Kinematics of Waves in the Solar Corona:

Analyzing Potential Shock Waves to Predict Solar Energetic Particle Fluxes in Space Weather

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Background

① In the solar corona, flares and eruptions can produce shock waves – waves that are travelling faster than the local Alfvén speed, the 'sound' speed in the presence of the Sun's magnetic field.

↳ Shock waves produce a signature in the radio spectrum known as a Type II Burst.

↳ A wave can be confirmed to be a shock by matching it to a Type II Radio Burst.

② Additionally, the Sun can eject solar energetic particles (SEPs) such as protons, electrons, and ions with high kinetic energy greater than 10 MeV, a level that is 50,000 times more energetic than the solar wind.

◎ Events with high SEP fluxes can be triggered by (1) flares at the surface of the Sun or (2) shock waves in the solar corona linked to coronal mass ejections (CMEs).

◎ Some of these large SEP flux events hit the Earth.

↳ This can instigate dangerous space weather with the power to damage satellites and put the health of astronauts in space at risk.

◎ Only ~1% of shock waves associated with CME result in large SEP events.

↳ By studying shock waves, we hope to find a correlation in which ~1% of those solar events produce large SEP events at the Earth.

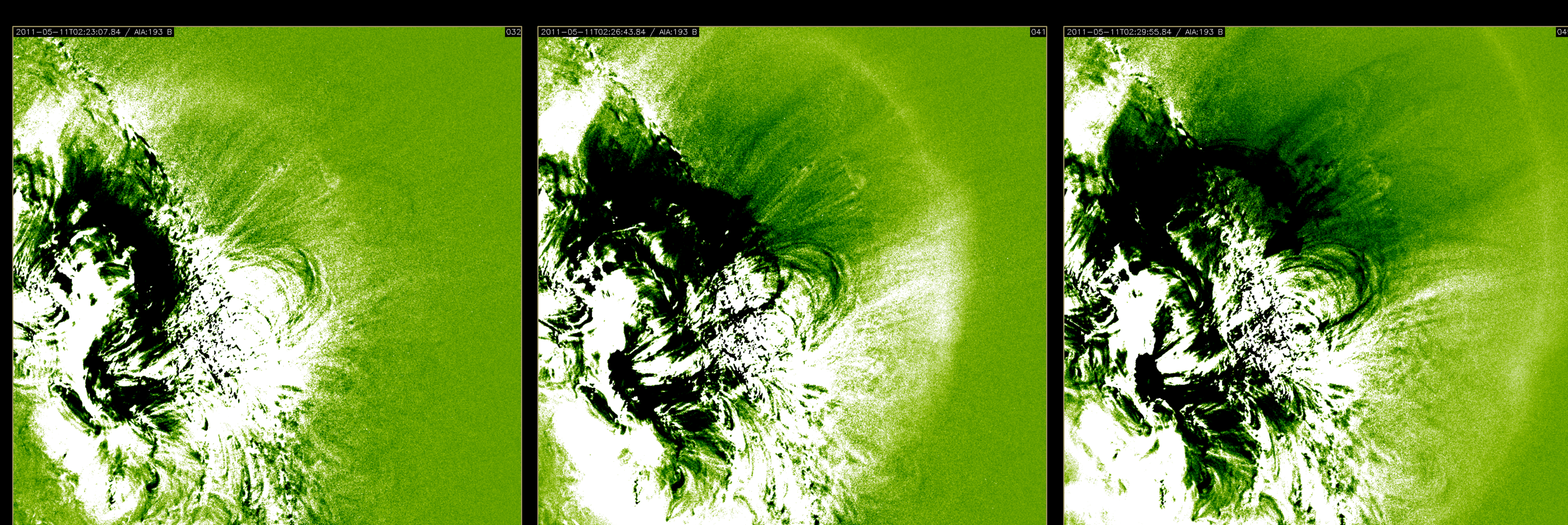

Figure 1 (Above) – These images show the propagation of the May 11th, 2011 candidate shock wave. The wave expands both radially and laterally in time, suggesting that it is in fact a wave and not a loop.

Project

◎ The Atmospheric Imaging Assembly (AIA) has a high 12 second cadence that makes it possible to better identify coronal shock waves and analyze their kinematics compared to that of previous instruments which used a 5 minute cadence.

↳ A typical shock wave stays in AIA's field of view for less than 20 minutes.

↳ We searched only for off-limb events, as their profiles and radial propagation are easier to analyze.

◎ Short Term Goals

① Identify shock wave candidate events along with possibly associated Type II Bursts.

② Make kinematics measurements – radial velocities and acceleration – for each candidate event propagating in the radial direction with a strong radial profile.

◎ Future Work

① Determine statistics on coronal waves.

② Determine if shocks can accelerate particles to greater than 10 MeV by measuring the acceleration of SEPs in the corona.

③ Find a correlation between coronal shock waves and large SEP events.

◎ In 30 months of AIA data (1/11 – 6/13), we identified 15 off-limb candidate events.

↳ Of these 15 events, we found Type II Radio Bursts associated with 7 of them.

↳ By tracking the wave feature over time in the radial direction, we were able to make kinematics measurements for 6 out of these 15 events.

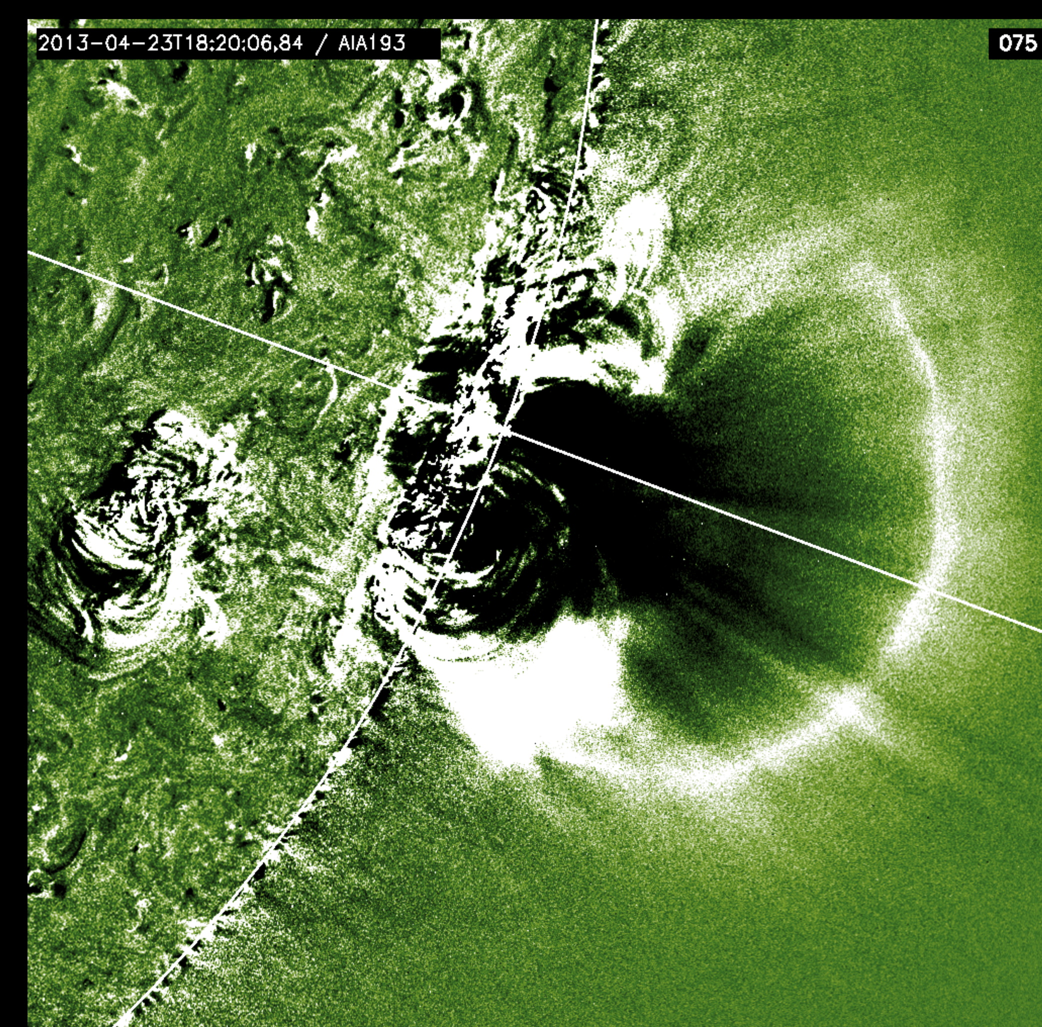

Figure 2 (Above) – This image shows a single frame of a base difference movie of the April 23rd, 2013 candidate event. 'Green-scale' is used to better distinguish the wave front, which appears in white. Along the radial white line, we plotted the intensity of the frames at each time step (e.g. Figure 3).

Date [UTC Time] (Location)	Flare Class	Type II Burst
01/25/11 [11:56] (SE)	?	No
01/28/11 [00:45](NW)	M1.3	No
02/11/11 [12:30] (NE)	?	No
08/09/11 [08:00] (NW)	X6.9	Yes
10/20/11 [03:05] (NW)	M1.6	No
07/28/12 [20:35] (SE)	M6.1	Yes
09/15/12 [22:50] (NW)	B9.6	Yes
10/07/12 [20:15] (NE)	C1.2	No
05/01/13 [02:15] (NE)	?	No

Table 1 (Above) – Nine (9) candidate events with no kinematics measurements

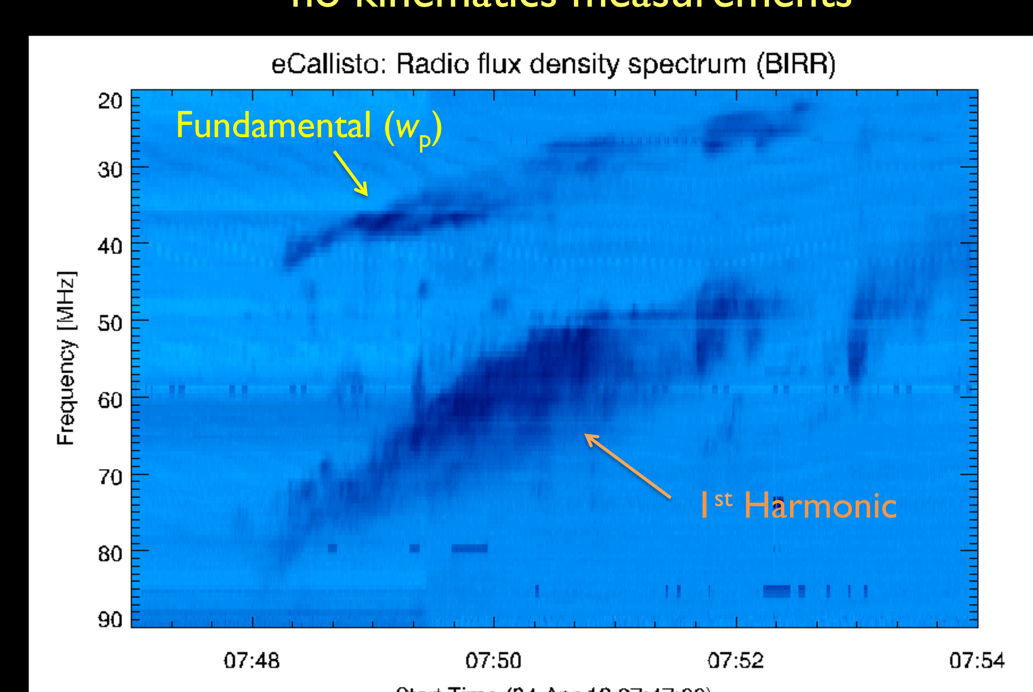

Figure 4 (Above) – This is a frequency-time plot showing the radio spectrum on April 24th, 2012. A Type II Radio Burst can be seen in dark blue. The emission occurs at the fundamental plasma frequency (w_p) and its 1st harmonic, which depend on the local electron density (n_e) that decreases at larger radii.

Analysis

① To distinguish the waves in the movies, we subtracted a base image from each frame.

② We tracked the waves' propagation along the radial direction over time.

③ We then plotted the intensity of the image along the radial axis as a function of time.

④ In the resulting distance-time plots, the waves should be seen accelerating to larger and larger radii over time.

⑤ We fit parabolas to the wave propagation to measure its kinematics. Depending on the quality of the distance-time plot, points on the curve were chosen manually or automatically.

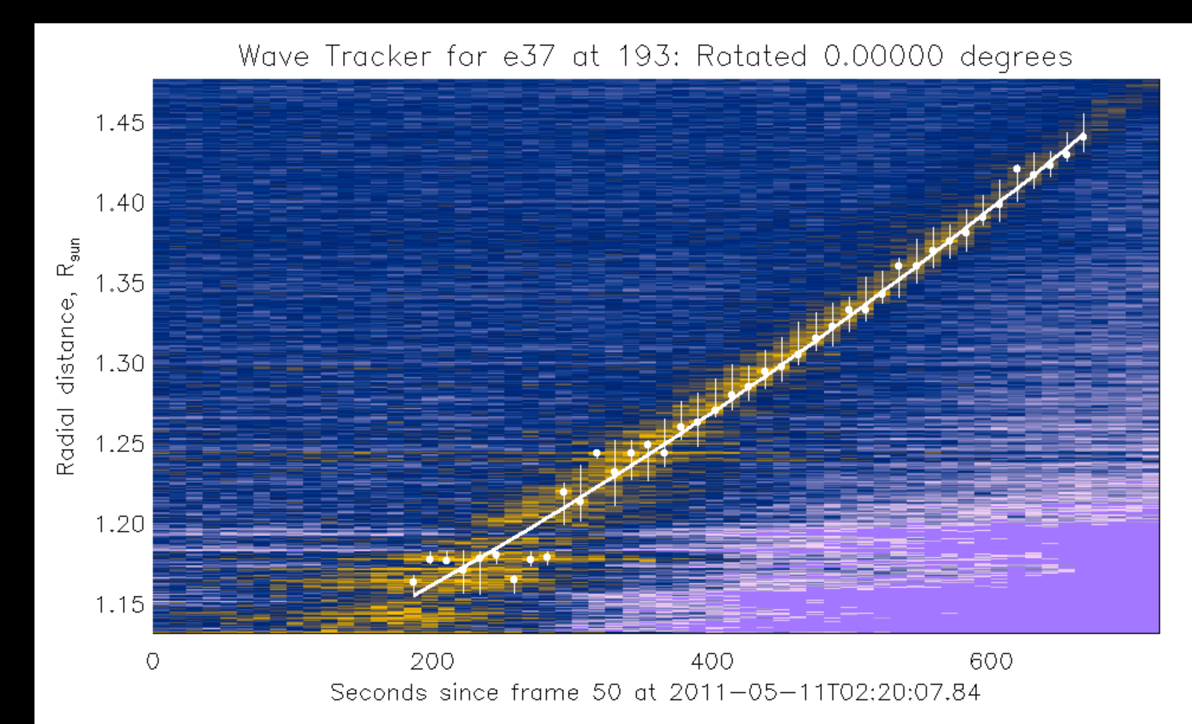

Figure 3 (Left) – This is a distance-time plot highlighting the radial propagation of a wave that occurred on May 11th, 2011. This is the cleanest example of these plots. The gold curve shows the wave. The purple blob tracks a different feature closer to the surface. A white dot marks the wave at each time step. A parabola is fit to these dots.

Results

We identified 15 off-limb potential shock wave events in 30 months of AIA data. Details for these events are presented in Tables 1 & 2.

Date [UTC Time] (Location)	05/11/11 [02:10] (NW)	08/04/11 [03:50] (NW)	11/09/11 [13:00] (NE)	04/24/12 [07:25] (NE)	05/26/12 [20:30] (NW)	04/23/13 [18:05] (SW)
Flare Class (ABCMX)	B8.1	M9.3	M1.1	C3.7	?	?
Type II Burst	Yes	Yes	Yes	Yes	No	No
Initial Velocity (km/s)	281.0	758.1	483.3	651.1	-10.7	286.4
↳ Error	9.57	154.2	36.6	131.2	108.4	51.5
Final Velocity (km/s)	510.0	2094.0	731.9	637.4	418.3	461.5
Acceleration (km/s)	0.424	9.277	0.740	-0.063	1.788	0.608
↳ Error	0.022	2.057	0.128	0.519	0.463	0.279

Table 2 (Above) – Six (6) candidate events with kinematics measurements

Conclusions

◎ Results

① We measured the final velocity of the events to be between 418 and 2094 km/s.

② Although we did not confirm any of the events to be shock waves, we would expect a shock wave to have a velocity of at least several hundred km/s, which is consistent with our results.

◎ The Next Steps

① Analyze the remaining candidates which did not propagate in the radial direction.

② Confirm some of the shock waves by matching them to their respective Type II Radio Bursts. The frequency-time plots of the Type II Bursts can be thought of as distance-time plots since the emission frequency depends on distance.

↳ If the emission is coming from a shock wave, the frequency-time plot (e.g. Figure 4) should align with the wave propagation in the distance-time plot (e.g. Figure 3).

References:

Kozarev et al., 2011, ApJL, 733, 25 Ma et al., 2011, ApJ, 738, 160 Temmer et al., 2010, ApJ, 712, 1410 Veronig et al. 2010, ApJL, 716, 57