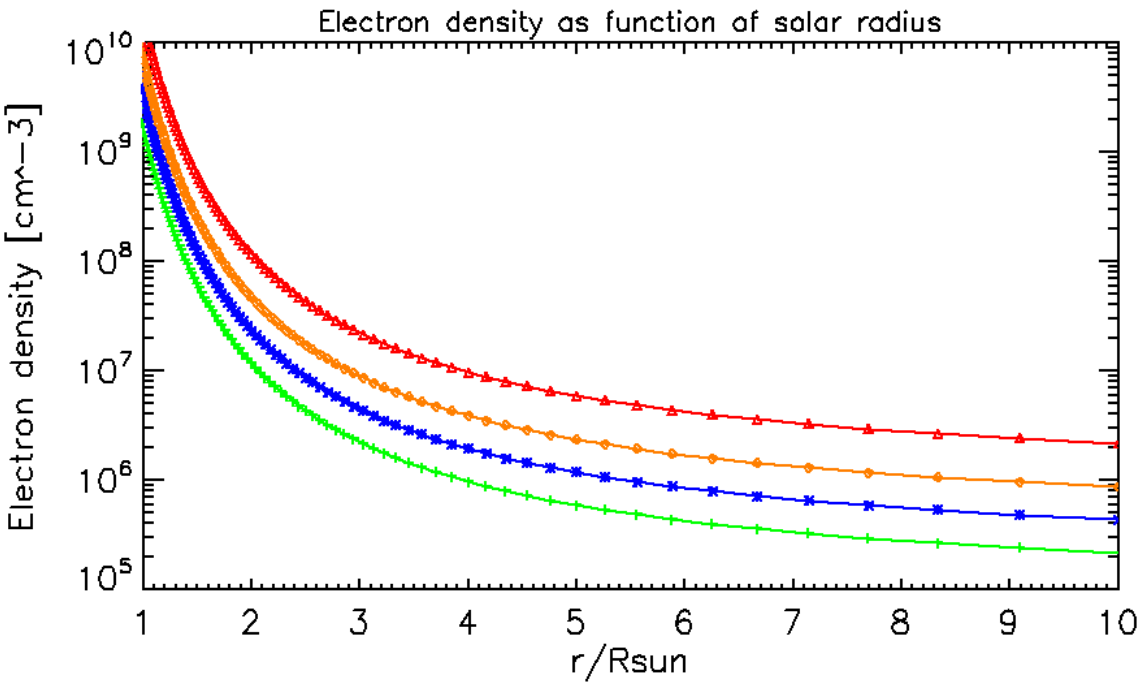

Figure 2: Electron density as function solar radius after Newkirk [Newkirk 1961]. Green (+) presents Newkirk model 1 for quiet Sun, blue (*) model 2 for slightly active Sun, orange (rhomb) model 3 for more active Sun and red (Δ) model 4 for very active Sun. Discussions how one would know when to use quiet, slightly active, active and very active Sun are still ongoing. Different scientists have different opinions about it.

From equation (2) we can derive the plasma density (Ne) as function of emission frequency (f) as shown in equation (3)

$$Ne = \left[\frac{f}{8.977}\right]^2 \qquad [\text{Hz, m}^{-3}] \tag{3a}$$

$$Ne = \left[\frac{f}{8.977\ 10^3}\right]^2 \qquad [\text{Hz, cm}^{-3}] \tag{3b}$$

$$Ne = \left[\frac{f}{8.977\ 10^{-3}}\right]^2 \qquad [\text{MHz, cm}^{-3}] \tag{3c}$$

$$Ne = \left[\frac{f}{8.977\ 10^{-6}}\right]^2 \qquad [\text{MHz, m}^{-3}] \tag{3d}$$

The emission takes place at the fundamental (f) frequency or its harmonic (h) which is an issue as we can see in the type II burst plots below. Without data from the low frequency range, we are never sure whether we are dealing with fundamental or harmonic emission. To be really sure about fundamental or harmonic emission, we need additional observations at frequencies below 100 MHz, which are recognizable in the semi-transparent ellipsoid in figure 3.

Abbreviations:
AU Astronomical unit
CMD Coronal Mass Ejection
IDL Interactive Data Language
LPDA Logarithmic Periodic Dipole Array
LHCP Left Hand Circular Polarization
MHD Magneto Hydro Dynamic
NASA National Aeronautics and Space Administration
RHCP Right Circular Polarization

Modeling

A simple density model (beside some other more complex ones) is the Newkirk model shown in equation (4) below and plotted in figure 2.

$$Ne(r) = 4.2\ 10^4\ \alpha\ 10^{\left(\frac{4.32}{r}\right)} \qquad [\text{cm}^{-3}]\text{, after Newkirk} \tag{4a}$$

$$Ne(r) = 4.2\ 10^{10}\ \alpha\ 10^{\left(\frac{4.32}{r}\right)} \qquad [\text{m}^{-3}]\text{, after Mann} \tag{4b}$$

where α is the multiplication factor for the Newkirk density model of the corona and r is the radial distance of the Sun surface in units of Rsun where Rsun = 6.958 10^5 km. Taking the base-10 logarithm of equation (4a)

$$\log(Ne) = \log(4.2\ 10^4) + \log(\alpha) + 4.32/r \quad [\mathrm{cm}^{-3}] \tag{5}$$

Equation (5) can now be solved for r as function of electron density Ne.

$$r(Ne) = \frac{4.32}{\log(Ne) - \log(\alpha) - \log(4.2\ 10^4)} = \frac{4.32}{\log\left(\frac{Ne}{\alpha\ 4.2\ 10^4}\right)} \quad [\mathrm{km}] \tag{6}$$

As soon as we have two radial distances r1 and r2 at two different times t1 and t2 of the type II radio burst we can derive the velocity of charged particles penetrating interplanetary space.

$$v = \frac{\Delta r}{\Delta t}\ Rsun = \frac{r2 - r1}{t2 - t1}\ Rsun \quad [\mathrm{km/s}] \tag{7}$$

Now, using equations (3 and 6), we can derive r in a few steps:

1. Read the frequency of interest from the spectrogram
2. Calculate the electron density according to equation (3)
3. Decide for the Newkirk model (1, 2 or 4) depending on level of solar activity
4. Calculate radial distance r(Ne) following equation (6)
5. Repeat steps 1. through 4. for a second frequency on the ridge of the burst
6. Put both times and both radial distances into equation (7) and get the speed of the shock wave.

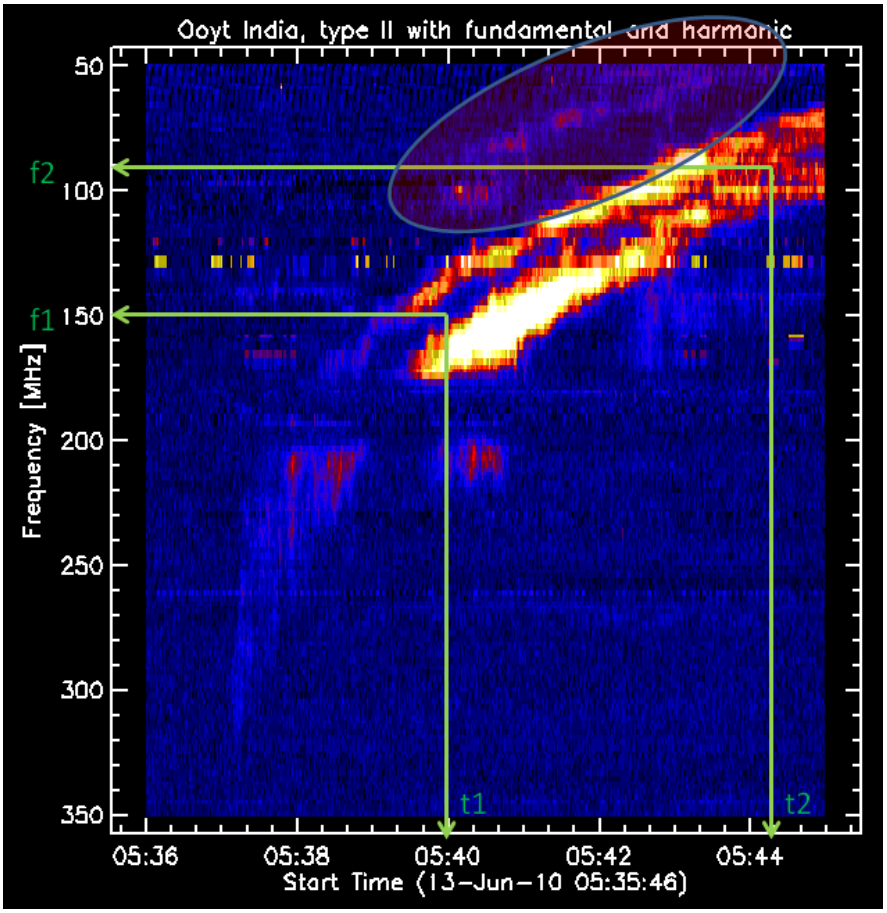

Figure 3: Type II radio burst observed in Ooty/India with an LPDA. Plot shows fundamental emission inside of the semitransparent ellipsoid, 1st harmonic and band-splitting (bright structure). We are allowed to derive the time and frequency from the harmonic emission but we have to be aware to apply the equations to the fundamental part of the burst.

Analysis of Figure 3

t1 = 05:40:00, t2 = 05:44:20 → Δt = t2 – t1 = 260 s
$f1_h$ = 150 MHz → f1 = $f1_h$/2 = 75 MHz (conversion of harmonic to fundamental)
$f2_h$ = 90 MHz → f2 = $f2_h$/2 = 45 MHz (conversion of harmonic to fundamental)

$$Ne(f1) = \left[\frac{f1}{8.977\ 10^{-3}}\right]^2 = 6.96\ 10^7 \qquad [cm^{-3}]$$
$$Ne(f2) = \left[\frac{f2}{8.977\ 10^{-3}}\right]^2 = 2.51\ 10^7 \qquad [cm^{-3}]$$

r(Ne1) = 1.6506 [km]
r(Ne2) = 1.9868 [km]

$$v = \frac{\Delta r}{\Delta t} Rsun = \frac{1.9868-1.6506}{260\ s} * 6.958\ 10^5 km\ = 900\ km/s$$

Natchimuk Gopalswamy (NASA) [Gopalswamy 2012] taking into account a much more complex method and more parameters got for the same flare between times 05:36:54 and 05:41:54 a speed range of 531 km/s ... 721 km/s. So with our 'simple' code we get an error of about 25%.

Finally, there is a lot of room to improve the models and the assumptions. The reader may try to figure out the shock wave speed of figure 4. Irish colleagues have recently provided an IDL code to derive the shock wave speed based on the simple Newkirk model described above. Interested readers can get a copy of the code by sending a corresponding email to the author.

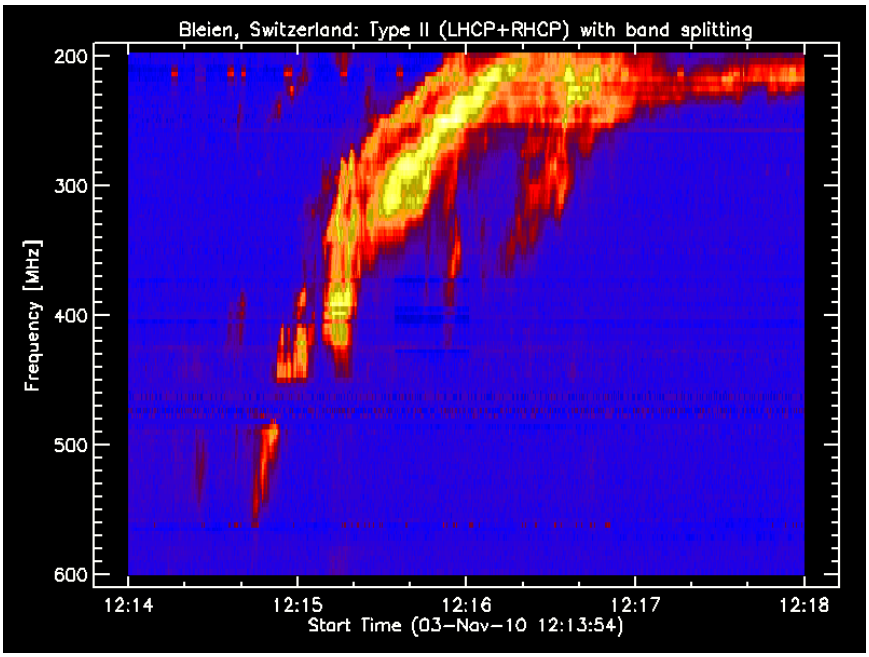

Figure 4: Type II radio burst observed in Bleien/Switzerland with a 7m dish (I = LHCP + RHCP). Does plot show fundamental and/or 1st harmonic? We are not quite sure but there is a weak indication at 12:15 UT between 200 MHz ans 250 MHz. Most probably, the bright structure shows the 1st harmonic. It also shows band splitting and herring bone structures.

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- Private communication with Nat Gopalswamy NASA, P. Zucca TCD and A. Benz ETH Zurich.

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