Determination of plasma physical properties across collisionless shocks driven by solar eruptions

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Abstract

Over the last decades, the availability of continuous observations of the solar atmosphere (the corona) from space allowed to study in great details solar eruptions, namely Coronal Mass Ejections (CMEs). For major CMEs, it was shown that coronagraphic observations acquired in Visible Light (VL) band contain faint arch-shaped intensity increases surrounding the eruption front, that have been identified as compression fronts due to CME-driven interplanetary shock waves. This paper reviews recent results on the physics of CME-driven shocks as obtained with the analysis of VL and UV coronagraphic images, EUV full disk images, combined with radio dynamic spectra and MHD numerical simulations. Combination of these data allowed us to infer unique information on the plasma across the shock surface, such as the density compression ratio, but also the Alfvénic Mach numbers and the magnetic field compressions all along the shock fronts; the reliability of these results has been also tested with numerical MHD simulations.

1. Introduction

The Sun is a continuous source of plasma particles filling the interplanetary space with stationary processes (leading to the solar wind flow) or sporadic impulsive events (leading to solar eruptions). Among different solar eruptive phenomena, Coronal Mass Ejections (CMEs; Webb & Howard 2012) are probably the most spectacular: the expelled huge plasma bubbles affect all planetary systems they encounter and a significant fraction of the whole Heliosphere (Witasse et al. 2017), reaching its boundaries and maybe even the interstellar medium (Intriligator et al. 2015). Major solar eruptions are often associated with a large variety of dynamic phenomena: solar flares, erupting prominences, interplanetary shock waves, and high-energy particle acceleration (SEPs). When the accelerated plasma bubble and the energetic particle streams are directed towards the Earth, their impact on the magnetosphere may cause major geomagnetic storms with important consequences (see e.g. Schrijver 2015).

Images acquired by visible-light (VL) coronagraphs (such as LASCO on-board SOHO and COR1-COR2 on-board STEREO missions) provide unique information (integrated along the line-of-sight in the optically thin corona) on large scale properties of CME plasmas, such as distribution of density, mass, kinetic and potential energies in 2D (see e.g. Ying et al. 2019) and even in 3D (with polarization ratio technique and other methods; see e.g. Mierla et al. 2009). Information derived from VL coronagraphs were greatly enhanced by UV spectra acquired by the UV Coronagraph Spectrometer (UVCS) on-board SOHO, providing also electron and kinetic temperatures, non-thermal plasma motions, and elemental abundances (e.g. Bemporad et al. 2007). On the other hand, the triggering and early evolution of CMEs can be explored only with EUV solar disk imagers and spectrometers, that show the inner corona (below 2 R_{sun}). First studies were performed with the EIT imager on-board SOHO (e.g. Dere et al. 1997), TRACE (e.g. Madjarska et al. 2015), the EUVI imagers on STEREO providing the first ever stereoscopic views (e.g. Susino et al. 2014), and SWAP on PROBA-2, providing unprecedented large field-of-view EUV images (e.g. West & Seaton 2015). More recently, the availability of high-cadence (12 s) and high-resolution (0.6 "/pix) images by the six AIA telescopes on-board the SDO mission, revolutionized the field, allowing multi-temperature analysis of plasma involved in CMEs (e.g. Patsourakos et al. 2009).

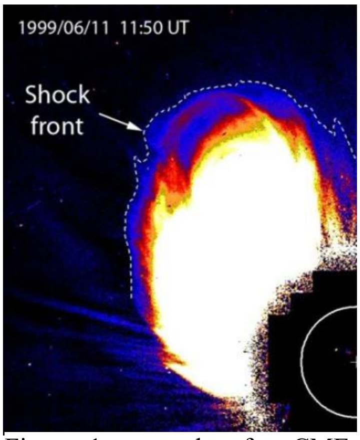

Figure 1: example of a CME-driven shock front (Bemporad & Mancuso 2011). The bottom right half-circle shows the Sun behind the instrument occulter.

Over the last 16 years, VL and EUV observations of CMEs have been employed (in combination with other data) to exploit a fundamental plasma physical process: the excitation of collisionless shocks ahead expanding CMEs (Fig. 1) and the possible acceleration of SEPs across the shock. This paper quickly summarizes most recent results obtained on these topics.

2. Summary of recent results

Sharp, bright rims ahead of fast CMEs occasionally observed by VL coronagraphs (e.g., Vourlidas et al., 2003; Ontiveros and Vourlidas, 2009) and EUV imagers (e.g. Patsourakos, Vourlidas, and Kliem 2010) are now considered as evidence of shocks driven by CME bubbles expanding with a speed much larger than the local magnetosonic speed v_{ms}, that depends on the local values of sound (c_s) and Alfvén (v_A) speeds, and on the shock inclination angle (θ_{sh}) between the up-stream magnetic field and the normal to the shock surface. For this reason, reconstructions of 3D shock kinematic from EUV and VL images and comparison with the extrapolated magnetic field lines became recently an increasingly important topic (e.g. Rouillard et al. 2016; Mancuso et al. 2019). Analysis of EUV images shows that across CME-driven shock fronts the EUV intensity evolution is complex, with different behaviours in different band-passes (e.g. Ma et al. 2011) as a consequence of plasma compression and heating going on across the shocks, and allows for the determination of densities and temperatures across CMEs and the driven waves (e.g. Wan et al. 2016). Very recently, a careful analysis of EUV observations of a shock wave allowed for the first time to take into account the line-of-sight integration effects and to derive the plasma compression ratios at different temperature intervals across the wave expanding ahead of the eruption (Frassati et al. 2019); this analysis demonstrates that for the considered event the observed wave is simply a compression wave, and that the shock forms higher-up (and later-on) during the eruption.

Despite the above important recent results, one of the major open problems limiting our understanding of CME-driven shock formation and SEPs acceleration is the current lack of measurements of coronal magnetic fields. The coronal magnetic field lines are usually extrapolated starting from measurements of photospheric fields with many different methods and assumptions, but there are no ways to test the reliability of these methods in the intermediate corona where shocks form. Hence, development of new methods capable of providing information on local magnetic fields met by shock waves is very important. A new technique to measure coronal fields crossed by CMEs has been proposed for instance by Gopalswamy & Yashiro (2011) by applying the Farris & Russell's (1994) relation between the standoff distance ΔR of an interplanetary shock and the radius of curvature R_c of the driver. The technique has been successfully applied to CME-driven shocks observed in VL coronagraphic images, EUV disk imagers, and WL Heliospheric imagers, but the measurements are limited to the 1D radial profile of the magnetic field met at the nose of the shock wave. In the same years, an innovative approach was first proposed by Bemporad & Mancuso (2010) who demonstrate that it is possible to combine VL and UV intensities measured across shock waves to derive not only the density compression ratios all along the shock fronts, but also (with MHD Rankine Hugoniot equations) the plasma temperatures across the shock and – remarkably – the strength of up- and down-stream magnetic fields, as well as the deflection of the fields across the shock surface (see review by Bemporad et al. 2016). Moreover, Bemporad & Mancuso (2011) demonstrate that this information can be derived from VL data alone, if an empirical formula they proposed for the Alfvénic Mach number in the general case of an oblique shock is applied all long the shock front. These methods were also tested with numerical MHD simulations performed by Bacchini et al. (2015) and successfully applied by Susino, Bemporad & Mancuso (2015) to derive the first ever 2D image of magnetic fields strengths in the intermediate corona (2 R_{sun} to 12 R_{sun}).

3. Conclusions and future perspectives

Despite recent encouraging results, we still do not understand the formation of shock waves in the corona and associated particle acceleration. The future new generation of space-based multi-channel coronagraphs (such as Metis on-board Solar Orbiter and ASPIICS on-board PROBA-3) will hopefully provide a new view of these fascinating phenomena.

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