Advances in Astronomy and Space Physics, **2**, 157-160 (2012)

The energy sources of CME acceleration

H. Allawi[1,2]*, *S. Pohjolainen*[1]

[1]University of Turku, Department of Physics and Astronomy, Tuorla Observatory, Piikkiö, Finland
[2]Thi Qar University, Department of Physics, Nasryia, Iraq

We investigate the possibility that during the fast acceleration phase of a coronal mass ejection (CME), a freely propagating shock wave could be launched. We test this hypothesis by calculating the speeds of blast waves by using the Taylor-Sedov equation in changing density solar atmosphere, and compare these speeds with the radio type II burst speeds during the CME event on 17 February 2000. The matching speeds and the realistic value of the blast wave energy, 10^{24} J, lead us to suggest that the CME acceleration phase may involve shocks separating from the initial CME driver.

Key words: Sun: Coronal Mass Ejections (CMEs); Sun: radio radiation; Shock waves; Plasma emission

INTRODUCTION

Solar eruptions are often associated with shock waves that are able to accelerate particles, electrons and protons [8]. Solar shock waves can be divided into two different types: blast waves and driven shocks. A typical example of a blast is a solar flare where the magnetic energy is released instantaneously and the blast wave propagates into the surrounding medium until the energy is spent and the blast dies out. A driven wave, on the other hand, can gain in energy while the shock propagates, and in the solar atmosphere shocks driven by coronal mass ejections (i. e., ejected plasmoids) are typical examples. A long-standing research issue is the energy released in these eruptions. And more specifically, what is the origin and mode of shock waves that can accelerate particles to high energies.

Propagating shock waves in the solar corona can be detected by the trail they may leave in radio emission. Shock-accelerated electrons cause oscillations in the surrounding plasma, and these oscillations emit radio waves at the local plasma frequency and its harmonics. In the solar corona, these are known as radio type II bursts. As the plasma frequency f_p depends only on the local electron number density n_e by $f_p = 9\sqrt{n_e}$ (SI units), the propagating shocks can be followed in the atmosphere if we know how the electron density changes along the path of propagation. For reviews on the formation of radio waves see, e. g., [1, 7], and references therein.

Coronal mass ejections (CMEs) are known to show three distinctive phases: initial slow rise, fast acceleration period, and a later more steady propagation. The shocks associated with CMEs are generally considered to be driven waves, but there is also some discussion whether blast waves could still occur in the early phases of CME development (for a review on solar shock waves see, e. g., [14]). One possibility would be the fast acceleration phase, if a freely propagating shock (i. e. behaving like a blast wave) could separate from the CME-driven shock. This method would also give an estimate of the blast wave energy, to be compared with the estimates of CME kinetic energy. However the usual energy estimate $E = \frac{1}{2}mv^2$ contains large uncertainties due to the problem of estimating mass of CME m from coronagraph images. Further on the mass of 'halo'-type CMEs cannot be measured at all, this would complement the current CME energy estimates. In order to test this suggestion, we analyse here one type II burst to see if its propagation is compatible with the blast wave scenario. Additionally we are able to bring in the focus what is the energy involved.

APPLICATION OF THE BLAST WAVE SCENARIO

Blast waves in their most simple form can be described with the Taylor-Sedov equation [10, 12],

$$R(t) = C\left(\frac{Et^2}{\rho}\right)^{1/5}, \tag{1}$$

where E is the initial energy of the source, t is the time since the blast start, ρ is the mass density of surrounding medium, and $R(t)$ is the radius of the blast wave at time t. The constant C depends on the density of surrounding medium(gas), and in many cases it can be assumed as unity. Therefore knowing the

*habeeb.allawi@utu.fi

radius of the blast, the time since the blast start, and the mass density of the surrounding medium, one can deduce the initial energy. Blast waves eventually decay and slow down when no extra energy is supplied to the system.

The problem of applying the Taylor-Sedov equation in solar corona is the changing density of the atmosphere along the path of propagation. A detailed electron number density model has been constructed by Vršnak et al. [13], to define the number densities in the solar corona and interplanetary space all the way to Earth (for this, it is called a 'hybrid' model). For the Taylor-Sedov equation the electron number densities must be changed to mass densities. Because the proton contribution to the mass density is significant, we use here the helium-to-hydrogen density ratio of $n_e = 1.1 n_H$, and get the total mass density as $\rho = 1.09\, n_e\, m_H$, see [3].

A rough approximation for the changing density can be described as

$$\rho = \rho_0 \left(\frac{R_0}{R}\right)^{\beta}, \tag{2}$$

where ρ_0 and R_0 are the density and distance of a known reference point (for example at Earth distance, 1 AU, the mass density is known to be $\approx 10^{-20}\,\mathrm{kg\,m^{-3}}$, see Fig. 1), ρ and R are the density and distance in question, and β gives the slope of density change (in this solar wind model β also represents the changing plasma beta value). More precise and detailed treatment of the changing density can be found in, e. g., [9, 11]. Fig. 1 also shows the heliocentric distance region of 2–5 $\mathrm{R}_\odot$ where solar energetic particles (SEPs) are thought to be injected or accelerated [4, 5].

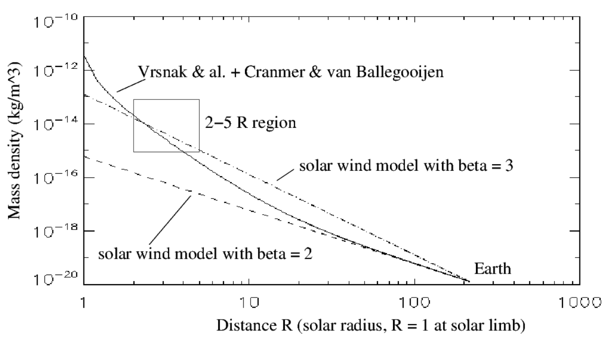

Fig. 1: Solar wind mass densities with different values of β (dashed lines) compared to the calculated mass densities from the 'hybrid' number density model (solid line). The reference point R_0,ρ_0 is at Earth distance. The box 2–5 $\mathrm{R}_\odot$ shows the most interesting region in the solar corona, in respect to acceleration of energetic particles.

Inserting Eq. (2) into Eq. (1) and differentiating, $u = dR/dt$, we get $t = \frac{2R}{(5-\beta)u}$. Substituting this into Eq. (1) and using $C = 1$ we get

$$R = \left[\left(\frac{2}{5-\beta}\right)^2 \frac{E}{\rho_0 R_0^{\beta} u^2}\right]^{1/(3-\beta)}, \tag{3}$$

from which shock velocity u can be determined at distance R when the initial blast wave energy E and the slope of density decrease are known from ρ_0, R_0, and β.

ANALYSIS OF THE 17TH OF FEBRUARY 2000 EVENT

We apply here the blast wave scenario to a solar flare-CME event on 17th of February 2000 which was associated to a type II radio burst. The idea is to estimate the energy of blast wave by comparing the speeds of observed type II to the speeds of calculated blast shock, assuming that the blast is created at the moment when the type II burst appears in the spectrum.

The 'halo' type CME propagated with a speed of $728\,\mathrm{km\,s^{-1}}$ (linear fit to all the time-distance data points) and the source region was located at S29 E07, with a GOES M1.0 class flare starting at 20:17 UT [2].

In this event the burst emission is observed to drift from 6 to 2.6 MHz (frequency of fundamental plasma), and as usual the emission is somewhat fragmented and possibly also band-split, see Fig. 2. At time t0 (regarded as the shock/blast wave start) the emission frequency was 6 MHz, which corresponds to a heliocentric height of 4.1 $\mathrm{R}_\odot$ (Vrsnak et al. atmospheric model, [13]). At time t3 (3 MHz) the height was 5.7 $\mathrm{R}_\odot$. The difference of the height, 5.7–4.1 $\mathrm{R}_\odot$, is then the distance travelled by the type II burst/shock wave in time t3–t0 (1.6 $\mathrm{R}_\odot$). We calculated the type II speeds at selected time intervals and the obtained type II speeds were $1010\,\mathrm{km\,s^{-1}}$ for t1–t0, $910\,\mathrm{km\,s^{-1}}$ for t2–t1, and $500\,\mathrm{km\,s^{-1}}$ for t4–t3.

For the Taylor-Sedov equation and density change we calculated the mass density at t0, at 4.1 $\mathrm{R}_\odot$ height, to be $8{\times}10^{-16}\,\mathrm{kg\,m^{-3}}$. At time t3, at 5.7 $\mathrm{R}_\odot$ height, it was $2{\times}10^{-16}\,\mathrm{kg\,m^{-3}}$. The slope of density change is hence obtained with β=0.5, within the travelled distance of 1.6 $\mathrm{R}_\odot$. The difference of shock propagation in changing density is illustrated with the time–distance curves in Figs. 3, 4. These Figs. also show the measured distances of the CME front (leading edge) and the calculated type II burst heights.

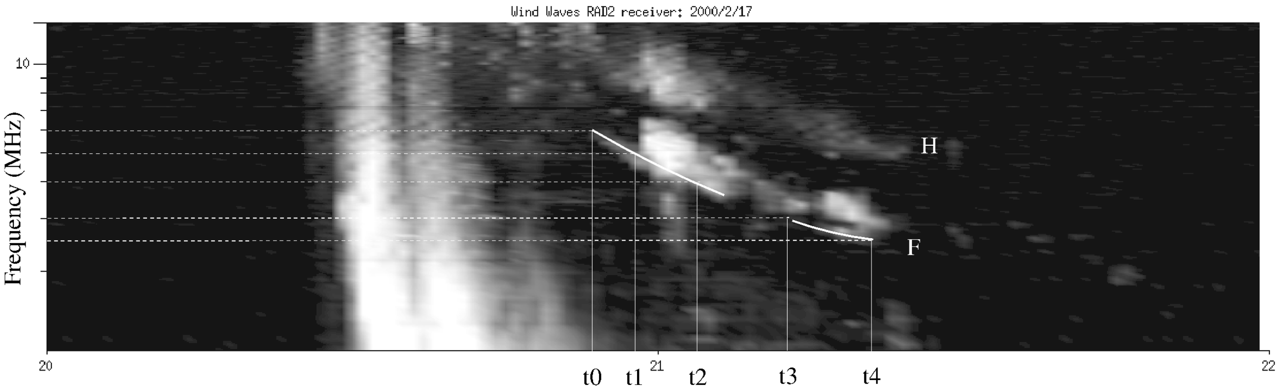

Fig. 2: Solar type II burst on 17th of February 2000. Both fundamental (F) and harmonic (H) lanes are visible. The frequency-drifting emission is recorded at t0...t4 time instants. The radio dynamic spectrum recorded at 20 – 22 UT at 1 – 14 MHz is from the Wind/WAVES experiment.

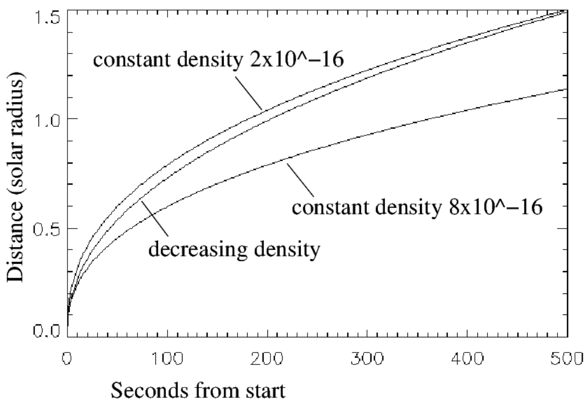

Fig. 3: The effect of density change to shock propagation: time-distance curves (from the start of the shock) for two constant densities ($8{\times}10^{-16}$ and $2{\times}10^{-16}\,\mathrm{kg\,m^{-3}}$) and a changing density, from 8 to $2{\times}10^{-16}\,\mathrm{kg\,m^{-3}}$ with a slope of $\beta = 0.5$. Note how rapidly the initial shock velocity decreases.

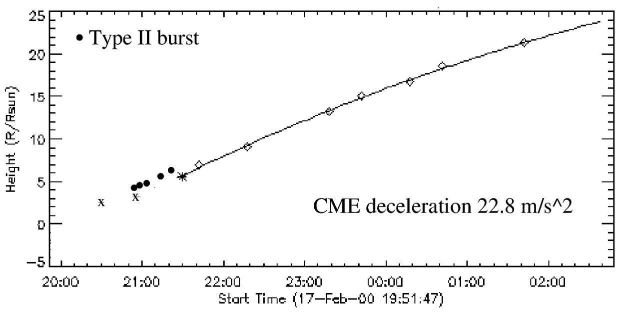

Fig. 4: Heights of the observed CME front (stars and diamonds) and type II burst (filled black circles) on 17th of February 2000 (LASCO CME data).

The best fit for the blast wave speeds was obtained using a blast energy of $E = 10^{24}$ J, which produced blast wave speeds of $1100\,\mathrm{km\,s^{-1}}$ at t1, $720\,\mathrm{km\,s^{-1}}$ at t2, $520\,\mathrm{km\,s^{-1}}$ at t3, and $460\,\mathrm{km\,s^{-1}}$ at t4.

To compare these values with the speeds of type II, we calculated the average speeds of blast wave for the same time intervals as for the type IIs, and these were $915\,\mathrm{km\,s^{-1}}$ for t2–t1 and $490\,\mathrm{km\,s^{-1}}$ for t4–t3. From this excellent match of speeds we conclude that the type II burst was indeed behaving like a blast wave shock, i. e. decreasing in velocity after the initial input of 10^{24} J energy.

CONCLUSIONS

The origin of coronal shock waves is still not completely understood. As e. g. in [6] it has been recently mentioned in analysis of flare-associated slow CMEs, that there are two possible physical interpretations, namely a blast wave sparked by a pressure pulse of a flare or a piston-driven shock due to a CME. In our analysis we have tested if a blast wave-type shock can separate from a CME-driven shock, by calculating speeds of shock from the radio type II burst that was associated with a halo type CME on 17th of February 2000. The speeds of type II burst were compared to the calculated speeds of blast wave, which were obtained using a corresponding atmospheric mass density model. From the matching speeds we conclude that the radio type II burst was indeed propagating like a blast wave, with an initial energy input of 10^{24} J and initial speed of $1100\,\mathrm{km\,s^{-1}}$.

The used method depends heavily on the estimated start time of blast wave. As the type II burst start depends on the local plasma conditions, it may not be the true shock wave start. Furthermore, as intense flare emission usually conceals the type II burst emission start, the separation of the freely propagating wave from the shock driver would have to happen well after the flare impulsive phase in order to be visible and identifiable. To reliably verify the separation we need high-time resolution observations of the CME, with simultaneously recorded radio spectral data.

ACKNOWLEDGEMENT

The data used in this work were obtained from the web archives of the LASCO CME Catalog (generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory) and the Wind WAVES instrument website.

REFERENCES

[1] Cairns I. H., Knock S. A., Robinson P. A. & Kuncic Z. 2003, Space Sci. Rev., 107, 27
[2] Cane H. V., Richardson I. G. & von Rosenvinge T. T. 2010, J. Geophys. Res., 115, A08101
[3] Cranmer S. R. & van Ballegooijen A. A. 2005, ApJS, 156, 265
[4] Kahler S. 1994, ApJ, 428, 837
[5] Kocharov L. & Torsti J. 2002, Solar Phys., 207, 149
[6] Magdalenić J., Marqué C., Zhukov A. N., Vršnak B. & Žic T. 2010, ApJ, 718, 266
[7] Melrose D. B. 1980, Space Sci. Rev., 26, 3
[8] Reames D. V. 1999, Space Sci. Rev., 90, 413
[9] Rogers M. H. 1957, ApJ, 125, 478
[10] Sedov L. I. 1954, 'Methods of similarity and dimensionality in mechanics', Gostekhizdat, Moscow
[11] Summers D. 1975, A&A, 45, 151
[12] Taylor G. 1950, Royal Society of London Proc. Series A, 201, 159
[13] Vršnak B., Magdalenić J., Zlobec P. 2004, A&A, 413, 753
[14] Warmuth A. 2007, Lecture Notes in Physics, Berlin Springer Verlag, 725, 107