

In the format provided by the authors and unedited.

Multiple regions of shock-accelerated particles during a solar coronal mass ejection

Diana E. Morosan ^{1,2*}, **Eoin P. Carley**^{1,3}, **Laura A. Hayes**^{1,3}, **Sophie A. Murray** ^{1,3}, **Pietro Zucca**⁴, **Richard A. Fallows**⁴, **Joe McCauley**¹, **Emilia K. J. Kilpua**², **Gottfried Mann**⁵, **Christian Vocks**⁵ and **Peter T. Gallagher**^{1,3}

¹School of Physics, Trinity College Dublin, Dublin, Ireland. ²Department of Physics, University of Helsinki, Helsinki, Finland. ³School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin, Ireland. ⁴ASTRON, Netherlands Institute for Radio Astronomy, Dwingeloo, The Netherlands. ⁵Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany. *e-mail: morosand@tcd.ie

Multiple Regions of Shock-accelerated Particles during a Solar Coronal Mass Ejection

Diana E. Morosan^{1,2,*}, Eoin P. Carley^{1,3}, Laura A. Hayes^{1,3},
Sophie A. Murray^{1,3}, Pietro Zucca⁴, Richard A. Fallows⁴,
Joe McCauley¹, Emilia K. J. Kilpua², Gottfried Mann⁵,
Christian Vocks⁵, Peter T. Gallagher^{1,3}

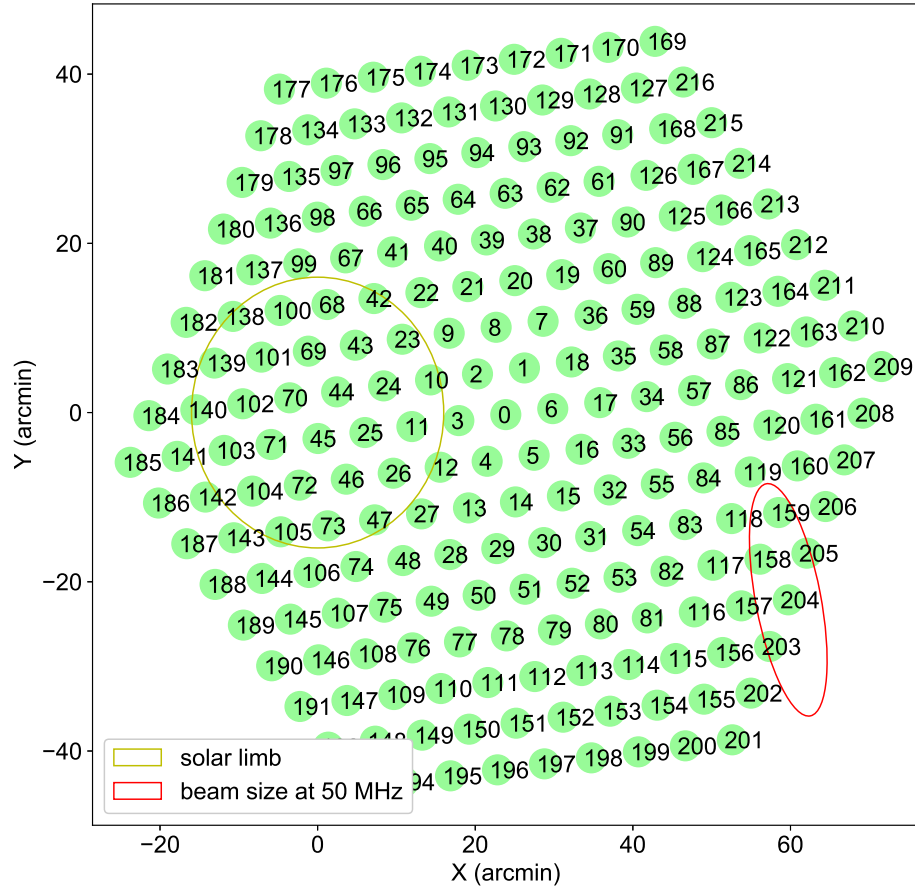
1. School of Physics, Trinity College Dublin, Dublin 2, Ireland.
2. Department of Physics, University of Helsinki, P.O. Box 64, Helsinki, Finland.
3. School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin, D02 XF85, Ireland.
4. ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands.
5. Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany.

*morosand@tcd.ie

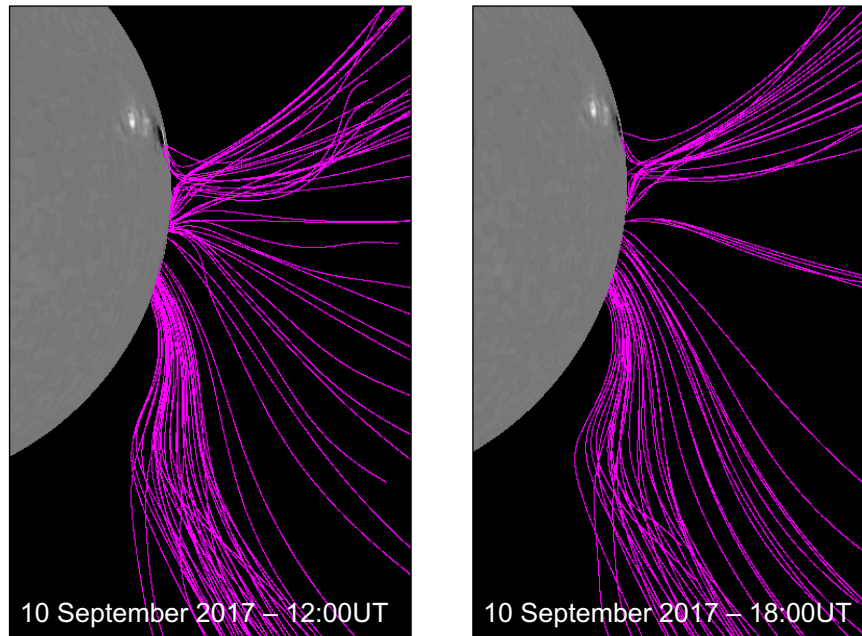
Supplementary Movie

In order to clearly identify the movement of the radio sources with the EUV wave and the northern CME flank, we produced a movie of the CME in AIA 211 Å running difference images, overlaid with filled contours of the radio sources at frequencies of 35–50 MHz (left panel of each movie frame). The filled contours represent the 70% to maximum intensity levels of each radio source. The right panel of each movie frame shows the dynamic spectrum containing the three herringbone groups observed with the LOFAR core. The panels in Figure 2 represent still images of the CME and accompanying radio sources from the Supplementary Movie.

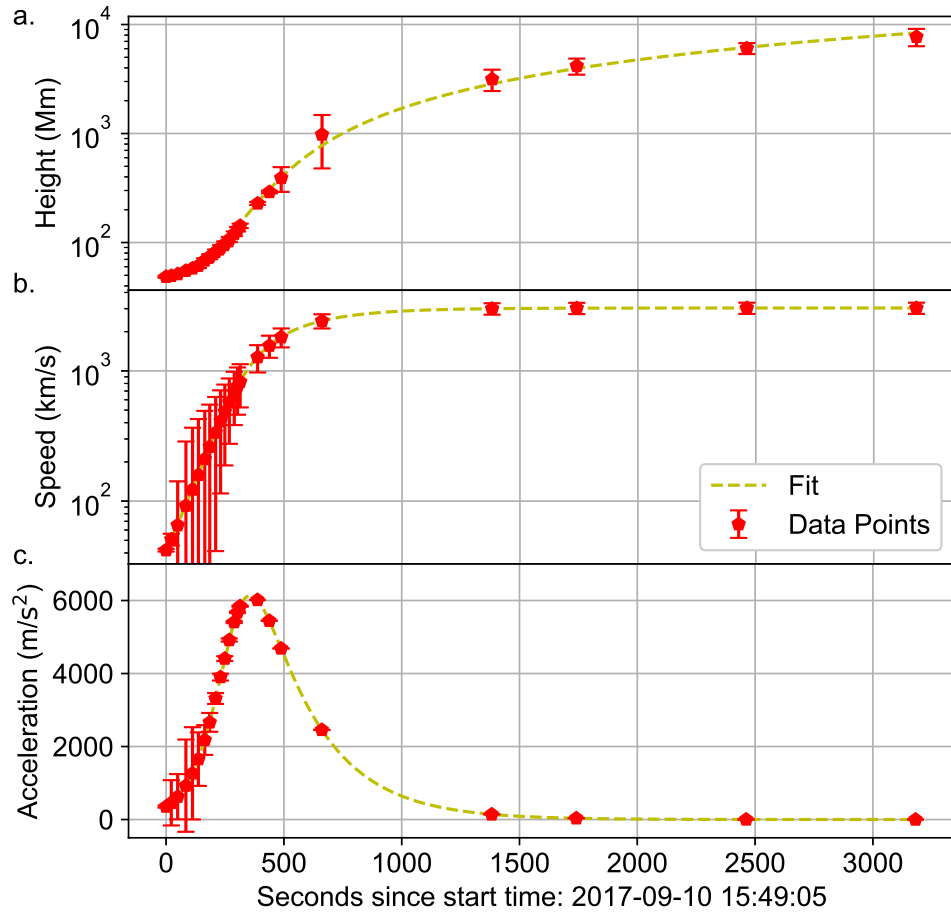
Supplementary Figures



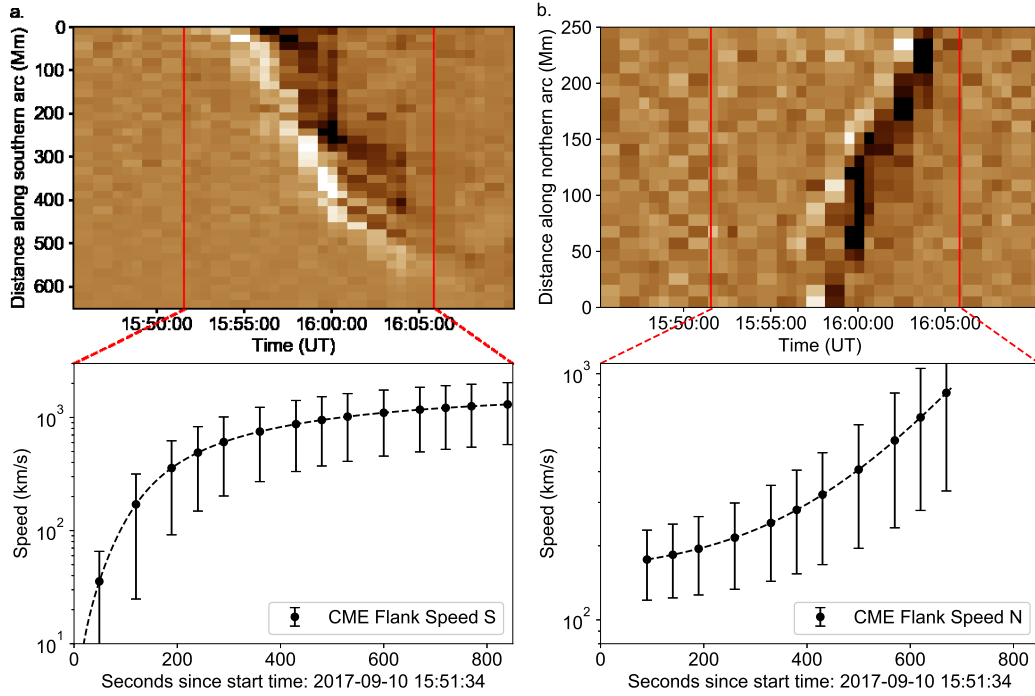
Supplementary Figure 1: Tied-array beam pattern used to observe the Sun on 10 September 2017 at 16:00 UT. The yellow circle denotes the visible solar limb, while the red circle denotes the FWHM of each beam at a frequency of 50 MHz.



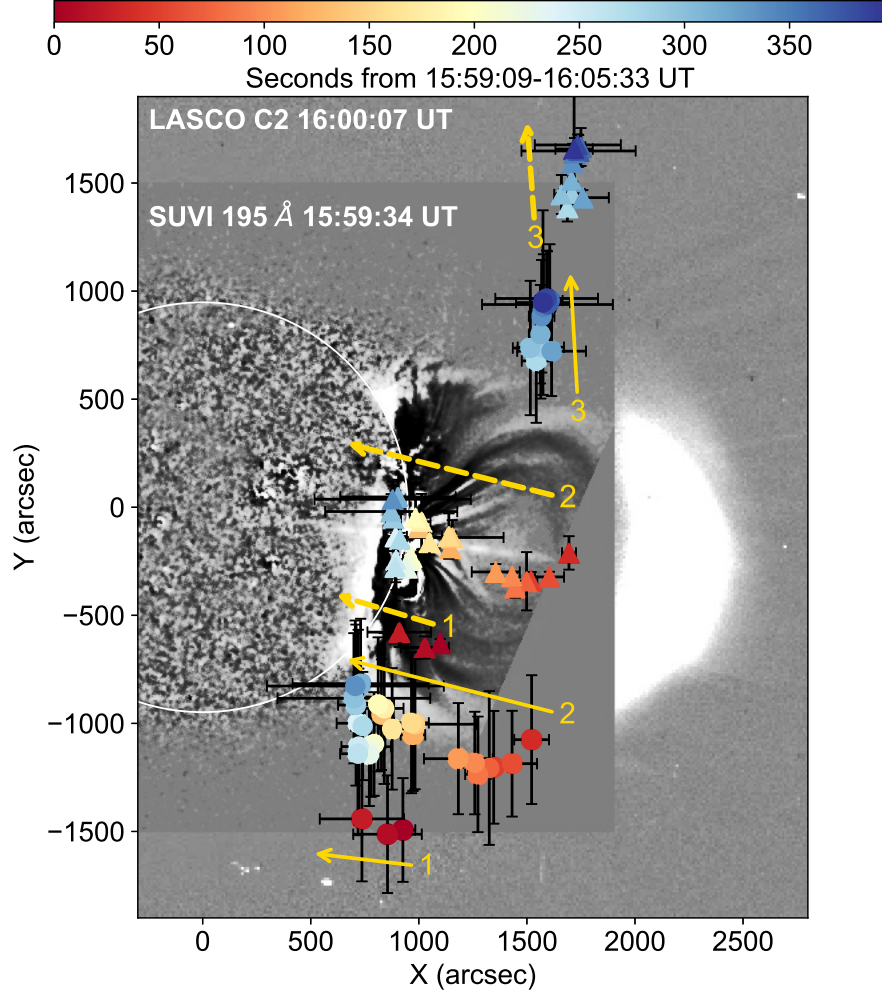
Supplementary Figure 2: Example of magnetic field lines extrapolated using the PFSS solution on 10 September 2017 before (left) and after the CME occurred (right). An extensive area of open field lines can be seen at the western solar limb in both panels. Bent or deflected open magnetic field lines can also be seen in a south-westerly direction before and after the CME occurred.



Supplementary Figure 3: (a) Height-time profile of the CME based on AIA, SUVI and LASCO C2 and C3 data points. (b) Speed-time profile obtained by taking the first numerical derivative of (a). (c) Acceleration-time profile of the CME obtained by taking the second numerical derivative of (a). The dashed yellow line in each panel represents the best fit to the data.



Supplementary Figure 4: *Top:* J-maps of the CME expansion extracted from SUVI 193 Å images, along the southern (a) and northern (b) flanks. The J-maps show the evolution in time of the pixels located inside the arcs in Figure 5b. The J-maps show the movement of the CME flanks outwards along the arcs by tracing the drifting features. *Bottom:* Speed of the CME through time along the southern flank (a) and northern flank (b). The CME fit is denoted by the dashed black line in each panel. The flank speed of the CME was fitted with equation (3) from the Methods section at the southern flank, while the northern flank that shows slower expansion was fitted with a velocity function containing a simple exponential acceleration component.



Supplementary Figure 5: Composite image of SUVI 193 Å running difference image of the CME at 15:59:34 UT and LASCO C2 running difference image of the CME at 16:00:07 UT. Overlaid are the centroids of the radio shock signatures colour-coded through time from 15:59:09 UT to 16:05:33 UT. The triangles represent the centroids of the radio sources before ionospheric corrections were applied while the circles represent the centroids corrected for the ionosphere. The error bars of the uncorrected sources represent the errors in estimating the centroid using the Gaussian fit technique, while the errors of the corrected sources represent the errors due to the Gaussian fit and the errors resulting from errors in estimating the ionospheric corrections. The yellow arrows represent the direction of movement of the three herringbone groups for the uncorrected sources (dashed lines) which is the same as the direction of movement for the corrected sources (solid lines).