Localizing the Source of Type II Emission Around a CME with SunRISE & MHD Simulations

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NESS Site Visit
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OUTLINE

• SunRISE’s Primary Science
• Intro to MHD and SunRISE Pipeline
• Making & Scoring Synthetic Spectra
• Geometrical Data Cuts
• Geometrical and Plasma Parameter Data Cuts
• Discussion & Conclusions
SUNRISE INTRODUCTION

- SunRISE – Sun Radio Interferometer Space Experiment
- Heliophysics Explorers Mission of Opportunity ($55 M)
- Almost done with Phase B
- Will launch mid 2023
- 6 CubeSats in GEO Graveyard Orbit
- Can see below Ionospheric Cutoff
PRIMAR..... SOLAR TYPE II & III BURSTS

\[ f \text{(kHz)} = f_p = 9\sqrt{n} \text{(cm}^{-3}\text{)} \]
CMES AND SEPS

- 2 types of SEP events: gradual and impulsive

- Gradual SEP events linked to Type II Bursts Generated near CME driven shock?

- Impulsive SEP events linked to Type III Bursts Generated by electron beams from jets?

- Frequency drift marks speed of wave generation site through the heliosphere
• Frequency drift marks speed of wave generation site through the heliosphere

• Local Plasma Frequency depends on local electron density

\[ \omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} = 8.98 \text{kHz} \sqrt{n_e / \text{cm}^3} \]

• Type III data used to create average density profiles over 1 AU (LeBlanc et al.)
**SunRISE Objective 1**

Discriminate competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location and distribution of Type II radio emission relative to expanding CMEs 2–20 Rs from the Sun, where the most intense acceleration occurs.

**SunRISE localization performance satisfies requirements with margin at all altitudes.**

<table>
<thead>
<tr>
<th>Localization Requirement</th>
<th>4 Rs (v = 1.0 MHz)</th>
<th>12 Rs (v = 0.4 MHz)</th>
<th>8 Rs (v = 0.8 MHz)</th>
<th>20 Rs (v = 0.26 MHz)</th>
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**Models**

1. Parallel Shock Ahead of CME
2. Perpendicular Shock from Flank Expansion
3. Reconnection Behind CME
4. Enhanced Turbulence from Compression
PAST SYNTHETIC SPECTRA FROM MHD

Models
1. Parallel Shock Ahead of CME
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Synthetic Spectra from Shock Front Nose

Synthetic Spectra from Shock Flank

Synthetic Spectra from Current Sheet

Synthetic Spectra from Diffuse Lobe

Interpolated WIND Waves R1+R2 data
SUNRISE RECOVERED RADIO EMISSION

Previous version used rotated simulation to show limb event

MHD Geometrical Derived Synthetic spectra

Visual Proof of Scientific Sufficiency: SunRISE recovered localizations over time

Hypothesis 1: Shock & Compression Acceleration in Front of CME
Hypothesis 2: Shock & Compression Acceleration on CME Flanks
Hypothesis 3: Magnetic Reconnection at Current Sheets
Hypothesis 4: Non-local Acceleration Process
PIPELINE OVERVIEW

Data Collected in Space

SunRISE Orbit Simulation
Phase Noise
GNSS Data
Position and timing for 5 S/C
CME Radio Burst Simulation
Radio Noise
Plasma, Galactic, Instrumental
DH Data
40 frequency channels, 2 pol, 5 S/C

Processing on the Ground

Baselines
S/C pairwise separations
Correlate
Visibilities for each frequency channel and polarization
Dirty Images
Sum of visibilities
CLEAN Images
Image processing output to remove sidelobes
Fit Bursts
Fit 2D Gaussian to visibilities
Burst Propagation Dataset
Burst localization and frequency over time

Simulations to create test data
Spacecraft Data
SOC Pipeline

KEY
Snapshots from a AWSoM 2-Temperature MHD Simulation of a Radio-Loud CME on May 13, 2005

Manchester et al. 2014
EXAMPLE OF MHD EXTRACTION TO SUNRISE

Gaussian convolved binary map over 6 kHz range

Imported to CASA truth image, given flux value

Run through SunRISE pipeline & extract Gaussian fit
IMAGING PIPELINE AT 1.5 MHZ

1. Simulation informed input emission distribution
2. Dirty Image with sidelobes
3. CLEANed Image with sidelobes removed
4. 2D Gaussian fit to data & put into context of CME Coronagraph Movie


SIGNAL TO NOISE CALCULATION

• Assume 5 m dual polarization isotropic dipoles (electrically short)
• 4096 channel Polyphase Filter Bank, 0-25 MHz, 6100 Hz channels, 6.6 ms / sec integration, 0.1 sec cadence
• Type II Signals ≈ Galactic & Plasma Noise
• Array: 6 spacecraft, 2 polarizations improves the sensitivity by a factor of 8.5

\[
\sigma = \frac{2 k_B T_{sys}}{\eta_s A_{eff} \sqrt{N(N-1)(N_{IF} \Delta T \Delta \nu)}}
\]

Taken from SunRISE CSR
CASE STUDY: 2005/05/13 CME
REAL WIND DATA & FIT CME PROFILE

Interpolated WIND Waves R1+R2 data

- Fundamental, \( r_0 = 2.0 \, R_s, v_0 = 2500.0 \, \text{km/s}, a = -26.7 \, \text{m/s} \) over 17.9 hours
- Harmonic, \( r_0 = 2.0 \, R_s, v_0 = 2500.0 \, \text{km/s}, a = -26.7 \, \text{m/s} \) over 17.9 hours

Reiner 2007 velocity fit
CREATING AN ANALYTIC GAUSSIAN PROFILE

Interpolated WIND Waves R1+R2 data

- Fundamental, $r_0 = 3.0 \ R_s$, $n_e$/cc @ 1 AU = 8.0
- Fundamental, $r_0 = 2.0 \ R_s$, $n_e$/cc @ 1 AU = 11.0
- Fundamental, $r_0 = 1.0 \ R_s$, $n_e$/cc @ 1 AU = 15.0

kHz

10^2
10^3
10^4

Hours past 2005/05/13 midnight

0 2 4 6 8 10 12 14 16 18 20

dB of intensity/Background
CREATING AN ANALYTIC GAUSSIAN PROFILE
Creating an analytic Gaussian profile

Type II Gaussian Stencil, Column Normalized

Yields "Scoring Stencil"

May be compared to synthetic spectra

Normalized so 1 point/timestep possible

Rewards spectra matching middle frequency
Snapshots from a AWSoM 2-Temperature MHD Simulation of a Radio-Loud CME on May 13, 2005

Manchester et al. 2014
SYNTHETIC SPECTRA OF MHD DATA CUTS

Wind/WAVES Observed Radio Spectra

Synthetic Data Interpolated to Wind Cadence, Score: 28.99
Shock Front Nose

Synthetic Data Interpolated to Wind Cadence, Score: 0.02
Current Sheet Region

Density x 3.5 Enhanced Region

Entropy x 4 Enhanced Region

Temperature > 3.5 MK (Current Sheet)
ZOOMING INTO ENTROPY SHOCK

FrontBit plot, time 8
Shock Front Bit Ind 0
Full Clean Cut
Good Cut, No radial cut, 3x3 chunk around $(6^\circ, -12^\circ)$

Bad Cut, No radial cut, 3x3 chunk around $(-42^\circ, -3^\circ)$
SCORING SPECTRA SIMILARITY OVER SHOCK GEOMETRY

- Similarity Scores of Longitude/Latitude Synthetic Spectra Cuts
- Normalized Similarity Compared to Stencil
- All (non-artifact) entropy enhanced data included

- Only data points with distance > 0.7*maxr included

- Only data points with distance > 0.8*maxr included
$V_{HT} = \frac{\hat{n} \times (V_u \times B_u)}{B_u \cdot \hat{n}}$

de Hoffmann-Teller frame velocity?

Frame where the convective electric field vanishes on both sides of the shock

Highly correlated with in situ Langmuir Waves (Pulupa et al. 2010)

Features of this over shock surface matches similarity structure
GLOBAL SPECTRA WITH DE HOFFMANN-TELLER THRESHOLD

Synthetic Data Interpolated to Wind Cadence, Score: 53.43

\[ t > 0.9 \times \text{maxr}, \quad V_{HT} > 2000 \text{ km/s} \]

Interpolated WIND Waves R1+R2 data

Wind/WAVES Observed Radio Spectra

Synthetic Data Interpolated to Wind Cadence, Score: 24.71

\[ t > 0.7 \times \text{maxr}, \quad V_{HT} > 2000 \text{ km/s} \]

Interpolated WIND Waves R1+R2 data

Wind/WAVES Observed Radio Spectra
Synthetic Data Interpolated to Wind Cadence, Score: 28.12
Entropy Shock Flank Bit Ind 810
Longitude -33 - -30 degrees, Latitude 0 - 3

3x3 chunk around (-30°, 0°), r > 0.9*maxr, V_{HT} > 2000 km/s

Synthetic Data Interpolated to Wind Cadence, Score: 67.15
Entropy Shock Flank Bit Ind 663
Longitude 6 - 9 degrees, Latitude -12 - -9

3x3 chunk around (6°, -12°), r > 0.7*maxr, V_{HT} > 2000 km/s
SIMILARITY SCORES WITH DE HOFFMANN-TELLER THRESHOLD

1 hour normalized, $r > 0.9 \times \text{maxr}, V_{HT} > 2000\ km/s$

2 hour normalized, $r > 0.9 \times \text{maxr}, V_{HT} > 2000\ km/s$
RECOVERED EMISSION 2

FrontBit plot, time 8
Entropy Shock Flank Bit Ind 663
Longitude 6 - 9 degrees, Latitude -12 - 9

Synthetic data interpolated in wind latitude, score: 66.17
Entropy Shock Flank Bit Ind 663
Longitude 6 - 9 degrees, Latitude -12 - 9
DISCUSSION

• SunRISE can distinguish between different theories of type II emission at CMES, informing theories of particle acceleration.

• Together with MHD simulations, SunRISE can inform what plasma parameters are important for particle acceleration

• Preliminary simulations indicate the emitting parts of the shock are likely those with high VHT,

• For 2005 case study, the eastern edge (left) of the shock is active in the first 40 minutes or so dominating the emission, then falling off

• The western and southern edges of the shock are also seen to have points with consistently high VHT, with a maximum similarity centered around \((6^\circ, -12^\circ)\)
VELOCITY OF SIMULATED CME SHOCK

![Graphs showing the height and speed of simulated shocks over time, and the velocity of the simulated shock.](image-url)
Figure 2. Radio measurements of the 2010 November 13 type III burst. (a)-(b) Fixed-frequency light curves of the radio flux density recorded by STEREO-A and STEREO-B for four frequency channels. The red lines show median values in the given time intervals. The dashed lines denote peak fluxes and last points above the median values. The green lines show the results of decay time fitting (Equation (1)).

Krupar 2018 + 2020

Scattering Screen

\[ \Theta \approx \arctan\left(\frac{\tau_c}{1 \text{ AU}}\right) \approx \frac{\tau_c}{1 \text{ AU}} \]

Scattering Angle

Valid for \( \tau_c \ll 1 \text{ AU} \) down to 0.3 MHz

~ 1 AU + \( \tau_c \) meters traveled

Sky View, Rings expand over time from disk

\(~ 0.1 \text{ AU} \) to \(~ 1 \text{ AU} \)
Scattering Screen

\[ \sim 1 \text{ AU} + \tau c \text{ meters traveled} \]

\[ \sim 0.1 \text{ Rs} \quad \sim 1 \text{ AU} \]

SCATTERING

\[ \sim \tau c \]

\[ \Theta \approx \arctan\left(\frac{v_{\text{AU}}}{1 \text{ AU}}\right) \approx \frac{\tau c}{1 \text{ AU}} \text{ Scattering Angle} \]

Valid for \( \tau c \ll 1 \text{ AU} \) down to 0.3 MHz

Also 0.1 Rs distance to scattering screen \( \ll 1 \text{ AU} \), implying near right angle in propagation triangle (Bastian 1994, Eqn)

\[ \Theta \approx \arctan\left(\frac{\tau c}{1 \text{ AU}}\right) \approx \frac{\tau c}{1 \text{ AU}} \text{ radians is *Maximum* scattering angle width in sky for e-} \]

folding time \( \tau \),

Valid for \( \tau c \ll 1 \text{ AU} \) down to 0.3 MHz

Or angular distance of scattered light out from source after \( \tau \) sec limited by speed of light

\[ \Theta = 6.8 \text{ deg} \text{ at } 1 \text{ e-folding time } \tau = 60 \sec \text{ at } 1 \text{ MHz (STEREO data 2018)} \]

\[ \Theta = 1.47 \text{ deg} \text{ at } 1 \text{ e-folding time } \tau = 13 \sec \text{ at } 10 \text{ MHz (PSP data 2020)} \]
Krupar et al. 2014
17:20 to 18:10 UT on 28 January 2008
apparent source size $\gamma_B$ and flux density of a Type III
Figure 5. Example radio bursts displaying circular polarization above $\sim 6$ MHz. In each plot, the top panel shows the Stokes intensity ($I$), while the second panel shows the relative circular polarization Stokes $V/I$. Negative $V/I$ in blue, indicates RHC polarization. In each spectrogram plot, the dotted line indicates the time profile of the leading edge of the burst. The bottom two panels show time profiles of $I$ and $V/I$ at a frequency of 10 MHz, showing how the polarization is localized near the leading edge of the burst and is absent at later times. The time of maximum circular polarization is indicated in these panels with a red dotted line.