Transient Mass Loss in Active Stars and Observation Methods

Michael Crosley
Rachel Osten
Outline

• Exoplanets and Habitability Concerns
• Coronal Mass Ejections
  • Traditional Detection Methods
  • CME-Flare and Solar-Stellar Connections
• Type II Radio Burst
  • Solar Example
  • Modeling and concerns
• Pretend the Sun is a Star
  • Multi-wavelength analysis and initial results
• LOFAR
  • Results and Additional Considerations
Habitable Zone

Stellar mass (relative to Sun)

Radius of orbit relative to Earth's

Habitable Zone

Mars

Earth

Venus
Coronal Mass Ejections (CME)

LASCO C3 (4-30 $R_\odot$) Image of a solar CME

- $M > 10^{13}$ kg
- $V \sim 100 - 3000$ km/s
- 1-5 times a day
Solar vs. Astronomical Coronagraphs

Harrison et al. (2005) specs for STEREO coronagraphs

Stellar CME at 2 R* at 5 pc: Separation of 0.5 mas = 0.0005 as.
# Eruptive Events

<table>
<thead>
<tr>
<th>Observational Signature</th>
<th>Sun</th>
<th>Stars*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flare</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Nonthermal Hard X-ray Emission</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Incoherent Radio Emission</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Coherent Radio Emission, m-dm-cm</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>FUV Emission Lines (transition region)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hot Blackbody Optical-UV</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Coronal Emission Lines and Continuum</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Optical/UV Chromospheric Emission Lines</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Coronal Mass Ejection</strong></td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Radio Type II Burst</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>High Velocity Outflows from Escaping Material</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Scintillation of Background Radio Sources</td>
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<td>?</td>
</tr>
<tr>
<td>Coronal Dimming's</td>
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</tr>
<tr>
<td>NH Increases in X-Ray Flare Spectra</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Pre-flare dips prior to Impulsive Phase</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Effects of CMEs on Stellar Environment</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Flare/CME Connections</td>
<td>✓</td>
<td>?</td>
</tr>
</tbody>
</table>

Reference is Osten 2017, in **Impacts of Exoplanetary Space Weather on Climate and Habitability of Terrestrial Type Exoplanets** (in prep.)
CME Connections to Flares (solar)

![Graphs showing CME association rate vs. Fp, Ft, and T.]

\[ \frac{1}{2} M_{CME} v^2 = \frac{E_{rad}}{\epsilon_f} \]

\[ M_{CME} = K_M E_{GOES}^\gamma \]

Osten & Wolk 2015, based on Emslie et al. 2012 and Drake et al. 2013

Aarnio et al. 2012
Drake et al. 2013

Yashiro et. al 2006
Low Freq. (16.5 – 33.0 MHz)
Bursts on AD Leo

Konovalenko et al. (2012)
Solar Type II Burst

Feb. 13, 2011
Description of the Type II burst

\[ \nu_A = 2.03 \times 10^{11} \frac{B}{\sqrt{n}} \]

\[ \nu_p = \sqrt{\frac{ne^2}{\varepsilon_0 m_e}} \]

\[ \frac{d\nu}{dt} = \frac{\partial \nu}{\partial n} \frac{\partial n}{\partial h} \frac{\partial h}{\partial s} \frac{\partial s}{\partial t} \]

\[ = \left( \frac{\nu}{2n} \right) \left( -\frac{n}{H_0} \right) (\cos \theta) (\nu_s) = -\frac{\nu \nu_s \cos \theta}{2H_0} \]
CME Mass from Flare Energy

\[ \text{Implied CME mass (g)} \]

\[ \log_{10} \text{X-ray Flare Energy (erg)} \]

- Aarnio et al. (2011)
- Drake et al. (2013)
Connecting CMEs and Flares

- Empirical Relation (Aarnio 20011, Drake 2013)

\[ M_{CME} = AE^\gamma \]

- Energy Equipartion (Osten, Wolk 2015)

\[ \frac{1}{2} M_{CME} v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}} \]

\[ E_{GOES} = \left[ \frac{A \epsilon v^2}{2} f_{GOES} \right]^{\frac{1}{1-\gamma}} \]

\[ v = \sqrt{\frac{2}{A \epsilon f_{GOES}}} (E_{GOES})^{\frac{1-\gamma}{2}} \]
Solar Comparison

The criteria used for data selection:

1. Flare is M or X-class
   • Peak flux above $10^{-5}$ or $10^{-4}$ W/m²
2. Associated CME observed at LASCO
3. The CME had a type II burst associated to it

Listed as `poor' in the SOHO/LASCO catalog
Non-exponential shape
Multiple signals, but chose the exponential shaped event.
Barometric Model

Crosley et al. 2017, submitted
Velocity

\[ \frac{d\nu}{dt} = -\frac{\nu v_s \cos\theta}{2H_0} \]

Crosley et al. 2017, submitted
Comparing Vel. \[ v = \sqrt{\frac{2}{A \varepsilon f_{GOES}}} (E_{GOES})^{\frac{1-\gamma}{2}} \]
Mass

Crosley et al. 2017, submitted
Comparing Mass

\( \frac{1}{2} M_{CME} v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}} \)

\( M_{CME} = A E^\gamma \)

Crosley et al. 2017, submitted
Kinetic Energy

Crosley et al. 2017, submitted
Comparing KE

\[ \frac{1}{2} M_{CME} v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}} \]

Crosley et al. 2017, submitted
Energy

\[ E_{\text{GOES}} = \left[ \frac{A \epsilon v^2}{2} f_{\text{GOES}} \right] \frac{1}{1-\gamma} \]
LOw Frequency ARray (LOFAR)

• LBA 10-90 MHz
• HBA 110-190 MHz
• Beam-Formed Mode
  • Combine collecting area into coherent ‘array beams’
    • Correct for geometric and instrumental time an phase delays for pointing
    • Restricted FoV, but full cumulative sensitivity of the combined stations
  • 5.12μs time resolution (van Haarlem et al. 2013)
  • 0.763-195 kHz frequency resolution (van Haarlem et al. 2013)
  • On and Off beam observation mode
YZ Canis Minors (CMi)

- 5.93 pc away (Perryman et al. 1997)
- $0.34 M_\odot$ (Lim et al. 1987)
- $\sim0.36 R_\odot$ (Mullan et al. 1992)
- B at flare sites between $B = 50 – 100G$ (Raassen et al. 2007)
- $n$ of $3 \times 10^{10}$ cm$^{-3}$ for quiescent state to $< 5 \times 10^{12}$ for hotter plasma (Ness et al. 2004)
  - expect bursts between $\sim1500 - 10$ MHz
- Coronal T of $10^7$ K (Dupree et al. 1993)
- 0.4 flares/hour with energies above U-band energy of $5 \times 10^{31}$ (Lacy et al. 1976)
- Low frequency (1500 – 300 MHz) microwave events observed (Kundu & Shevgaonkar 1988)
What Can We Expect?

Crosley et al. 2016
LBA Example

Crosley et al. 2016
Measuring Drift Rate

Crosley et al. 2016
Geometric Considerations

• On Sun, preferentially shock towards base of corona
• Susino et al. 2015 found an example solar CME which was fully super Alfvénic at 4 solar radii

\[ S_\nu \propto \frac{\nu^2}{c^2} \int T_b \, d\Omega \]

Byrne 2012
Observational Uncertainties

\[ S_\nu \propto \frac{\nu^2}{c^2} \int T_b d\Omega \]

Crosley et al. 2016
Moving Forward

- 60 Hours of EQ Peg Observations
  - Partial multi-wavelength observations
- Pursue large field surveys?
- More sensitive Observatories to push limits further

- Thank you!