Exploiting a catalog of triangulated shock waves to study their kinematics and their roles in the acceleration of SEPs

Manon Jarry,* Alexis Rouillard,* Illya Plotnikov,* and Athanasios Kouloumvakos*

*IRAP, CNRS, Université Toulouse III-Paul Sabatier, Toulouse, France

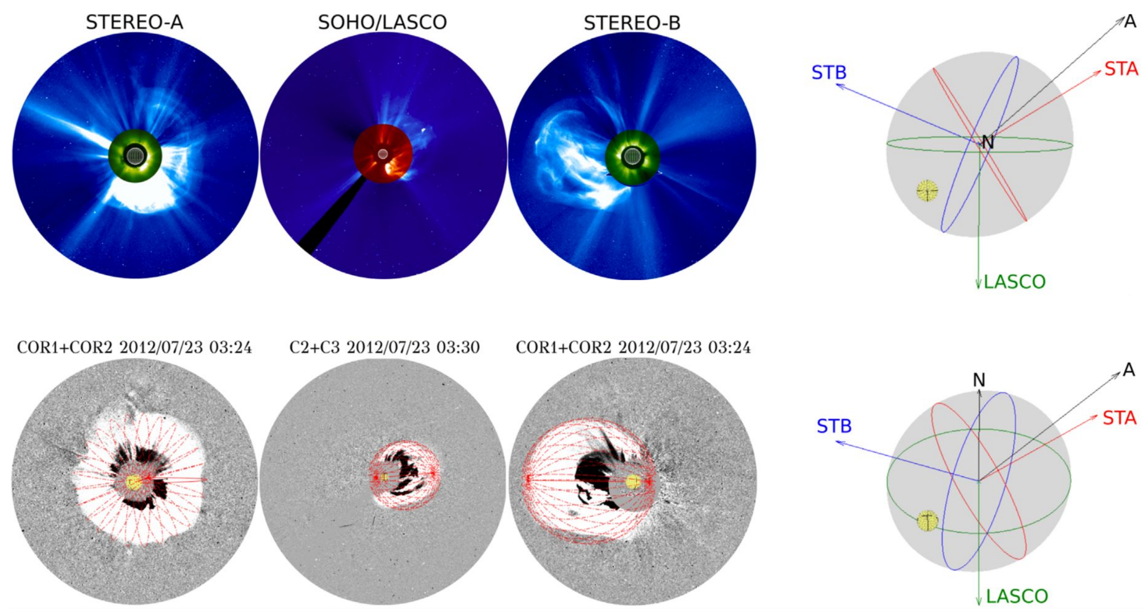
Abstract

Shock waves driven by Coronal Mass Ejections (CMEs) are strong candidates to explain the acceleration of solar energetic particles (SEPs) We present the analysis of 32 CMEs that produced strong pressure waves in the solar corona during their eruption.

We concluded that they have in average a radial velocity 1.45 times greater than their lateral velocity and that they keep their spherical shape during their propagation. We add that the SOHO/LASCO catalog has a strong tendency to underestimate the real CME speeds because of the projection effect due to the observation from a single vantage point. Finally, we confirm the correlation between the soft X-ray flux and the speed of the CME.

Keywords : Sun : Coronal Mass Ejection (CME), Sun : flare, Sun : soft X-ray, Sun : shock waves

Introduction



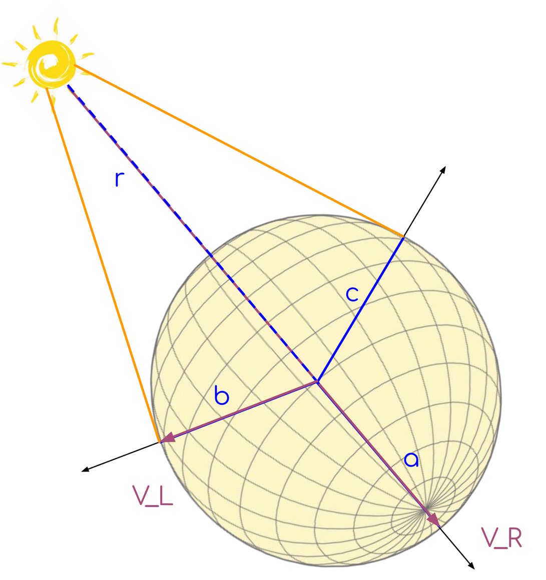
The mechanisms that produce solar energetic particles (SEPs) are still highly debated, but coronal shock waves have been proposed as efficient particle accelerators that may be implicated in this production. SEPs events can reach the Earth in a few minutes after the flare and be a threat to satellites and ISS astronauts.

Thanks to the multiplication of missions these last years, the observations of CME have evolved. Initially single view point observation provided kinematic parameters projected in the plane of the sky. They are now from multiple vantage points and allow to reconstruct their more realistic 3D ellipsoidal shapes.

Using this technique, Kouloumvakos et al. (2019) created a catalog of 32 CMEs events associated to strong pressure waves in the solar corona. We analysed them in order to better understand and predict these events, and report here important statistical information on their kinematic evolution and possible links with the acceleration of SEPs.

Shock waves

Shock waves are modeled as dynamic ellipsoids whose dimensions are defined as a major half-axis a(t) as well as two minor half-axes b(t) and c(t) for the lateral sides. In most cases, we find that b(t) = c(t). The lateral expansion velocity of the shock wave is defined as V_L(t). The radial velocity V_R(t) is the derivative of r + a, with r the distance from the center of the ellipse to the surface of the Sun. Studying the ratio b(t)/a(t) and its evolution, we noticed that on average, this ratio is approximately 1, meaning that the shock waves presents a spherical expansion. For most events (65%), the shock wave first undergoes a sudden increase before stabilizing at around 20 solar radius. We also looked at the ratio V_R(t)/V_L(t) which have an average of 1.45, and compared the speed given in largely used single viewpoint SOHO/LASCO CME catalog and our V_R(t).



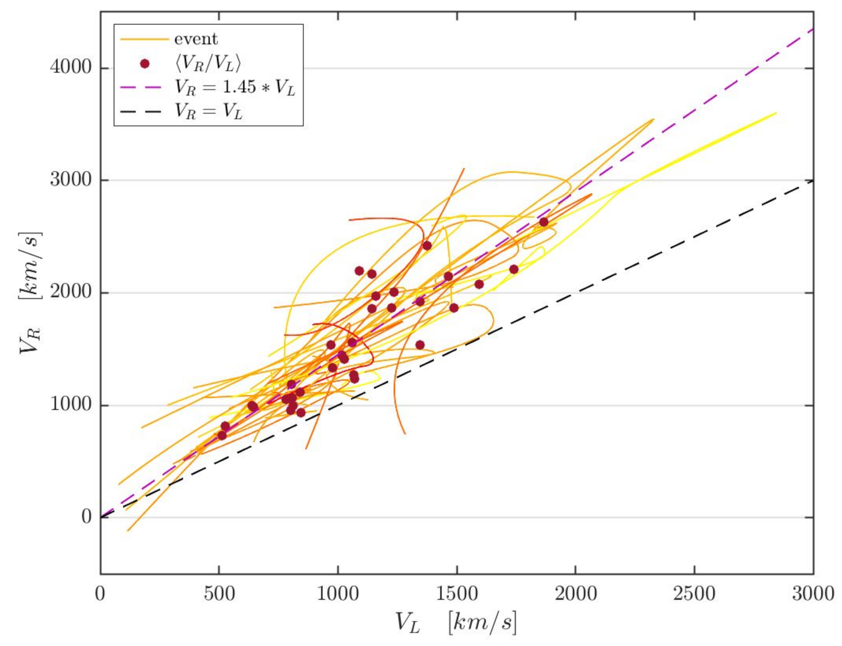
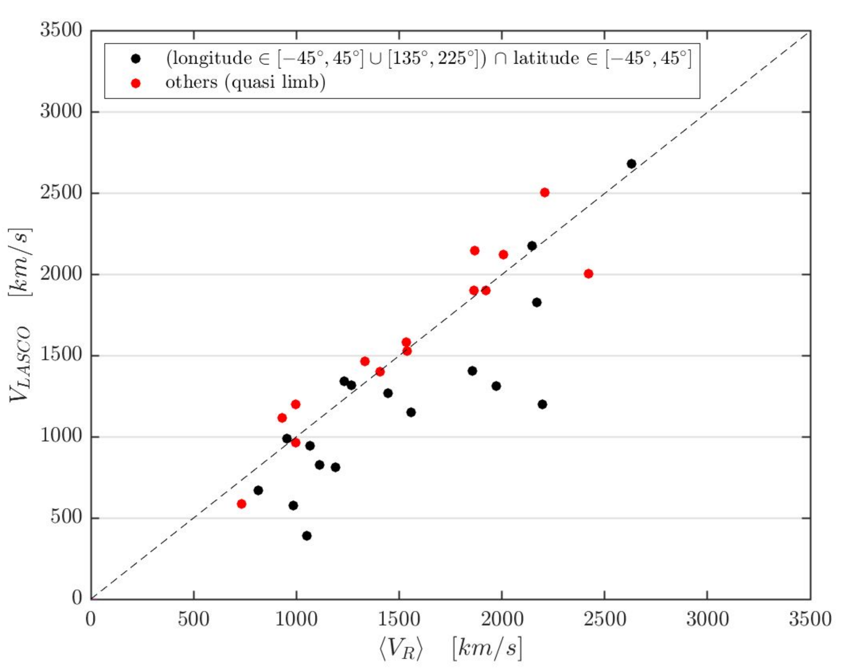
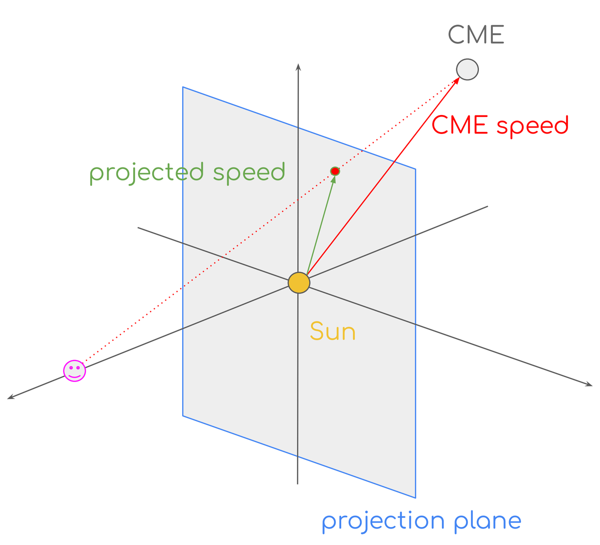


Figure representing the evolution of the radial speed as a function of the lateral speed, for the 32 events. Each point corresponds to the mean V_R(t)/V_L(t) ratio for a given event, and the colors are assigned according to the solar activity (a more intense red is related to a greater number of sunspots on the day of the event). The black dotted line represents V_R = V_L and the purple line represents the global average of the ratio of the two speeds that we found, i.e V_R ~ 1.45*V_L.

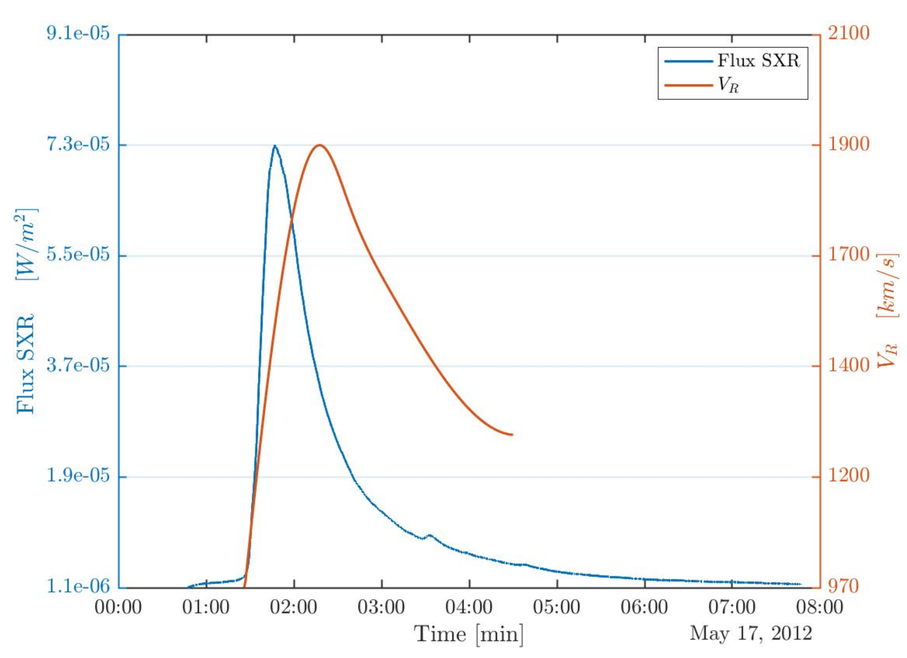


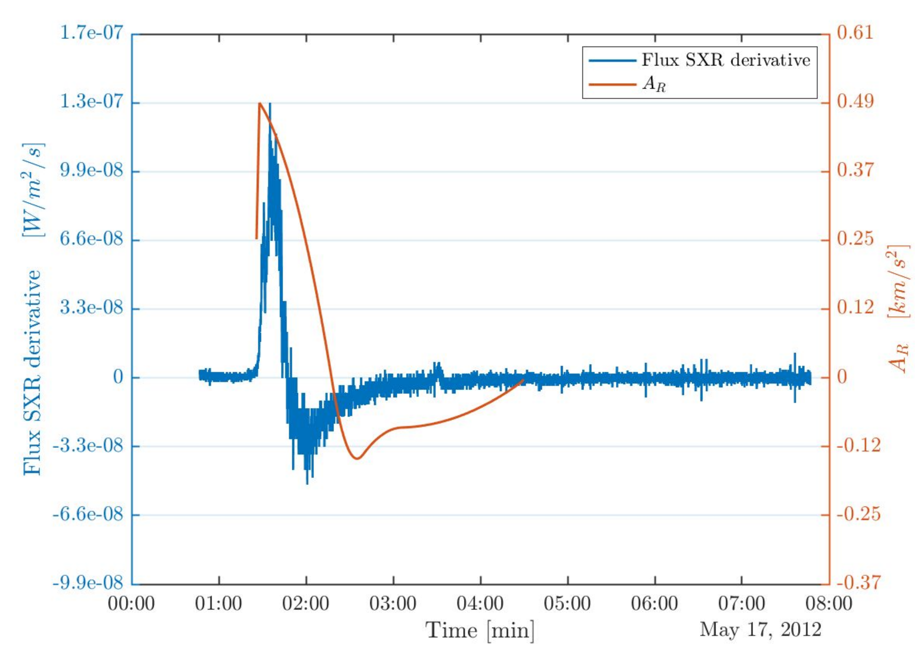


Figures : (left) Represent for each event the CME speed from the SOHO/LASCO catalog as a function of the radial speed V_R(t) from Kouloumvakos catalog. The colors correspond to two different areas of CME emergence on the surface of the Sun.
(right) Diagram showing the projection of a CME 3D speed on a plane corresponding to the view from a distant observer. The 2D speed obtained is like speeds given in the SOHO/LASCO catalog, while the 3D speed corresponds to what we have in the Kouloumvakos catalog, obtained through a multiple vantage points observation.

We systematically compared the profile of X-ray emission produced by flares and the shock kinematics. Figures below show an example of the temporal correlation between this emission (in blue) and the shock wave radial speed (in red), and their derivatives.

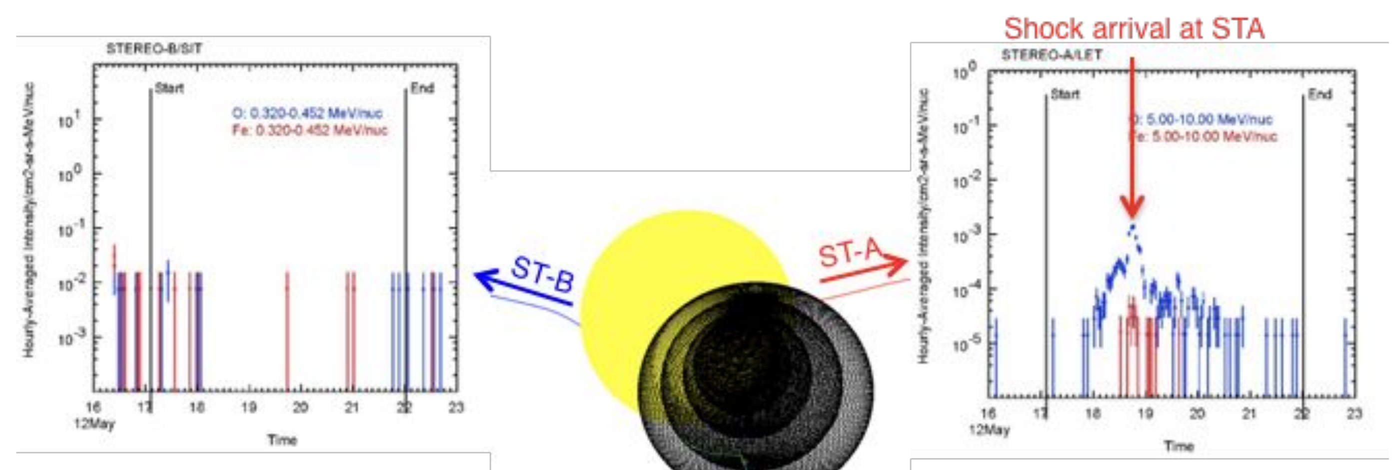
Figures :
(left) Time evolution of the soft X-ray emission during May 17, 2012 flare observed by GOES (blue) and radial speed (red) from our catalog ;
(right) Derivative of the soft X-ray flux from GOES (blue) and radial acceleration (red).





Space Weather

Thanks to the link between the soft X-ray flux and the kinematics of the shock wave, we can try to improve the Shock tool* of IRAP, an online prediction tool for CMEs, by adding a forecast composant from temporal variations of soft X-ray flux. Using the shock information we will be able to predict a possible SEP event and its characteristics based on the field line that connects the shock surface to an in-situ measuring instrument. In this way we will be able to complete later the IRAP tool to make it a shock and SEPs prediction tool, and to be able to use it as a space weather application.



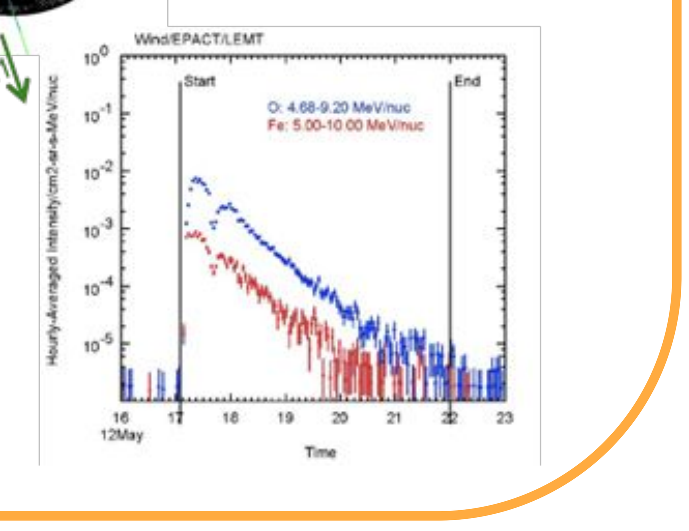


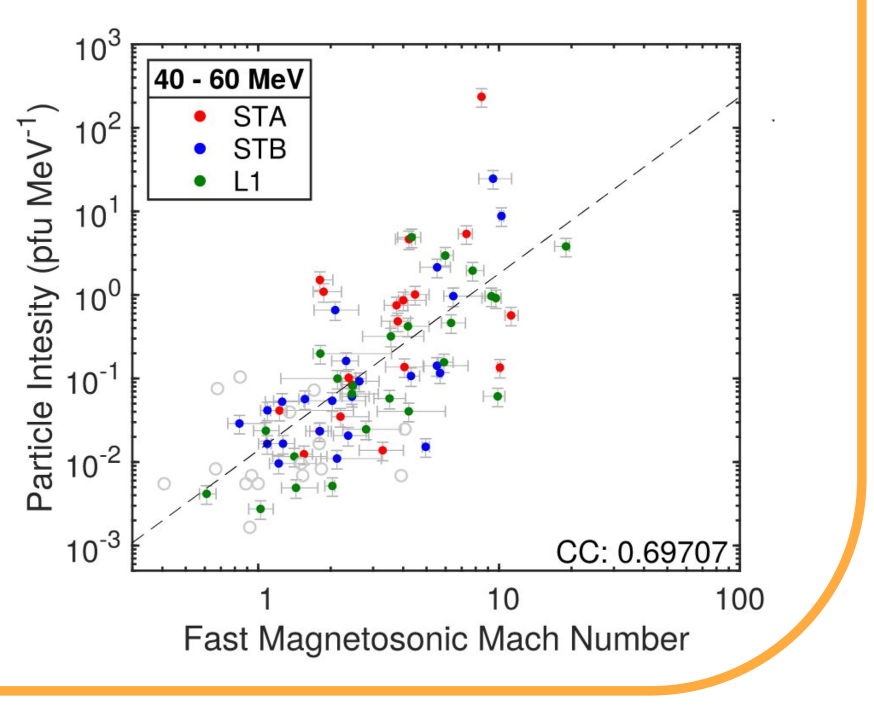
Figure representing the particle flux received during a SEP event as a function of time for different observation vantage point. This principle could be used to add SEP prediction to the online IRAP Shock Tool and make space weather.

* http://connect-tool.irap.omp.eu/shock-tool

Solar Energetic Particles

Temporal variations and composition of SEPs flux can be analyzed in-situ with instruments like LEMT on board Wind, or like SIS and ULEIS on board ACE to name a few. Thanks to the 3D reconstruction of the shock wave shape, we have information on its entire surface as well as their temporal variations. We can then couple them with in-situ measurements and thus better study the creation of SEPs, and work on space weather. An example of a result already obtained by Kouloumvakos et al (2021) is this correlation between the Mach number value at the shock surface and the particle flux intensity on the connected magnetic field line.

Figure representing the particle intensity as a function of the fast Magnetosonic Mach Number, from Kouloumvakos et al. (2021). Each color corresponds to a different in-situ measurement instrument connected to a different magnetic field line, in the energy range from 40 to 60 MeV. We can see a correlation between the two values.



Conclusion and future work

This work try to synthesize the known information on shock waves parameters and their correlations with soft X-rays and SEPs, while going further to complete and clarify these links.

As a continuation of this study, we will compare the composition of the SEPs, including abundance ratios (such as Fe/O or Fe/C) with the shock geometry that typically evolves quickly along the magnetic field lines connected to the spacecraft recording the SEPs. Better understanding of the particle acceleration related to solar eruptions is crucial to improve the forecasting capabilities.

Bibliography

Bemporad et al. (2014) ; Cane et al. (1988) ; Dal Lago et al. (2003) ; Gopalswamy (2018) et al. (2009) ; Janvier et al. (2013, 2015) ; Jarry et al. (2022 in prep) ; Kollhoff et al. (2021) ; Kouloumvakos et al. (2019, 2020, 2021) ; Kwon et al. (2014, 2015) ; Plotnikov et al. (2017) ; Poirier et al. (2021) ; Reames (1999, 2014, 2021a, 2021b) ; Rouillard et al. (2012, 2016) ; Schwenn et al. (2005) ; Shen et al. (2013) ; Temmer et al. (2008, 2009, 2010) ; Tylka et al. (2005, 2006) ; Wang et al. (2006) ; Yashiro et al. (2004) ; Zhang et al. (2001, 2004)