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

Dr Peter Young
NASA Goddard Space Flight Center, USA
Northumbria University
NASA Heliophysics
Science Mission Directorate (SMD) [$6.2B]

- Earth Science [$1.9B]
- Planetary [$2.2B]
- Astrophysics [$1.4B]
- Heliophysics [$0.7B]

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)
Solar Dynamics Observatory (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: April 2019

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

Medium-Class Explorer (MIDEX)
- Proposals due in Sep 2019
EUV & SXR instrument basics
High resolution spectra: $(\lambda / \Delta \lambda) \geq 1000$
Long-term goal
Simultaneous imaging and spectroscopy at multiple wavelengths, and a cadence of seconds.

an added bonus would be polarimetry!
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

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

A 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

Hi-C 2.1 (17.2 nm)

SDO/AIA (17.1 nm)

CORONA

Multilayer coatings
Imaging slit spectrometers

EIS

SPICE SW

SPICE LW

IRIS

Wavelength / Å

200 400 600 800 1000 1200 1400

CORONA

TRANSITION REGION

CHROMOSPHERE
Launch: February 2020

SPICE has excellent temperature coverage through atmosphere

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength</th>
<th>Temp</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>O VI</td>
<td>1031.9</td>
<td>300 kK</td>
</tr>
<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>
</tr>
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</table>
SPICE: connection to the solar wind
SPICE: active region outflows

• All active regions show persistent outflow patches (blue) in coronal spectral lines (Fe X-XVI) of 10-20 km/s

• The patches also show repeating high velocity (100 km/s) jets

Will SPICE see the outflows?

• Best lines are Si XII λ499, λ520 [2nd order]
• Ne VIII is too cool

Sakao et al. (2007, Science)
SPICE: Element abundances

- Mg/Ne FIP bias at 0.7 MK is the key measurement for SPICE [Mg VIII/Ne VIII]

- **What can we expect?**
  - fan loops will show high FIP bias (4-10)
  - good ratio for coronal holes & plumes
  - will quiet Sun show FIP bias?
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

Intensity / $10^3$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$

Wavelength / Å

Fe XIX $\lambda592.2$ 9 MK
Fe XX $\lambda721.6$ 10 MK
Fe XXII $\lambda845.6$ 13 MK
Fe XVIII $\lambda974.9$ 7 MK
Fe XXI $\lambda1118.1$ 9 MK
Fe XXI $\lambda1354.1$ 11 MK
Solar-C/EUVST

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

[Proposed to JAXA and NASA (2018)]
EUNIS

• First high resolution spectra at 90-110 Å in many years!

GSFC rocket launch 2019
EUNIS and the AIA 94 Å channel

- Early AIA data analysis suggested CHIANTI was not modeling this channel correctly.
- EUNIS will provide new high-resolution spectra in this range.
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: 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
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: spectral deconvolution

- Multiple slits lead to spectral overlap
- Addressed with new spectral decomposition code
- Now resolves velocity & DEM ("VDEM")

For most spatial positions, the dominant lines will be clean; code only needed for ambiguous locations.

Cheung et al. (2019, arXiv)
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 2019 August
- imaging slit spectrometer (grazing incidence)
- spectral resolution ≈ 500
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
Bragg Crystal Spectrometers

- High-res spectra in narrow wavebands
- No spatial information
- Heritage from SMM, Yohkoh, RESIK
- Next iteration: SOLPEX (KORTES)
**Low-to-medium resolution spectra**

- FOXSI-SMEX
  - Imager (DSI) will have low-res spectra
  - STC will have med-res spectra, but no imaging

**MinXSS (Cubesat)**
- Similar to STC on FOXSI
FOXSI-SMEX

- Led by NASA-Goddard (PI: Steven Christe)
- Follow-on to RHESSI
- Direct imaging (grazing incidence 😊)
- Extendable boom (similar to NuSTAR)
- 5-60 keV, thus does not have $\gamma$-ray capability
- $\approx 10$ arcsec spatial resolution

Two telescopes at the end of an extendable boom

FOXSI enables weak coronal sources to be imaged
**Microcalorimeters**

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

Hitomi SXS spectrum of Perseus Cluster (Nature, 2016)
A platform that combines EUV, soft X-rays and hard X-rays is highly desirable for studies of energetic phenomena!