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Determining the Frequency of Coronal Heating with the Marshall Grazing Incidence X-ray Spectrometer [**MaGIXS**]

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Motivation

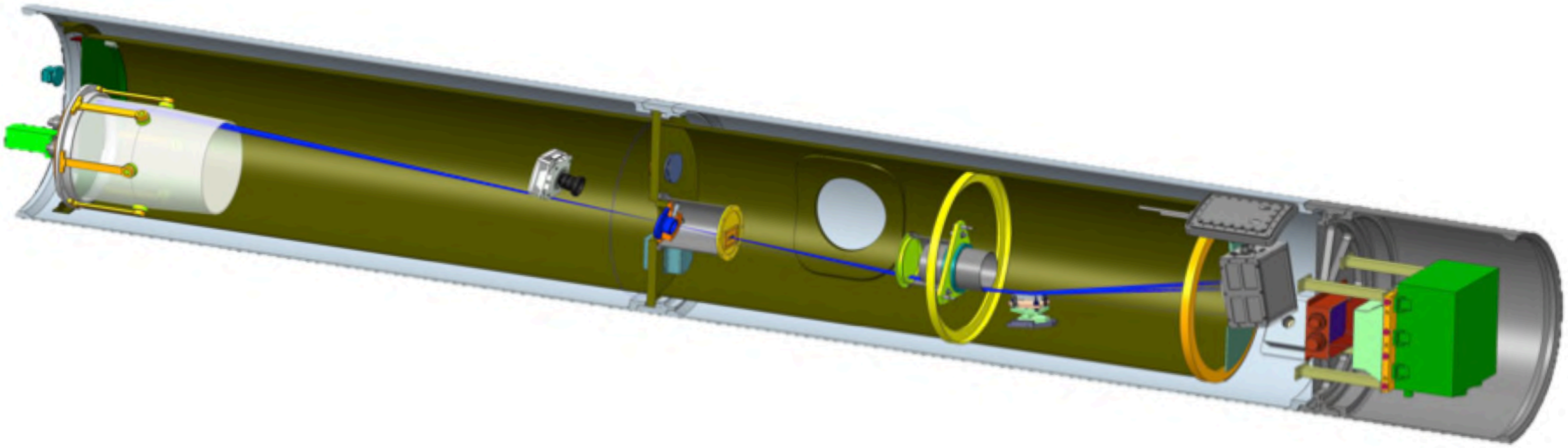
X-ray spectroscopy provides unique capabilities for answering fundamental questions in solar physics since it is dominated by emission lines formed at high temperatures – particularly in the wavelength range of 6 – 25 Å, which has strong lines from Fe XVII – Fe XXV and other important diagnostic lines.

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

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.

Instrument Design



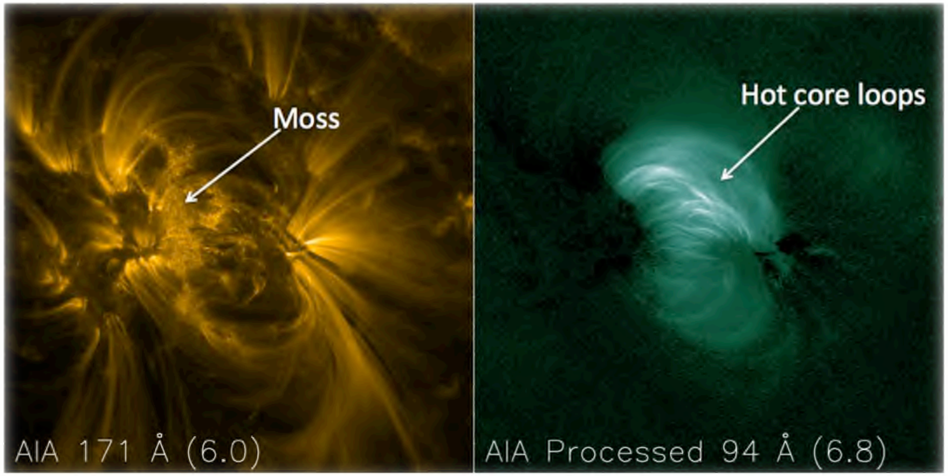
Telescope: Wolter Type-I
Effective Focal Length ~ 1 m

Spectrograph: Two matched parabolic mirrors + Grating

6.0 - 24.0 Å (0.5 - 2.0 keV)
11 mÅ / pixel
2.8 arcsec / pixel

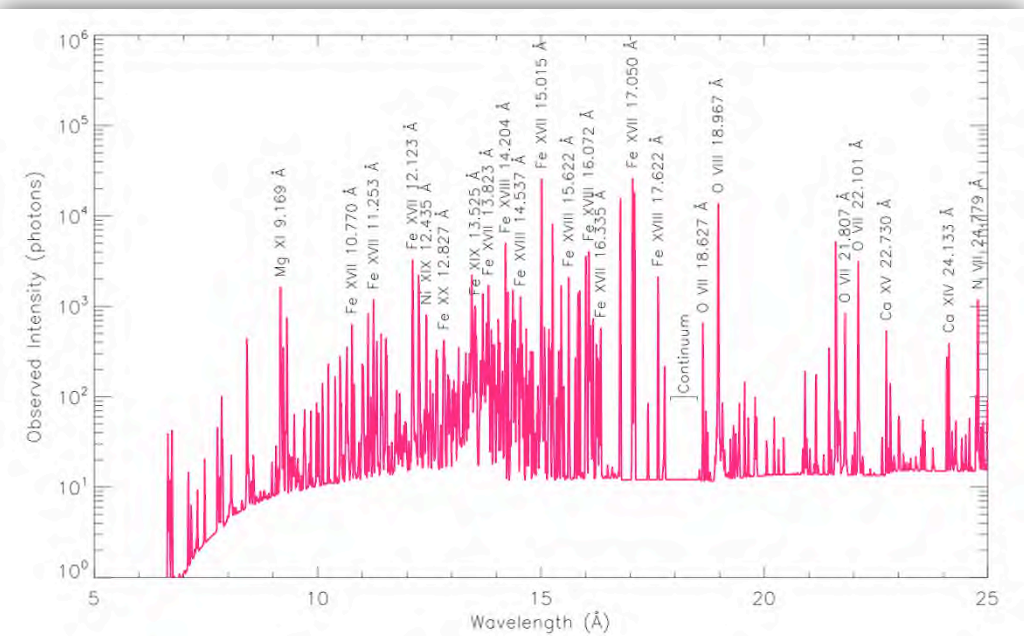
Grating: Blazed Planar Varied Line Space

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.

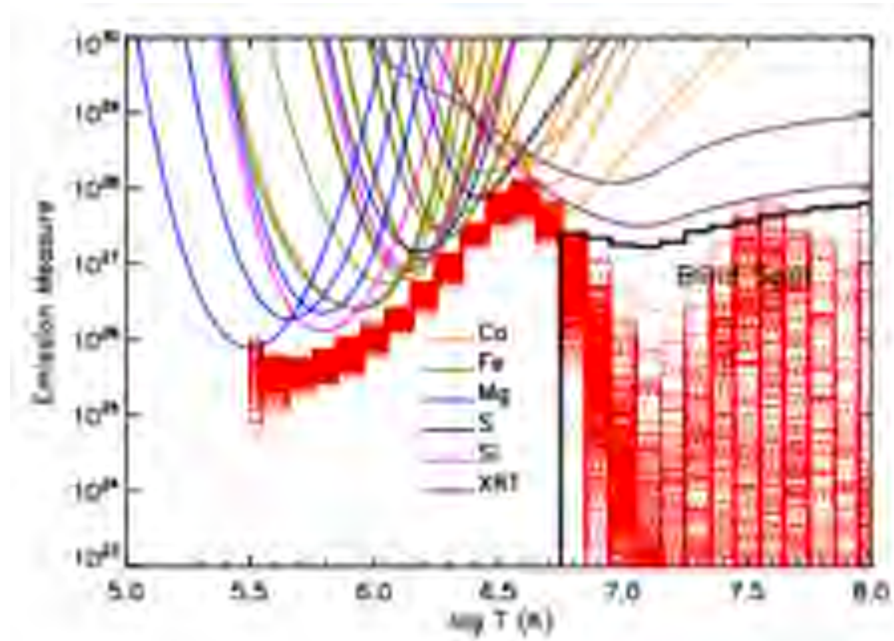
López Fuentes & Klimchuk 2010; Van Ballegooijen 2012; Warren et al. 2012, Winebarger et al. 2011; Tripathi et al. 2011, Viall & Klimchuk, 2013

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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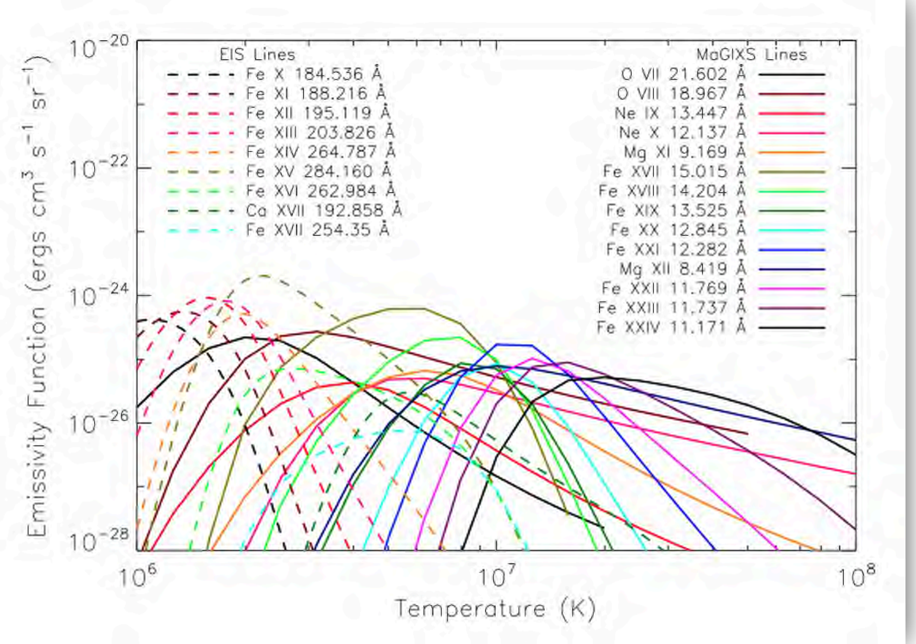

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Only in the soft X-ray wavelength range of MaGIXS can we observe the Fe XVII/XVIII/XIX/XX spectral lines and other high-temperature lines on the same detector through the same optical path.

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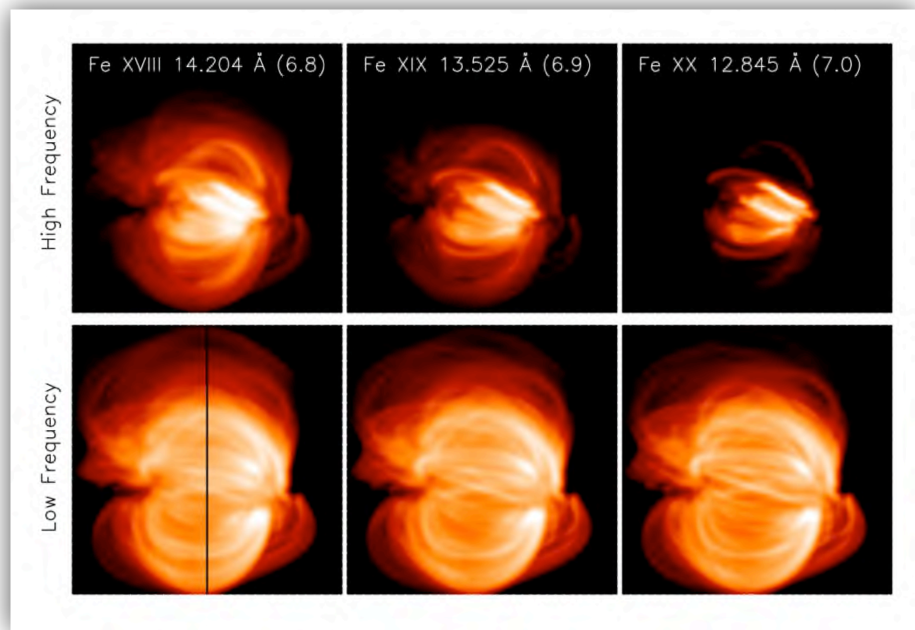
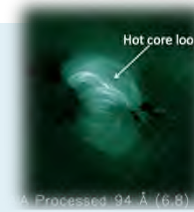
High-temperature, low-emission plasma



Simulated active region core using 0-D EBTEL:

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

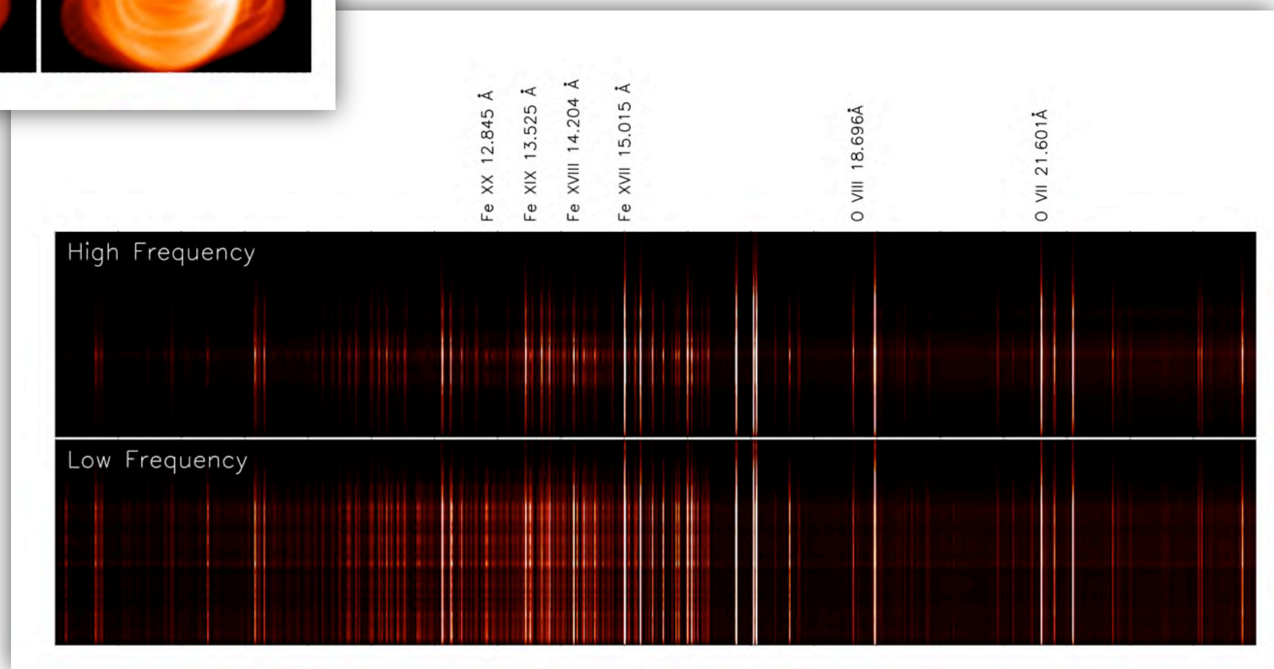


Expected emission quite different at higher temperature lines.

Simulated MaGIXS spectra

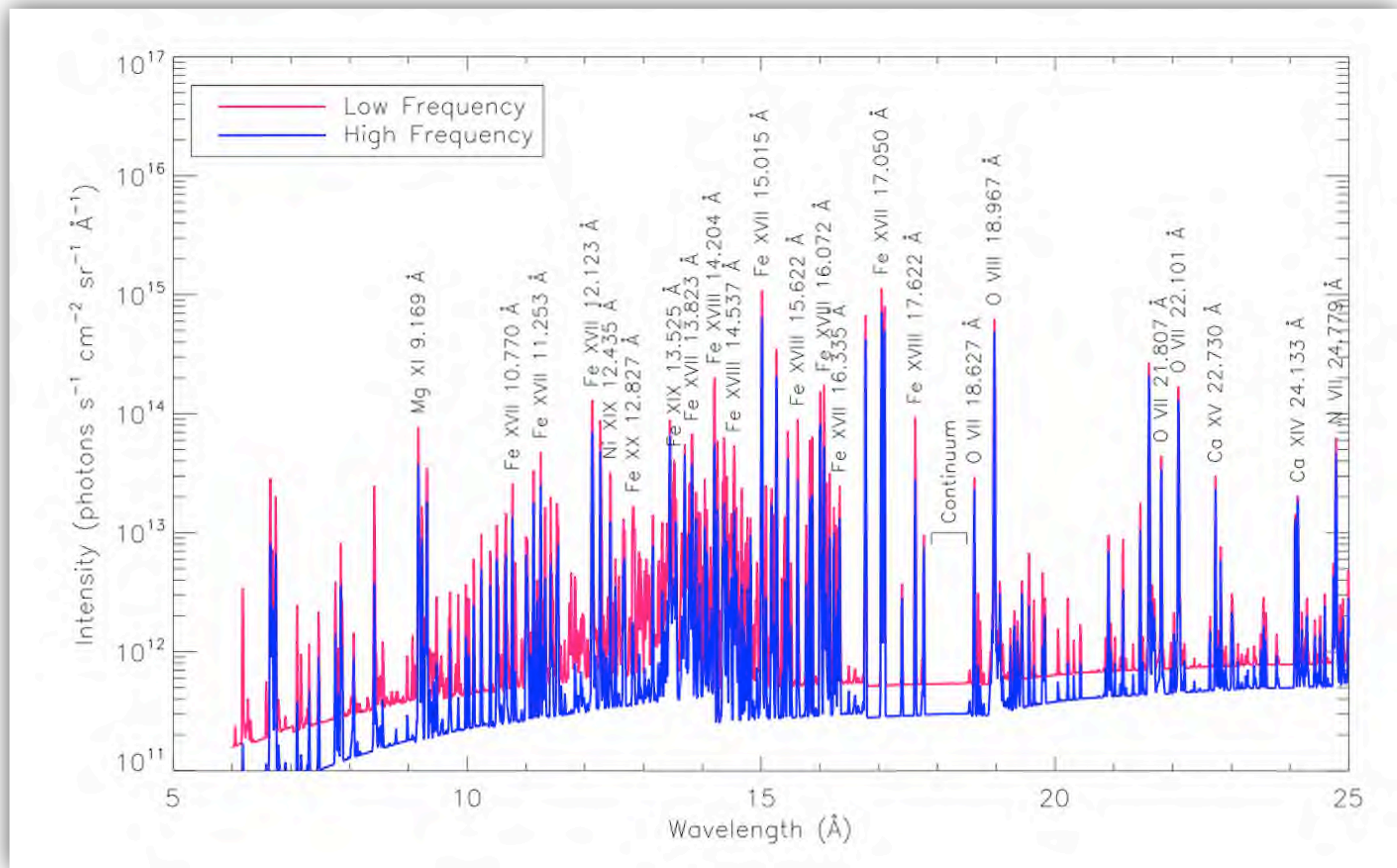
Biggest difference in Fe XX (12.845 Å).

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?

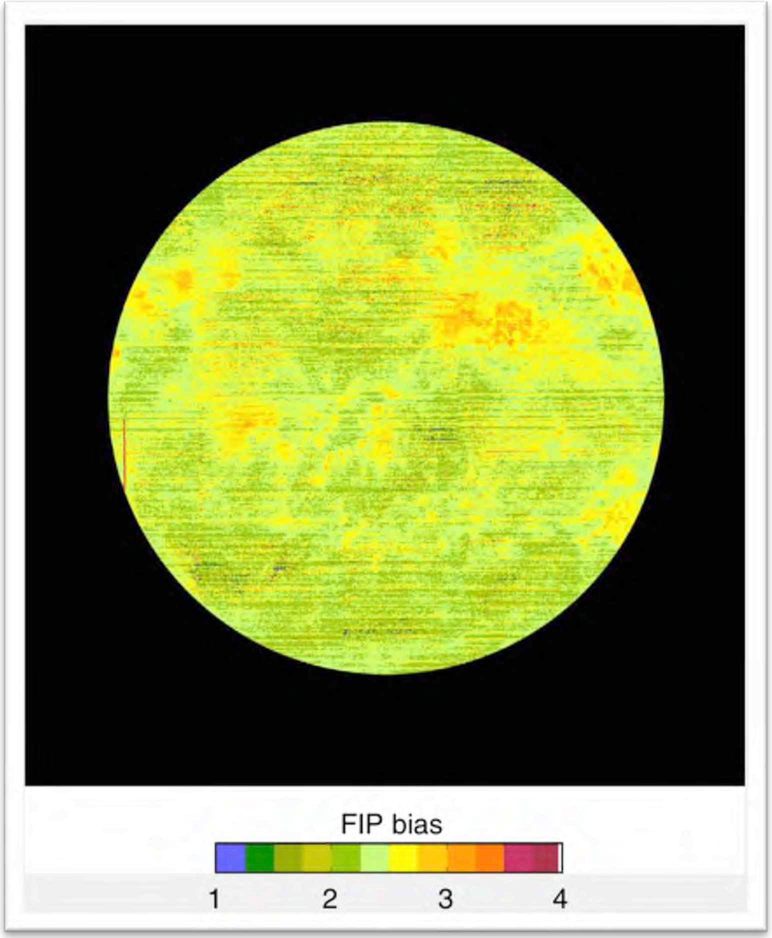
FIP effect: *Low first ionization potential elements (e.g., Fe and Si) enhanced by a factor of ~ 2 – 4 in the corona.*

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*

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



***Hinode*/EIS composition map**

Photospheric : *(Flares)*

Coronal : *(Evolved ARs)*

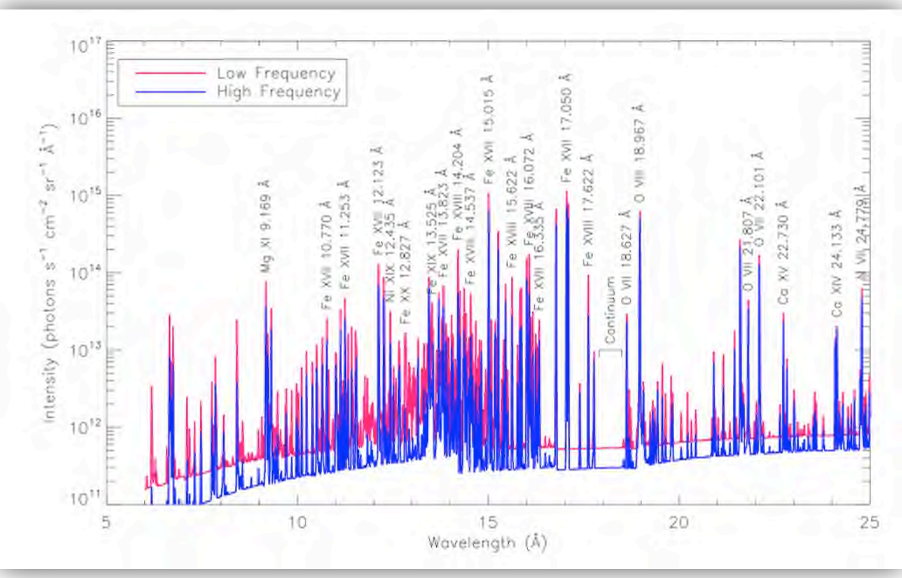
Evan & Pounds 1968; Veck & Parkinson 1981; Raymond et al. 1997; Sylwester et al. 2010; Brooks et al. 2014; Del Zanna 2006

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

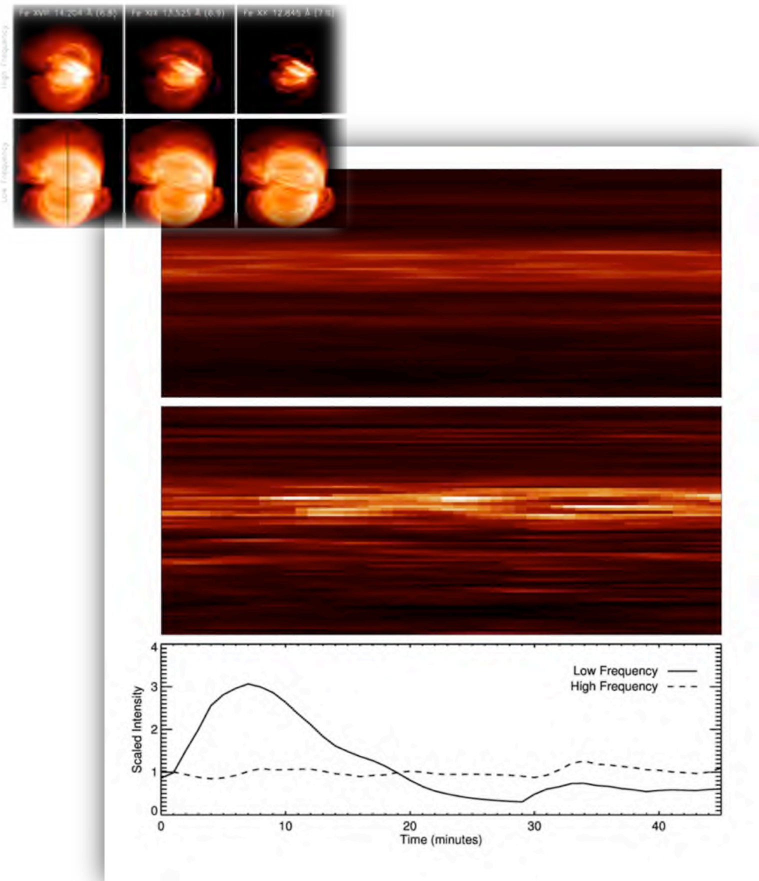


Compare FIP bias to structure lifetime and determine absolute abundances from continuum around 18 Å.

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