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Mysteries of the 17 May 2012 Solar Event Responsible for GLE71: CME and Shock Wave Development and Statistical Hints from the Spectra of Near-Earth Protons

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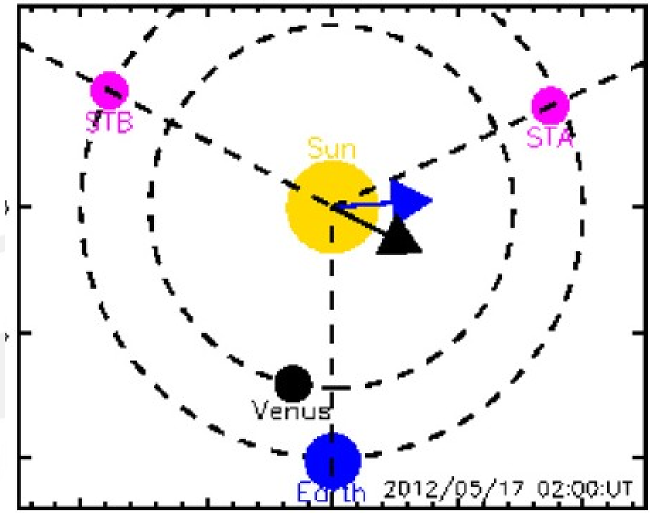
Introduction



•The 17 May 2012 solar event (M5.1 flare, CME 1580 km/s) caused GLE71 ($p \to n$, 73 GLEs in 82 years)

•The spectrum of near-Earth protons from 60 MeV to 1.2 GeV has been accurately measured

•Shen et al. (2013):

Two fast CMEs generated two bow shocks

•Rouillard et al. (2016):

Reconstructed ellipsoidal shape of a single shock front

•Both studies assumed that bow shock was excited by a fast CME, but did not measure motions of erupting structures and CME

Unresolved Issues

- Were there two CMEs or only one? Two shock waves or only one?
- Were bow shock(s) formed from very beginning?
  - Or as usual: piston shock → blast wave → bow shock or decay?
- When accelerated exclusively by a shock wave, high-energy protons arrive at Earth later than low-energy ones → **is velocity dispersion analysis applicable?**
- No clarity on any of possible sources of accelerated protons. Flare and/or shock?
- To better understand them, motions of erupting structures and CME components need to be measured
- Measurement results make it possible to establish the sequence of phenomena and identify causal relationships. These will help in understanding the CME development that still remains unclear

CME and Eruptions

CME: LASCO-C2, C3

F: 1600 km/s

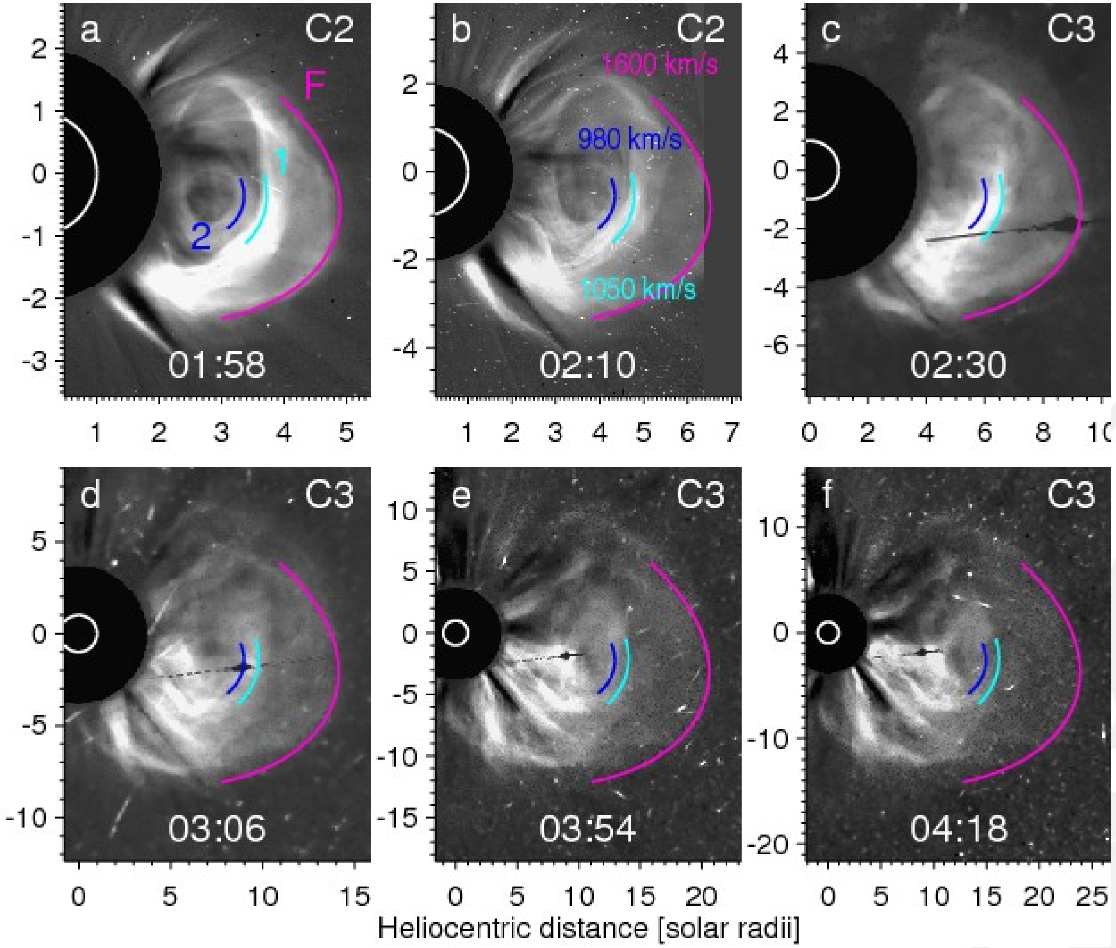
(CME catalog: 1580 km/s)

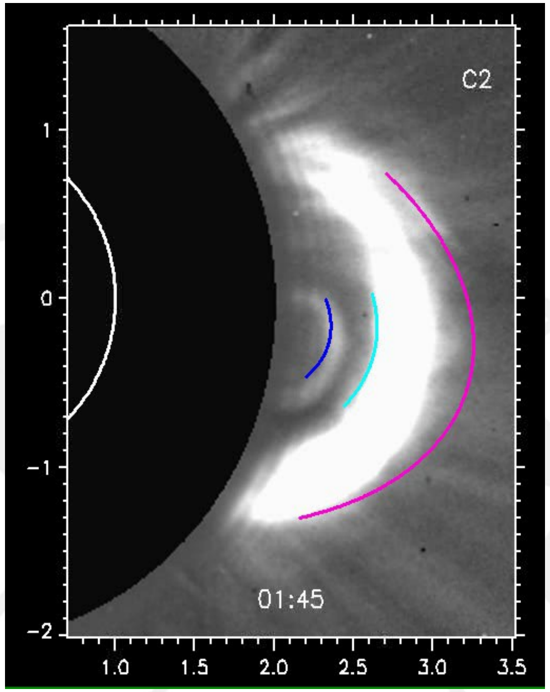
1: 1050 km/s

2: 980 km/s

– Only one CME

– Bow-shock excitation inside it is impossible





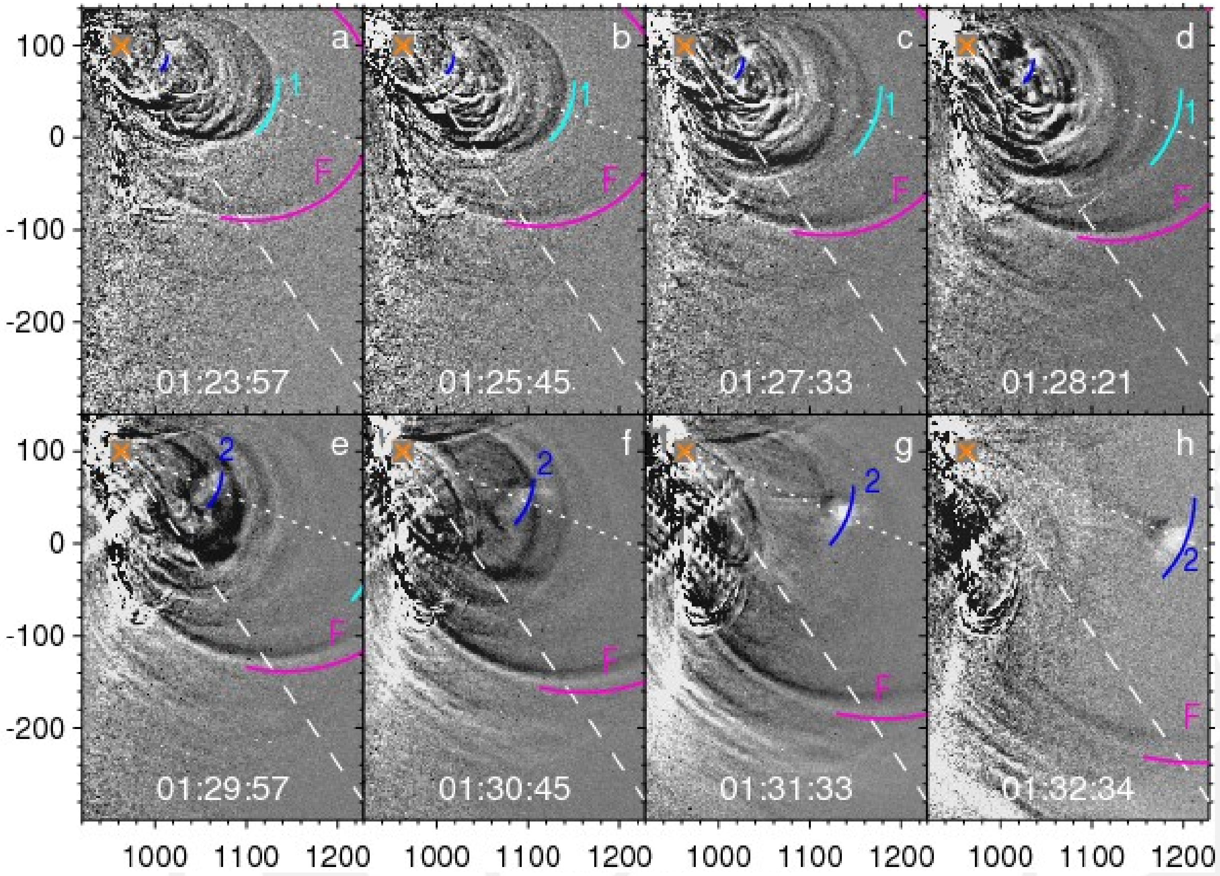
Structural components of self-similarly expanding CME (LASCO)

Two Major Eruptions

Acceleration: combination of Gaussians

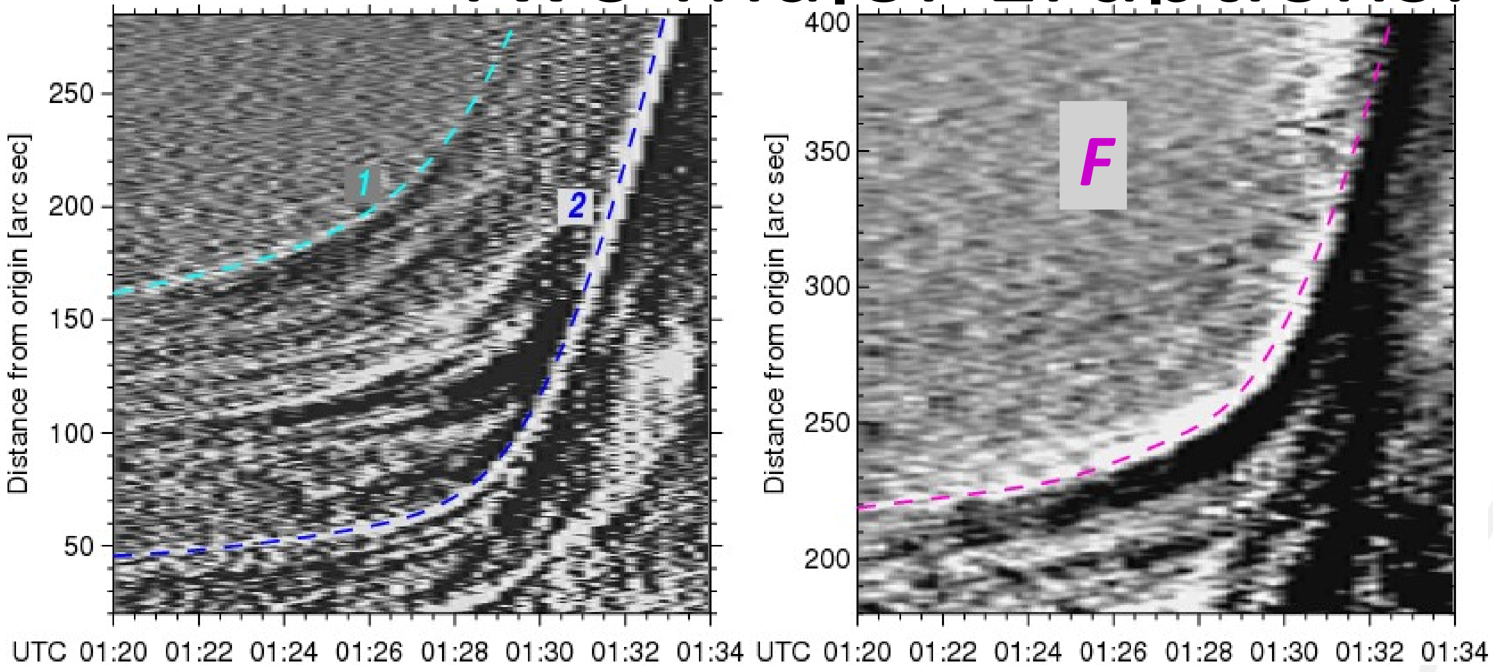
Two ways of manual measurements :

1. Fitting leading edges of moving features on images
2. Fitting one-dimensional profiles (along inclined dashed lines)

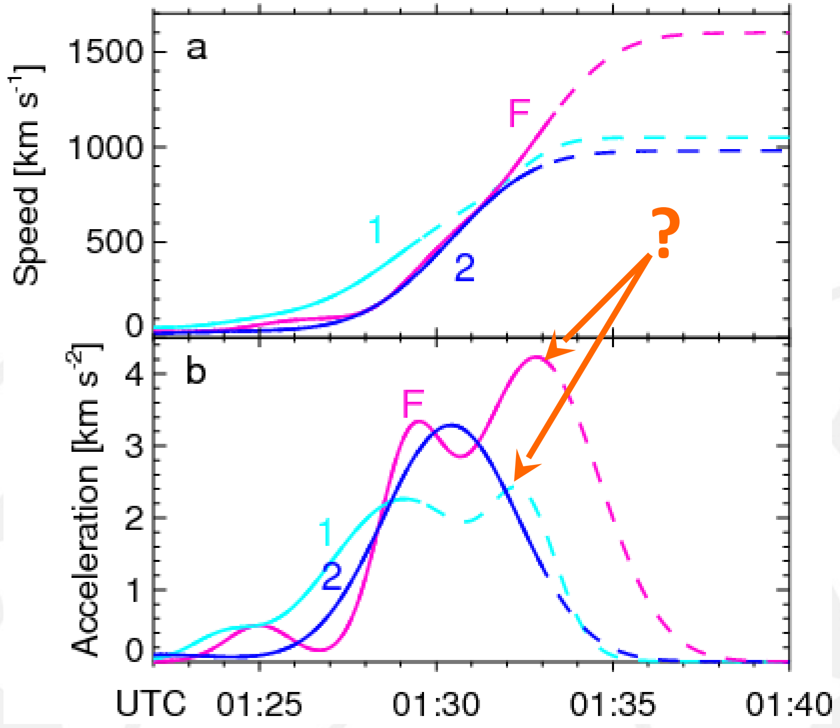


AIA 193 Å difference images with outlines

Two Major Eruptions: Kinematics



One-dimensional profiles



Speed and acceleration

- Knowing final speeds, we identify features F and 2 with CME components
- Structure 1 between them. Second acceleration episodes are unclear

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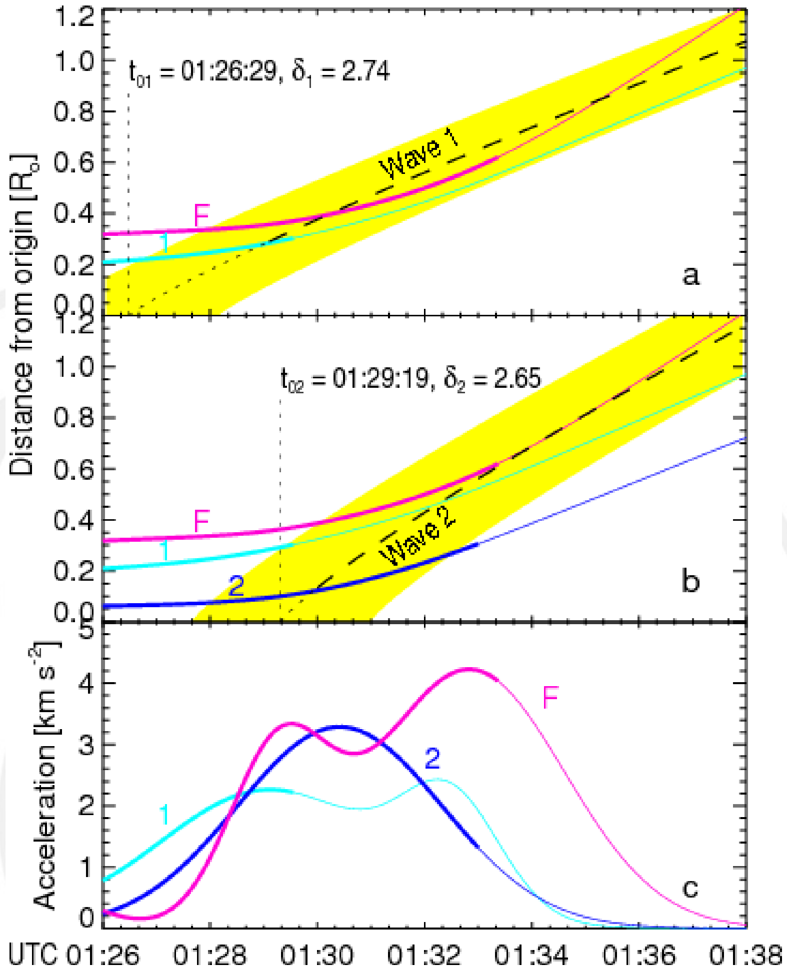
Unclear Acceleration Episodes

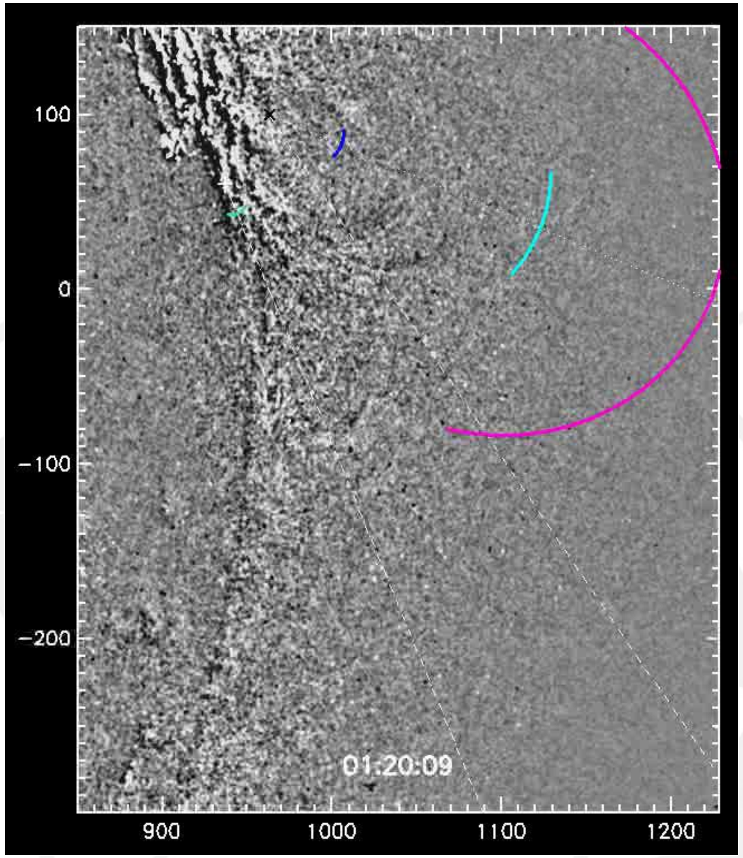
- Accelerations of structures 1 and 2: > 2 km/s^2 (> 7$g_\odot$) led to strong wavelike disturbances
- Their propagation speed
  - *initially the fast-mode speed*
  - *then decreases due to the loss of driver energy*
- Smooth shapes of acceleration pulses show that shock discontinuity has not yet been formed. Nevertheless, waves propagate in the same way: $x \propto t^{2/(5-\delta)}$, t_0 - onset, δ - density-falloff exponent $n_e = n_0(x/h_0)^{-\delta}$
- Yellow shadings – zones of influence of the waves:
  - horizontal width ≈ FWHM of acceleration pulses
- Each eruption excited a disturbance that, propagating outward, accelerated all structures above it



Kinematics of structures 1, 2, F and propagation of two waves

Disturbances

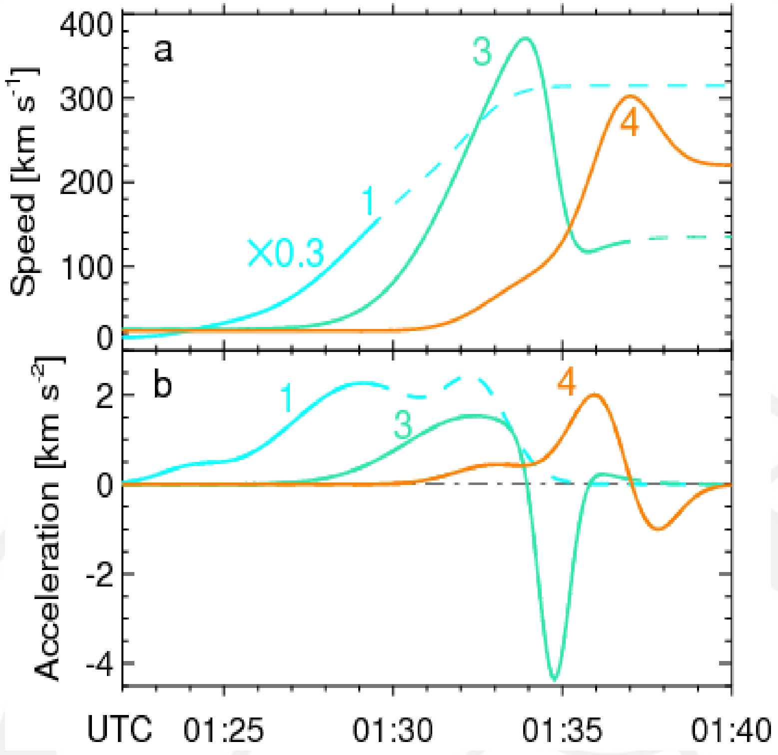
- Yellow ellipses correspond to zones of greatest wave steepness
- Other arcs are the same as previously (1, 2, F)
- Disturbance visible at bottom left: EUV wave
- Additional analysis of Proba 2/SWAP 174 Å images with a larger field of view confirmed: each eruption caused a disturbance that accelerated all structures above it

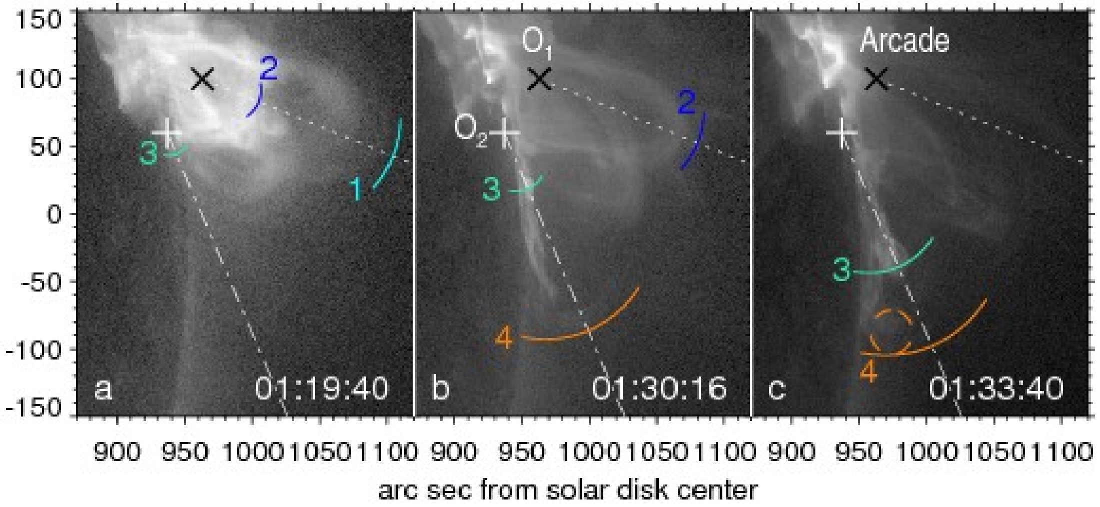


Motion of structures 1, 2, F and two waves on difference images AIA 193 Å

Motions near the Limb

- Speeds of features 3 and 1 varied similarly
- Radial speed of feature 4 was ≈ 100 km/s
- Features 3 and 4 moved too slowly and too late to become parts of the fast CME
- Idea of Shen et al. (2013) relating near-the-limb motions to another fast CME is not confirmed

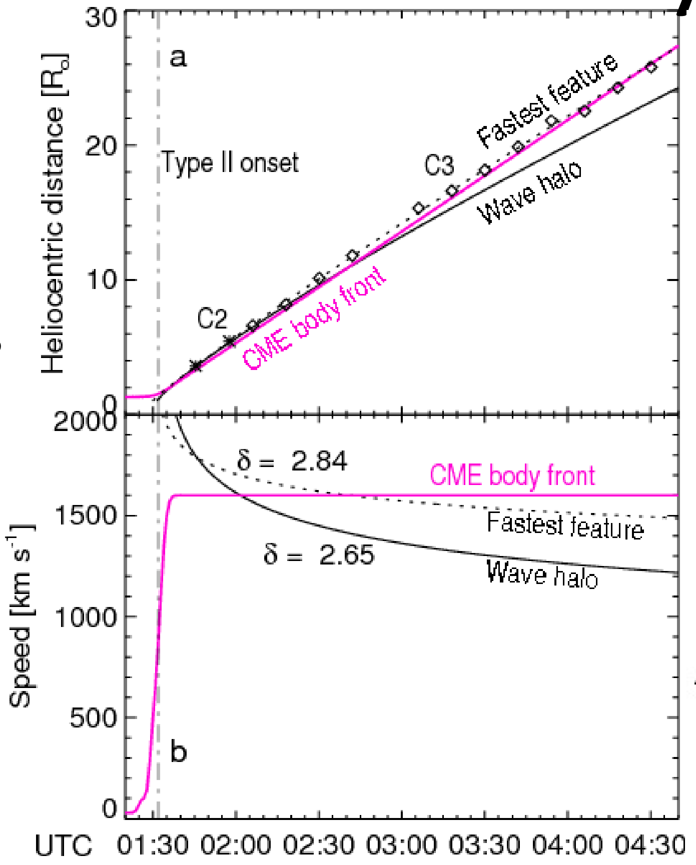




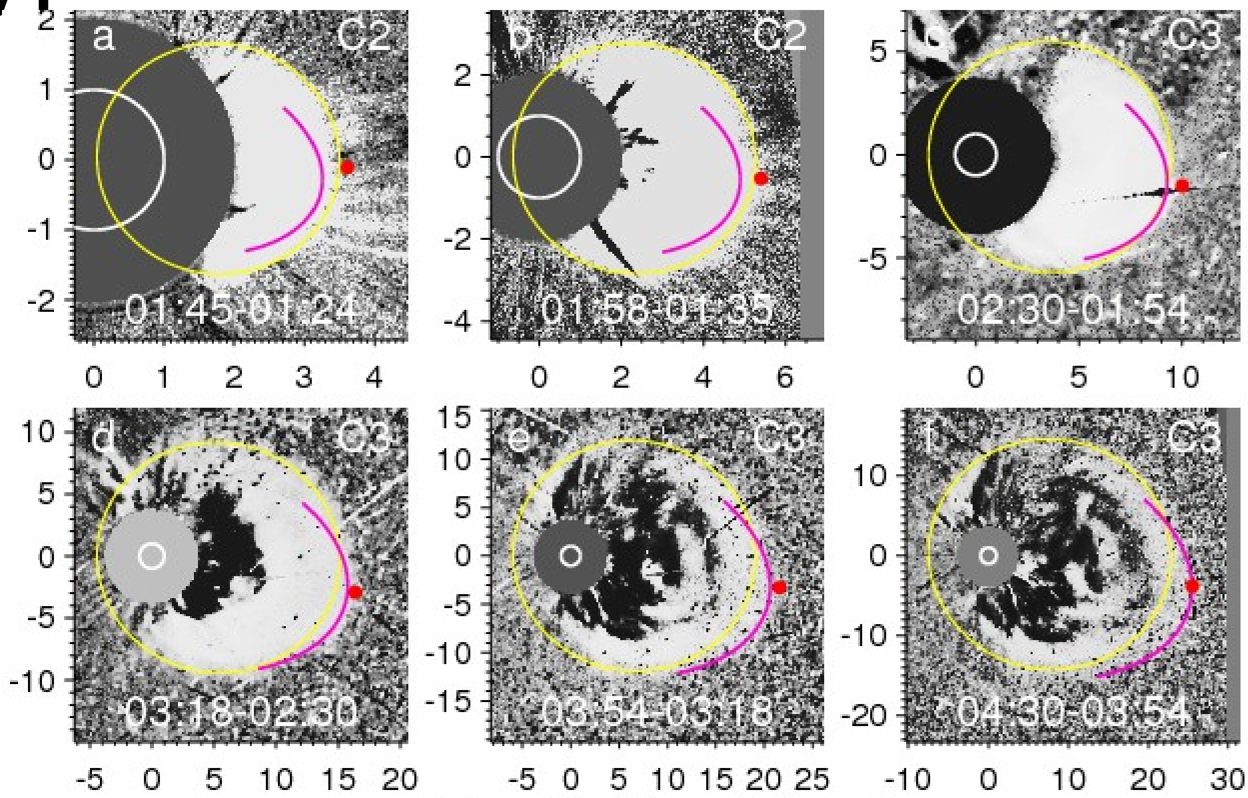
Movement of feature 3 could be due to detachment of southern leg of erupting magnetic-flux rope, whose top was feature 1. Feature 3 probably stopped when detachment region reached flux-rope's base. By hitting prominence 4, this flux-rope's leg destabilized it and caused it to slowly erupt

Waves and Type II bursts

- **Shock wave**:
  - Judging by its speed
  - Dash-dotted line: onset of Type II burst
- All wave traces initially propagate as **blast waves**
- Leading front at r > $10R_\odot$ began to transform into **bow shock**
- Motion of leading front agrees with CME catalog fastest feature
- Rear and flank parts of halo resemble **blast wave**



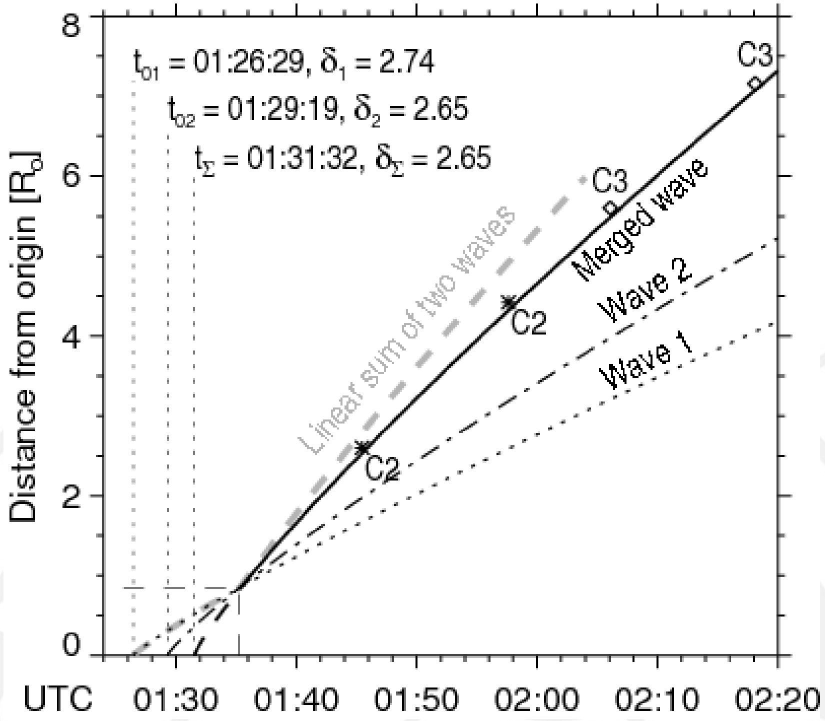
Leading wave front slowed down less than rear and flanks of halo



Wave halo outlined by yellow ellipses in LASCO-C2 and -C3 difference images. Purple arcs outline CME-body edge. Red dots represent measurements from CME catalog

Shock-Wave History

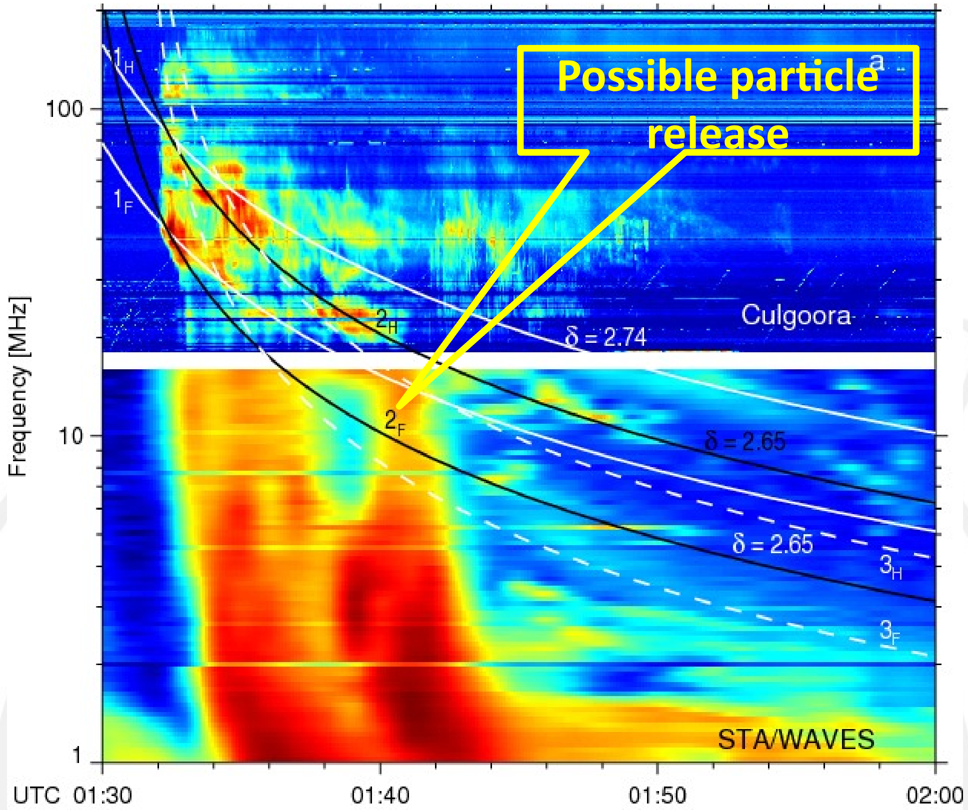
- Two eruptions caused wavelike disturbances with an interval of about one minute
- Each wave propagated into regions of lower fast-mode speed and soon became a shock wave
- Wave 2 appeared behind wave 1 and caught up with it differently in different direction
- Two waves merged into a single shock. Its speed is less than the sum of speeds of initial waves, but resulting shock is stronger and faster and has apparent onset time later than each of initial waves
- Wave halo in LASCO images was a shock-wave trace that formed when two initial disturbances merged



Merging of two nonlinear waves into stronger one. Dashed lines: initial waves 1 and 2. Gray dashes: linear summing their speeds. Black curve: wave halo in LASCO images. Its dashed part is extension to the virtual onset time t_Σ

Type II Radio Emission

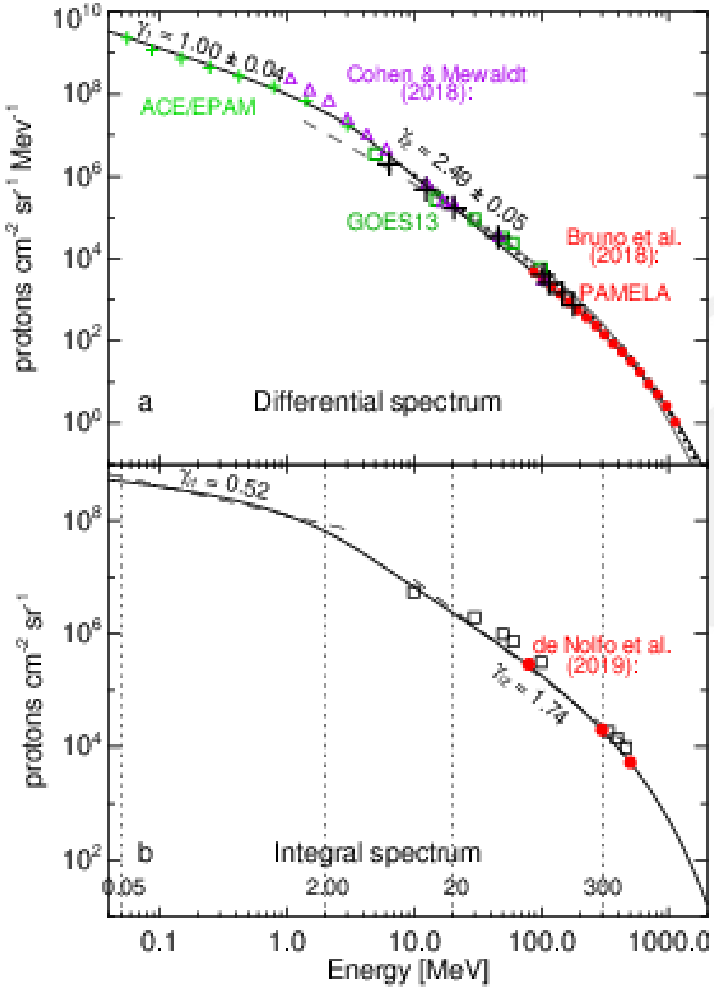
- Dynamic spectrum: superposition of emissions from different sources
- Type II structure reflects multi-ray coronal structure crossed by shock
- Complex structure of this Type II suggests passage of > 1 shock
- Knowing t_0 and δ of three possible shock waves, we trace their trajectories without trying to associate burst structures with a specific shock wave
- Trajectories reproduce the drift of bands and blobs on decameters and hectometers, not contradicting the slopes of metric structures
- Type III burst starting at 01:39:30 suggests release of electrons trapped in expanding flux rope, tracers of accelerated protons. This time is close to estimate of Rouillard et al. (2016) of particle release time of 01:37:20 from velocity-dispersion analysis . The shock wave had not yet become bow shock wave at that time

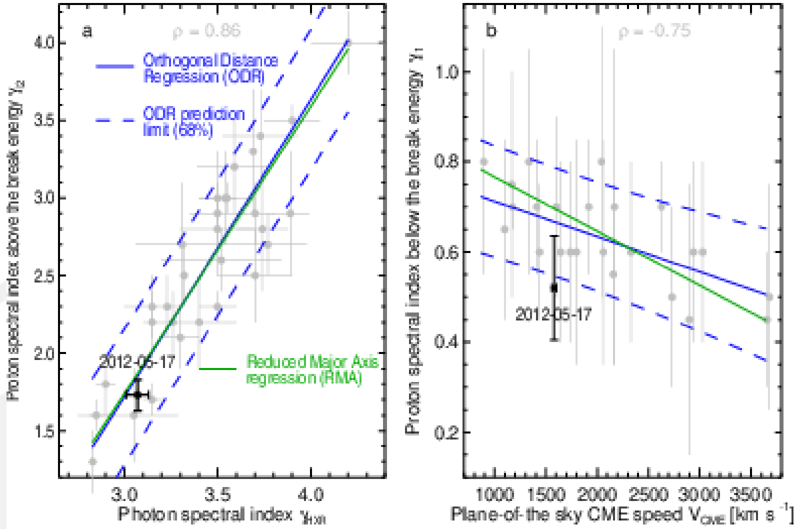


Dynamic spectrum composed from Culgoora and STEREO-A/WAVES data

SEP Spectrum and Statistical Suggestions

- We reconstructed total proton-fluence spectra from fractions of MeV to 1 GeV and compared the slopes in different energy ranges with results of statistical analysis of other proton events
- The slope of the integral proton-fluence spectrum at energies < 2 MeV correlates with CME speed
- The slope of the spectrum at energies 20 – 300 MeV correlates with photon index of HXR emission





During CME liftoff, piston shock initially forms. It is characterized by CME acceleration $a \approx V_{CME}/\Delta t$ with Δt being duration of flare's impulsive phase. **No correlation was found between *a* and highest-energy slope of proton-fluence spectrum in GLEs**

V.V. Grechnev, V.I. Kiselev, A.M. Uralov, N.S. Meshalkina, K.A. Firoz, A.L. Lysenko, Mysteries of the 17 May 2012 Solar Event Responsible for GLE71. I. CME Development and the Role of Disturbances Excited by Eruptions (2024, Solar Physics, in press).

Conclusions

- Two structures erupted one after another within 1.3 minutes and became parts of **only one CME**. Near-the-limb feature was not related to another fast CME. The two-CME scenario of Li et al. (2012) is not relevant for this event.
- Each of the two eruptions caused a disturbance that accelerated all structures above it. Subsequent steepening of the disturbances due to steep falloff of the Alfvén speed quickly formed shock discontinuity.
- Shock wave in this event (as well as others) developed from **piston shock to blast wave, and at distances of ≈10$R_\odot$ started transforming into bow shock ahead of CME nose and its near flanks.** Additional complication was merging of two waves into a stronger one and differently in different directions.
- When the first erupting structure reached a height of ≈ 1$R_\odot$, dynamic spectra show a signature of particle release at a time close to the estimate of Rouillard et al. (2016). However, it is not obvious that the authors' approach applies until bow-shock regime is established.
- Piston shocks are easily excited by impulsive mechanism, when surrounding fast-mode speed is not crucial. Piston shocks appear in weak events and without CMEs. Moving away from piston, shock wave then propagates as blast wave. Relationship between the speed of piston (CME) and surrounding Alfvén speed determines subsequent shock-wave history: if CME is fast, it becomes bow shock; if CME is slow or absent, it fades away.
- Proton-fluence spectra indicate that CME-driven bow shocks are mainly responsible for lower-energy protons, while higher-energy protons are mainly flare-accelerated. This is statistically dominant pattern, allowing for exceptions.

Thank you for your attention!

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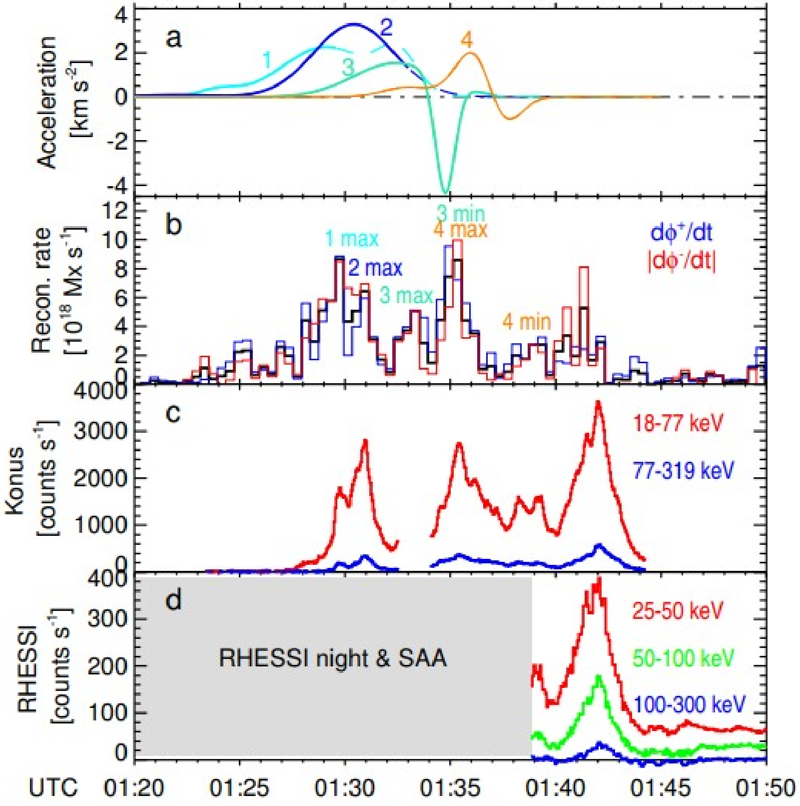
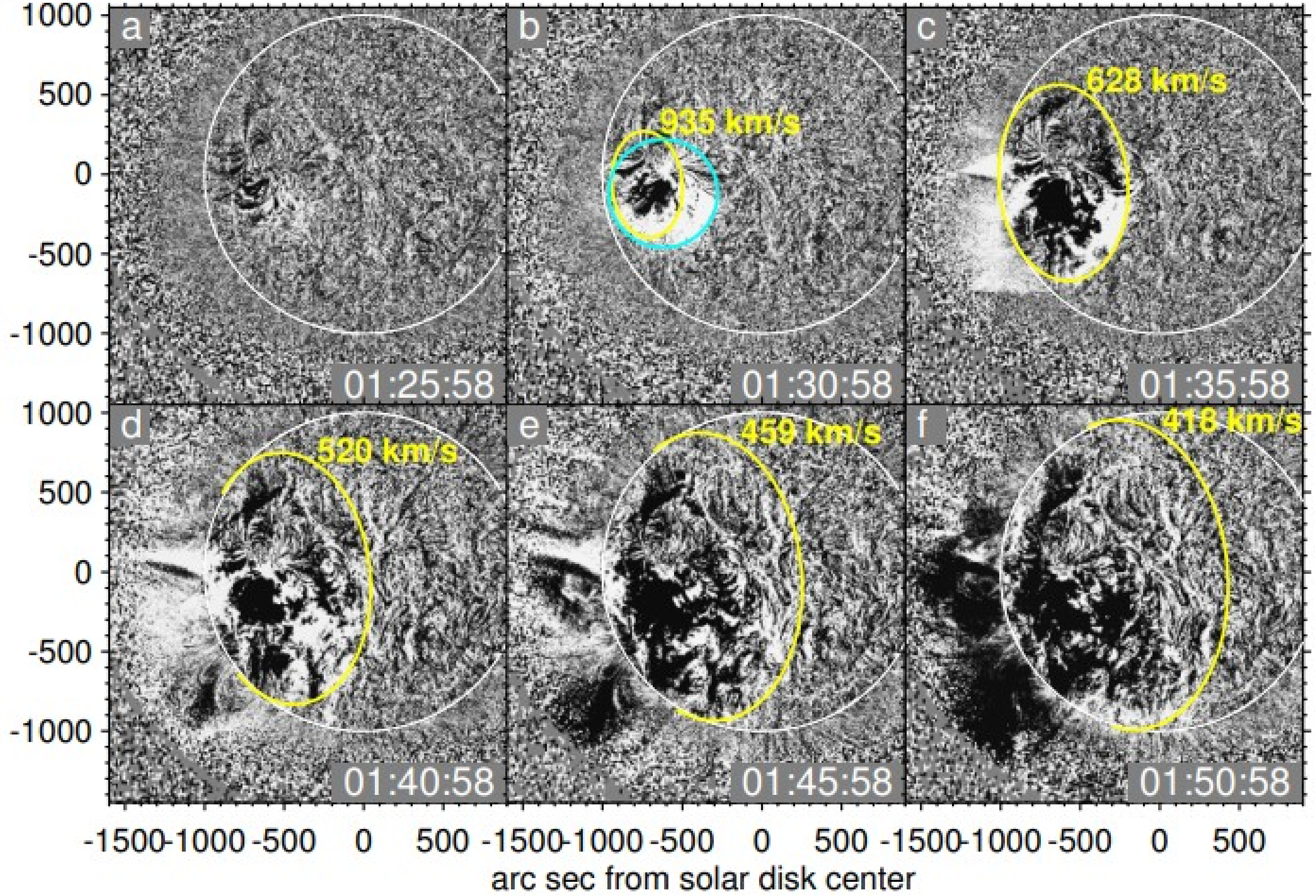


Figure 20. Comparison of temporal profiles of different characteristics of the event. **a**) Accelerations of erupting features 1, 2, 3, and 4. **b**) Temporal profiles of the magnetic-flux change rate. The *thin-blue line* presents the positive polarity, the *thin-red line* presents the negative polarity by the absolute value. The *thick-black line* presents the average of the two polarities. The *color labels* indicate maxima and minima of acceleration pulses corresponding to increases in the magnetic-flux change rate. **c**) HXR burst observed by *Wind/Konus*. **d**) RHESSI observations of the final part of the HXR burst. Its preceding part was missed (*gray shading*). RHESSI background levels are shifted up by 25 (50 – 100 keV) and 50 (25 – 50 keV) to show the burst better.



EUV wave visible in STEREO-A/EUVI 195 Å images. *Cyan circle* with a radius of $0.34\,R_{\odot}$ in panel **b** outlines the outer boundary of the first EUV-wave disturbance. *Yellow ellipses* correspond to the shock-wave propagation in an isotropic medium with $t_0 =$ 01:28:00 and $\delta = 1.8$. *Yellow legends* indicate the EUV-wave speeds calculated from this fit. *White circles* denote solar limb. The times of the images were corrected to account for the light travel time from the Sun to Earth and STEREO-A.