Corrugated Features in Coronal-mass-ejection-driven Shocks: A Discussion on the Predisposition to Particle Acceleration

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Abstract

The study of the acceleration of particles is an essential element of research in heliospheric science. Here, we discuss the predisposition to the particle acceleration around shocks driven by coronal mass ejections (CMEs) with corrugated wave-like features. We adopt these attributes on shocks formed from disturbances due to the bimodal solar wind, CME deflection, irregular CME expansion, and the ubiquitous fluctuations in the solar corona. In order to understand the role of a wavy shock in particle acceleration, we define three initial smooth shock morphologies each associated with a fast CME. Using polar Gaussian profiles we model these shocks in the low corona. We establish the corrugated appearance on smooth shock by using combinations of wave-like functions that represent the disturbances from the medium and CME piston. For both shock types, smooth and corrugated, we calculate the shock normal angles between the shock normal and the radial upstream coronal magnetic field in order to classify the quasi-parallel and quasi-perpendicular regions. We consider that corrugated shocks are predisposed to different processes of particle acceleration due to irregular distributions of shock normal angles around the shock. We suggest that disturbances due to CME irregular expansion may be a decisive factor in origin of particle acceleration. Finally, we regard that accepting these features on shocks may be the starting point for investigating some questions regarding the sheath and shock, like downstream jets, instabilities, shock thermalization, shock stability, and injection particle processes.

Key words: plasmas – shock waves – Sun: coronal mass ejections (CMEs) – Sun: magnetic fields – Sun: particle emission

1. Introduction

Coronal mass ejections (CMEs) are sporadic phenomena in solar surface that reconfigure notably the global coronal magnetic field (e.g., Low 2001; Liu et al. 2009). The super-magnetosonic CMEs (>800 km s\(^{-1}\)) create a coronal shock wave in distances of \(\sim 1.5 R_\odot\) (e.g., Ma et al. 2011; Zucca et al. 2014; Gopalswamy et al. 2016), evidenced through the radio Type II burst (Wild & McCready 1950; Uchida 1960), and Moreton waves (Moreton 1960; Moreton & Ramsey 1960). Together with the shock wave, the sheath structure is established by accumulating coronal plasma by the CME compression on the medium. The shock and sheath generate conditions appropriated for particle acceleration (e.g., Zank et al. 2000; Manchester et al. 2005; Kozarev et al. 2013). In the shock wave, the particles are accelerated mainly through the diffusive shock acceleration process (e.g., Bell 1978a, 1978b; Blandford & Ostriker 1978). These types of particles are known as gradual solar energetic particles (electrons, protons, and ions, hereafter SEPs; Reames 1999, 2013).

Some CMEs exhibit the shock signatures in the CME flanks or in the CME nose regions (e.g., Ontiveros & Vourlidas 2009), consequently some events show the origin of SEPs in shock flanks (e.g., Kahler 2016), or at the shock nose (e.g., Reames et al. 1997; Reames 1999). In large SEP events, the fastest CMEs (~2000 km s\(^{-1}\)) associated with the Ground Level Enhancement (GLE) events, the particle acceleration can occur from \(\sim 2.0\) to \(\sim 4.0 R_\odot\), with an average of \(\sim 3.0 R_\odot\) (e.g., Reames 2009; Gopalswamy et al. 2012). The SEPs are accelerated in the shock supercritical regions. In these regions the downstream Alfvénic Mach number, \(M_A\), is larger than the critical Mach number, \(M_{\text{crit}}\), for which the flows and sound velocities are equivalent (e.g., Edmiston & Kennel 1984). According to the shock normal angle, \(\theta_{\text{bn}}\), between the shock normal and the upstream magnetic field, the supercritical shock can be manifested by two phases: the quasi-parallel \((0 \leq \theta_{\text{bn}} < \pi/4)\) and quasi-perpendicular \((\pi/4 \leq \theta_{\text{bn}} < \pi/2); Balogh & Treumann 2013\). Recently, Bemporad & Mancuso (2011) and Bemporad et al. (2014) analyzed the CME-driven shock that occurred on 1999 June 11. In this shock the authors found supercritical and subcritical conditions in the shock nose and flanks, respectively, at distances of \(\sim 2.6 R_\odot\). The authors affirm that their results are important to locate the zones of particle acceleration.

In recent years some studies have evidenced the importance of taking into account realistic properties of the solar corona and of the CMEs in studies of acceleration and transport of the SEPs. For example, Manchester et al. (2005) showed the relevance of sheath structure and bimodal SW. Bemporad & Mancuso (2011) showed the existence of supercritical regions in the shock front, Schwadron et al. (2015) analyzed the role of expansion and acceleration of a CME on particle acceleration. Recently, Petukhova et al. (2017) explored the dependence of the particle spectra with the initial CME radius. Kong et al. (2017) showed that shocks can accelerate particles more efficiently when propagating in a streamer-like magnetic configuration than in the radial configuration.

In this work, we are interested in discussing the predisposition to particle acceleration in corrugated shock fronts. For this, we compare two shock morphology types: smooth and corrugated. For both cases, we identify the quasi-parallel and...
quasi-perpendicular regions by calculating the angle $\theta_{Bn}$ throughout the shock angular width. The smooth shocks are modeled by assuming three fast CMEs each with different morphology and in different latitude locations (e.g., Ontiveros & Vourlidas 2009). With these, we analyze the predisposition to particle acceleration in all latitudes. We construct the corrugated shocks imposing wave-like or undulation features from perturbations of surrounding media as bimodal solar wind (SW), boundary wind (e.g., Manchester et al. 2005; Savani et al. 2010; Stakhiy et al. 2015), fluctuations of solar corona properties (e.g., Warmuth & Mann 2005; Evans et al. 2008; Zucca et al. 2014) and corrugated from deflection and irregular expansion of the CME piston (e.g., Xie et al. 2009; Shen et al. 2011; Kay et al. 2013, 2015; Kay & Opher 2015), and CME irregular expansion (e.g., Evans et al. 2011). Our calculation suggests some constraints between smooth shock morphology and the physical process defined through the shock normal angles. Our results for the corrugated shocks show the diversification of the quasi-parallel and quasi-perpendicular regions that directly affect the acceleration rate and the energy of the particles accelerated. Finally, we note that irregular CME expansions may be the most decisive factor in the predisposition of CME-driven shocks to accelerate particles.

This paper is organized as follows. In Section 2, we construct the shocks’ morphologies in polar coordinates, and the corrugated shocks by imposing wave-like features on smooth shocks. In Section 3, we identify the quasi-parallel and quasi-perpendicular regions through the shock width, in order to recognize some SEP constraints in the upstream shock region. Finally, we provide a discussion and our conclusions in Section 4.

2. Methodology

In the same trend of incorporating realistic properties in studies of particle acceleration, our work focuses on discussing the predisposition of the wavy or corrugated shocks to the SEP phenomenon. A few years ago, Susino et al. (2015) showed the CME-driven shock of 2011 June 7 between heliocentric distances from 2 to 12 $R_\odot$ and angular width of 110° by images of coronagraphs C2 and C3 of LASCO/SOHO. The authors show the shock front’s location with the irregular shock shape features, see Figure 5 in Susino et al. (2015). Similar irregular shock fronts were detected in the CME-driven shock of 1999 June 11 (Bemporad & Mancuso 2011, 2013; Bemporad et al. 2014). In order to understand the relevance of the corrugated shocks, we compare two shock morphology types: smooth and corrugated shocks. With this, our methodology is structured in two steps. First, in Section 2.1, we model the smooth shocks. Second, in Section 2.2, we impose the undulations on top of a smooth shock, in order to mimic the disturbed shocked region due to external turbulence or subject to instabilities.

Figure 1 illustrates the side view configurations of the six CME-driven shocks analyzed in this paper. We consider three CMEs: CME 1, CME 2, and CME 3 and their shock waves in different latitudinal locations (green, blue, and orange thick lines, these color features are conserved through the paper). Panels (a)–(c) show the smooth CMEs and their shocks. These shock morphologies have similar features to the events of 1999 September 11 (here assumed in the equator region), 1997 November 6, and 1998 June 4 analyzed in Ontiveros & Vourlidas (2009). Our interest in these shock morphologies is to study all the intervals of latitude considering shock 1 at CME 1 nose, shock 2 at CME 2 flanks, and shock 3 at the intermediate latitude. For these CMEs, we consider high velocities $\gtrsim 1500$ km s$^{-1}$ and cone-like structure in a three-part structure: core, cavity, and frontal loop (Illing & Hundhausen 1985). The CME-pause and coronal magnetic field lines (MFLs) are indicated by red and black thin lines, respectively. In all cases, the sheath structure (yellow shadow) is assumed and the CME magnetic reconnection is neglected. Panels (d)–(f) illustrate our model of corrugated CME pistons and shocks. For the six cases, we analyze the shock width in order to provide a general diagnostic of shock normal angles. But particularly, we adopt the supercritical shocks conditions at the convex regions indicated by the green, blue, and orange transverse lines. We consider that these regions have high Mach numbers, due to their faster expansion velocity, relative to the other shock regions (e.g., Bemporad & Mancuso 2011; Bemporad et al. 2014).

2.1. Coronal Smooth Shock Model

We model the smooth shock surface with polar Gaussian plots, $S_m(\phi)$, as a function of latitude coordinate, $\phi$ (e.g., Wood & Howard 2009; Wood et al. 2010, and Wood et al. 2011 for CMEs). The subscript $m$ with values $m = 1, 2, 3$ identify the shock morphology associated with each CME, see Figure 1. The shock locations are adjusted close to $\sim 3.0 R_\odot$ according to the coronal distances of shock formation at $\sim 1.5 R_\odot$ (e.g., Ma et al. 2011; Zucca et al. 2014; Gopalswamy et al. 2016), particle acceleration onset between $\sim 2.0$ to $\sim 4.0 R_\odot$ (e.g., Reames 2009; Gopalswamy et al. 2012), and supercritical shock detections $\sim 2.6 R_\odot$ (e.g., Bemporad & Mancuso 2011; Bemporad et al. 2014).

We build the smooth shocks, $S_m(\phi)$, from an initial parabolic-like shape profile

$$h(\phi) = \exp\left(-\frac{\phi^2}{2}\right).$$

From CME observation it is possible to consider that these parabolic-like shapes can be more realistic than circular profiles due to the nonuniform ejecta driver. Close to the SEP onset ($\sim 3.0 R_\odot$), we define the first shock surface, $S_1(\phi)$ as a multiple of $h(\phi)$

$$S_1(\phi) = 2.8 \, h(\phi).$$

This shock is the simplest CME-driven shock morphology. $S_1(\phi)$ has been chosen in order to mimic the CME event of 1999 September 11 studied in Ontiveros & Vourlidas (2009; here adapted for the equator region).

The shocks $S_2(\phi)$ and $S_3(\phi)$, Figures 1(b) and (c), are more complex than $S_1(\phi)$. In order to establish these shocks, we start from $h(\phi)$ in combination with an auxiliary function structured as the sum of polar Gaussian functions

$$p_m(\phi) = \sum_{i=-9}^{9} a_i \exp \left[-b_i \left(\phi - \frac{i \pi}{20}\right)^2\right].$$

The mathematical flexibility of the $p_m(\phi)$ function through its parameters of amplitude ($a_i$), width ($b_i$), and locations ($i\pi/20$), and the positive range ($\geq 0$) of the Gaussian profiles, allow $S_2(\phi)$ and $S_3(\phi)$ to be written as a combination of $h(\phi)$ and $p_m(\phi)$ as

$$S_2(\phi) = 1.5 \, h(\phi) + p_2(\phi),$$

and

$$S_3(\phi) = 2.3 \, h(\phi) + p_3(\phi).$$
The 1.5 and 2.3 multiples of the $h(\phi)$ function are taken assuming the shock close to $3.0 R_{\odot}$. Table 1 shows the positive constants $a_i$ and $b_i$. These are adjusted in order for the shocks $S_2(\phi)$ and $S_3(\phi)$ to be latitudinally symmetric and mimic the shock shape of 1999 May 27 and 1998 June 4 (Ontiveros & Vourlidas 2009), respectively.

**Figure 1.** Scheme of meridional views of CME 1, CME 2, and CME 3 and their shocks. We show three different CMEs, structured in core, cavity, and frontal loop (Illing & Hundhausen 1985). For all situations we considered a sheath structure (yellow shadow) formed behind the shocks. The CME-pause and coronal magnetic field lines (MFL) are indicated by the red and black thin lines, respectively. Panels (a)–(c) indicate the smooth shocks. For the three CME cases, the shock signatures (green, blue, and orange thick lines) are assumed in different latitudinal locations. The shock morphology preserves similar features to the events of 1999 September 11 (here assumed in the equator region), 1997 November 6, and 1998 June 4 studied in Ontiveros & Vourlidas (2009). Our interest with these three morphology types is to study all intervals of latitude. Panels (d)–(f) show our propose of corrugated shocks. We model this type of shock by imposing wave-like features from bimodal SW (e.g., Manchester et al. 2005), CME deflection (e.g., Kay et al. 2013, 2015), CME irregular expansions (e.g., Evans et al. 2011), and ubiquitous fluctuations of density and magnetic field of the solar corona (e.g., Warmuth & Mann 2005; Evans et al. 2008; Zucca et al. 2014). For the six cases, we calculate the shock normal angles throughout the shock width in order to provide a general diagnostic of the predisposition to particle acceleration in the shock front. But particularly, we adopt the supercritical shock conditions at the convex regions (rounded, indicated by the green, blue, and orange transverse lines) assuming that these regions maintain high expansion velocity (e.g., Bemporad & Mancuso 2011; Bemporad et al. 2014).
flows in the downstream region, similarly to the heliosheath (e.g., Opher et al. 2007, 2009). The CMEs can be affected by their irregular expansion due to the imbalance among internal magnetic and gas pressure, and external pressure of solar corona. It may allow some CME regions to expand more rapidly than others by dynamical pressure effects.

Besides the small-scale factors on shocks may be the ubiquitous irregularities of the density and magnetic field in the solar corona that give rise to fluctuations in the Alfvén velocity, therefore the shock front may be modified (e.g., Warmuth & Mann 2005; Evans et al. 2008; Zucca et al. 2014). In this paper we do not take into account the CME rotations (e.g., Lynch et al. 2009; Yurchyshyn et al. 2009) in order to guarantee the shock coplanarity hypothesis (e.g., Balogh & Treumann 2013). Also we neglected the CME interactions (e.g., Lugaz et al. 2017 and references therein), but we highlight that these may substantially affect the shock fronts as well. Also we consider that shock disturbances may be consequences of the CME driver evolution, one reason could be internal reconnection as suggested by Ferro et al. (2014).

The complexity of the CMEs, solar corona, and SW allow their perturbations in the shock to be random. As an initial approximation in this work we model these disturbances through wave functions. Mathematically we define the corrugated shocks, $C_m(\phi)$, imposing tenuous undulations on smooth shocks $S_m(\phi)$ by addition of a supplementary function $k(\phi)$

$$C_m(\phi) = S_m(\phi) + k(\phi).$$

The $k(\phi)$ is defined as the sum of smaller corrugated functions

$$k(\phi) = k_1(\phi) + k_2(\phi) + k_3(\phi),$$

where

$$k_1(\phi) = \sum_{i=-1}^{1} 0.15 \exp \left[ -30 \left( \phi - \frac{2i\pi}{9} \right)^2 \right],$$

and

$$k_2(\phi) = \sum_{i=-3}^{3} 0.1 \exp \left[ -60 \left( \phi - \frac{i\pi}{9} \right)^2 \right].$$

Figure 3 shows the functions $k(\phi)$ (blue line), $k_1(\phi)$ (maroon line), $k_2(\phi)$ (green line), and $k_3(\phi)$ (red line). The $k_1(\phi)$ function, Equation (8), is intentionally structured with three wave crests, in order to represent the disturbances on shock caused by the SW interfaces together with the fast and slow SW. With the $k_2(\phi)$ function, Equation (9), we represent the disturbances due to the irregular CME expansion. In the $k_3(\phi)$ function, Equation (10), we take into account the minor disturbances in the shock induced by fluctuations in the density, Alfvén velocity or magnetic field strength of the solar corona. The amplitudes of the $k_1(\phi)$ (~15% $R_\odot$), $k_2(\phi)$ (~10% $R_\odot$), and $k_3(\phi)$ (~5% $R_\odot$) compose a corrugated function $k(\phi)$ with maximum amplitude of 30% $R_\odot$ and crest angular width of the ~$\pi$/6 rad (~30°) indicated by the blue shadow. With $k_1(\phi) > k_2(\phi) > k_3(\phi)$ amplitudes, we scale the effect of the bimodal SW, CME irregular expansion and fluctuations of solar corona as large, medium, and small scales for ~3.0 $R_\odot$ distances. In Figure 2(b) we show the corrugated shocks $C_1(\phi)$ (green line), $C_2(\phi)$ (blue line), and $C_3(\phi)$ (orange line).

### Table 1

| i  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----|---|---|---|---|---|---|---|---|---|---|
| $\omega_1$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 2.5 | 0.6 | 1.0 | 0.2 |
| $\omega_2$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| Shock 2 |
|--------|
| $\omega_1$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 2.5 | 0.6 | 1.0 |
| $\omega_2$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| Shock 3 |
|--------|
| $\omega_1$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 2.5 | 0.6 | 1.0 | 0.2 |
| $\omega_2$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
Reames 2009; Gopalswamy et al. 2012. For both shock types we identify the quasi-parallel and quasi-perpendicular regions. The green, blue, and orange transverse lines at convex (round, regions with high expansion velocity) regions indicate the locations where we assumed the supercritical shock conditions (e.g., Bemporad & Mancuso 2011; Bemporad et al. 2014). The gray half-circle represents the Sun.

Figure 2. Reconstruction of the shocks presented in Figure 1. Panel (a) shows the function $h(\phi)$ (black dashed line) Equation (1), together with the smooth shocks $S_1(\phi)$ (green line), $S_2(\phi)$ (blue line), and $S_3(\phi)$ (orange line), Equations (2), (4), and (5), respectively. In panel (b) we show the corrugated shocks $C_1(\phi)$ (green line), $C_2(\phi)$ (blue line), and $C_3(\phi)$ (orange line) Equation (6). The gray shadow between 2.5 and 3.5 $R_S$ corresponds to the region where the shocks are analyzed. In this interval we consider the shock formation ($\sim$1.5 $R_S$, e.g., Ma et al. 2011; Zucca et al. 2014; Gopalswamy et al. 2016) and particle acceleration ($\sim$3.0 $R_S$, e.g., Reames 2009; Gopalswamy et al. 2012). For both shock types we identify the quasi-parallel and quasi-perpendicular regions. The green, blue, and orange transverse lines at convex (round, regions with high expansion velocity) regions indicate the locations where we assumed the supercritical shock conditions (e.g., Bemporad & Mancuso 2011; Bemporad et al. 2014). The gray half-circle represents the Sun.

Figure 3. Corrugated function $k(\phi)$ ($R_S$), Equation (7) (blue line), and its contributions $k_1(\phi)$, Equation (8) (maroon line), $k_2(\phi)$, Equation (9) (green line), and $k_3(\phi)$, Equation (10) (red line) in the function of the polar angle coordinate, $\phi$. With $k_3(\phi) > k_2(\phi) > k_1(\phi)$ amplitudes, we scale the effect of the bimodal SW, CME irregular expansion and fluctuations of solar corona as large, medium, and small scales for $\sim$3.0 $R_S$ distances. The $k(\phi)$ function is imposed on smooth shocks $S_n(\phi)$, Equations (2), (4), and (5), to construct the corrugated shock, $C_n(\phi)$, Equation (6). The blue shadow indicates the amplitude of 0.3 $R_S$ and the angular width $\sim\pi/6$ rad ($\sim$30°) of the larger undulations.

3. Calculation

In order to understand the predisposition of particle acceleration in undulated shock fronts, we compare the distributions of quasi-parallel and quasi-perpendicular regions along the smooth and corrugated shocks shown in Figures 1 and 2. We identify these regions by calculating the shock normal angle, $\theta_{\text{Bn}}$, between the shock normal, $\mathbf{n}$, and the upstream coronal magnetic field, $\mathbf{B}^\text{up}_\text{cor}$. We assume a steady global coronal magnetic field with open MFLs in the polar regions and closed field lines at low latitudes of the equator; we also consider the bimodal structure of the SW (e.g., Manchester et al. 2004). For distances larger than the source surface radius, in our calculation at 2.5 $R_S$ (e.g., Altschuler & Newkirk 1969), we consider the $\mathbf{B}^\text{up}_\text{cor}$ disposed radially in the upstream region (e.g., Bemporad et al. 2014 and references therein). The supercritical shock regions in our models are assumed in the radial configuration of the $\mathbf{B}^\text{up}_\text{cor}$, i.e., $>2.5 R_S$. In this range, we do not take into account the closed field structures that are ubiquitous in the solar corona for distances $<2.5 R_S$. We point out that, in an eventual interaction of the shock wave with the closed MFLs, the $\theta_{\text{Bn}}$ values may change to values close to $\sim\pi/2$; this is due to the orthogonality between normal shocks and closed MFLs. In this interaction it is possible to assume the curvature of the shock larger than the curvature of the closed field lines. For this condition, Kong et al. (2016) suggest that particles (electrons in Kong et al. study) are swept by shock toward the shock flanks where they are accelerated.

In Figures 4(a) and (b) we compare the smooth and corrugated shocks (black thick lines) and CME piston (gray shadow), CME-pause (red line), sheath or downstream (yellow shadow), upstream (orange shadow), and the angles $\theta_{\text{Bn}}$ between $\mathbf{n}$ (red arrows) and $\mathbf{B}^\text{up}_\text{cor}$ (black thin arrows). In the corrugated shock, we characterize the undulations with a lower amplitude than that in the CME piston. In order to show the contrast between two shocks types, we use the parabolic shock morphology, i.e., like shock 1. The cartoon illustrates some features in shocks. (i) The magnetic deflection between the downstream MFLs that drape the CME and the upstream radial MFLs for $>2.5 R_S$ (e.g., Bemporad & Mancuso 2010, 2011; Bemporad et al. 2014; Bacchini et al. 2015; see Figure 7 in Bemporad et al. 2014). This deflection is also mentioned in Liu et al. (2011) as the rotation of the magnetic field in the downstream. This deflection is explained by the shock transit
on the magnetic field that drape the CME (e.g., Bacchini et al. 2015). Additionally, some MHD numerical shock studies show the magnetic field amplification in the downstream region and the parallel upstream magnetic field disposition explained through that perpendicular downstream magnetic field is not advected (e.g., Falceta-Goncalves & Abraham 2012; Rocha da Silva et al. 2015). (ii) The turbulent behavior in the shock is indicated by means of curved black arrows in the sheath region (e.g., Manchester et al. 2005). (iii) The blue filamentary structures in the upstream regions illustrate the quasi-parallel (Q–||) regions where the particles can be removed more easily. These structures may be similar to the field aligned structures in the magnetospheric shock in the Q–|| regions (e.g., Omidi et al. 2014). The distribution of the quasi-parallel (blue upstream filamentary structures) and quasi-perpendicular regions illustrate our results shown in Figure 5 for both shock types.

3.1. Shock Normal Angles Calculation

We calculated the angles, θ_{Bn}, between the normal of the shock, \( \mathbf{n} \), and radial magnetic field, \( B_{\text{cor}}^{\text{up}} = ||B_{\text{cor}}^{\text{up}}|| \mathbf{r} \), along the shock

\[
\cos \theta_{Bn} = \frac{\mathbf{n} \cdot B_{\text{cor}}^{\text{up}}}{||B_{\text{cor}}^{\text{up}}||} = \mathbf{n} \cdot \mathbf{r}.
\]

(11)

We introduce \( \mathbf{n} \), by rotating the tangential vector, \( \mathbf{\tau} \), to the shock. This process consists of three steps: First, we define the shock surface, \( S(\phi) \) (also corrugated shocks, \( C_m(\phi) \) Equation (6)), as a parametric function \( (\phi) \) of \( \phi \), i.e.,

\[
S(\phi) = \langle \phi, S \rangle.
\]

(12)

Second, we calculate the tangential vector, in polar components \( (\hat{\phi}, \hat{r}) \),

\[
\mathbf{\tau} = \hat{\phi} + S_\phi \mathbf{r}.
\]

(13)

with \( S_\phi = \frac{dS}{d\phi} \). Third, we rotate \( \pi/2 \) rad, in order to find the unitary normal vector

\[
\mathbf{n} = -S_\phi \hat{\phi} + \mathbf{r} \quad (S_\phi^2 + 1)^{1/2}.
\]

(14)

With Equations (11) and (14), we find the angle \( \theta_{Bn} \)

\[
\theta_{Bn} = \arccos(S_\phi^2 + 1)^{-1/2} \quad \text{rad}.
\]

(15)

Figure 5 shows the shock normal angles for the smooth, \( \theta_{Bn}^\text{sm}(\phi) \), and the corrugated \( \theta_{Bn}^\text{cr}(\phi) \) shocks, with \( m = 1, 2, 3 \), shown in Figure 2. Panel (a) shows the \( \theta_{Bn} \) values for the three smooth shocks, while panels (b), (c), and (d) show separately the \( \theta_{Bn}^\text{sm}(\phi) \) (black dotted line), and \( \theta_{Bn}^\text{cr}(\phi) \) (colored continuous line) plots. The color plots are associated with the colored features presented in this paper, i.e., the shocks 1, 2, and 3 in green, blue, and orange, respectively. The yellow and white background shadows indicate the quasi-parallel (Q–||), 0 ≤ \( \theta_{Bn} \leq \pi/4 \) and quasi-perpendicular (Q–⊥, \( \pi/4 < \theta_{Bn} < \pi/2 \)) ranges of \( \theta_{Bn} \).

In Figure 5(a), the angle \( \theta_{Bn}^\text{sm}(\phi) \) (green line) oscillates from quasi-perpendicular to parallel angles between flanks to the nose of the \( S_1(\phi) \) (green line in Figure 2). In this case there is only one point where the shock is completely parallel, i.e., \( \theta_{Bn} = 0 \) rad. The \( \theta_{Bn}^\text{cr}(\phi) \) (blue line), is more complex in comparison with \( \theta_{Bn}^\text{sm}(\phi) \). \( \theta_{Bn}^\text{cr}(\phi) \) oscillate from quasi-perpendicular in shock flanks to the quasi-parallel to quasi-perpendicular values close to \( \pm \pi/6 \). The \( \theta_{Bn}^\text{cr}(\phi) \) (orange line) can be considered an intermediate morphology, between those of \( S_1(\phi) \) and \( S_2(\phi) \), i.e., like deflection of the \( S_1(\phi) \) or \( S_2(\phi) \). It is interesting that the \( \theta_{Bn}^\text{cr}(\phi) \) profile can be interpreted translational to the \( \theta_{Bn}^\text{cr}(\phi) \) or \( \theta_{Bn}^\text{cr}(\phi) \). For the three shock cases we do not find \( \theta_{Bn} \) angles of perpendicular cases, i.e., \( \theta_{Bn} = \pi/2 \) rad, between normal shock and radial \( B_{\text{cor}}^{\text{up}} \). But we comment that \( \theta_{Bn} \) can be \( \pm \pi/2 \) in situations where the CME-driven shock preserves like-pointed sharp features, possibly due to fast CME expansions.
We find that any shock shape may be interpreted as a composition of a convex (outward curvature) and concave (inward curvature) shapes as \( S_1(\phi) \). Consequently, its \( \theta_{\text{Sm}}^C(\phi) \) profiles also may be a composition of \( \theta_{\text{Sm}}^C(\phi) \). This can be inferred by comparing shocks 1 and 2. The \( S_1(\phi) \) profile shows a convex profile and consequently its \( \theta_{\text{Sm}}^C(\phi) \) exhibits a “V” shape. \( S_1(\phi) \) can be interpreted as two convex regions similar to \( S_1(\phi) \) at extremes. The second finding is the interesting behavior between shock 1 and shock 3. Figure 2(a) shows \( S_3(\phi) \) as a deflection of \( S_1(\phi) \). This deflection effect may be considered in Figure 5(a) as an angular translation of \( \theta_{\text{Sm}}^C(\phi) \) with respect to \( \theta_{\text{Sm}}^C(\phi) \). \( \theta_{\text{Sm}}^C(\phi) \) shows differences for \( \phi < \pi/6 \) rad due to the variations in amplitude and shock angular width of \( S_3(\phi) \) with respect to \( S_1(\phi) \).

Figures 5(b)–(d) show the effects of the wave-like features of \( k(\phi) \), Equation (7), on the smooth shocks by comparing the \( \theta_{\text{Sm}}^C(\phi) \) (colored continuous lines) and \( \theta_{\text{Sm}}^C(\phi) \) (black dotted lines). The \( C_m(\phi) \) and \( \theta_{\text{Sm}}^C(\phi) \) do not show constraints similar to previous ones for the smooth shock. Besides, the small amplitude of \( k(\phi) \), i.e., \( \leq 0.3 \, R_\odot \), drastically affects the \( \theta_{\text{Sm}} \) values. The most visible differences between \( \theta_{\text{Sm}}^C(\phi) \) and \( \theta_{\text{Sm}}^C(\phi) \) are the consecutive changes of \( \theta_{\text{Sm}} \) and extreme values in \( \theta_{\text{Sm}}^C(\phi) \). The undulations notably multiply the parallel angles, i.e., \( \theta_{\text{Sm}} \approx 0 \) rad, along the shock’s width, but do not allow the existence of the perpendicular angles, the latter being similar to the smooth shocks. The quasi-parallel and quasi-perpendicular regions maintain different behaviors that can show different rates of acceleration. The fast reconnection rate in quasi-perpendicular regions is a consequence of a small coefficient of diffusion. Besides, it is known that short acceleration times, are important factors for the acceleration of the particles, e.g., Desai & Giacalone 2016 and references therein.

4. Discussion and Conclusions

The CME-driven shock formation in the low corona is a phenomenon that involves several physical processes as particle acceleration (e.g., Manchester et al. 2005; Kozarev et al. 2013). Recently, some works show the relevance of including realistic features of the solar corona and CMEs in...
studies of SEPs (e.g., Schwadron et al. 2015; Kong et al. 2017; Petukhova et al. 2017). In this work, we discuss the predisposition to acceleration of particles in shocks with wave-like features imposed from ubiquitous disturbances of the solar corona, SW, and the corrugated CME piston. These wavy shocks are known as corrugated shocks (e.g., Gardner & Kruskal 1964; Landau & Lifshitz 1987). Our work is motivated from observations shown in Susino et al. (2015), where the authors show an irregular shock front between 2 and 12 R⊙, and 110° angular width. Similar shock fronts were evidenced in Bemporad & Mancuso (2011, 2013) and Bemporad et al. (2014) at ~2.5 R⊙ distances, in the CME event of 1999 June 11. In this paper we calculate the shock normal angles, θBN, in order to interpret the physical process at the shock front (e.g., Balogh & Treumann 2013). With θBN, we identify the quasi-parallel (0 ≤ θBN ≤ π/4) and the quasi-perpendicular (π/4 ≤ θBN ≤ π/2) regions, associated with particle acceleration. We do not study the evolutionary process in the shock, in contrast, we analyze the shock at ~3.0 R⊙, in order to understand the predisposition of injection of the particle through θBN, during the early stages of the shock where the particle acceleration is high (e.g., Desai & Giacalone 2016).

In this paper, we analyze three different CME-driven shock morphologies from Ontiveros & Vourlidas (2009). In Figure 1, we show CME 1, CME 2, and CME 3, with respective shocks located in different latitudes, i.e., CME nose (CME 1), both CMEs flanks (CME 2), and superior CME flank (CME 3). We define the smooth shocks Sm(φ), with m = 1, 2, and 3, Equations (2), (4), and (5) through polar Gaussian plots as functions of the polar angular coordinate, φ, see Figure 2(a). The corrugated shock Cm(φ), Equation (6), shown in Figure 2(b), is defined from Sm(φ) in addition to a complementary function k(φ), Equation (7), shown in Figure 3. Our study is focused on ~3.0, according to the shock formation, i.e., ~1.5 R⊙ (e.g., Ma et al. 2011; Zucca et al. 2014; Gopalswamy et al. 2016), and SEPs onset ~3.0 R⊙ (e.g., Reames 2009; Gopalswamy et al. 2012), for this reason we assume an amplitude of less than 30% R⊙ in k(φ). We consider that wavy features in shocks are consequences of the disturbances from SW medium and CME deflection (k1(φ), Equation (8)), irregular CME expansions or initial configuration of the CME (k2(φ), Equation (9)), and minor disturbances from the solar corona, e.g., due to the fluctuation of density and Alfvén speed (k3(φ), Equation (10)).

For the case of the smooth shocks, we find constraints between the shocks’ surfaces and their θBN angles. Each shock shape can be interpreted like a sum of convex an concave contributions, i.e., like a compound of the profile of shock 1, S1(φ), Equation (2). Consequently, its θBN profile may be a combination of θBN(φ). For a situation similar to the shock decentralization, possibly due to deflection of CME or the effect of external factors like a coronal hole (e.g., Wood et al. 2012), its θBN profile can be written as the shock normal angles of shock nondecentralized, i.e., the maximal and minimal θBN values may be preserved. Therefore, the morphology of the S1(φ) turns into a crucial element for interpreting other complex shocks like shock 2, S2(φ) Equation (4), and shock 3, S3(φ) Equation (5). The main diagnosis in the corrugated shocks is the fast oscillation of θBN through the polar angle φ. Figure 5 shows how the θBN(φ) changes drastically compared to the smooth shocks. The different amplitude and frequency in the components of k(φ), i.e., k1(φ), k2(φ), and k3(φ), modify the θBN profile of the smooth shocks. From Figure 3, the k2(φ) function may be the most relevant source of disturbances in the shock. This function preserves intermediate amplitude and frequency values k1(φ) and k3(φ), which represent the irregular shock features due to initial CME magnetic configurations and imbalance of magnetic pressures between CME and corona. Our results of θBN(φ) do not evidence constraints similar to the smooth shock case. The θBN oscillation from quasi-parallel to quasi-perpendicular values along the corrugated shocks evidence particles accelerated with different energy. Giacalone (2005) show that in quasi-perpendicular regions the particles are accelerated to high energies due to different coefficients of diffusion in these regions (e.g., Desai & Giacalone 2016 and references therein). With results of corrugated θBN we consider that the role of disturbances from solar corona, SW, and irregularities in the CME, may be relevant factors that define the energy of particles accelerated in the shock front.

In this work, we do not study the evolution of the shock morphology, but Susino et al. (2015) observations suggest that shock morphology evolution preserves the initial irregularities. In this way, the initial profile is a starting point for analyzing the shock evolution. Moreover, if the most notable shock attributes are preserved, the quasi-parallel and quasi-perpendicular regions will also be conserved. With this hypothesis, the particle acceleration region in the shock may be maintained in the shock front, possibly with the exception of the angular width. Our idea of corrugated shocks suggests that the injection of particles through the shock may be complex due to the dependence of injection velocity with θBN (e.g., Li et al. 2012; Balogh & Treumann 2013). In this way, the disturbances from coronal medium and corrugated CME piston may completely modify the SEP production along the shock.

We understand that the physics of the corrugated CME-driven shocks is more complex than described here. The disturbances studied in this paper depend on several factors, such as ubiquitous fluctuations of the CME and solar corona properties, or even solar cycle phase. The corrugation features in CME-driven shocks are aleatory phenomena. Therefore, the perturbations on CME piston and shock, may be more complex than shown here. In this way, future work, simulations, or observations may exhibit some differences compared to our investigations. We considered that corrugated CME-driven shock may be a relevant element for the understanding of the population and transport of SEPs through interplanetary space. These wave-like features on the shocks may also be the starting point for new research topics in the sheath region, e.g., like the downstream jets and secondary shock, similar to that detected in the magnetosheath (Hietala et al. 2009; Hietala & Plaschke 2013); the sheath evolution process, e.g., like density variations and flows, e.g., Kelvin–Helmholtz instability (Manchester et al. 2005); and particle acceleration in sheath region in high density regions (pile-up regions in Das et al. 2011; e.g., Kozarev et al. 2013).

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