Future prospects for EUV and soft X-ray solar spectroscopy missions

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NASA Heliophysics
Science Mission Directorate (SMD) [$6.2B]

- Heliophysics [$0.7B]
  - Earth Science [$1.9B]
  - Planetary [$2.2B]
  - Astrophysics [$1.4B]
  - Solar Physics
    - Heliospheric Physics
    - Space Weather
    - Geospace physics
    - Earth’s atmosphere (ITM)
Current NASA Solar Missions

SOHO (1995) - led by ESA
Hinode (2006) - led by JAXA
STEREO (2006)
SDO (2010)
IRIS (2013)
[Parker Solar Probe (2018)]

**EUV & Soft X-ray instruments**
- Hinode: EIS & XRT
- STEREO: EUVI
- SDO: AIA & EVE
- IRIS
NASA Heliophysics Mission Opportunities

Small Explorer (SMEX)
- Five missions selected for Phase A study in 2017
- MUSE, FOXSI, PUNCH, MEME-X, TRACERS
- Final selection: any time now

Mission of Opportunity
- Proposals submitted in Nov 2018
- EUVST, COSIE

Medium-Class Explorer (MIDEX)
- Proposals due in Sep 2019
EUV & SXR instrument basics
The “thermal” Sun
Science topics addressed by EUV & SXR spectroscopy

Seismology, wave heating
- Propagation of Alfvén waves through atmosphere
- Dissipation (resonance absorption; KH instability)

Coronal heating
- Small-scale heating and cooling
- Nanoflares: evaporative upflows
- Braiding of loop structures

Eruptions
- Energy build-up
- CME dynamics

…and “non-thermal” science
- non-thermal broadening
- non-Maxwellian diagnostics
- non-Gaussian line profiles
High resolution spectra: \((\lambda / \Delta \lambda) \geq 1000\)
Note: limits set by C IV at 1550 Å, and Fe/Ni feature at 8 keV
Long-term goal
Simultaneous imaging and spectroscopy at multiple wavelengths, and a cadence of seconds.

Images at cadences of seconds
Hi-res spectra at each pixel
NORMAL INCIDENCE

Sub-arcsecond imaging

EUV (> 50 Å)  
[EIS, AIA, IRIS]

GRAZING INCIDENCE

Arcsecond imaging

X-rays (< 50 Å)  
[XRT]

COLLIMATORS

Fourier imaging

X-rays (< 50 Å)  
[RHESSI]

Photon sieves/Fresnel zone plates may give milli-arcsec imaging
Fresnel Zone Plate

- Replaces the primary mirror in an optical system
- Alternating rings of open and closed aperture
- Light is focused through diffraction
- Can achieve \textit{milli-arcsec} imaging in the EUV!
- Downside: needs high-accuracy formation-flying (~100 metres separation)
- Kipp et al. (2001, \textit{Nature}) discussed use for X-rays

A \textit{photon sieve} replaces the rings with holes, giving structural stability
Development underway at NASA-Goddard (Adrian Daw, Doug Rabin)
The EUV spectrum: 50 - 1600 Å
Hi-C flight, Aug 2018
0.3” imaging

AIA 171

Hi-C 2.1 (17.2 nm)

Multilayer coatings

"Traditional" normal incidence spectrometer design
**Imaging Spectroscopy**

- Sun is imaged through a narrow slit
- A single exposure gives a spectrogram
- Scanning the slit across the Sun builds up an image
Imaging slit spectrometers

- EIS
- SPICE SW
- SPICE LW
- IRIS

Wavelength / Å

200 400 600 800 1000 1200 1400
Launch: February 2020
SPICE will have excellent temperature coverage through atmosphere

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength</th>
<th>Temp</th>
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<tbody>
<tr>
<td>H I</td>
<td>1025.7</td>
<td>15 kK</td>
</tr>
<tr>
<td>C II</td>
<td>1037.0</td>
<td>45 kK</td>
</tr>
<tr>
<td>C III</td>
<td>977.0</td>
<td>90 kK</td>
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<tr>
<td>O IV</td>
<td>787.7</td>
<td>140 kK</td>
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<tr>
<td>O VI</td>
<td>1031.9</td>
<td>300 kK</td>
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<tr>
<td>Ne VIII</td>
<td>770.4</td>
<td>600 kK</td>
</tr>
<tr>
<td>Mg IX</td>
<td>706.1</td>
<td>1 MK</td>
</tr>
<tr>
<td>Si XII</td>
<td>520.7 (x2)</td>
<td>2 MK</td>
</tr>
<tr>
<td>Fe XVIII</td>
<td>974.9</td>
<td>7 MK</td>
</tr>
<tr>
<td>Fe XX</td>
<td>721.6</td>
<td>10 MK</td>
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Font size indicates expected line strength
SPICE: connection to the solar wind

Flare/coronal heating connoisseurs will be interested in hot lines…
SPICE: hot lines in the UV

Atomic levels for hot Fe ions

~ 10 eV

Emission lines in ultraviolet

~ 100 eV

Emission lines in X-rays
SPICE: hot lines in the UV
EUNIS

- First high resolution spectra at 90-110 Å in many years!
EUNIS and the AIA 94 Å channel

• Early AIA data analysis suggested CHIANTI was not modeling this channel correctly
• Del Zanna (2012, A&A) provided improved line identifications based on 1970’s spectra
• EUNIS will provide new high-resolution spectra in this range
Solar-C/EUVST

• The ultimate EUV slit spectrometer!
• Complete temperature coverage & 0.4” spatial resolution

[Proposed to JAXA and NASA (2018)]
Multislit Ultraviolet Solar Explorer (MUSE)

- 37 parallel slits give 2D “picket-fence” images of the corona at 0.3 arcsec resolution
- Have high resolution spectra at each spatial pixel
- Multilayer coatings minimize overlapping spectra
MUSE: what would spectra look like?

Generally the intended lines are dominant. Weak, contaminant lines are present though.

Simulation for 171 and 284 channels by A. Daw
MUSE: technical details

**Spectrograph**

25 cm EUV telescope multi-slit spectrograph
- 0.167 arcsec pixels w/ 0.4 arcsec resolution
- 37 parallel slits separated by 4.67 arcsec & 0.4 Å
- raster FOV:170”x170” in 12 steps of 0.4 arcsec
- 14.6 mÅ spectral pixel w/ 30 mÅ resolution

*Triple passband: bright, isolated lines*
- 108Å: Fe XIX & Fe XXI, effective area 2 cm² (hot loops, braiding, flares)
- 171Å: Fe IX, effective area 3.7 cm² (quiet Sun and active region)
- 284Å: Fe XV, effective area 1.8 cm² (active region)

**Imager**

20 cm EUV telescope
**Context imager**
- 0.143 arcsec pixels w/ 0.33 arcsec resolution
- FOV: 580”x290”

*Dual passband*
- 195Å: Fe XII & Fe XXIV, effective area 5 cm²
- 304Å: He II & Si X, effective area 0.8 cm²
COSIE

- Wide-field EUV coronal imager, with spectroscopy mode
- Led by SAO, with NASA-Marshall & Lockheed

The feed optic can flip over, switching between imaging and spectroscopy modes
The soft X-ray spectrum: 1 - 50 Å
1. Access to Fe XXV & XXVI, formed at >40 MK
2. Group of Fe lines from 11-17 Å
3. FIP diagnostics with (Fe, Ca, Si, Mg) vs. (Ar, Ne, O)
MaGIXS

- rocket to be launched 2020
- imaging slit spectrometer (grazing incidence 😞)
- spectral resolution ≈ 500

[Graph showing spectral data with labels Fe XVII-XXIV and energy range from 10 to 50 keV]
MaGIXS Science Objectives

1. Relative amounts of high temperature plasma in solar structures
   • Ratio of 3-5 MK plasma vs. 5-10 MK plasma

2. Element abundances (FIP effect)
   • Ratio of Ne or O vs. Mg or Fe

3. Temporal variability at high temperatures
   • Study light curves in several Fe XVII lines

4. Likelihood of non-Maxwellian distributions
   • Ratio of Fe XVIII lines to AIA 94 Å channel

- All science objectives relate to active regions as lines formed in 3-10 MK range
- MaGIXS would be great for flares, but unlikely during rocket flight
Crystal Spectrometers

- High spectral resolution ($\lambda / \Delta \lambda \geq 1000$)
- Bent crystal (BCS): spectra in narrow bands
- Flat crystal (FCS): scans over wavelength
- No spatial information
- Heritage from SMM, Yohkoh, CORONAS-F
- Next iteration of FCS: SOLPEX/RDS (KORTES)
Si-PIN and Si Drift Detectors (SDDs)

- Allow very compact, non-dispersive X-ray spectrometers
- Energy range: 1-20 keV [0.6-12 Å]
- Resolution ($\lambda / \Delta \lambda$) ≈ 50 [low]
- No imaging capability
- Used on several planetary missions [NEAR, Messenger, Chandrayaan]
- SDDs flown on MINXSS 1 & 2

**Future**

- INSPIRESat-1/DAXSS [CU-Boulder]
- XSM on Chandrayaan 2 [India, 2019]
- STC on FOXSI-SMEX [Marek’s talk]
CubIXSS

- 6U CubeSat mission concept
- Combines MINXSS-type spectrometers with slitless spectrograph (MOXSI)
- Extends wavelength range up to 55 Å
**Microcalorimeters**

- Enables simultaneous imaging & hi-res spectroscopy at sub-second cadence
- Flown for astrophysics (Hitomi, 2015)

**Hitomi SXS spectrum of Perseus Cluster**

*Nature, 2016*

**Future astro missions:**
- XRISM [2021, JAXA/NASA]
- ATHENA [2031, ESA]
- LYNX [2035, NASA]
A platform that combines EUV, soft X-rays and hard X-rays is highly desirable for studies of energetic phenomena!

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<th>On the way</th>
<th>Proposed</th>
<th>Long term</th>
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<td>Solar Orbiter / SPICE</td>
<td>MUSE</td>
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<td>Solar-C / EUVST</td>
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<td>Soft X-rays</td>
<td>MaGIXS</td>
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Talk available at https://pyoung.org/talks