LEM and M-SWCX

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Intro to the Magnetosheath

SWCX in the Earth’s exosphere:
- neutral targets mostly H in the exosphere,
- solar wind ion density increased by $4 \times$ due to shock
- strongest emission in cusps and magnetopause (MP)
- emission strongest along tangent to the MP
- emission has a broad spread of velocities

Magnetosheath is the brightest source of SWCX!

First observed by ROSAT as the “LTE”s.
Line Emission Mapper

- A proposed mission to study faint, extended X-ray emission in 0.2–2 keV band with high spectral resolution
- Large-area Si-shell X-ray mirror (Wolter type optic)
  - 1.5 m diameter, 4 m focal length
  - 10" HPD PSF
- X-ray microcalorimeter array
  - 30′×30′ FOV
  - 15″ pixels
  - 1-2 eV resolution
  - Possibly E down to 0.1?
- 1600 cm² at 0.5 keV
- TOO opportunities w/ 48 hour lead time
- L1 orbit
## Mission Comparison

<table>
<thead>
<tr>
<th></th>
<th>XMM</th>
<th>eROSITA</th>
<th>LEM</th>
<th>XRISM Resolve</th>
<th>ATHENA XIFU</th>
<th>HUBS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy band, keV</strong></td>
<td>0.3-11</td>
<td>0.1?–11</td>
<td>0.2–2</td>
<td>0.4–12</td>
<td>0.2–12</td>
<td>0.2–2</td>
</tr>
<tr>
<td><strong>Effective area, cm²</strong></td>
<td>0.5 keV</td>
<td>0.5 keV</td>
<td>6 keV</td>
<td>700</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>50 keV</td>
<td>0 keV</td>
<td>1600</td>
<td>50</td>
<td>6000</td>
<td>500</td>
</tr>
<tr>
<td><strong>Field of view</strong> (Equiv. Square)</td>
<td>26'</td>
<td>53'</td>
<td>30'</td>
<td>3'</td>
<td>5'</td>
<td>60'</td>
</tr>
<tr>
<td><strong>Grasp, 10⁴ cm² arcmin²</strong></td>
<td>50</td>
<td>216</td>
<td>140</td>
<td>0.05</td>
<td>12</td>
<td>180</td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>7.6–9.2’’</td>
<td>15’’</td>
<td>75’’</td>
<td>5’’</td>
<td>60’’</td>
<td></td>
</tr>
<tr>
<td><strong>Spectral resolution (FWHM)</strong></td>
<td>~40 eV (0.5 keV)</td>
<td>56–65 eV (0.5 keV)</td>
<td>1 eV central 7x7’’</td>
<td>7 eV</td>
<td>3 eV</td>
<td>2 eV</td>
</tr>
<tr>
<td></td>
<td>2 eV rest of FOV</td>
<td>2 eV rest of FOV</td>
<td>2 eV rest of FOV</td>
<td>2 eV</td>
<td>2 eV</td>
<td>2 eV</td>
</tr>
<tr>
<td><strong>Detector size (equiv. pixels)</strong></td>
<td>118 x 118</td>
<td>6 x 6</td>
<td>50 x 50</td>
<td>60 x 60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Orbit

Lyapunov Quasi-Halo, kidney shaped orbit in GSE Z=0 plane
Maximal GSE Y extent ~ 47º, with R~330 R_E
Extremes for four ~month-long periods each year
View Earth against ecliptic equator (±20º) - relatively smooth background for North Hemisphere winter observations - allows coordination with auroral campaigns
The Orbit

Lyapunov Quasi-Halo, kidney shaped orbit in GSE Z=0 plane
15" subtends 0.024 $R_E$ at the Earth, FOV subtends ~3 $R_E$ at the Earth
Allows a LOS tangent to the magnetopause relatively close to the nose of the MS
Cusp observations probably too close to the bright Earth
Simulations

• Assumed a median solar wind flux \(2.13 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}\)

• Used a SWCX spectrum constructed for the slow solar wind
  Carefully curated cross-sections, branching ratios, & abundances (VK & DK)
  LEM target launch during solar minimum → slow s.w. dominates
  Spectrum normalized to produce correct ROSAT LTE - \(n_{\text{sw}}\) relation
    (see Kuntz et al 2015) → spectral norm = scale factor × \(Q\)

• X-ray background model
Simulations

- X-ray background model
  - Use HaloSat data
  - Used Local Hot Bubble normalization from Snowden+ (1998)
    - corrected for SWCX by Lui+ (2017)
    - $kT_{LHB}=0.84$ from Bluem+ (2022)
  - Assume mean high North Galactic spectrum from Bluem+ (2022)
    - $kT_{soft}=0.166$
    - $kT_{hard}=0.69$
  - Assume Cappeluti+ (2017) unresolved X-ray background
  - Assume 1 count KeV$^{-1}$ s$^{-1}$ for instrumental background
Taking a FOV that is maximally filled with magnetosheath emission
- assuming 2 eV resolution but not accounting for thermal or velocity broadening
- assuming background emission at 0 km/s
- total counts/line is \( \sim 8.5 \times \text{max(count/ks/chan)} \)
Assuming a reliable background spectrum:

- **Easy**: species with at least one line with $\text{SWC}/\text{Total}=\bar{f} > 0.5$; at 10 ks, ~1000 counts
  
  Direct summation of counts sufficient

- **Moderate**: species with at least one line with $\bar{f} > 0.2$; at 10 ks, ~100 counts
  
  Fitting a small spectral interval required

- **Fainter lines/species can be extracted by fitting multiple small intervals of spectrum**
Simulations
And even better, the MS emission will be shifted with respect to the background!

From the OMNI database, the 95 percentile for solar wind speed ~640 km/s. Since the peak LOS velocity is ~0.75% of the free-flowing solar wind, → ~490 km/s is the highest LOS likely to be observed. However, we may not be lucky enough to observe it. Likely range of $v_{\text{rel}}$ accessible to LEM observations is 225-400 km/s ~ 0.2-0.35 energy resolution elements, readily detectable for lines with a few hundred counts. CMEs may reach higher velocities!
Simulation

• Using typical freeze-in $T(Z)$ to determine relative level populations, then using the X-ray emissivities to approximate the brightness of each species/charge state. (Logarithmic)
• LEM covers most of the species that contribute to the X-ray background, usually with multiple lines per species.

☐: ACE measures possible
×: Ulysses measures possible
○: Easy
◎: Medium

Odd $z$ species not included due to lack of data.

Most species/states accessible through fitting!
And X-ray important species will be the easiest.
Why?
Lab-Astro Motivation

• All astrophysical observations contaminated with SWCX
• Attempts to characterize SWCX emission problematic:
  • Lack of Data
  • cross-sections
    • don’t know correct ℓ distribution of the transferred e⁻
  • instantaneous solar wind ion abundances
    • in situ measures often don’t cover X-ray important species
    • In situ ion coverage limited and unlikely to improve
  • Temporally Variable

Observations of the magnetosheath provide the highest S/N spectrum
- does not provide a standard SWCX spectrum for background subtraction
- does provide information to model astrophysical charge-exchange
Astrophysical Motivation

- Even at CCD resolution we have measured differences in solar wind abundances using CX from comets (C V, C VI, N VI, N VII, O VII, O VIII)
- A LEM 10 ks exposure allows easy/medium measurement of many of the species previously measured with ToF instruments.
- Spectral fitting allows access to many more species.
- LEM can access species not available to ToF instr’s
  Rare species whose M vs. M/q falls near an abundant one
- LEM can access some odd-z elements
  Just need one line in quiet part of spectrum!
  (but not included here due to lack of data)

Solar Wind abundances are one of the three measures from which we derive the abundance of the Sun…
…LEM can contribute!
Heliophysics Motivation

Solar wind abundance in streamers (equatorial flow) is not the solar abundance. The solar wind abundance modified by:
- FIP fractionation
- mass fractionation
- many other fractionation processes (von Steiger & Zurbuchen 2016)

These processes are understood(?) by comparing photospheric abundances (optical/UV) with in situ abundances.

However, several important elements needed for comparison are not measured by in situ measures: S, P, and Ar, all of which are expected to be accessible in the X-ray.

SWCX spectra of the magnetosheath will provided abundances that can be used to understand these fractionation processes.
Space Physics Motivation

Imaging the magnetosheath in soft X-rays allows large scale mapping!
This motivates LEXI, SMILE, and STORM missions, but LEM can’t do that.
LEM can measure motion of the magnetopause!
Between 25th and 92nd percentile solar wind speed - motion is 20', almost the FOV.
Space Physics Motivation

The MP moves due to
- changes in the solar wind pressure ($nv^2_{sw}$) well understood
- reconnection - not understood!
  - how does reconnection actually “work”?
    - steady vs. bursty?
    - single step vs. incremental?
    - slow vs. fast?
→ watch MP in conjunction with
  - solar wind measures
  - auroral measures
Another motivation for SMILE & STORM…
…but LEM can do it too!
Space Physics Motivation

The STORM STM required:
- localization of the magnetopause to within 0.25 \( R_E \)
- for a 3 minute exposure
  (due to variability and reconnection time-scales)
- for times when \( n v_{sw} > 2.5 \times 10^8 \text{ cm}^{-2}\text{ s}^{-1} \)
LEM can do this by imaging the soft emission
- “nodding” across the magnetopause
- using model/measured cross-correlation techniques
  
  MonteCarlo \( \mapsto 1\sigma = 1.3 \text{ 2'} or \sim \pm 0.22 \ R_E \)
The magnetopause is expected to show ripples, waves, and other kinetic structures.
- The scale of these structures is expected to be 0.1-1 $R_E$ i.e., very uncertain.
There are expected to be high density foreshocks.
- Again, the details are relatively poorly constrained,
- but have a critical impact on energy deposition in the magnetosheath.

LEM’s relatively high angular resolution (compared to MPO based missions) will allow detection or constraint on all of these features.
Summary

The Earth’s magnetosheath provides the brightest SWCX emission.

Observations of the magnetosheath
- provide direct measurements of the important SWCX lines (i.e. the lines that will interfere with astrophysical observations)
- help determine of which ℓ-entry schemes are important

- allow study of solar wind abundances in species not (well) measured by in situ TOF instruments
- allow further exploration of the processes that modify the solar wind abundances compared the underlying solar abundances

- allow study of the magnetosheath at a spatial resolution un-matched by any currently accepted mission, certainly better than SMILE, and comparable to the planned (but not yet funded) STORM mission.