Quasiperiodic acceleration of electrons by a plasmoid-driven shock in the solar atmosphere

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Cosmic rays and solar energetic particles may be accelerated to relativistic energies by shock waves in astrophysical plasmas. On the Sun, shocks and particle acceleration are often associated with the eruption of magnetized plasmoids, called coronal mass ejections (CMEs). However, the physical relationship between CMEs and shock particle acceleration is not well understood. Here, we use extreme ultraviolet, radio and white-light imaging of a solar eruptive event on 22 September 2011 to show that a CME-induced shock (Alfvén Mach number 2.4–10.1) was coincident with a coronal wave and an intense metric radio burst generated by intermittent acceleration of electrons to kinetic energies of 2–46 keV (0.1–0.4 c). Our observations show that plasmoid-driven quasiperpendicular shocks are capable of producing quasiperiodic acceleration of electrons, an effect consistent with a turbulent or rippled plasma shock surface.

Coronal mass ejections are spectacular eruptions of magnetized plasma from the low solar atmosphere into interplanetary space⁴–¹². With kinetic energies of up to ~10⁵–10⁸ J (ref. ⁳), they are the most energetic explosive events in the Solar System and are often associated with plasma shocks and the acceleration of particles to relativistic speeds⁴–⁵. However, the underlying mechanism relating CMEs, shocks and particle acceleration is still a subject of intense debate⁶. By clarifying the inherent characteristics of these phenomena we learn not only about the nature of explosive plasma events but also about how they drive shocks and accelerate particles to high energies. Such processes occur throughout the Universe, playing a role in the acceleration of cosmic rays in supernovae and active galactic nuclei shocks⁷.

Shock associated with CMEs are often observed over a variety of spectral bands. At radiofrequencies, high-intensity (~10⁴ Jy) emissions, known as type II and type III bursts, are associated with coronal shocks and accelerated particles in the solar corona⁸. Fine structure in these radio bursts can often reveal a bursty nature to the shock particle acceleration⁹, which can reveal details of the internal shock structure¹¹,¹². At extreme ultraviolet (EUV) wavelengths, the shock or pressure pulse response of the corona to an eruption may be imaged as a bright pulse propagating across the entire solar disk at typical velocities of 200–400 km s⁻¹ (ref. ¹³). These coronal bright fronts (CBFs) are a regular feature of solar eruptive events and often exhibit wave-like properties such as reflection¹⁴, refraction¹⁵ and pulse broadening¹⁶. Like CMEs, CBFs are often accompanied by type II and type III radio bursts, with EUV and radio images revealing a spatial link between the phenomena that is suggestive of a common origin¹⁷–¹⁹.

It has been proposed that the common origin for these myriad phenomena may be a CME-driven shock²⁰–²⁰. In this scenario, the CME eruption drives a pressure pulse, observable in the low corona as a propagating wave-like CBF. Higher in the corona this same pulse forms a shock, accelerating particles and producing type II and III emission. However, much debate surrounds the suggestions that the CBF is a plasma pressure wave driven by a CME, and that the radio bursts, generated by accelerated particles, result from this same wave/shock system. The contention has arisen from attempts to explain non-wave kinematics of CBFs (ref. ²¹). Pseudo-wave theories are employed to describe this behaviour, where the erupting CME produces a large-scale restructuring of the coronal magnetic field, which results in a propagating bright pulse (through Joule plasma heating) that is not actually a driven wave²².

In this scenario, any relationship with shock observables is indirect. Further confusion is added by the possibility that high-energy particles in association with the eruption may be a consequence of magnetic reconnection in the flaring active region, and not the result of a shock²³.

Collectively, CMEs, CBFs and radio bursts provide direct measures of both shock kinematics and the characteristics of the accompanying accelerated particles. However, a common theory explaining these phenomena has yet to be verified. This lack of clarity can be ascribed to an EUV imaging cadence that was unable to match the fast time sampling of radio imaging and spectroscopy. Now, using the high image cadence of the Solar Dynamics Observatory (SDO), combined with fast time sampling radio images and spectra, we can reveal previously unseen characteristics of the relationship between these phenomena, proving that a CME-driven shock is the feature unifying these observations and that this shock is responsible for bursty electron acceleration. This greatly advances our understanding of the close relationship between solar eruptions, plasma shocks and their resulting EUV, radio and particle acceleration signatures.

CBF and radio source

On 22 September 2011 at 10:29 UT, an X-ray flare (GOES class X1.4) began in an active region located on the east limb of the Sun (NOAA active region 11302; N13E78). Approximately 11 min after the flare start time, a bright wave-like front (CBF) was observed propagating away from the southern edge of the active region in...
The 150 MHz source follows closely the CBF as it propagates around the east limb, indicating that they belong to a common structure. The intensity of the radio source is indicated by the colour bar on the right, showing the brightness temperature \( T_B \) of the source ranges between \(-10^7\) and \(10^8\) K. Such high intensities are indicative of coherent plasma emission produced by high-energy electron beams. The role of the CME in the event, as observed by the LASCO C2 coronagraph. The combination of the white-light coronagraph (C2) and the EUV images (AIA) reveals the full spatial extent of the CME bubble; that is, the frontal structure in white light has clear extensions back towards the solar surface, imaged at EUV. The locations of the radio source and CBF show that they clearly have a relationship with the southward CME flank. The dashed pink lines indicate the predicted height range of the radio emissions observed in the Nançay Decametric Array dynamic spectrum (Fig. 3b). A movie of this figure is available in Supplementary Movie 1.

For a movie and discussion of the multi-thermal nature of the CBF, see Supplementary Information and the last section.

To compare the motion of the CBF and radio source, the position angle trajectories were analysed (Fig. 2). Both the CBF and radio source clearly show common kinematics, with the two features having a consistent progression southward around the east limb. The solid lines show a fit of \( \theta(t) = \theta_0 + \omega t \) to the data, where \( \theta_0 \) is the starting position angle, \( \omega \) is the angular velocity, and \( t \) is time. The slope of each line gives \( \omega \), from which the velocity of the source may be obtained using \( v = r \omega \), where \( r \) is the distance of the source from the Sun’s centre. For the CBF, an angular velocity of \( 4.1 \pm 0.4 \times 10^{-4} \text{ rad s}^{-1} \) was obtained, resulting in a velocity of \( 283 \pm 40 \text{ km s}^{-1} \) at \( 1 R_{\odot} \). At \( 1.27 R_{\odot} \), the CBF was found to have an angular velocity of \( 5.4 \pm 1.3 \times 10^{-3} \text{ rad s}^{-1} \), resulting in \( v = 480 \pm 115 \text{ km s}^{-1} \). The 150 MHz source had an angular velocity of \( 6.2 \pm 0.1 \times 10^{-4} \text{ rad s}^{-1} \); the value for \( r \) of this source was estimated by directly converting frequency \( f_R \) to electron density \( n_e \) using the methods described in the Supplementary Information. This gave a height of \( 1.27^{+0.06}_{-0.09} R_{\odot} \) for the radio source, resulting in a velocity of \( 548^{+34}_{-46} \text{ km s}^{-1} \). This velocity is larger than the CBF velocity at \( 1 R_{\odot} \), but is comparable to the CBF velocity at \( 1.27 R_{\odot} \) (Fig. 2). The similar speeds and trajectories of the CBF and radio source suggest that they belong to a common propagating structure in the corona. Finally, the radio source speed was used to estimate its Alfvén Mach number \( M_A = v/v_A \), where \( v_A \) is the Alfvén speed determined from magnetic field and density measurements at the radio source height (see Supplementary Information). With \( v_A = 225^{+85}_{-35} \text{ km s}^{-1} \), the Alfvén Mach number of the radio source is \( 2.4^{+0.6}_{-0.4} \), showing that the source travelled in excess of the local wave speed in the corona. Finally, we note that a potential field source surface extrapolation reveals the presence of open and radial field in the south east quadrant of the corona (see Supplementary Fig. S2), revealing that the propagation was transverse to the magnetic field. This is an important aspect of quasiperpendicular shock orientation that we discuss in the last section.

Figure 1 | AIA 21.1 nm images over-plotted with NRH 150.9 MHz contours. a-f. The 150 MHz source follows closely the CBF as it propagates around the east limb, indicating that they belong to a common structure. The intensity of the radio source is indicated by the colour bar on the right, showing the brightness temperature \( T_B \) of the source ranges between \(-10^7\) and \(10^8\) K. Such high intensities are indicative of coherent plasma emission produced by high-energy electron beams. The role of the CME in the event, as observed by the LASCO C2 coronagraph. The combination of the white-light coronagraph (C2) and the EUV images (AIA) reveals the full spatial extent of the CME bubble; that is, the frontal structure in white light has clear extensions back towards the solar surface, imaged at EUV. The locations of the radio source and CBF show that they clearly have a relationship with the southward CME flank. The dashed pink lines indicate the predicted height range of the radio emissions observed in the Nançay Decametric Array dynamic spectrum (Fig. 3b). A movie of this figure is available in Supplementary Movie 1.

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accelerated electrons\textsuperscript{30}, travelling towards and away from the Sun; that is, to higher and lower frequencies. Similar features occur between 100 and 200 MHz (Fig. 3b), showing the same characteristics as herringbones (a bursty nature and decreasing intensity with respect to time). In a similar manner to the type III bursts, the beam velocity of herringbone electrons was estimated to be 0.15c, again showing the presence of near-relativistic electron acceleration in association with the presence of a shock. Whereas their structure in frequency reveals how fast these beams travel, their behaviour in time can reveal detailed temporal characteristics of the shock acceleration process. A wavelet analysis using a derivative of a Gaussian wavelet performed on a time series at 54 MHz reveals periodicity at 2–11 s (see Supplementary Fig. S1). Previous authors have attributed this bursty nature to rippling and inhomogeneity along the shock front, possibly revealing some level of instability or shock turbulence in the acceleration region\textsuperscript{32,33}; we discuss this in the last section. We note that the features at 100–200 MHz seem to be the extension of the herringbones into higher frequencies. These features in particular show good temporal correspondence with the radio source imaged by NRH; that is, they have a start–stop time comparable to the radio source. This is particularly apparent for the group of bursts at 10:52–10:56 UT (Supplementary Movie 1).

The radio emission in the dynamic spectra have all the hallmarks of shock generation with particle acceleration closely tied to the process. The association of shock radio activity with the imaged 150 MHz source suggests that the two observables have a common origin in a plasma shock. Overall, the position of the radio source at the southern flank of the CME, the transverse motion of the source (propagation parallel to the surface) and the zero frequency-drift of the herringbones is suggestive of a shock driven parallel to the surface by the flank expansion, similar to the assertion by refs 33,34. Indeed the association of the CBF with this radio activity is corroborative evidence of the wave/shock system at the flank. Further evidence of a shock having occurred in the corona was obtained using white-light observations, allowing us to study the position of this shock relative to the CME.

White-light CME and shock
A CME associated with this event was observed by the Large Angle Spectroscopic Coronagraph\textsuperscript{35} (LASCO), first appearing at 10:46 UT, with an apex heliocentric distance of \(\sim 2.6 R_\odot\) (Fig. 1c). The next available image shows the bright CME front with a fainter, secondary front at the southern flank (Fig. 4b). This two-front morphology is a common occurrence in white-light CME structure and constitutes a reliable signature of a CME front associated with a stand-off shock\textsuperscript{36}. To distinguish between the CME front and shock front, we performed a three-dimensional (3D) reconstruction of the CME using the elliptical tie-pointing method described in ref. 1 (Fig. 4d). This reconstruction reveals that the bright front outlined in the C2 coronagraph (ellipse in Fig. 4b) corresponds to the faint front outlined as a halo in STEREO-B COR1 (ellipse in Fig. 4c). Furthermore, the observations reveal that the secondary and extremely faint front at the southern edge of the CME (as imaged in LASCO/C2, Fig. 4b) cannot be considered as part of the CME structure, but is actually an associated shock front. We note that white-light shocks have been reported in the past, occurring both in the low corona as well as out to \(\sim 0.5\text{ AU}\) (refs 36,37). Here, we have employed a 3D reconstruction from multi-viewpoint observations to qualitatively confirm the presence of a shock at the southern flank of the CME, in the same region as the CBF and radio burst.

Plasma shocks and bursty particle acceleration
There has been much debate surrounding the assertion that CBFs are a wave phenomenon\textsuperscript{13}, with numerous authors suggesting a pseudo-wave theory\textsuperscript{22}. In the past, the association of CBFs with type II and type III bursts has been used as evidence against this pseudo-
wave interpretation and more in favour of the magnetohydrodynamic (MHD) wave paradigm. This study reveals that the CBF in this event was indeed closely associated with shock radio activity positioned on the flanks of an expanding CME. This kind of behaviour has been suggested before, but never directly imaged. It shows how a combination of radio and EUV imaging can reveal the evolution of plasmoid-driven shocks in the solar atmosphere.

Of further interest in this study is the likelihood of a quasiperpendicular orientation of the shock, as revealed by the potential field source surface extrapolation. Quasiperpendicularity is an essential aspect of the shock drift acceleration (SDA) mechanism, a process believed to be responsible for particle acceleration in planetary magnetospheres and solar radio bursts. This mechanism involves an adiabatic reflection of particles from the shock, with the energy gain sourced in the $\mathbf{V} \times \mathbf{B}$ electric field, where $\mathbf{V}$ and $\mathbf{B}$ are the upstream flow speed and magnetic field, respectively. A single reflection from the shock has limited energy gain; however, multiple reflections may produce relativistic energies, which is particularly important for low Mach number shocks such as that reported here ($M_\Lambda = 2.4^{+0.7}_{-0.3}$) and in ref. 44. This multiple reflection process may be explained by inhomogeneity in the shock front, a characteristic usually known as rippling. Two-dimensional hybrid simulations show that rippling is brought about by an instability and resembles a standing-wave mode of the shock surface. The presence of ripplons can lead to a quasi-sinusoidal variation in shock-normal orientation with respect to the upstream magnetic field. As the efficiency of SDA requires quasiperpendicularity, there will be sites on the shock front that provide efficient acceleration and sites that do not—a structure that may lead to magnetic trapping and multiple reflections, hence producing higher-energy particle acceleration.

The presence of ripples can produce quasiperiodic herringbones in three ways. First, it makes SDA more efficient and capable of producing the observed herringbone energies, especially when particle scattering is considered. Second, the periodic spatial variation in the acceleration efficiency of the shock could explain the bursty and quasiperiodic nature of the herringbones. Reference 12 suggests that shock front inhomogeneity brought about by MHD turbulence is a possible explanation of bursty herringbones. Reference 34 produced a detailed model of SDA from a rippled shock, specifically on the flanks of an expanding CME. Their results suggest that herringbones could be produced by accelerated electrons at spatially intermittent regions of quasiperpendicularity on a rippled shock surface. Third, ref. 32 also predicts that, if rippling is present, the upstream and downstream electron beams should have similar energies, which is not predicted for a uniform or smooth shock. A sample of the oppositely drifting herringbones in Fig. 3c shows that positive and negative frequency drifts are both $\sim 5 \text{ MHz s}^{-1}$, revealing that the upstream and downstream populations have similar energies (although we note the possibility that both positive and negative drifting herringbone features may be accelerated upstream, as suggested by the schematic of ref. 11). There is also the possibility that the herringbones may be associated with a...
termination shock of a reconnection outflow occurring behind the CME (ref. 47). In such a scenario, this shock would have a more indirect relationship with the CME propagation. However, the imaged radio source shows a good temporal correspondence with the shock activity in the dynamic spectra, especially between 10:52 and 10:56 UT, suggesting that the particle acceleration indicated in the spectra shares a close relationship with the propagating source.

Our observations reveal the need for a more detailed modelling of herringbone solar radio bursts. The quasiperiodic behaviour of herringbones provides a possible direct measure of shock inhomogeneity and the spatial scales over which the magnetic field varies in the shock and ambient corona; it may also provide a measure of the turbulence in these plasma flows. In the future, high-cadence EUV imaging from SDO, combined with sensitive radio imaging-spectroscopy observations from instruments such as the Low Frequency Array (LOFAR), will reveal unprecedented detail of plasma shocks and their role in particle acceleration. This may reveal the fundamental nature of a plasma shock process that is universal, but impossible to directly observe in any other area of astrophysics at present.

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Author contributions

E.P.C. performed the data analysis of the radio source kinematics, the radio burst analysis, the Allévin Mach number calculations, and the in situ particle analysis. E.P.C. also wrote the article. D.M.L. performed the data analysis of the coronal bright front and gave constructive advice on the writing of the article. J.P.B. performed the 3D reconstruction of the CME and gave advice on the white-light shock analysis section. P.Z. provided the density maps, and D.S.B. provided the magnetic field maps that were used in the radio source and CBF Mach number calculations. J.M. installed the electronic systems at RSTO. P.T.G. conceived of the project and guided data analysis and writing of the article.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.T.G.

Competing financial interests

The authors declare no competing financial interests.