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ORIGINAL ARTICLE

Super- and sub-critical regions in shocks driven by radio-loud and radio-quiet CMEs

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Abstract White-light coronagraphic images of Coronal Mass Ejections (CMEs) observed by SOHO/LASCO C2 have been used to estimate the density jump along the whole front of two CME-driven shocks. The two events are different in that the first one was a "radio-loud" fast CME, while the second one was a "radio quiet" slow CME. From the compression ratios inferred along the shock fronts, we estimated the Alfvén Mach numbers for the general case of an oblique shock. It turns out that the "radio-loud" CME shock is initially super-critical around the shock center, while later on the whole shock becomes sub-critical. On the contrary, the shock associated with the "radio-quiet" CME is sub-critical at all times. This suggests that CME-driven shocks could be efficient particle accelerators at the shock nose only at the initiation phases of the event, if and when the shock is super-critical, while at later times they lose their energy and the capability to accelerate high energetic particles.

Introduction

The last decades have seen a mounting interest of the scientific community in the study of the conditions at the Sun that can influence the performance of space-born and ground-based technological systems and that can affect human life and healt, namely the study of Space Weather. Our modern society became progressively vulnerable to disturbances associated with most powerful event occurring on the Sun, like solar flares (responsible for sudden terrestrial atmosphere heatings), Solar Energetic Particles (SEPs – which may damage satellite instrumentations and be dangerous for astronauts) and Coronal Mass Ejections (CMEs – responsible, among other effects, for geomagnetic storms).

In this regard, the formation of shock waves play an important role in the corona, because these waves are able to accelerate particles (electrons, protons, ions) up to near-relativistic energies. They are produced either as blast waves, due to the huge flare-induced pressure pulse, and/or piston-driven as bow shocks in front of fast Coronal Mass Ejections (CMEs). In the corona, they are detected in radio dynamic spectra, white-light images [1] and ultraviolet spectra [2,3]. The shock represents a discontinuity with a transmitted mass flow, which is decelerated from super- to sub-Alfvénic speed [4]. It is thus a

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dissipative structure in which the kinetic and magnetic energy of a directed plasma flow is partly transferred to heating of the plasma. The dissipation does not take place, however, by means of particle collisions. Collisionless shocks can be divided into super- and sub-critical [5]: the critical fast Mach number M_A^* is defined by equating the normal component of the downstream flow velocity in the shock frame to the sound speed. Supercritical shocks are important because usually produce much greater ion heating than subcritical shocks [6,7]. In contrast to sub-critical shocks, resistivity in super-critical shocks cannot provide all the necessary dissipation for a shock transition according to the Rankine–Hugoniot relationships. Thus, other processes like wave-particle interactions provide the dissipation required for supercritical shock formation. This is the reason why they are able to accelerate SEPs efficiently to high energies. The SEP acceleration efficiency also depends on the angle θ_{Bn} between the magnetic field and the normal to the shock surface. In fact, the expansion of the CME fronts likely induces the formation of both quasi-parallel (i.e. $\theta_{Bn} \sim 0°$) and quasi-perpendicular (i.e. $\theta_{Bn} \sim 90°$) shocks, at the nose of the CME front and at the CME flanks, respectively [8]. Because the ion acceleration rate is faster in perpendicular than in parallel shocks, it is believed that SEPs are mostly accelerated in perpendicular shocks [9,10]. Both kinds of shocks reflect ions, but in quasi-parallel shocks the combined geometries of the upstream field and of the typically curved shock surface is such that the reflected particles are enabled to escape upstream from the shock along the magnetic field. Hence, more in general, both quasi-parallel and quasi-perpendicular SEP accelerations are possible in CME-driven shocks.

Propagation of shocks in the solar corona and interplanetary medium is inferred from the detection of type II radio bursts (appearing as emission slowly drifting from high to low frequencies in dynamic radio spectra) which provide a direct radio signature of shocks [11]. Because every large SEP event is associated with a type-II burst, the latters are usually identified as strong indicators of particle acceleration by shocks. Usually, shocks producing a type-II burst are said to be "radio-loud" (RL), while those not producing a type-II burst are said "radio-quiet" (RQ), and the same terminology is applied to associated CMEs [12], even if this terminology is not fully correct because CMEs can be in general associated or not also with other kinds of radio emissions, like type-III and type-IV radio bursts [13,14]. Statistical studies [15] demonstrate that RL CMEs are faster, wider and associated with stronger X-ray flares, but slow ($v \ll 900$ km/s) RL-CMEs and fast ($v \gg 900$ km/s) RQ-CMEs are also observed, suggesting that conditions of the ambient corona (and in particular the local value of the Alfvén speed v_A) likely play a fundamental role in deciding the CME capability to accelerate shocks.

Thanks also to the availability of data acquired by STEREO spacecraft, [16] demonstrate that the type-II bursts (hence the CME-driven shocks) form when the CMEs are located at an heliocentric distance of ~1.5 solar radii, while weak or no shocks are observed around ~3–4 solar radii and that type II burst seems to end when the shock becomes subcritical. Hence, these results are in agreement with the idea that type-II bursts could be excited where the speed of the CME piston-driven shock exceed the local fast magnetosonic speed, which is expected to have a local minimum around 1.2–1.4 solar radii and a local maximum around 3.5 solar radii [17,18]. Nevertheless, the exact location in the corona where the super- and sub-critical shock forms and how they evolve is at present unknown. In this work we extend our previous identification of super- and sub-critical regions along shock fronts observed in white light coronagraphic images [19] by focusing on two CME-driven shocks: the first event was a RL fast CME, while the second one was a RQ slow CME. As we are going to show here, the formation or not of type-II bursts can be associated with the presence or not of a super-critical region at the "nose" (i.e. center) of the shock. Data analysis and results are described in the "Methodology and results" Section and discussed in the "Discussion and conclusions" Section.

Methodology and results

The two events studied in this work are shown in Fig. 1 (top) as white light images acquired by the SOHO/LASCO-C2 coronagraph. In particular, this figure shows a sequence of base difference images obtained by subtracting the intensity of the pre-CME corona to the CME images. The RL-CME, which occurred on 1999 June 11, was a fast event (propagating at a projected velocity of 1570 km/s) associated with a type II radio burst (detected by WIND/WAVES) and a C8.8 class flare (detected by GOES). On the contrary, the RQ-CME, which occurred on 2001 August 21, was a slow event (propagating at a projected velocity of 540 km/s) without radio burst and without flare. White light images have been employed first to derive the pre-CME coronal electron densities n_e (cm^{-3}): a good knowledge of the ambient corona electron density is important in order to estimate the shock compression ratio from the ratio between the white light intensities observed at

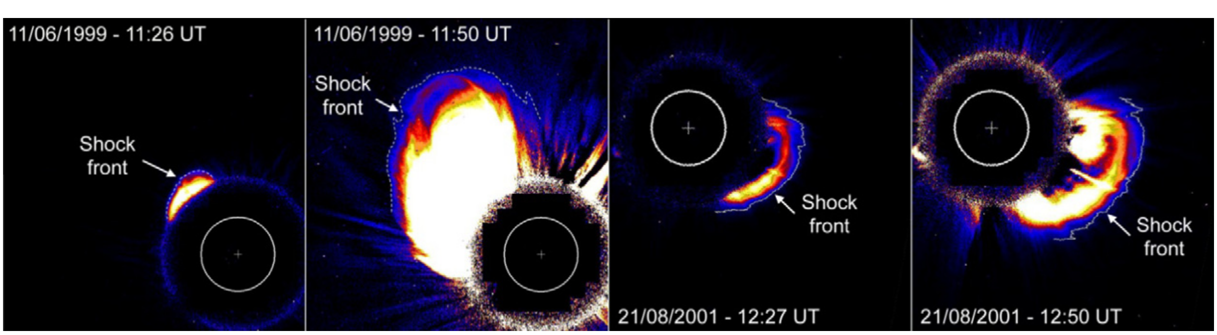

Fig. 1 Base difference LASCO/C2 images showing the location of the CME-driven shock front (dashed lines) for the radio-loud CME at 11:26 UT (left) and 11:50 UT (middle left) and for the radio-quiet CME at 12:27 UT (middle right) and 12:50 UT (right).