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The Marshall Grazing Incidence X-ray Spectrometer (**MaGIXS**)

Amy Winebarger
MSFC

Sabrina Savage (NASA MSFC)
Ken Kobayashi (NASA MSFC)
Patrick Champey (NASA MSFC)
David McKenzie (NASA MSFC)
Leon Golub (SAO)
Ed DeLuca (SAO)
Paola Testa (SAO)
Katherine Reeves (SAO)
Peter Cheimets (SAO)
Jonathan Cirtain (UVA)
Robert W. Walsh (Univ of Central Lancashire)
Stephen Bradshaw (Rice University)
Harry Warren (NRL)
Helen Mason (University of Cambridge)
Giulio Del Zanna (University of Cambridge)

Scientific Motivation

MaGIXS will make 4 unique observations that will determine the frequency of heating in quiescent active region structures:

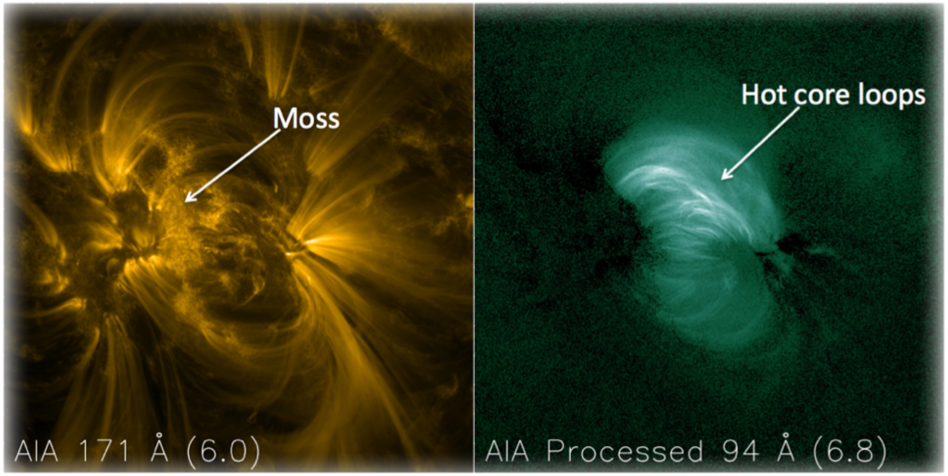
High-frequency heating (e.g., waves dissipation) :

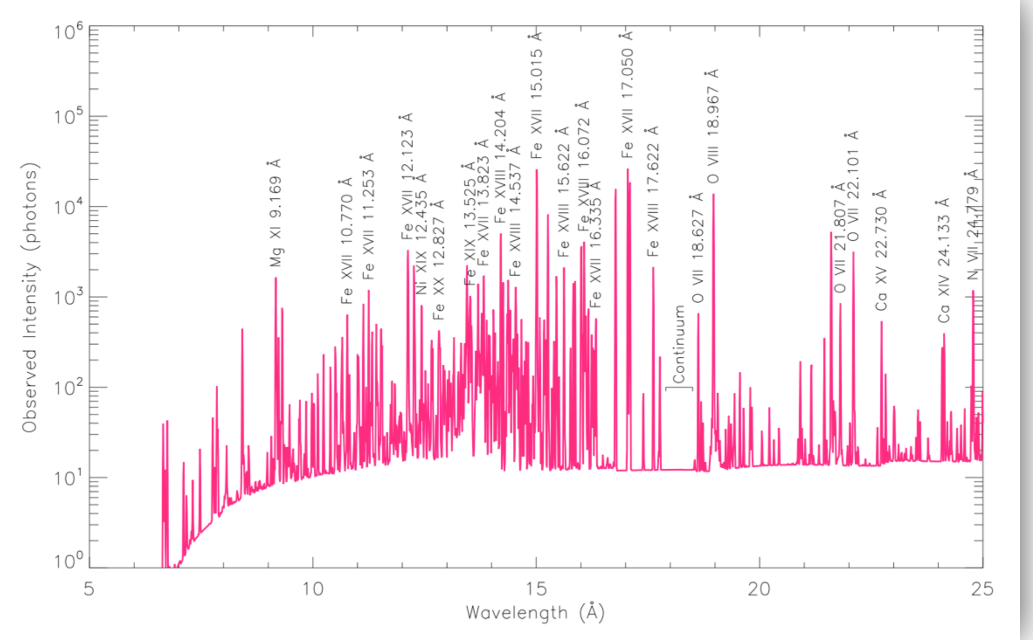
- No high temperature plasma
- FIP bias > 1
- Steady Fe XVII emission
- Maxwellian plasma distribution

Low-frequency heating (e.g., magnetic reconnection):

- High temperature (> 7 MK) plasma
- FIP bias ~ 1
- Dynamic Fe XVII emission
- Evidence for non-Maxwellian plasma distribution

GOAL: Determine Loop Heating Frequency in Solar Active Regions





Raging debate – How are coronal loops heated:

1. Sporadically via nanoflares?
2. Frequently via waves?

Current instrumentation optimized for measuring loop cooling, but **not sensitive enough at high temperatures to detect *heating event***.

Goal: Determine heating frequency by observing AR core loops in high temperature spectral lines.

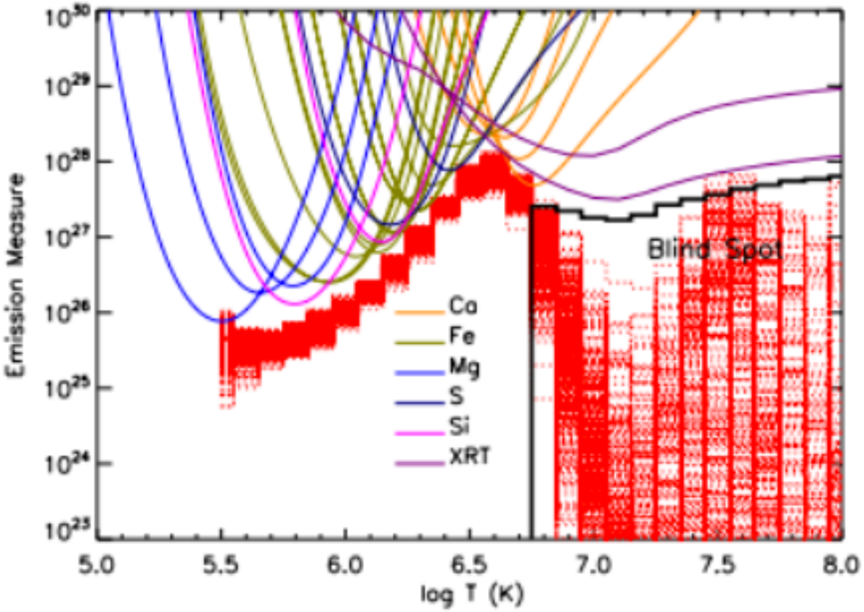
López Fuentes & Klimchuk 2010; Van Ballegooijen 2012; Warren et al. 2012, Winebarger et al. 2011; Tripathi et al. 2011, Viall & Klimchuk, 2013

High-temperature, low-emission plasma

Random heating of strands can make the loop's intensity appear steady regardless of dynamic heating along one strand.

Discriminator between high-[waves] **and low-**[nanoflares] **frequency heating:**

> **Relative amount of high-T** (5-10 MK) **to average-T** (~3-5 MK) **plasma.**



Blind spot for high-T, low-emission measure using *Hinode*'s XRT and EIS, so ***relative*** amounts of these plasma populations are not accurately known.

MaGIXS will be able to definitively detect and quantify high-temperature, low-emission-measure plasma in the active region core.

Kobelski et al. 2014; Klimchuk 2009; Schmelz et al. 2009; Teriaca et al. 2012; O'Dwyer et al. 2011; Winebarger et al. 2012; Testa et al. 2011, 2012

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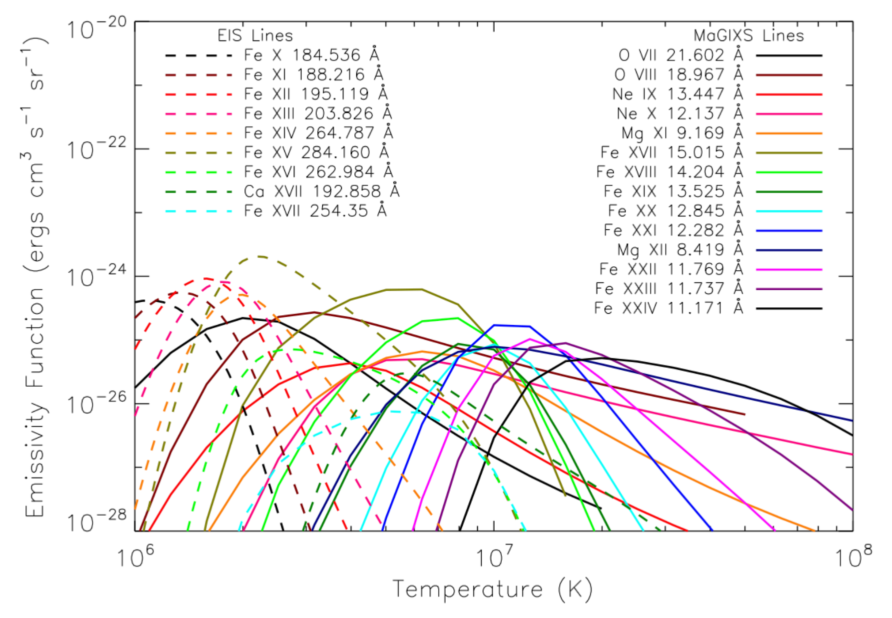

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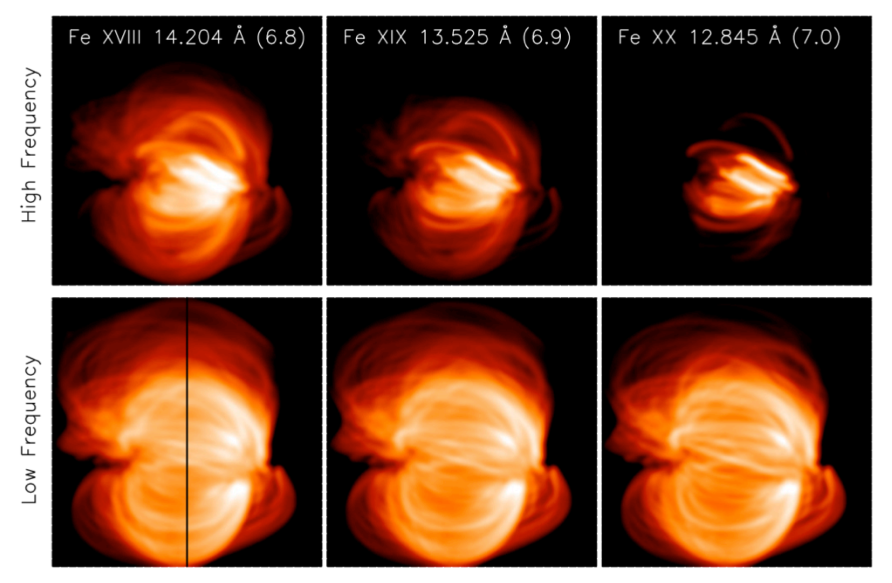
Only in the soft X-ray wavelength range of MaGIXS can we observe the Fe XVII/XVIII/XIX/XX spectral lines and other high-temperature lines on the same detector through the same optical path.

Kobelski et al. 2014; Klimchuk 2009; Schmelz et al. 2009; Teriaca et al. 2012; O'Dwyer et al. 2011; Winebarger et al. 2012; Testa et al. 2011, 2012

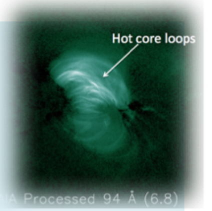
High-temperature, low-emission plasma



Simulated active region core using 0-D EBTEL:

- Random heating events
- Heating event cadence 1575 s versus 6300 s

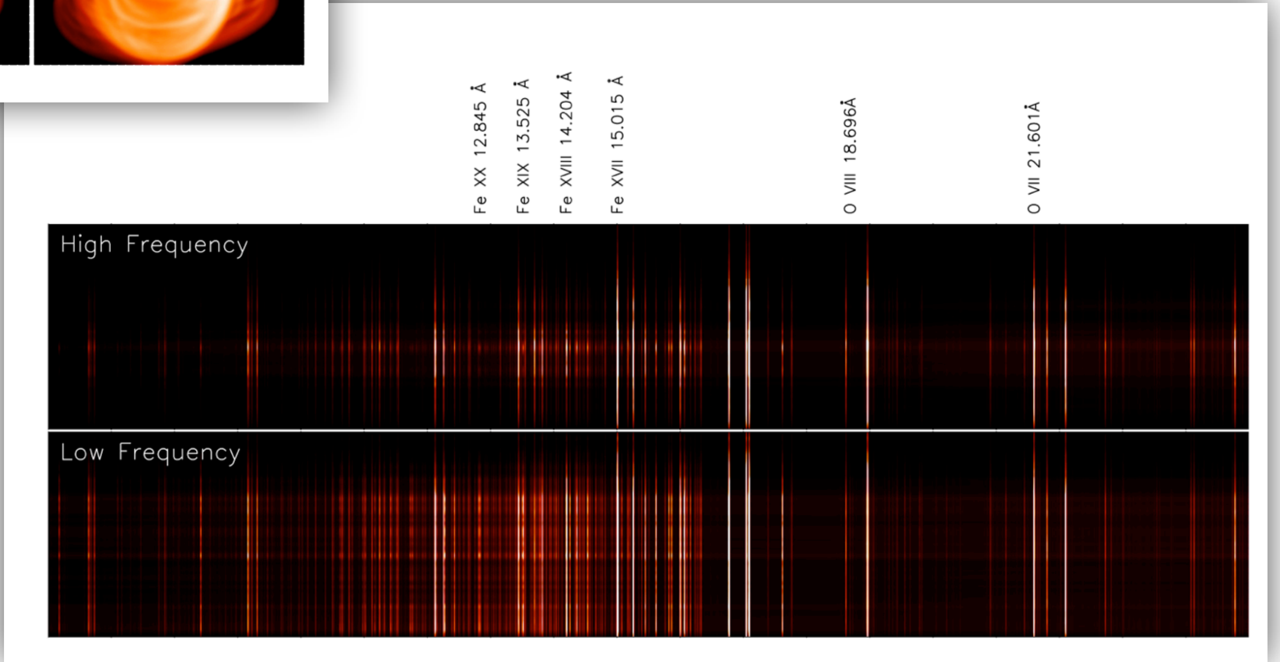
Expected emission quite different at higher temperature lines.



Simulated MaGIXS spectra

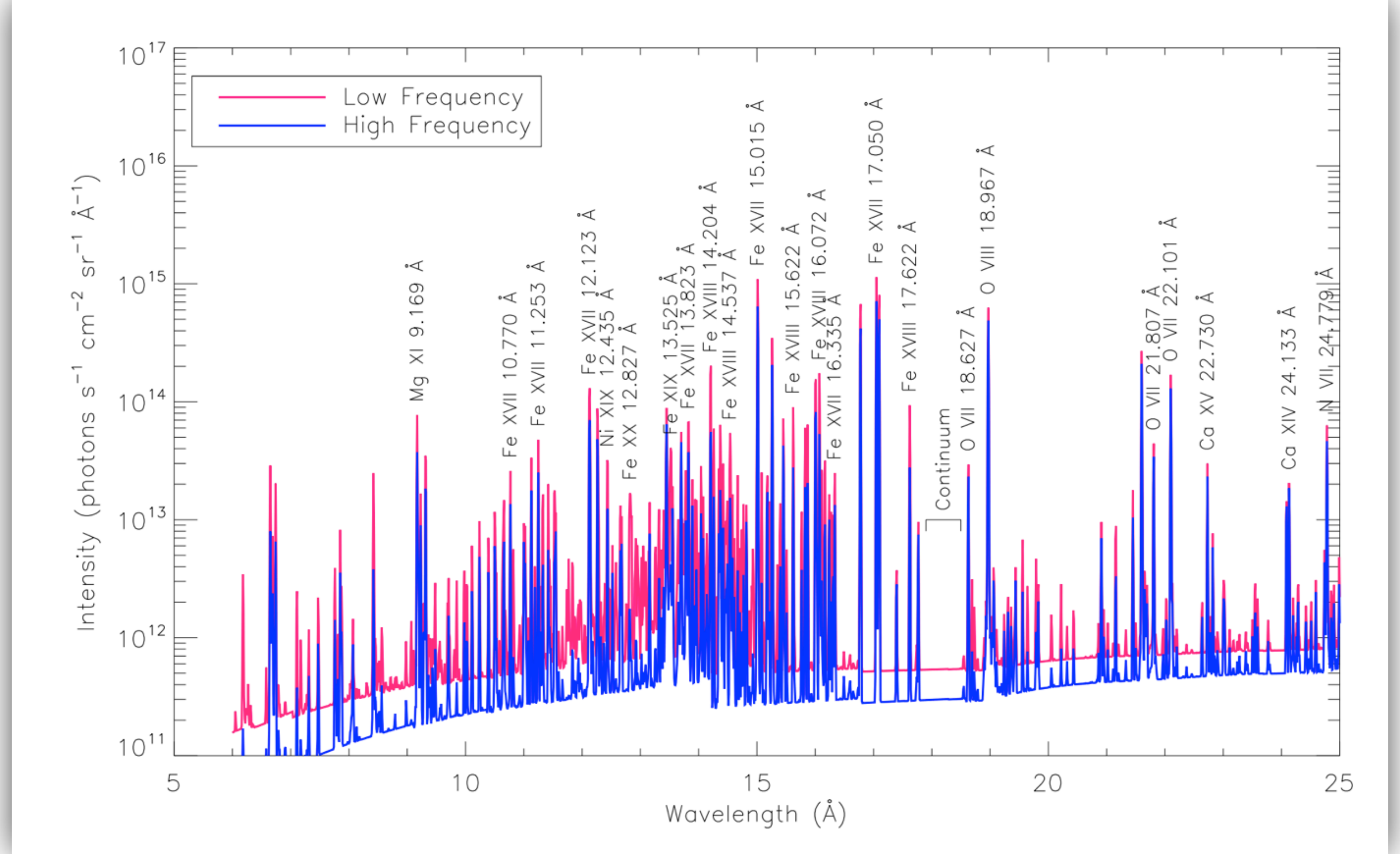
Biggest difference in Fe XX (12.845 Å).

Multiple high temperature spectra lines necessary for interpretation.



Warren et al. 2014; Klimchuk et al. 2008; Cargill et al. 2012; Warren & Winebarger 2006; Brosius et al. 2014

High-temperature, low-emission plasma



Simulated spectra from a single spatial position along the MaGIXS slit.

Non-equilibrium effects minimal for high temperature species (e.g., Fe XVII/XVIII/XIX/XX).

Reale & Orlando 2008; Bradshaw & Klimchuk 2011)

Elemental Abundances

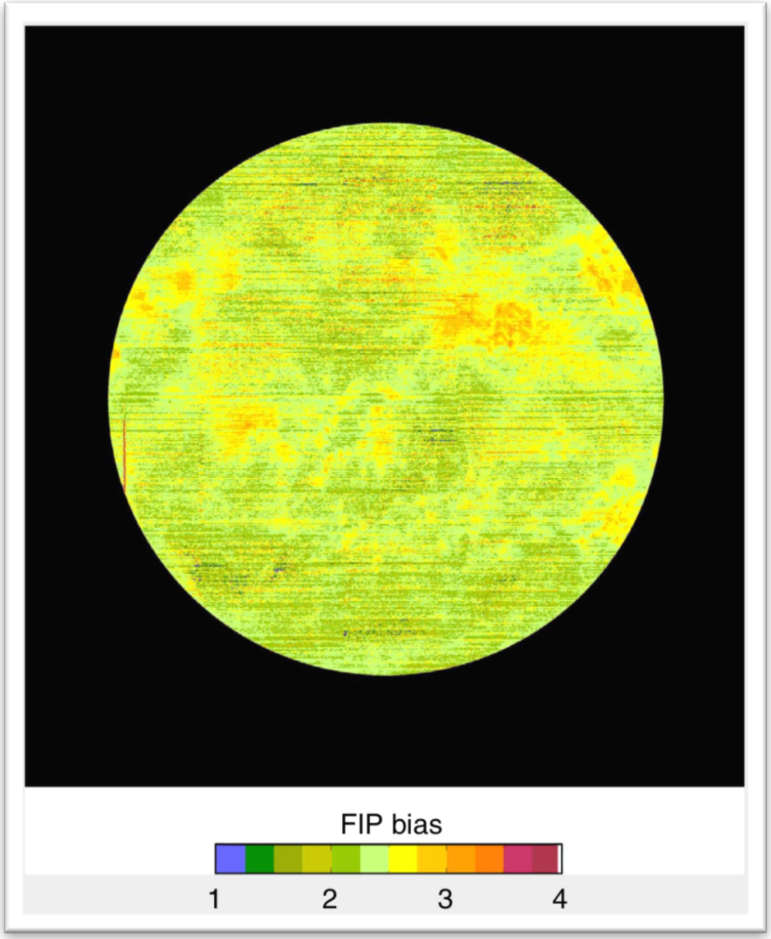
Puzzling mystery – Why do coronal and photospheric abundances not always match?

FIP effect: *Low first ionization potential elements (e.g., Fe and Si) enhanced by a factor of ~ 2 – 4 in the corona.*

Trends in variability indicate that the FIP bias is proportional to the plasma's time of confinement.

Abundance measurements may be an indicator of the frequency of heating.

- Photospheric: *sporadic*
- Coronal: *high frequency*



***Hinode*/EIS composition map**

Photospheric : *(Flares)*
Coronal : *(Evolved ARs)*

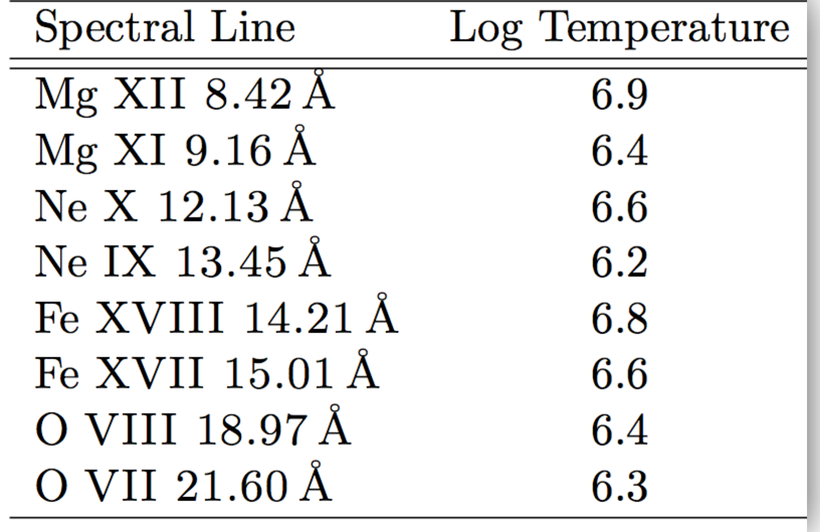
The **spatially and spectrally resolved MaGIXS solar spectrum** will provide relative and absolute abundances for determining the FIP bias in several AR structures.

Evan & Pounds 1968; Veck & Parkinson 1981; Raymond et al. 1997; Sylwester et al. 2010; Brooks et al. 2014; Del Zanna 2006

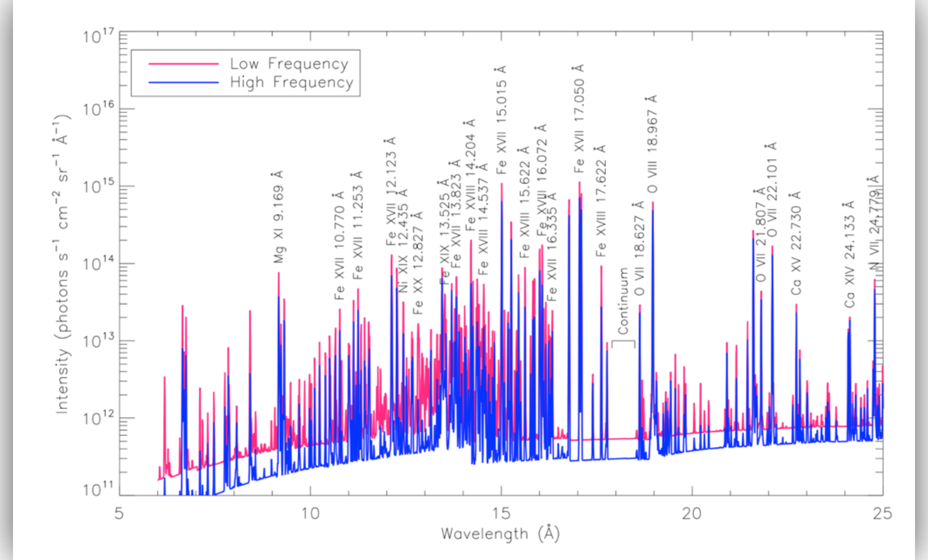
Elemental Abundances

Key spectral lines to be used for abundance analysis chosen due to highly reliable atomic data.

Relative abundances largely independent of plasma temperature.



Spectral Line	Log Temperature
Mg XII 8.42 Å	6.9
Mg XI 9.16 Å	6.4
Ne X 12.13 Å	6.6
Ne IX 13.45 Å	6.2
Fe XVIII 14.21 Å	6.8
Fe XVII 15.01 Å	6.6
O VIII 18.97 Å	6.4
O VII 21.60 Å	6.3

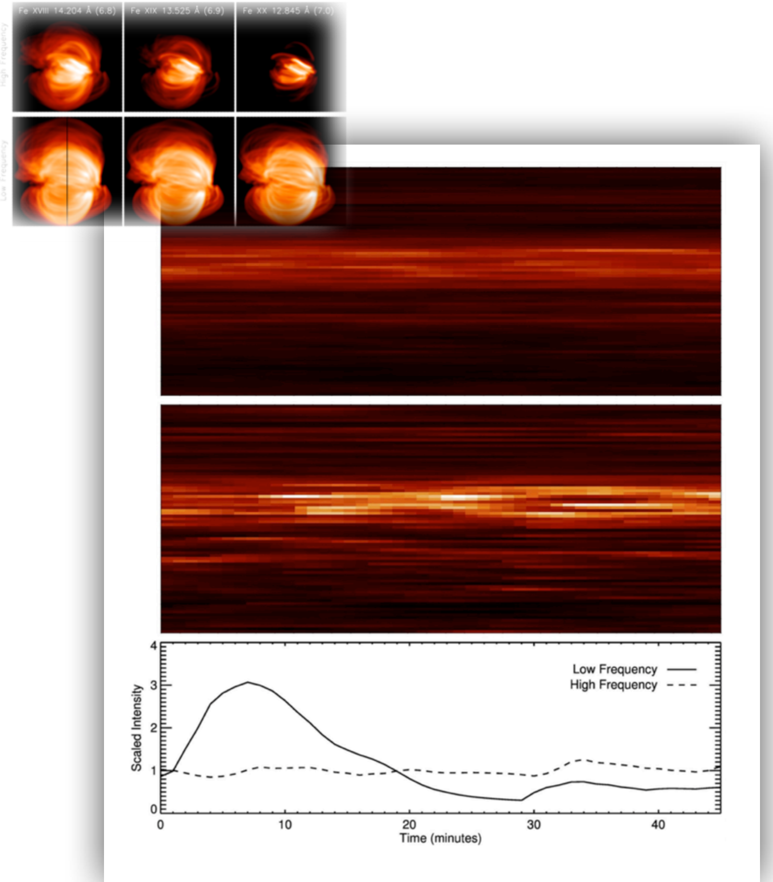


Compare FIP bias to structure lifetime and determine absolute abundances from continuum around 18 Å.

FIP effect used to understand chemical fractionation process taking place in the solar and stellar coronae, **which may be related to coronal heating process and frequency** via chromospheric Alvén waves.

Del Zanna 2006; Smith et al. 2009; Drake & Testa 2005; Huenemoerder et al. 2009; Henoux 1995; Drake 2003; Laming 2004, 2009

Fe XVII Fluctuations & Departure from Maxwellian Distributions



A statistical analysis of AR light curves can also be used to understand heating frequency:

Individual impulsive heating event (low frequency) = steep rise --> slower decay

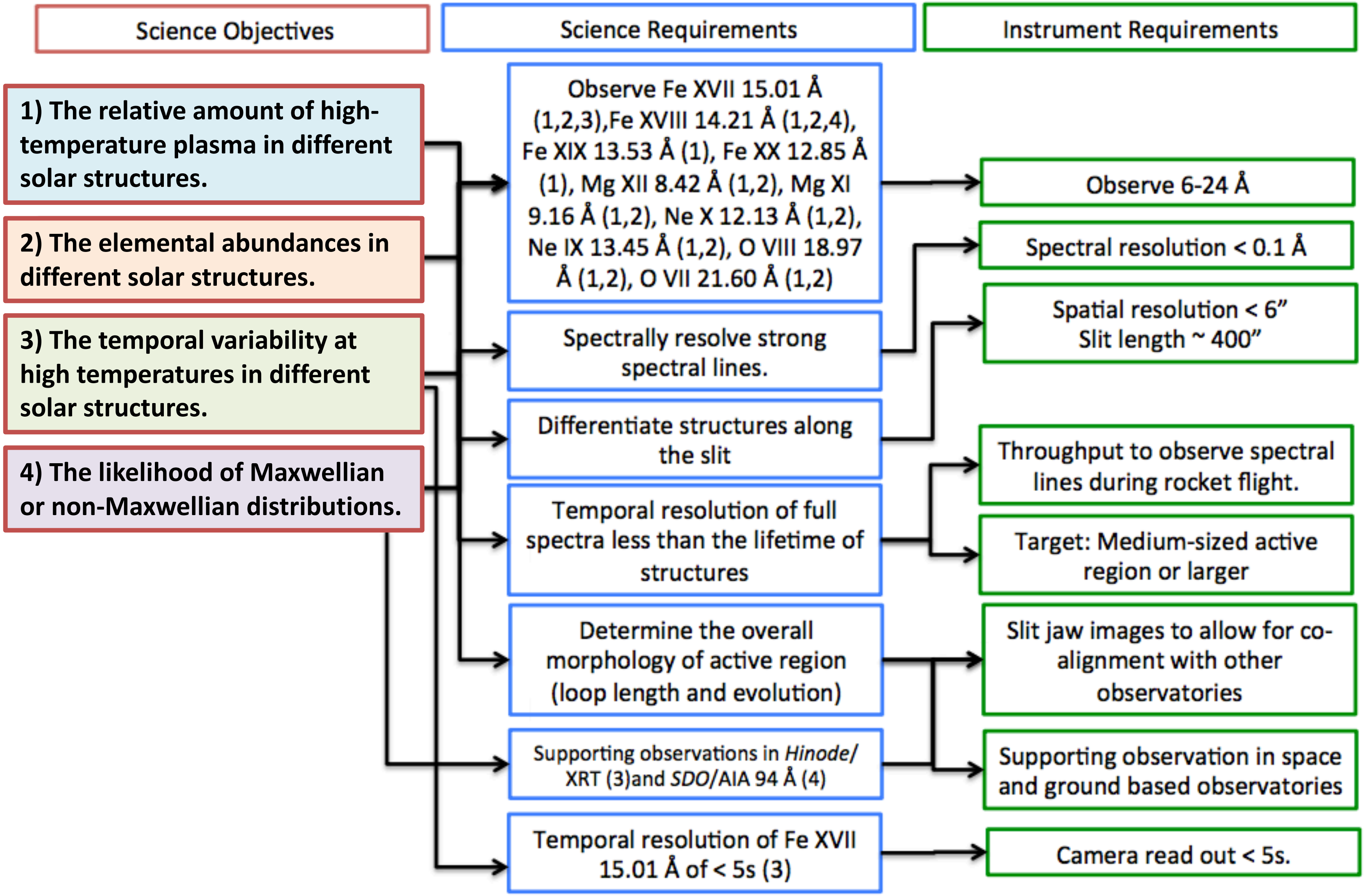
Impulsive heating results in a skewed distribution, *definitely measurable by MaGIXS***.** Use Fe XVII lightcurves to determine if *Hinode*/XRT skewness due to high temperature fluctuations versus cool contributions or noise.

If high-T variability confirmed, **timescales can be used to determine the heating frequency**.

Non-Maxwellian distributions would strongly indicate impulsive, infrequent coronal heating from magnetic reconnection or wave-particle interactions. MaGIXS spectral range optimal for this search due to high-energy excitation thresholds (e.g., ratio between Fe XVIII lines and *SDO*/AIA 94 Å bandpass).

Lopez Fuentes & Klimchuk 2010; Terzo et al. 2011; Dudik et al. 2014

Summary: Determine the frequency of heating in AR cores



Science Objectives

Science Requirements

Instrument Requirements

1) The relative amount of high-temperature plasma in different solar structures.

2) The elemental abundances in different solar structures.

3) The temporal variability at high temperatures in different solar structures.

4) The likelihood of Maxwellian or non-Maxwellian distributions.

Observe Fe XVII 15.01 Å (1,2,3),Fe XVIII 14.21 Å (1,2,4), Fe XIX 13.53 Å (1), Fe XX 12.85 Å (1), Mg XII 8.42 Å (1,2), Mg XI 9.16 Å (1,2), Ne X 12.13 Å (1,2), Ne IX 13.45 Å (1,2), O VIII 18.97 Å (1,2), O VII 21.60 Å (1,2)

Spectrally resolve strong spectral lines.

Differentiate structures along the slit

Temporal resolution of full spectra less than the lifetime of structures

Determine the overall morphology of active region (loop length and evolution)

Supporting observations in *Hinode*/XRT (3)and *SDO*/AIA 94 Å (4)

Temporal resolution of Fe XVII 15.01 Å of < 5s (3)

Observe 6-24 Å

Spectral resolution < 0.1 Å

Spatial resolution < 6”
Slit length ~ 400”

Throughput to observe spectral lines during rocket flight.

Target: Medium-sized active region or larger

Slit jaw images to allow for co-alignment with other observatories

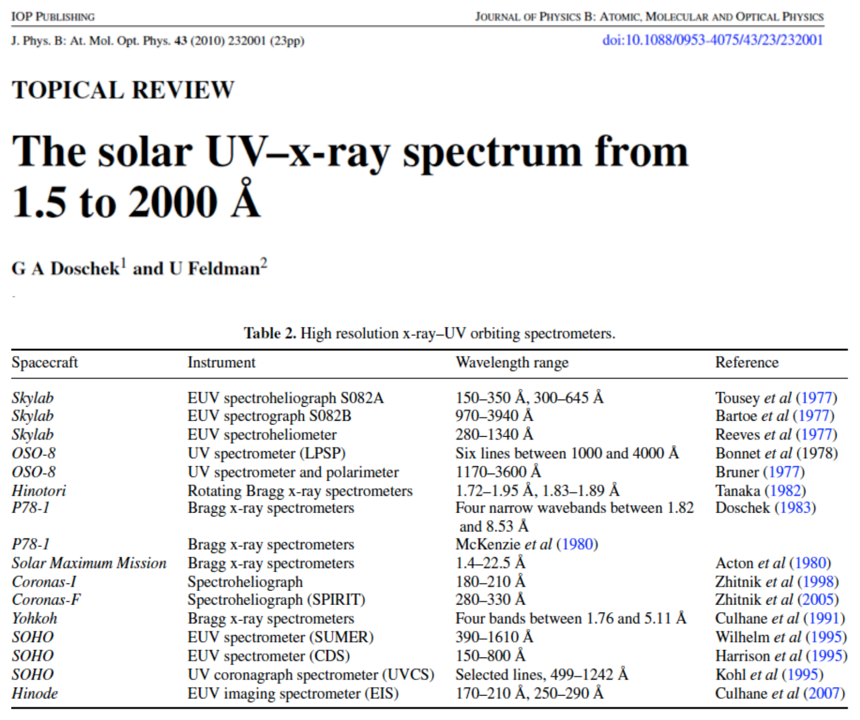
Supporting observation in space and ground based observatories

Camera read out < 5s.

Motivation

X-ray spectroscopy provides unique capabilities for answering fundamental questions in solar physics since it is dominated by emission lines formed at high temperatures – particularly in the wavelength range of 6 – 25 Å, which has strong lines from Fe XVII – Fe XXV and other important diagnostic lines.

***Yet, not since the 1970's have solar spectra in this wavelength range been spatially resolved*.**



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J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 232001 (23pp) — doi:10.1088/0953-4075/43/23/232001

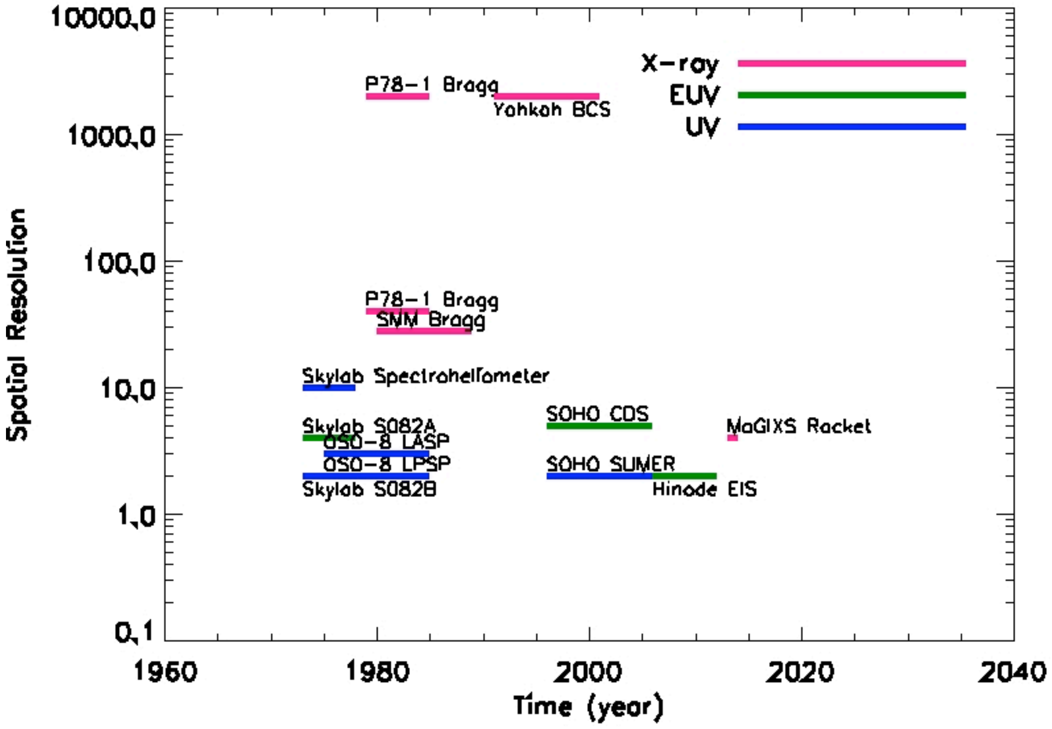
TOPICAL REVIEW

The solar UV–x-ray spectrum from 1.5 to 2000 Å

G A Doschek[1] and U Feldman[2]

Table 2. High resolution x-ray–UV orbiting spectrometers.

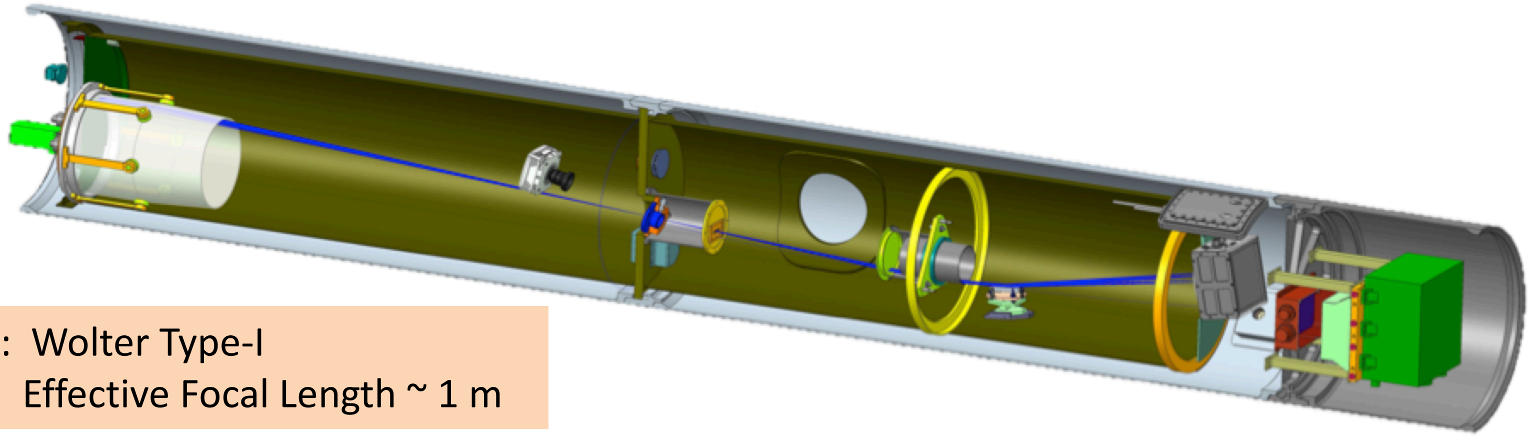
Spacecraft	Instrument	Wavelength range	Reference
Skylab	EUV spectroheliograph S082A	150–350 Å, 300–645 Å	Tousey *et al* (1977)
Skylab	EUV spectrograph S082B	970–3940 Å	Bartoe *et al* (1977)
Skylab	EUV spectroheliometer	280–1340 Å	Reeves *et al* (1977)
OSO-8	UV spectrometer (LPSP)	Six lines between 1000 and 4000 Å	Bonnet *et al* (1978)
OSO-8	UV spectrometer and polarimeter	1170–3600 Å	Bruner (1977)
Hinotori	Rotating Bragg x-ray spectrometers	1.72–1.95 Å, 1.83–1.89 Å	Tanaka (1982)
P78-1	Bragg x-ray spectrometers	Four narrow wavebands between 1.82 and 8.53 Å	Doschek (1983)
P78-1	Bragg x-ray spectrometers	McKenzie *et al* (1980)	
Solar Maximum Mission	Bragg x-ray spectrometers	1.4–22.5 Å	Acton *et al* (1980)
Coronas-I	Spectroheliograph	180–210 Å	Zhitnik *et al* (1998)
Coronas-F	Spectroheliograph (SPIRIT)	280–330 Å	Zhitnik *et al* (2005)
Yohkoh	Bragg x-ray spectrometers	Four bands between 1.76 and 5.11 Å	Culhane *et al* (1991)
SOHO	EUV spectrometer (SUMER)	390–1610 Å	Wilhelm *et al* (1995)
SOHO	EUV spectrometer (CDS)	150–800 Å	Harrison *et al* (1995)
SOHO	UV coronagraph spectrometer (UVCS)	Selected lines, 499–1242 Å	Kohl *et al* (1995)
Hinode	EUV imaging spectrometer (EIS)	170–210 Å, 250–290 Å	Culhane *et al* (2007)



Instrument Design

Using a novel implementation of corrective optics and a revolutionary concept for grazing incidence imaging spectroscopy, MaGIXS will measure, for the first time, the soft X-ray solar spectrum from 6 – 24 Å with ~6" resolution (2.8"/pixel) over an 8' slit.

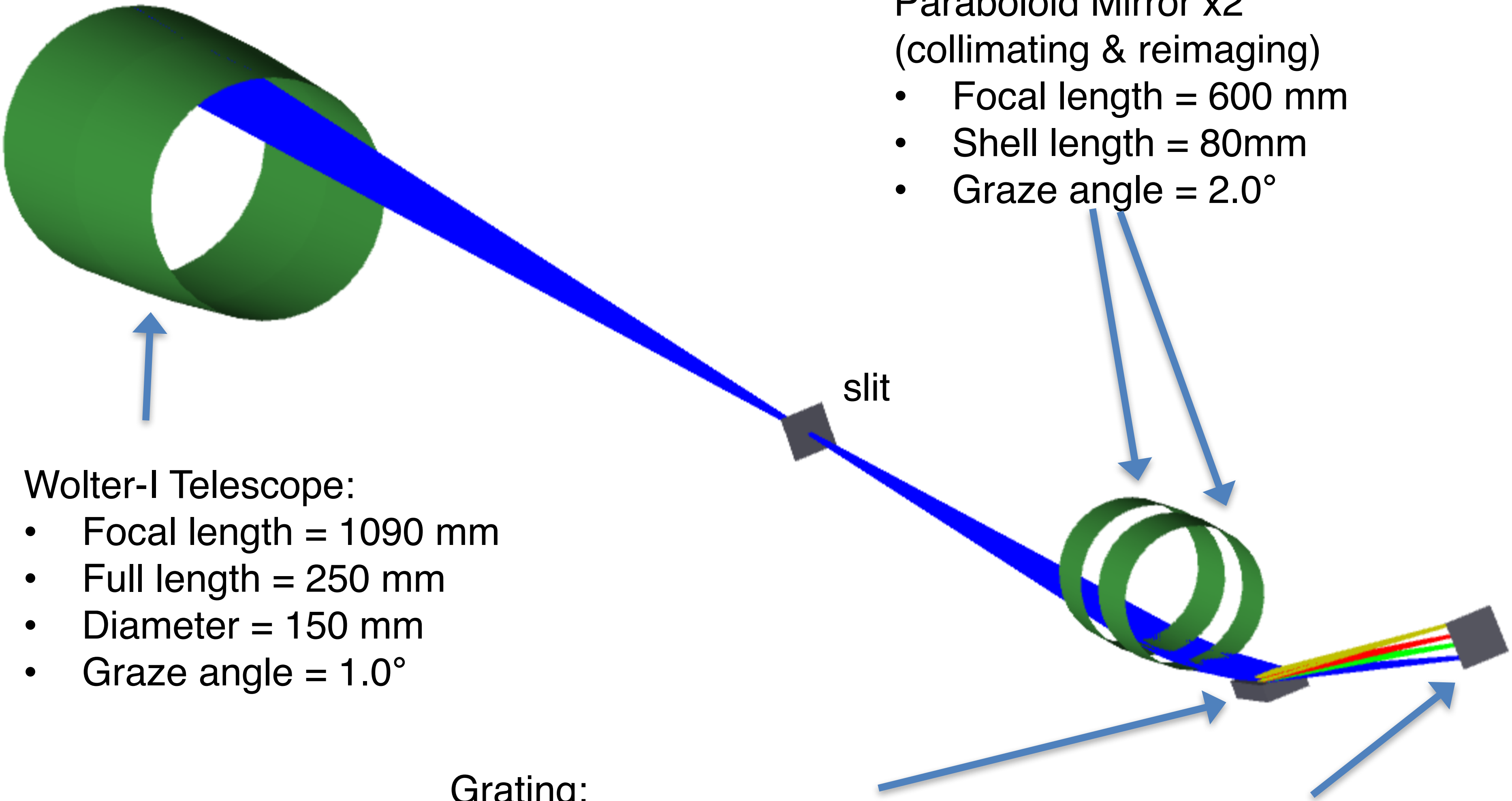
The MaGIXS mission **partnered with an instrument like the Focusing Optics X-ray Solar Imager (FOXSI)**, which observes higher energy (harder) X-rays than MaGIXS, on a satellite would be able to track the thermalization of the plasma and acceleration of particles during flares and CME formation.



Telescope: Wolter Type-I
Effective Focal Length ~ 1 m

Spectrograph: Two matched parabolic mirrors +
Blazed Planner Varied Line Space Grating
6.0 - 24.0 Å (0.5 - 2.0 keV)
11 mÅ / pixel
2.8 arcsec / pixel

Optical Design



Paraboloid Mirror x2
(collimating & reimaging)

- Focal length = 600 mm
- Shell length = 80mm
- Graze angle = 2.0°

Wolter-I Telescope:

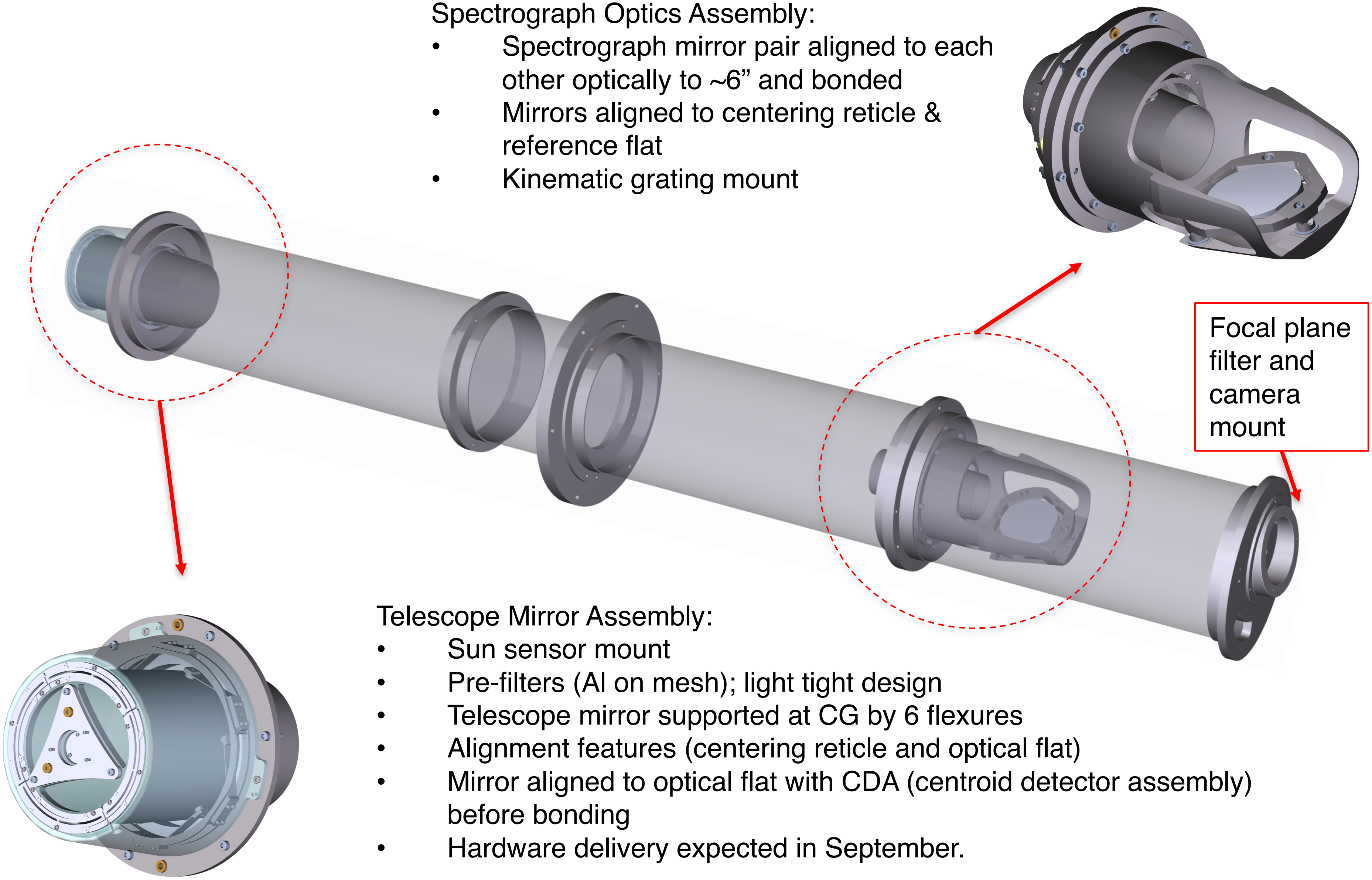
- Focal length = 1090 mm
- Full length = 250 mm
- Diameter = 150 mm
- Graze angle = 1.0°

Grating:

- Planar, 25 mm × 73 mm
- 1850 – 2500 lines/mm

Al/Polyimide filter +
2k×1k frame-transfer CCD

Instrument Design



Spectrograph Optics Assembly:

- Spectrograph mirror pair aligned to each other optically to ~6” and bonded
- Mirrors aligned to centering reticle & reference flat
- Kinematic grating mount

Focal plane filter and camera mount

Telescope Mirror Assembly:

- Sun sensor mount
- Pre-filters (Al on mesh); light tight design
- Telescope mirror supported at CG by 6 flexures
- Alignment features (centering reticle and optical flat)
- Mirror aligned to optical flat with CDA (centroid detector assembly) before bonding
- Hardware delivery expected in September.

Technological Challenges:

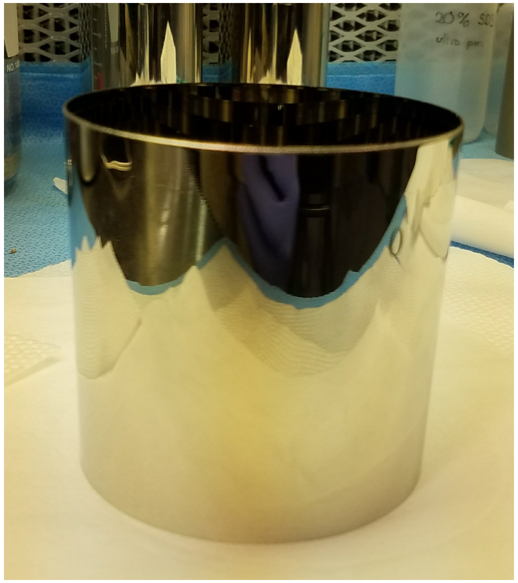
1) Optics manufacturing
2) Grating Development and Manufacturing
3) Alignment

Optics Development

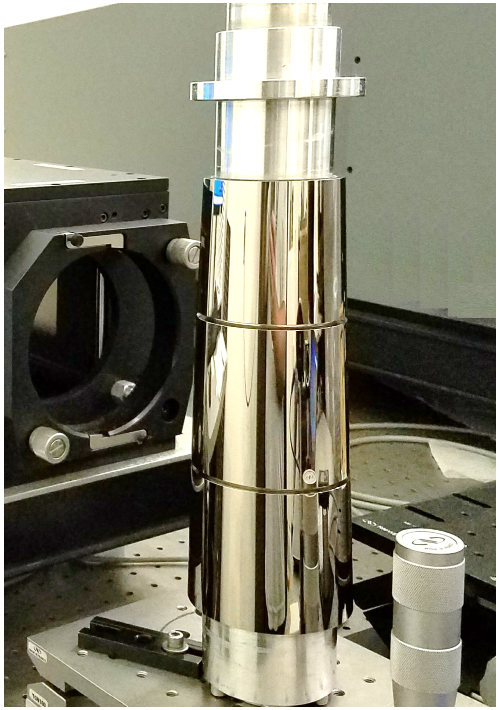
MaGIXS will use electroformed nickel replicated optics (FOXSI, HERO, ART-XC, IXPE, etc)

Unique Challenges:

- Short focal length, long segment length
- Large deviation from cones which exacerbates challenges with conventional lap polishing techniques and metrology
- High resolution requirement (< 6 arcsec HPD for the system, < 2 arcsec for each optic)
    - Typically Wolter-I replicated x-ray optics achieve 25-30 arcsecond HPD (FOXSI, ART-XC, IXPE)
    - Only way to achieve high resolution is to use advanced polishing systems, such as computer numerical controlled (CNC) polishers, like the ZEEKO



MaGIXS Spectrometer Shell

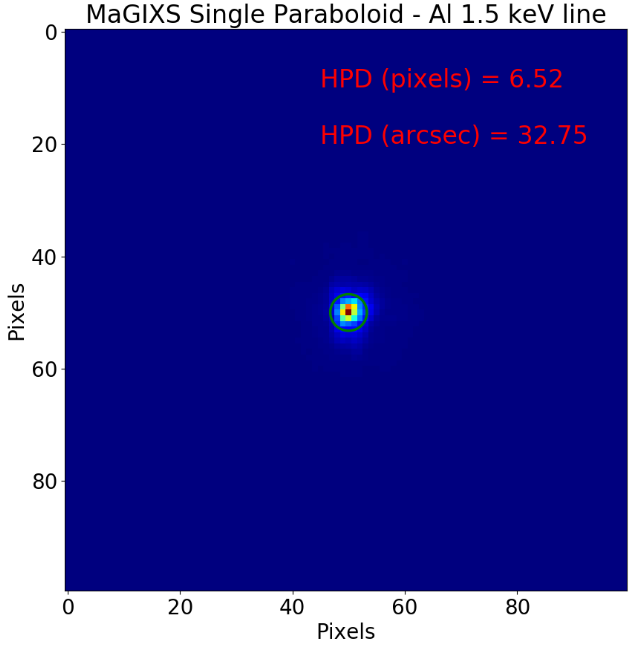


MaGIXS spectrometer mandrel

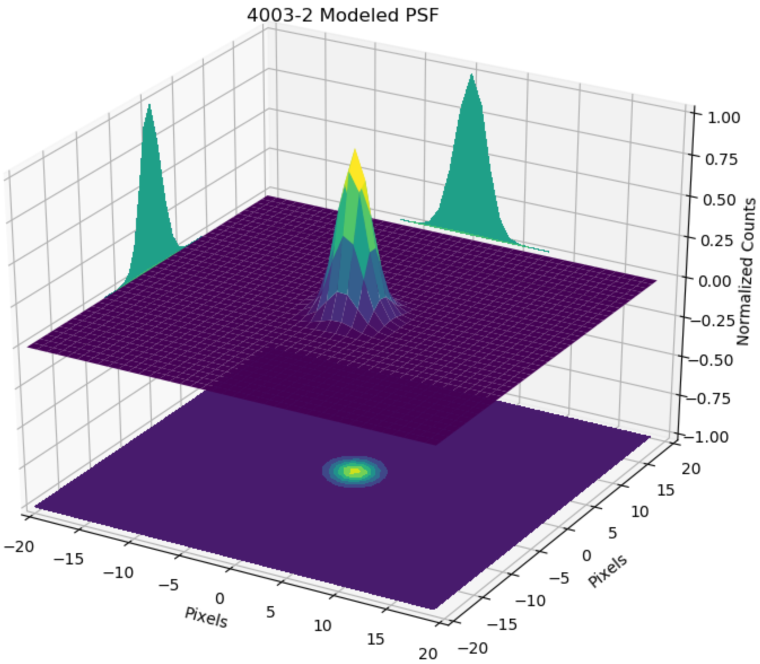
Optics Development

Current Status:

- Completed hand polishing of MaGIXS spectrometer and telescope mandrels
- Non-flight shells have been replicated and are currently being tested for HPD in Stray Light Facility.



MaGIXS Single Paraboloid - Al 1.5 keV line



4003-2 Modeled PSF

Next Steps:

- Further mandrel polishing using Zeeko polisher
- Computer generated hologram (CGH) and Zygo interferometer for metrology

Grating Development

Planar grating with varied line spacing

Challenges

- Blazed grating required for good efficiency at grazing incidence.
- Large variatrion in line spacing precludes use of holographic grating

Current Status:

- Electron-beam lithography + etching to be used
- Grating substrate is crystalline silicone with the {111} crystal orientation matched to the desired blaze angle
- KOH etching, with {111} plane of crystal acting as etch stop
- Substrate procured; fabrication preparation underway at Izentis LLC

Alignment

Challenge:

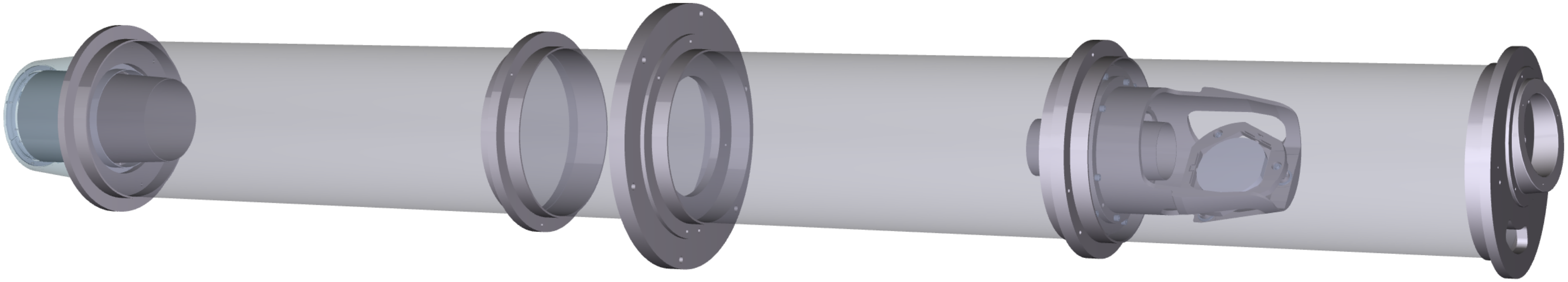
Obtaining and maintaining alignment of multiple grazing incidence optics along optical path to achieve 5” resolution in flight.

Alignment budget has been allocated to component level alignment including internal alignment of the TMA and SOA (completed by SAO) and mechanical structure of the optics bench.

Instrument alignment will occur at MSFC.

Initial alignment will occur in white light using reference mirrors.

Final alignment confirmation will occur in X-ray beam line (e.g., Stray Light Facility at MSC)



Summary

- The technological advances from MaGIXS development are far-reaching.
- Compelling reasons to continue to pursue X-ray spectroscopy in the soft X-ray wavelength range for longer term missions.
- MaGIXS will fly from White Sands Missile Range in summer 2019.