

Advancing Knowledge of the Coronal Heating Problem using the Sounding Rocket Platform



Dr. Amy Winebarger

NASA Marshall Space Flight Center

Career Path



91-95



95-99



99-01



10-??



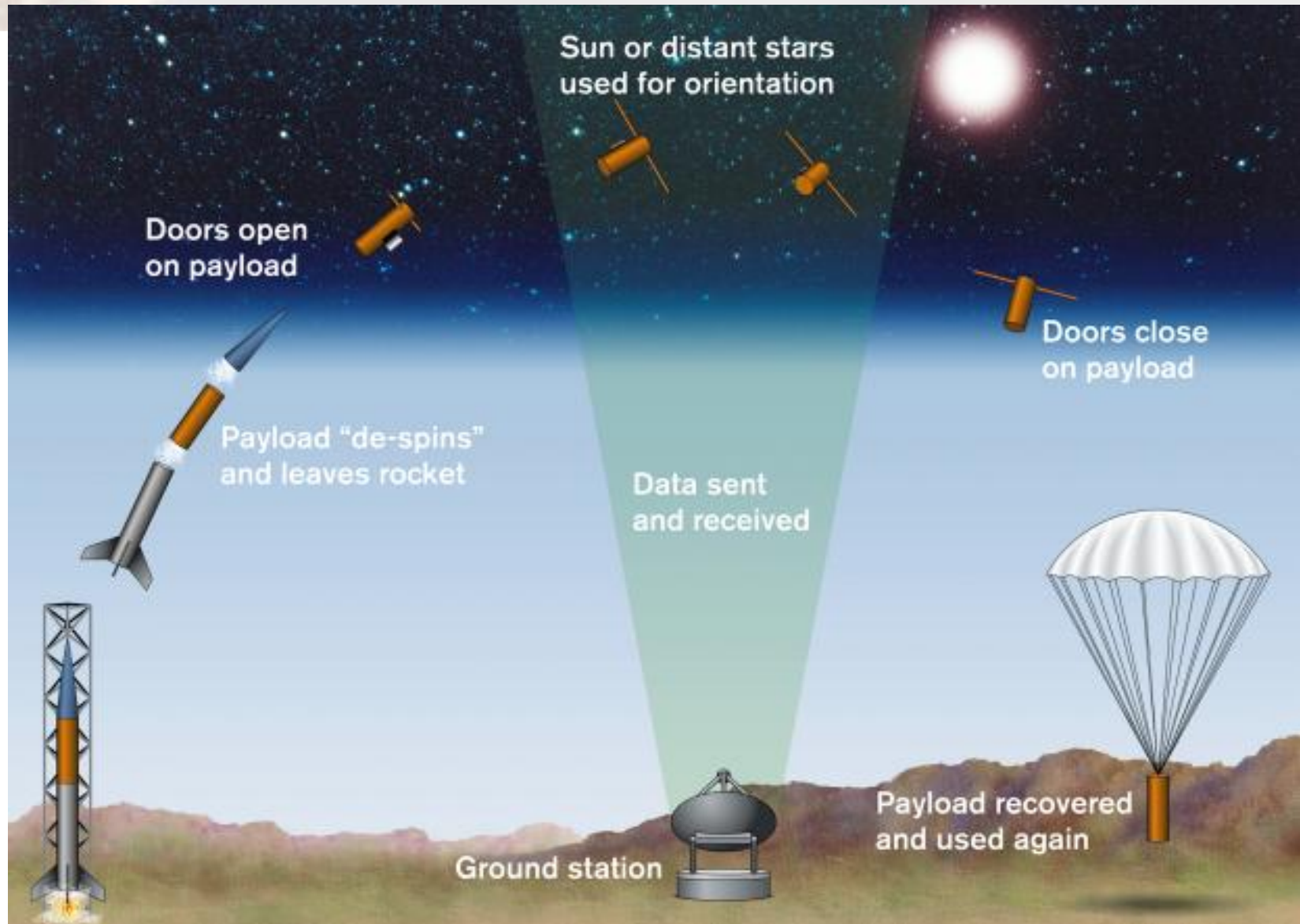
06-10



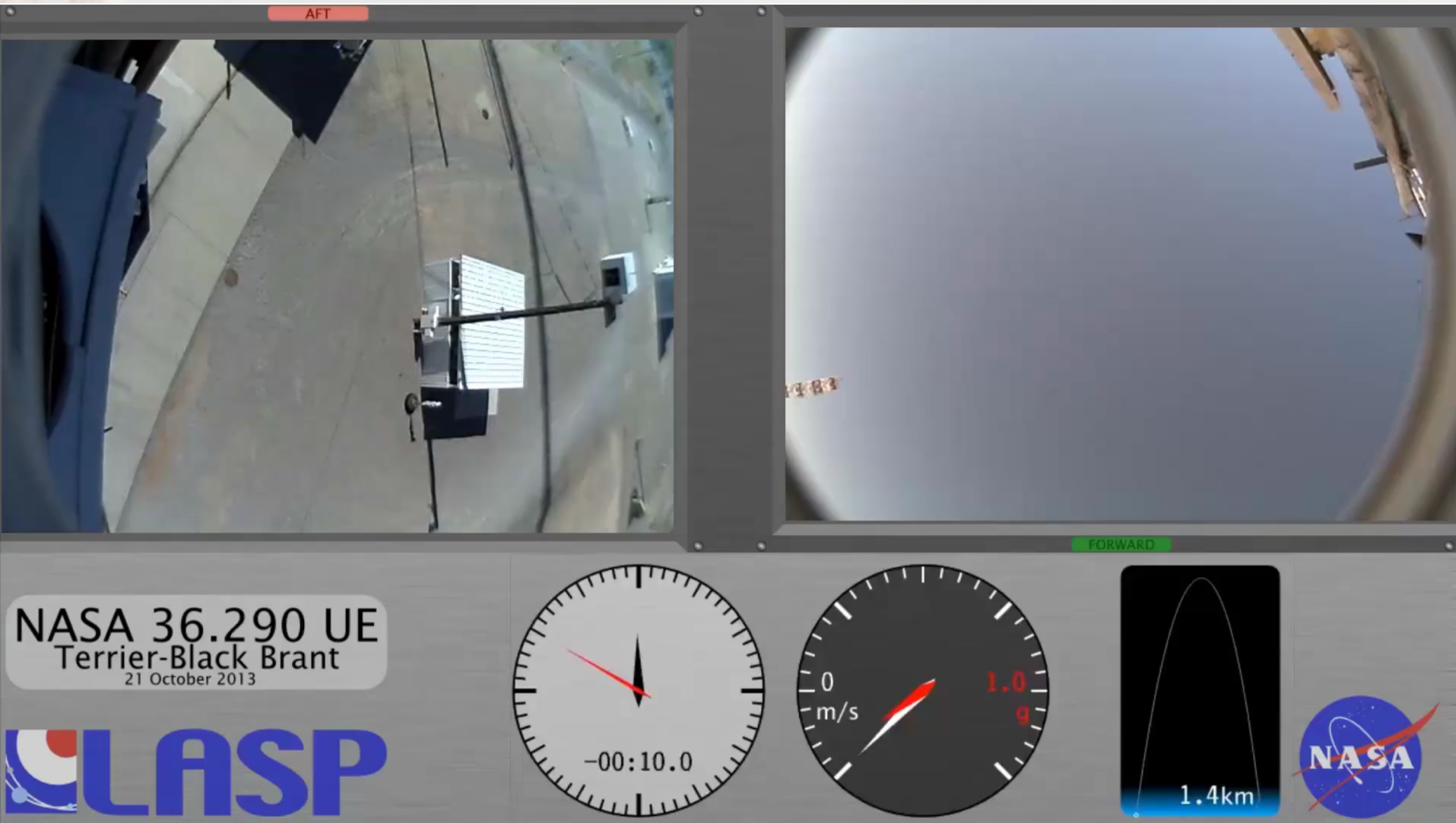
02-05



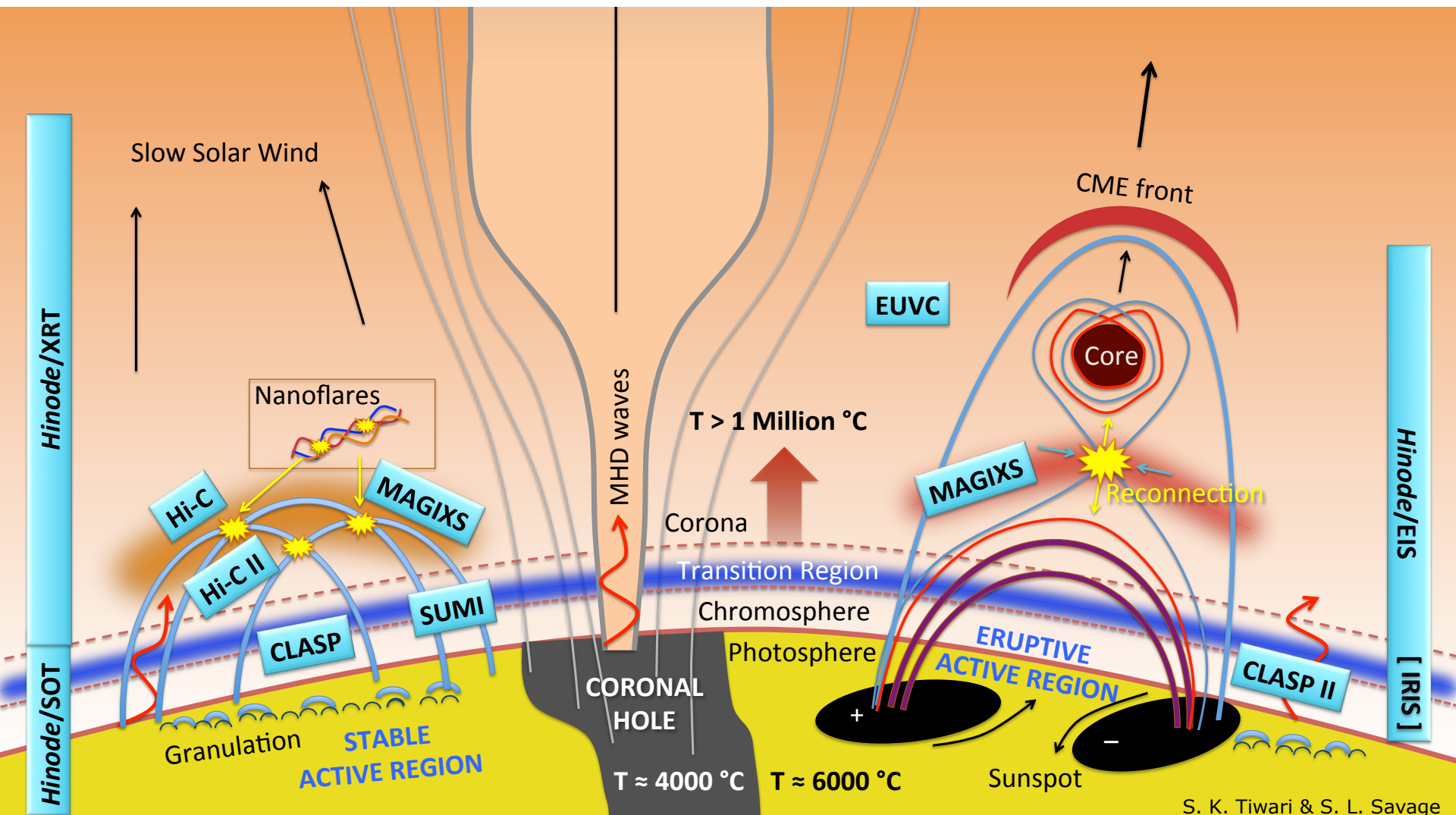
Sounding Rocket Program



Sounding Rocket Program



Sounding Rocket Instruments at MSFC



Sounding Rocket Instruments at MSFC

Hi-C 1 (J. Cirtain, PI)

Flew from WSMR on July 11, 2012

FLOWN
FUNDED

Hi-C 2 (J. Cirtain, PI)

Launched July, 2016 – no science data

Hi-C 2.1 (A. Winebarger, PI)

Launched May 29, 2018

CLASP 1 (A. Winebarger, PI)

Launched from WSMR on September 3, 2015

CLASP 2 (D. McKenzie, PI)

Will launch Spring, 2019

MaGIXS (A. Winebarger, PI)

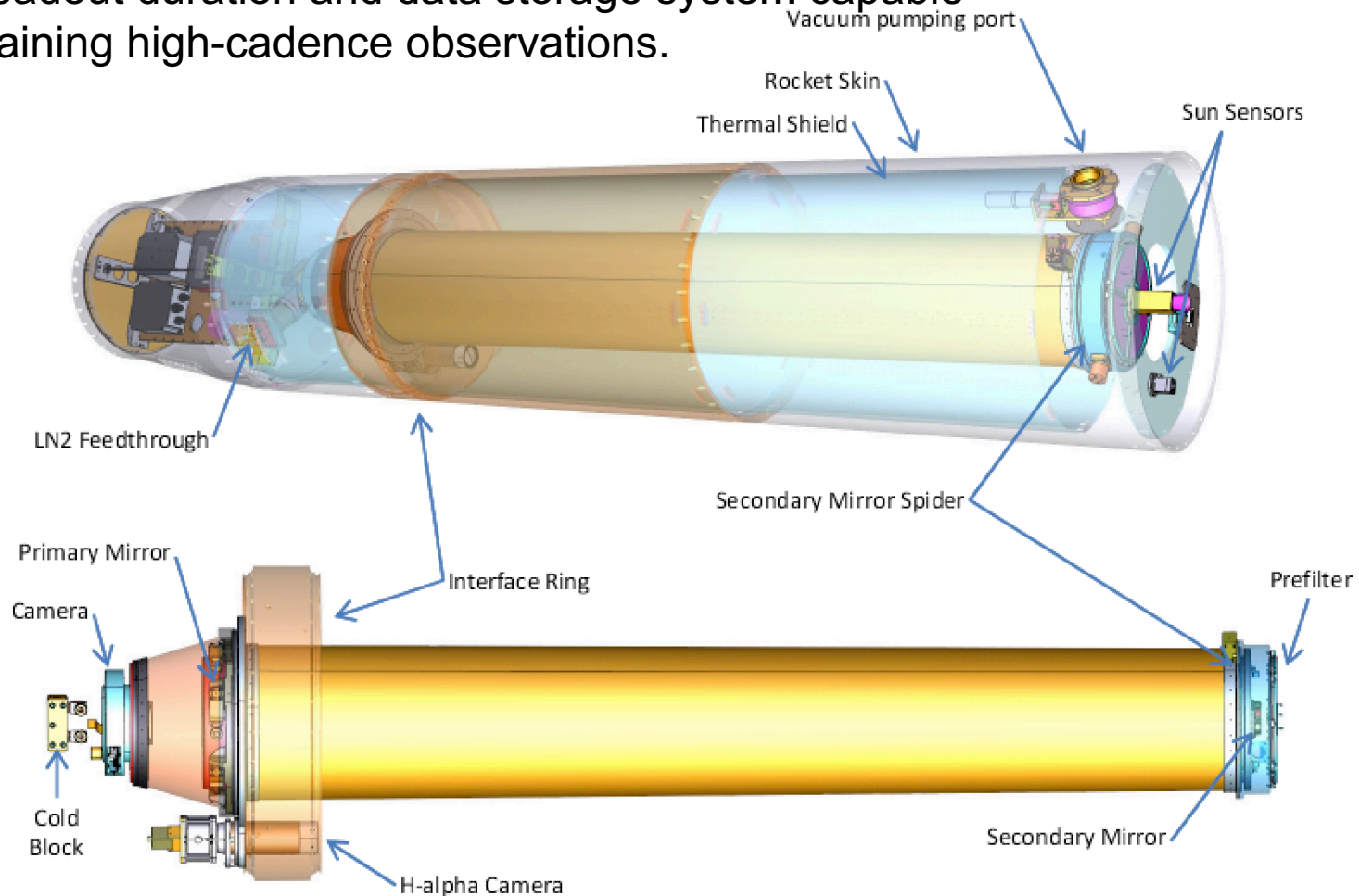
Will launch Summer, 2019

Goal for this talk –

- Scientific motivation for all instruments
- Give first results from flights
- Describe sub-orbital camera development at MSFC

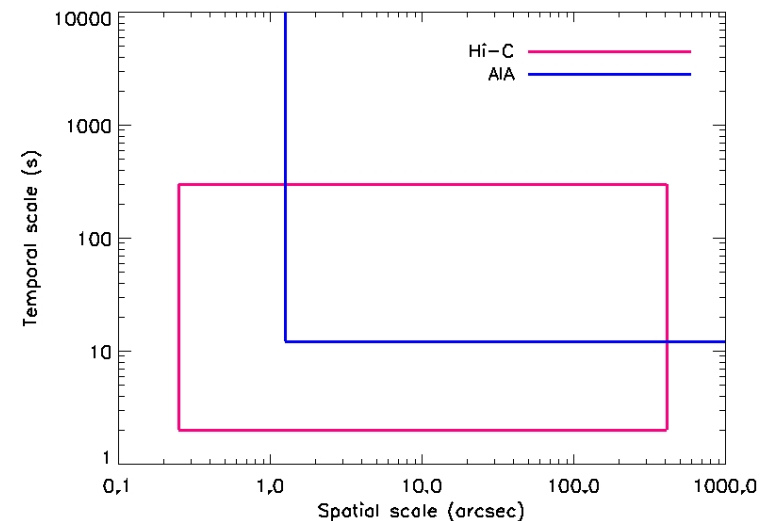
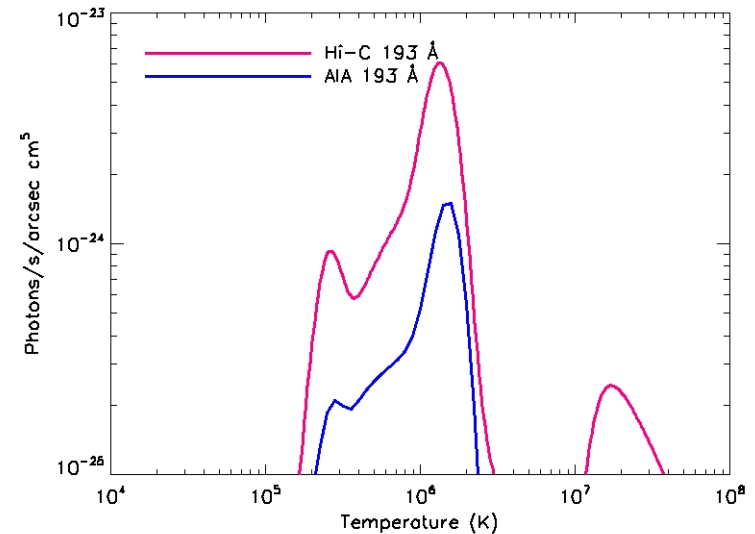
High-resolution Coronal Imager (Hi-C)

Telescope design capable of $\sim 150\text{km}$ spatial resolution
Pointing stability necessary to achieve resolution goal
Image readout duration and data storage system capable
of maintaining high-cadence observations.



High-resolution Coronal Imager (Hi-C)

- The Hi-C 193 Å passband is similar to the 193 Å passband on the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA).
- Hi-C has roughly 5 times the effective area of AIA.
- The cadence of Hi-C is 2.5 – 6 times better than AIA.
- Hi-C collected data for 345 s.
- Small shift in pointing during flight
- Full frame (4kx4k) data
 - 30 full resolution images
 - 2 s exposures / 5 s cadence
- Partial frame (1kx1k) data
 - 86 full resolution image
 - 0.5 s exposures / 1.4 s cadence

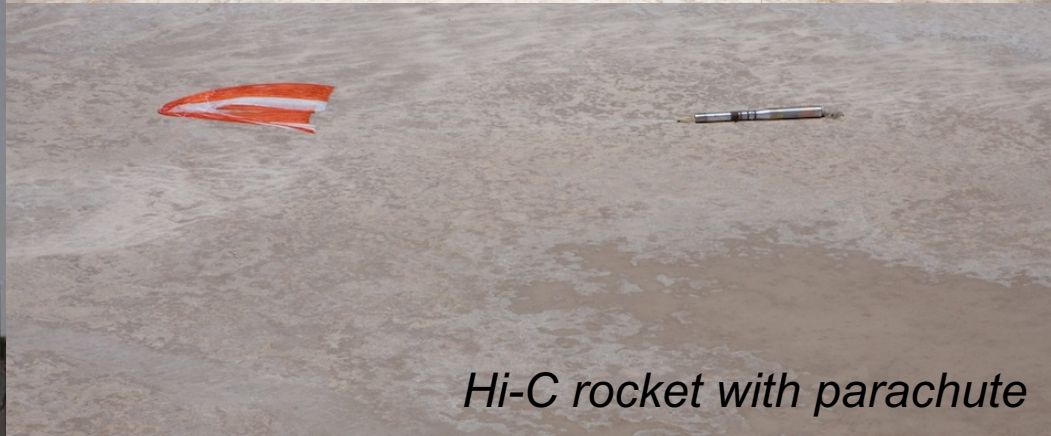


High-resolution Coronal Imager (Hi-C)

*Hi-C Launch
July 11, 2012*



Hi-C recovery team



Hi-C rocket with parachute

Hi-C 1 results

Hi-C 1 Launch
White Sands, NM
July 11, 2012



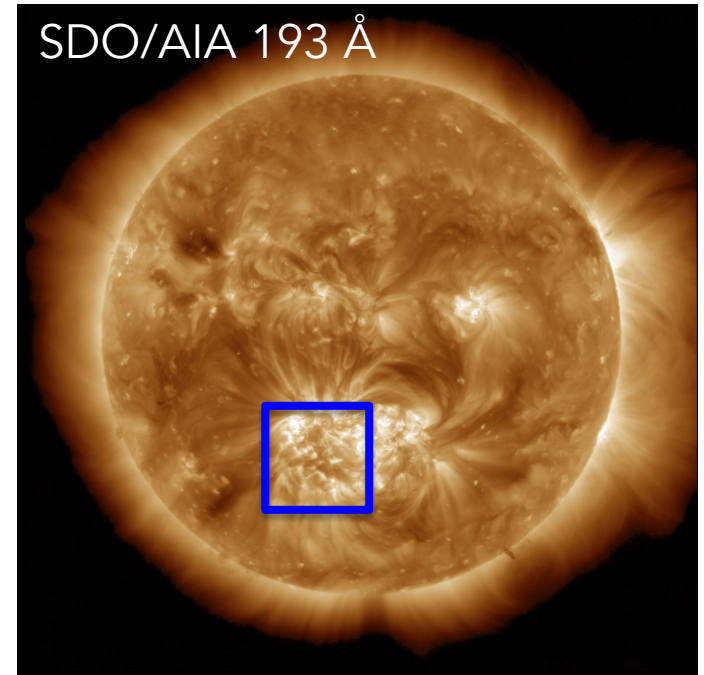
Active Region 11520 – 193 Å

26 publications for 5 minutes of data!

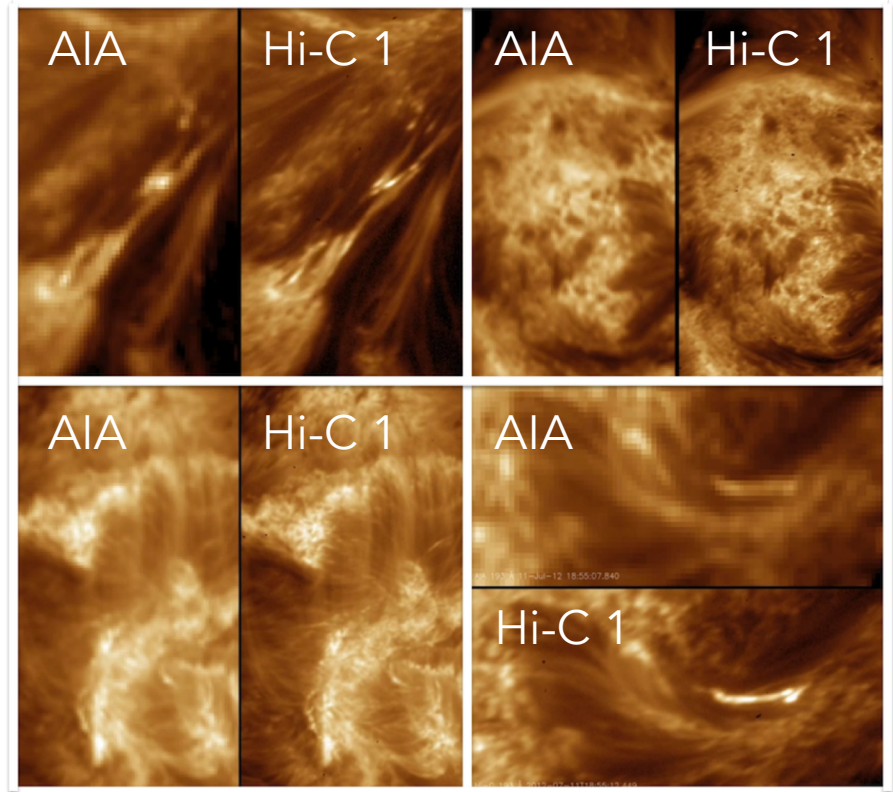
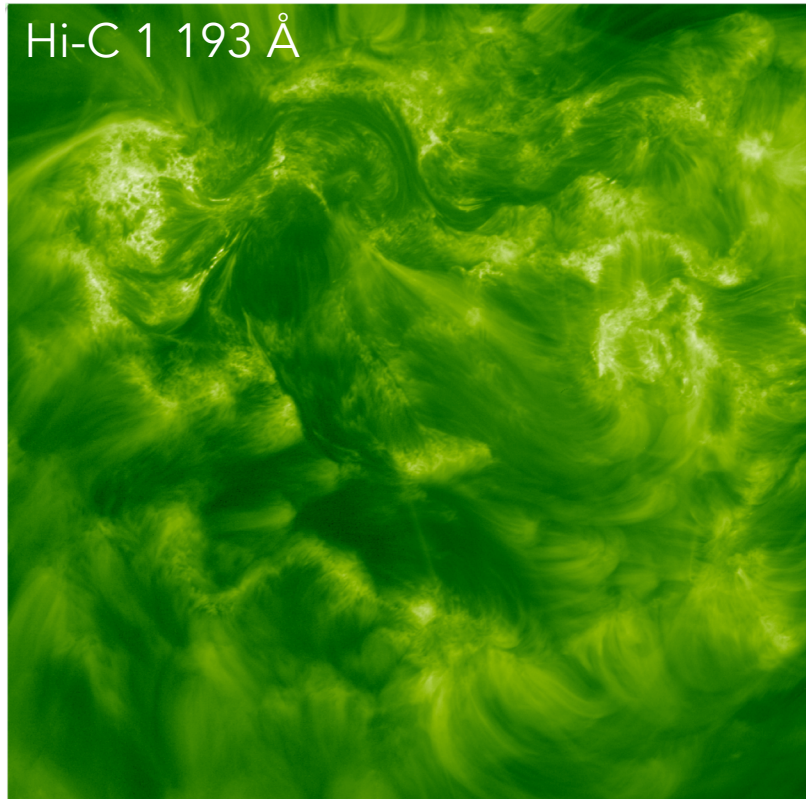
Science highlights:

- Braided loops triggering energy release through magnetic reconnection (*Cirtain et al. 2013, Nature*)
- Subflare triggers
- Nanoflare heating
- Loop sub-structure
- Moss dynamics
- Penumbral jets
- Flows along filament threads
- MHD waves

SDO/AIA 193 Å



Hi-C 1 results



Hi-C 2

*Hi-C 2 Launch
White Sands, NM
July 27, 2016*

Hi-C 2 mirror recoated to explore the important Chromospheric-Coronal Connection by targeting specific candidates likely to contribute to coronal heating:

1. Type II spicules
2. Hot active region core loops

Updates for re-flight:

- Cooler bandpass centered on **172 Å**
- Significant improvement in camera quality (new MSFC-build designed for super low noise)
- **IRIS!**

Hi-C 2 results

Hi-C 2 Launch
White Sands, NM
July 27, 2016

Fantastic flight performance
verification of the low-noise
MSFC-built camera.

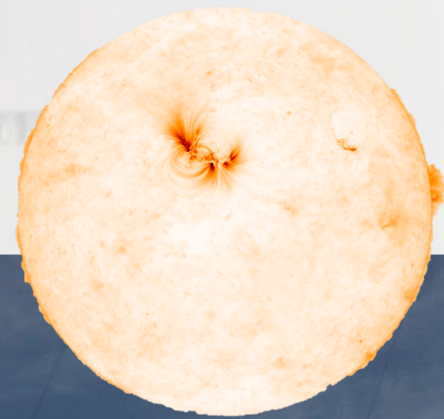
$\sim 7e^-$

$\sim 7e^-$

$\sim 13e^-$

$\sim 8e^-$

Hi-C 2.1



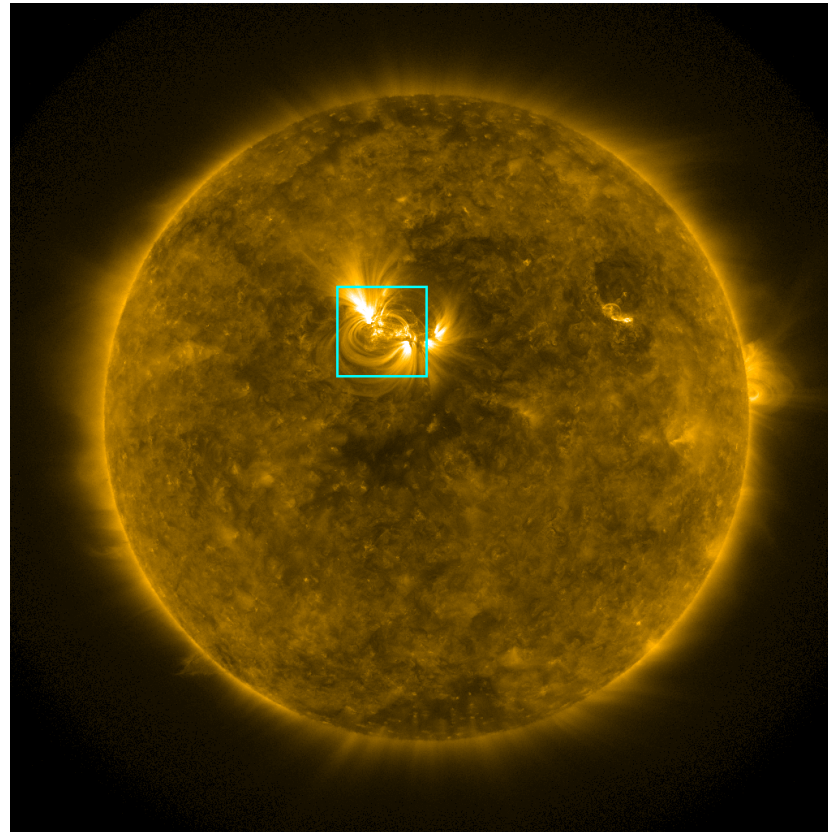
Hi-C 2.1 Launch
White Sands, NM
May 29, 2018



Hi-C 2.1 Observations

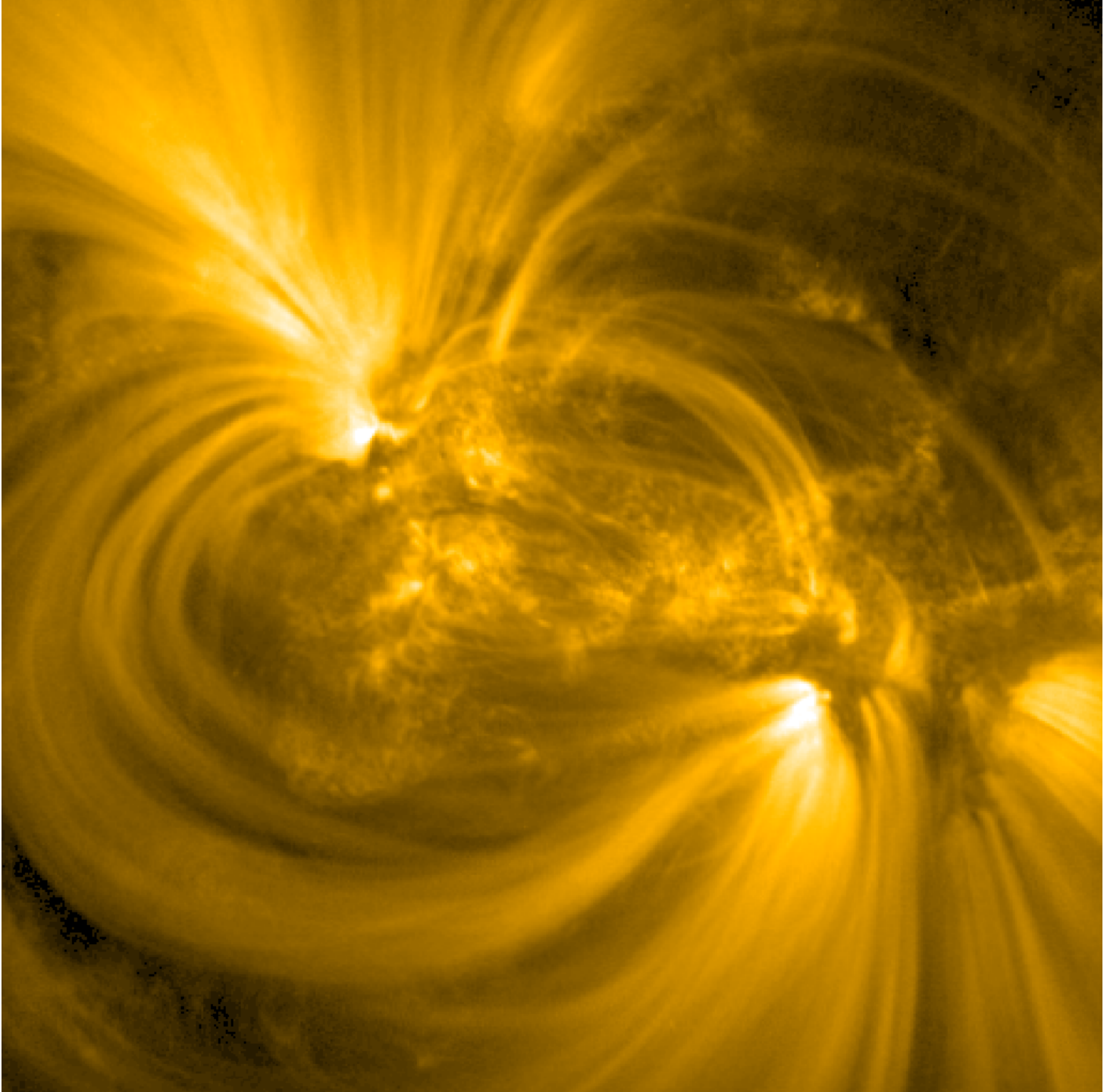
2018 May 29
18:54 UT

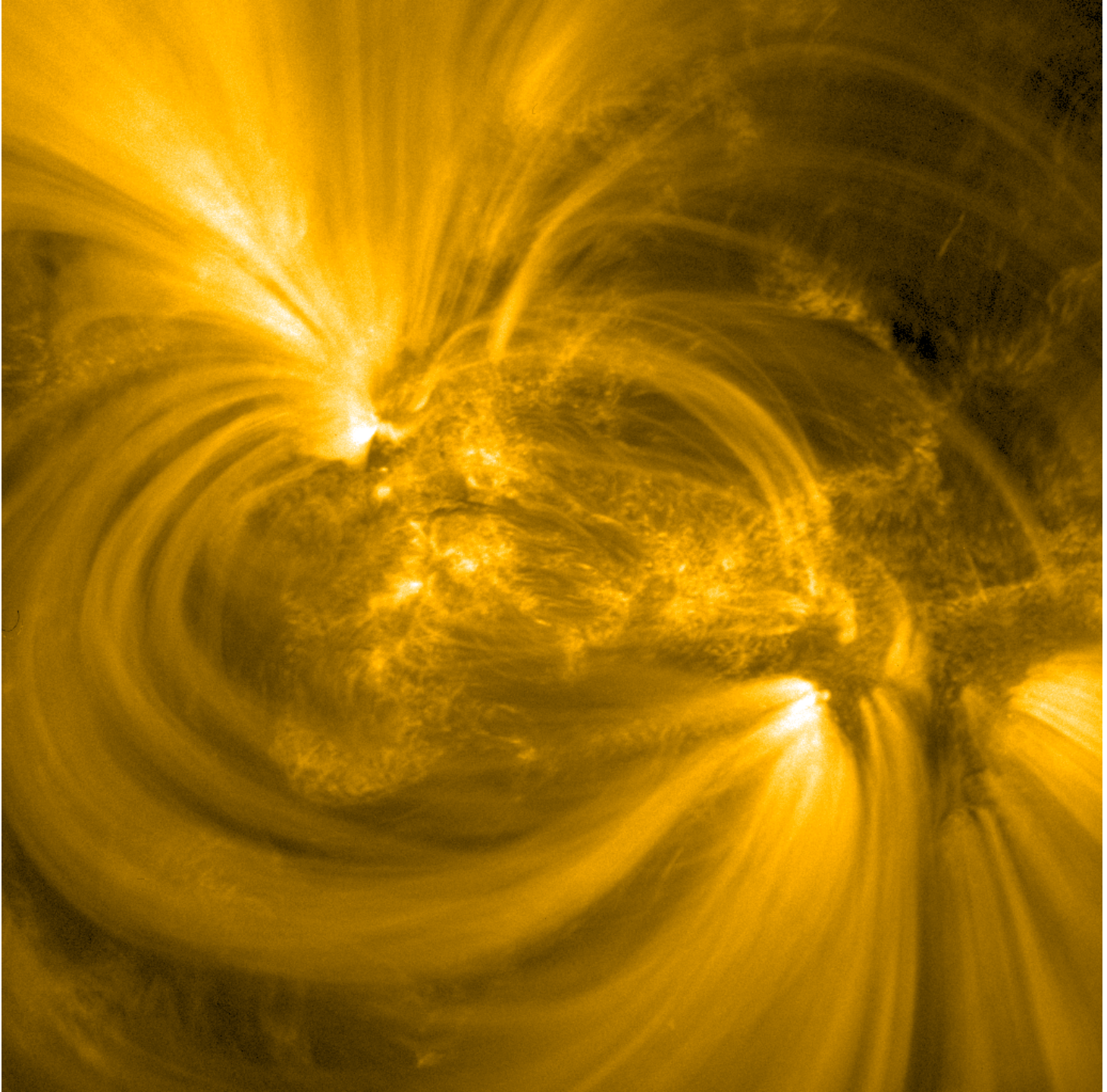
Target: AR 12712



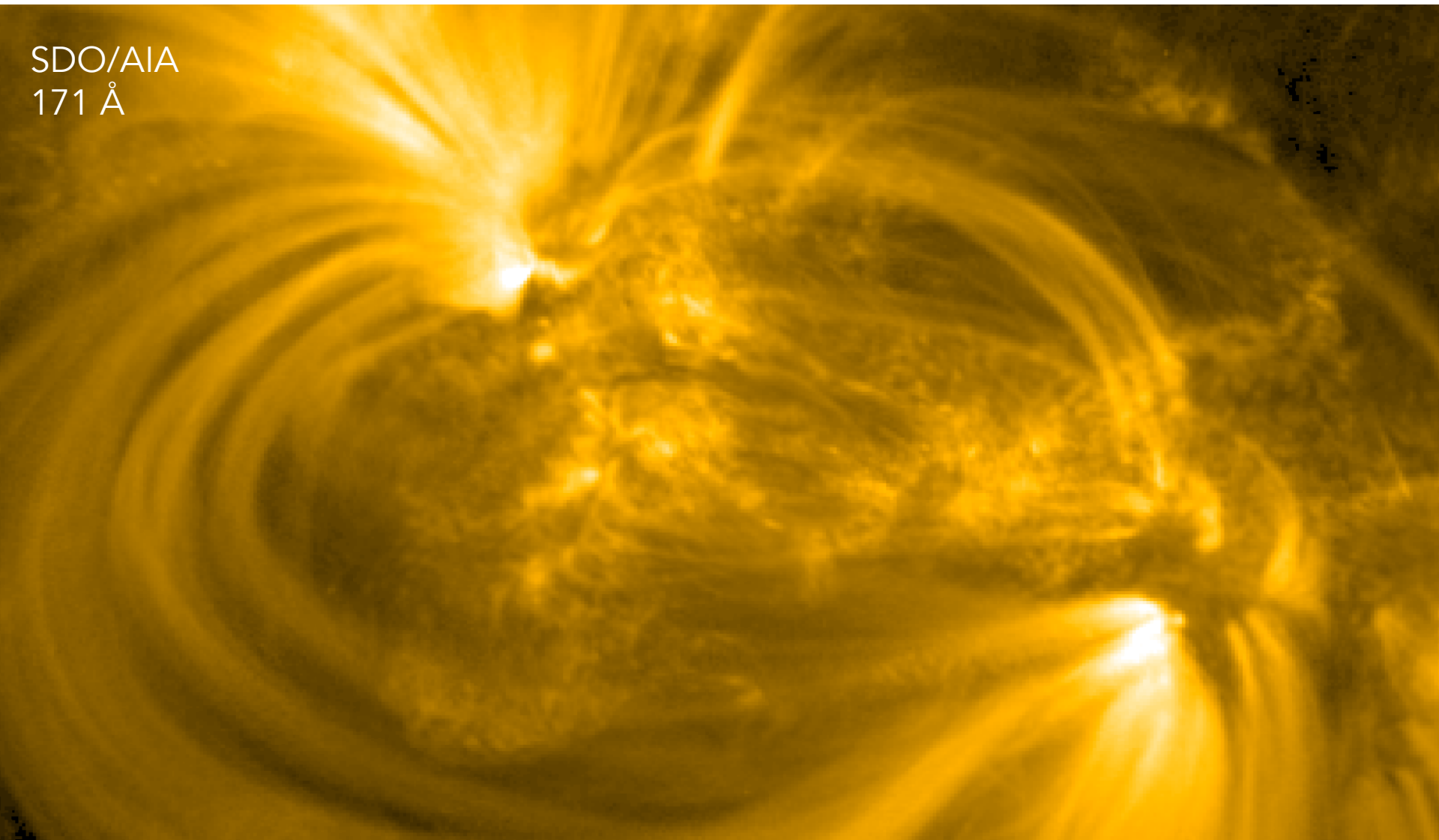
~ 15 minute flight

~ 5 minutes of solar
viewing data

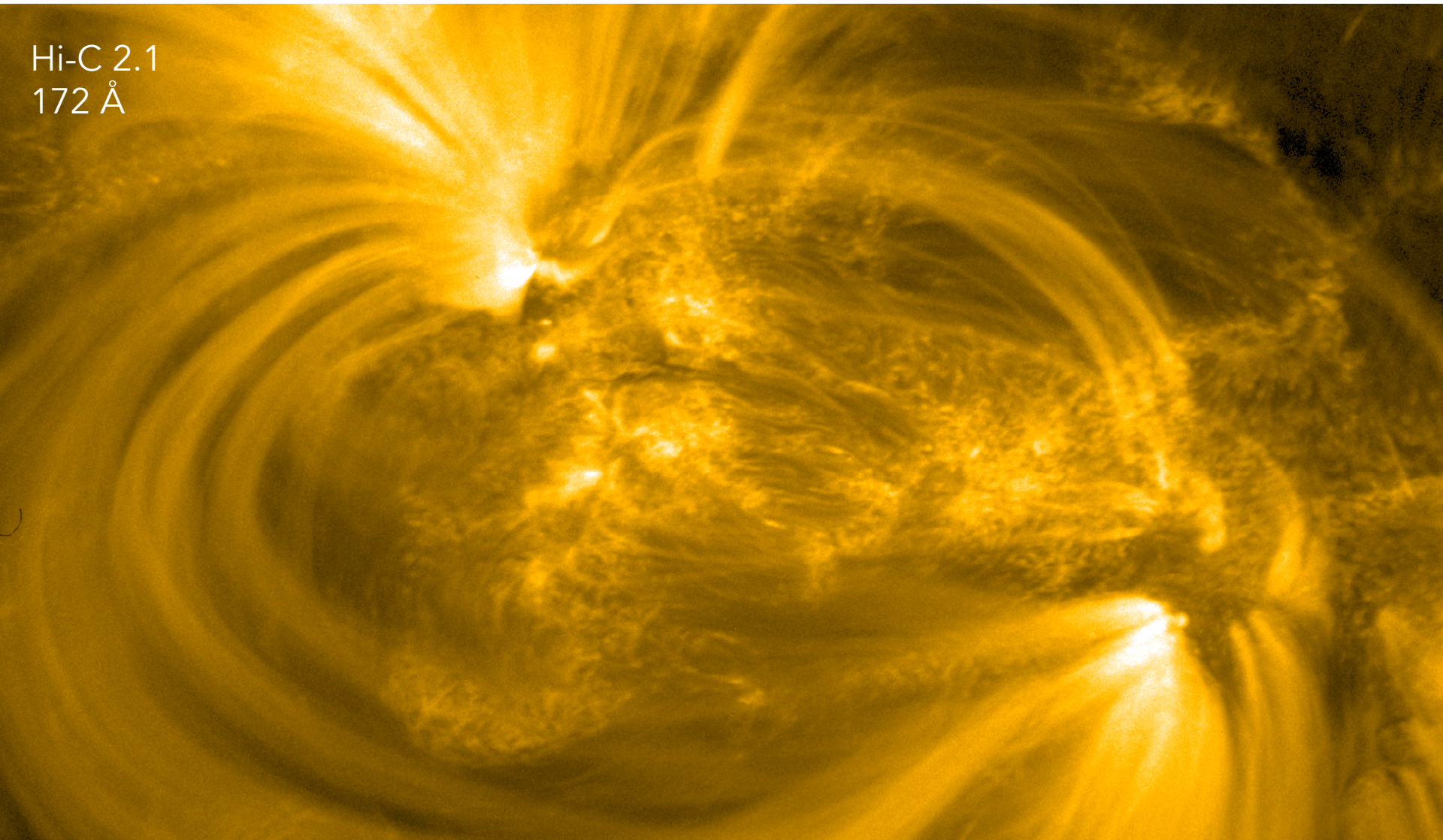


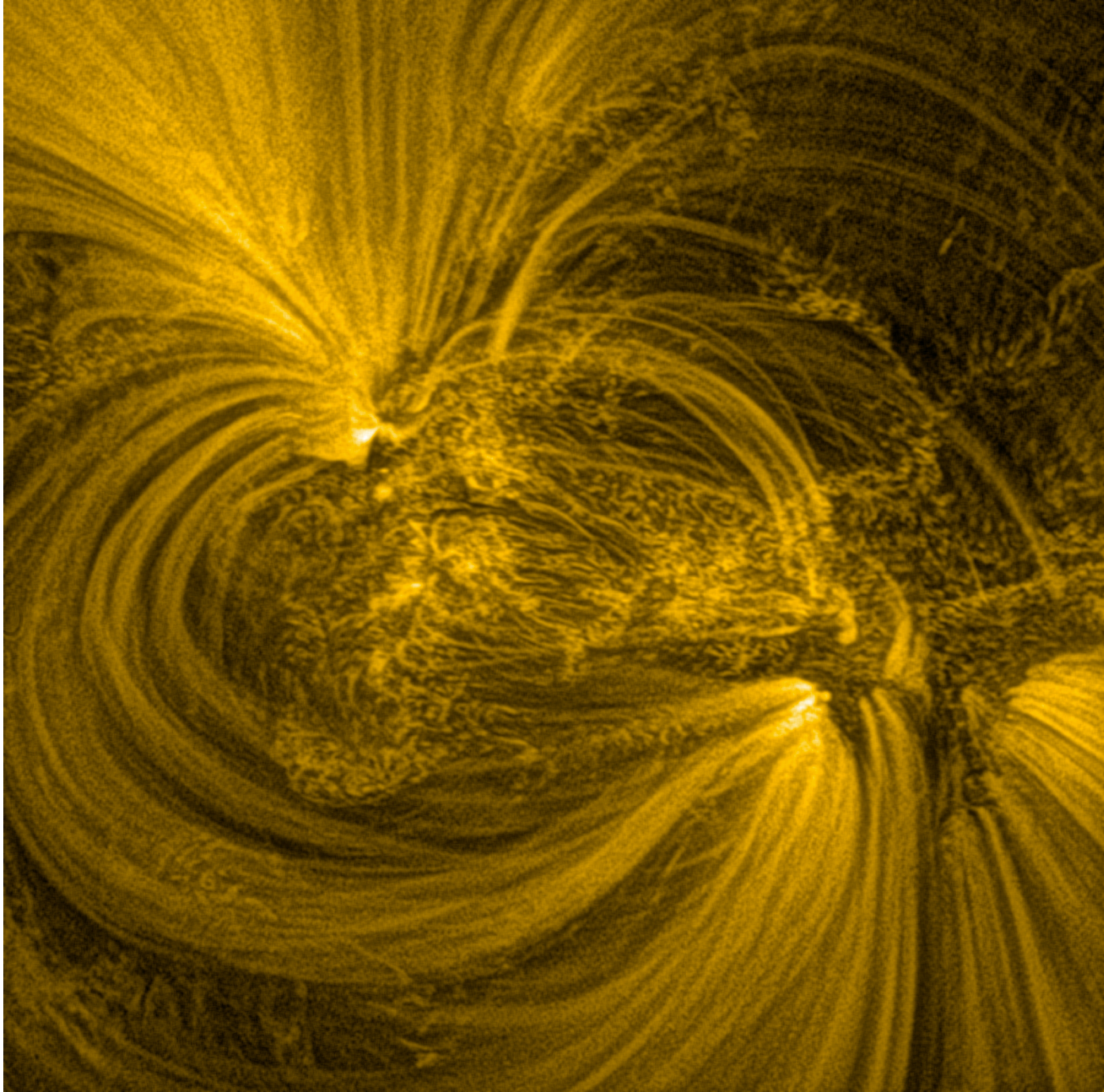


SDO/AIA
171 Å



Hi-C 2.1
172 Å





Hi-C 2.1



Hi-C 2.1



Why the chromosphere? Why now?

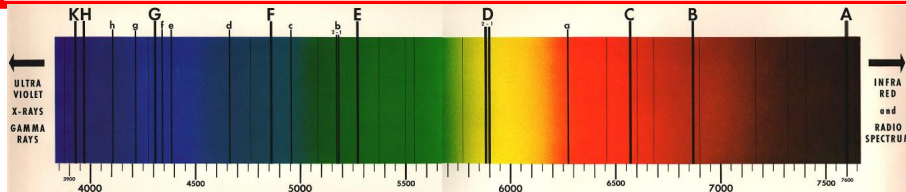
SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.

- Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
- Determine how magnetic free energy is transmitted from the photosphere to the corona.
- Discover how the thermal structure of the closed-field corona is determined.
- Discover the origin of the solar wind's dynamics and structure.

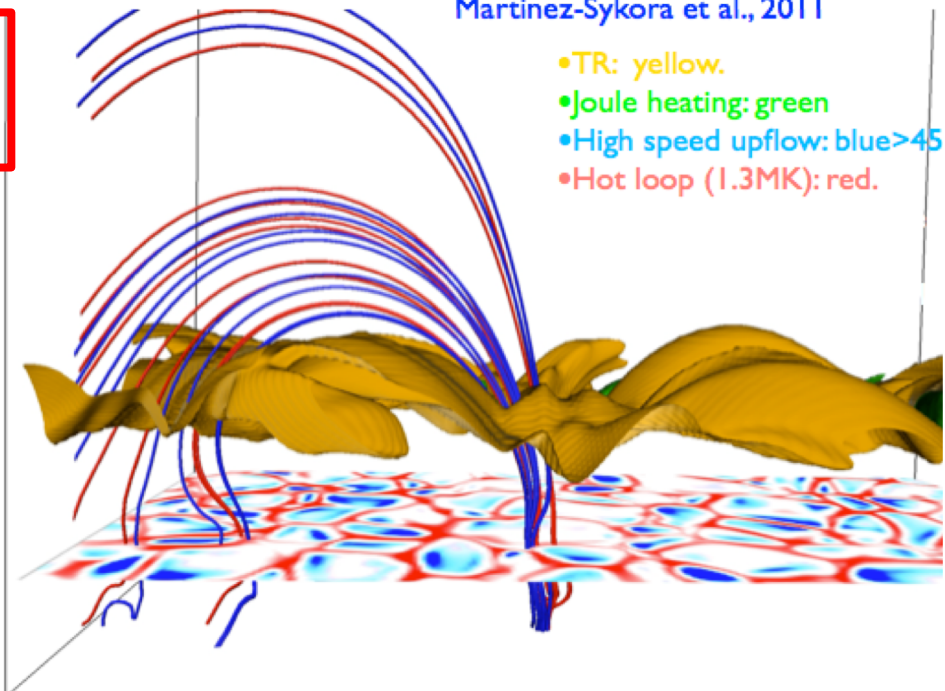
Solar and Space Physics: A Science for a Technological Society, 2013

Advances in theoretical modeling of the chromosphere and transition region allow for prediction and interpretation of the results.

Magnetically sensitive spectral lines formed in chromosphere are not in the visible wavelength range, so measurements have to go above atmosphere.



Martinez-Sykora et al., 2011



Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

Science Goal 1: Detect scattering polarization in the wings of Lyman-alpha.

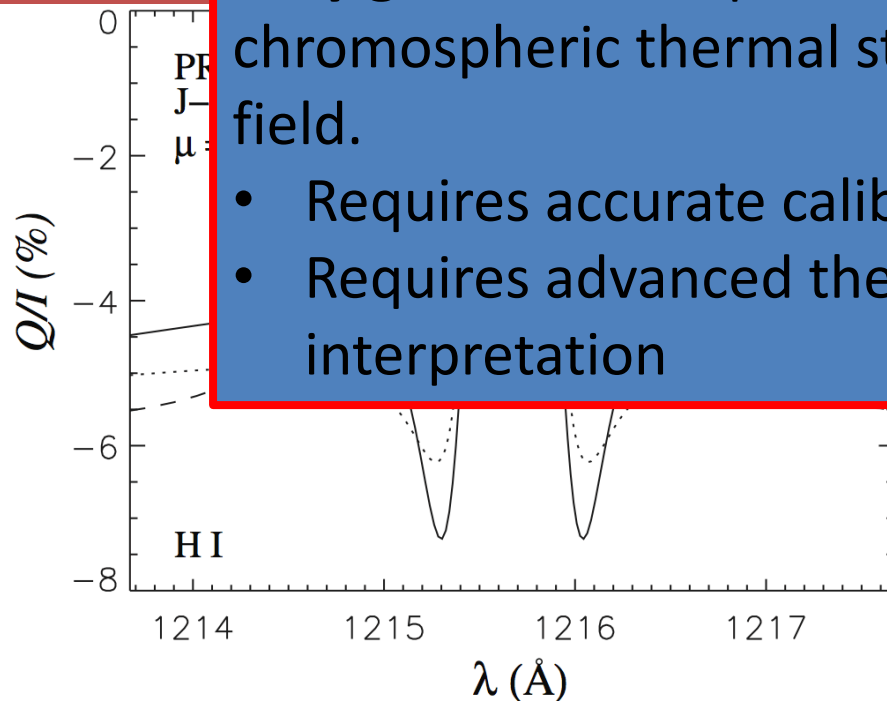
- Sensitive to the thermal structure of the chromosphere.
- Not sensitive to magnetic field
- Magnitude

Science Goal 2: Detect polarization in the line core.

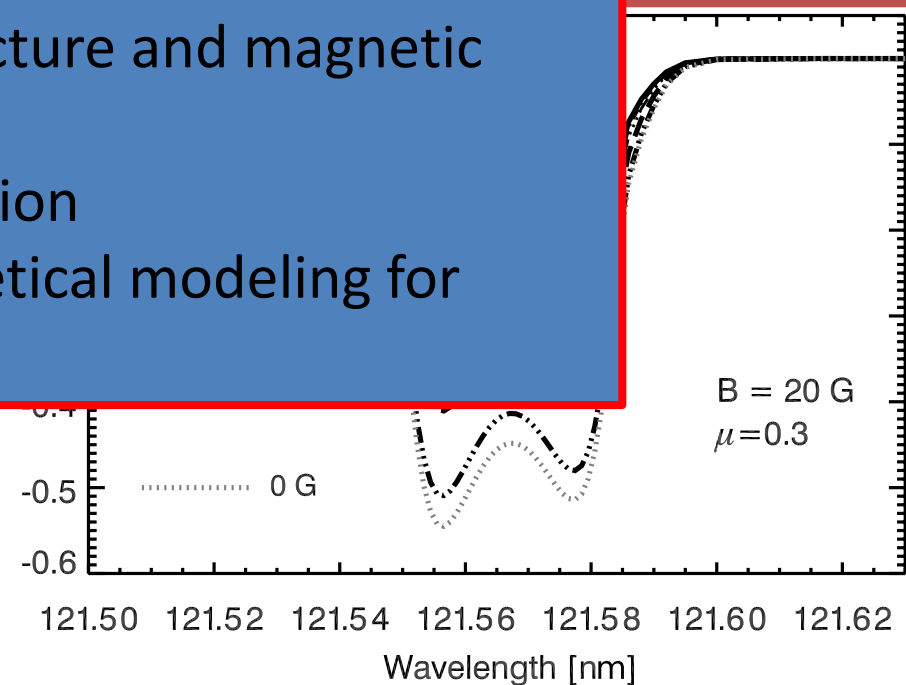
- Modified by the magnetic field through Hanle effect
- Magnitude of the polarization is $\sim 0.1\%$
- Accuracy required technological advances in vector systems

Holy grail: Use the polarization to infer the chromospheric thermal structure and magnetic field.

- Requires accurate calibration
- Requires advanced theoretical modeling for interpretation

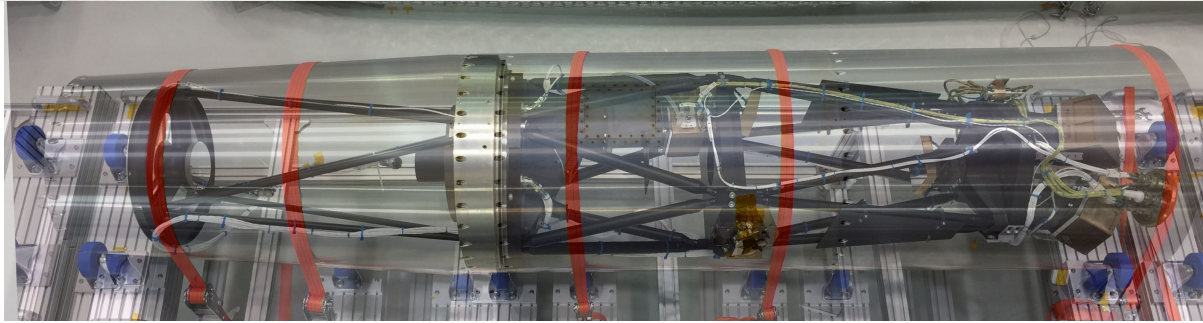


Belluzzi et al. 2012



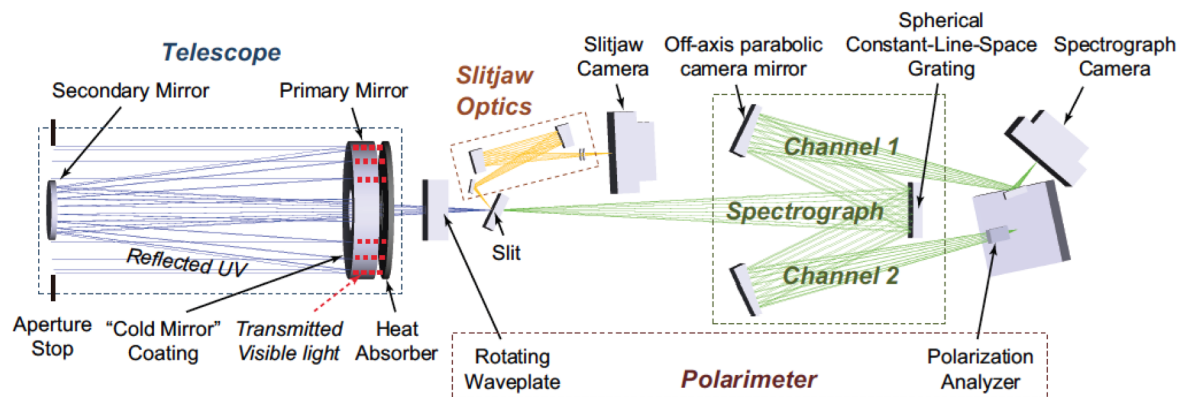
Trujillo Bueno et al. 2011

Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)



CLASP is a dual channel spectropolarimeter to measure the polarization of Lyman-alpha.

CLASP was designed and built through an international partnership. Scientists from 11 organizations and 6 countries form the CLASP team. Primary teams and responsibilities are listed below.



MSFC/USA (PI: A. Winebarger) – Cameras, avionics, project management, coordination w/ NASA launch team

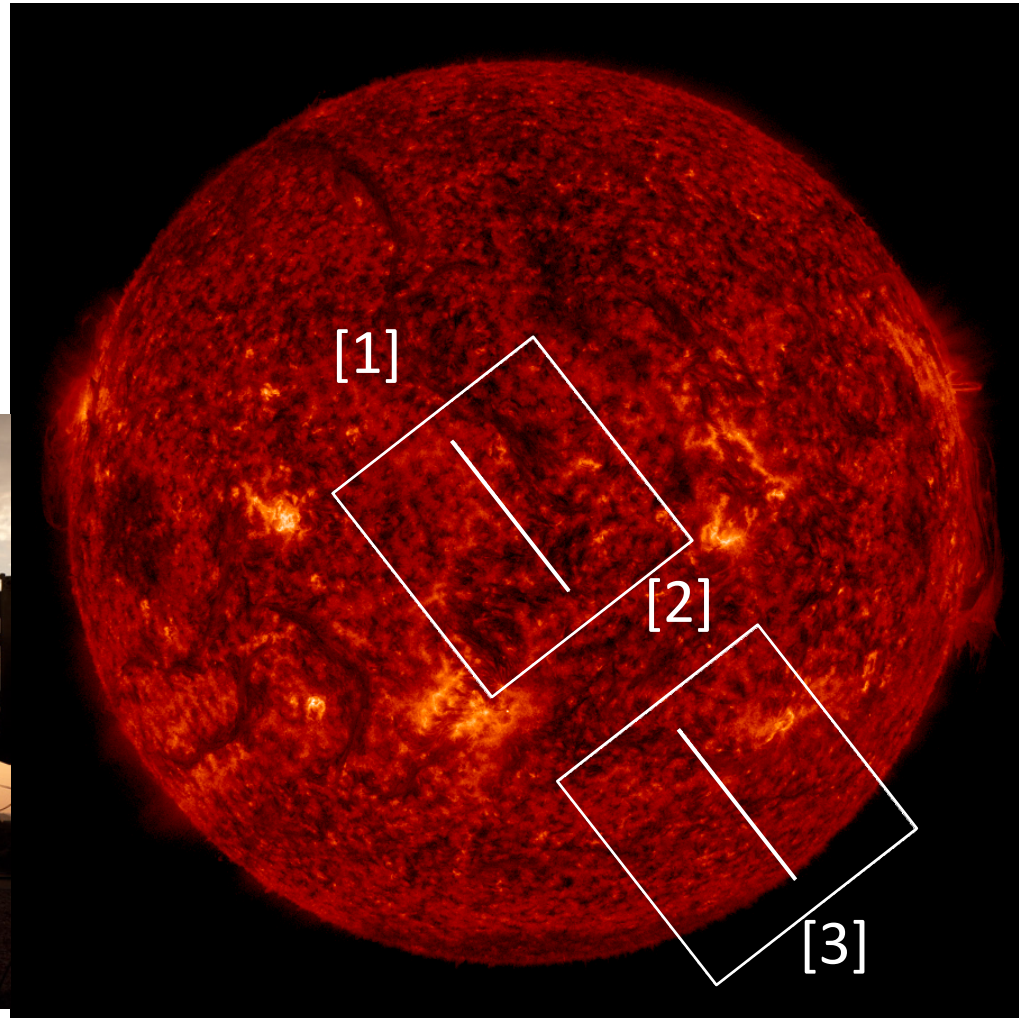
NAOJ & JAXA/Japan (Co-PI: R. Kano) – Optics & opto-mechanics, instrument structure

IAS/France (Co-PI: F. Auchère) – Diffraction Grating

IAC/Spain (Co-PI: J. Trujillo Bueno) – Theoretical predictions and modeling of the Hanle effect

Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

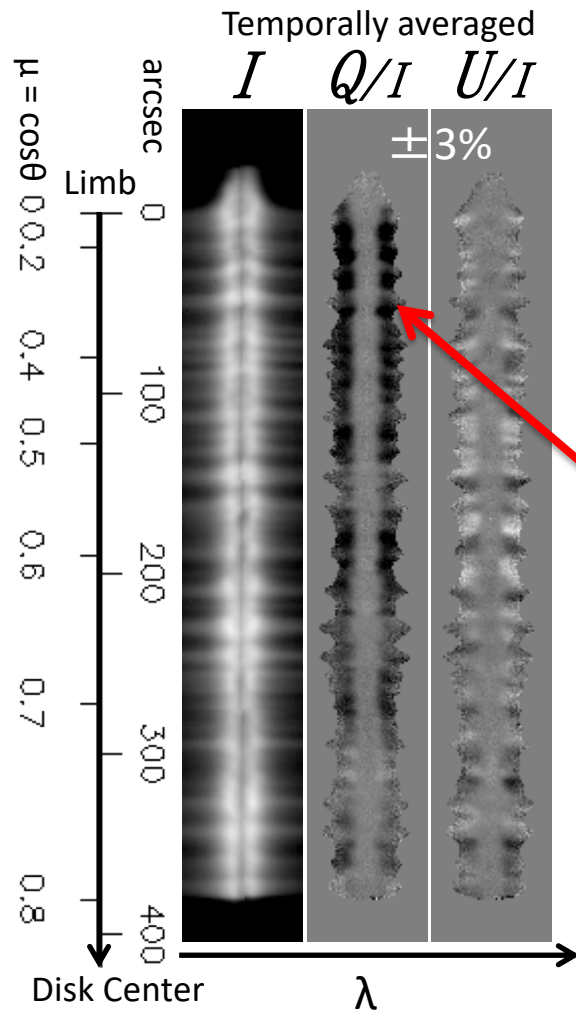
CLASP was launched on September 3, 2015 from White Sand Missile Range



Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

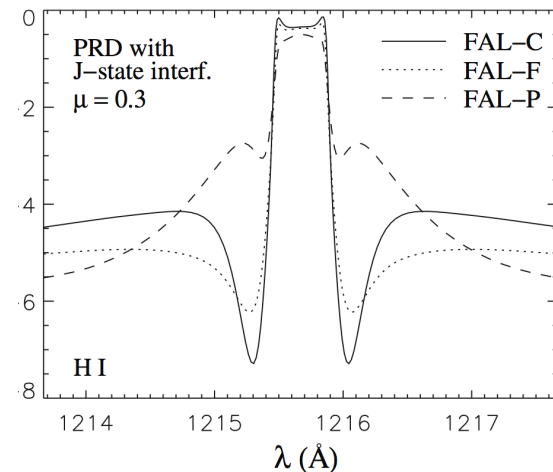
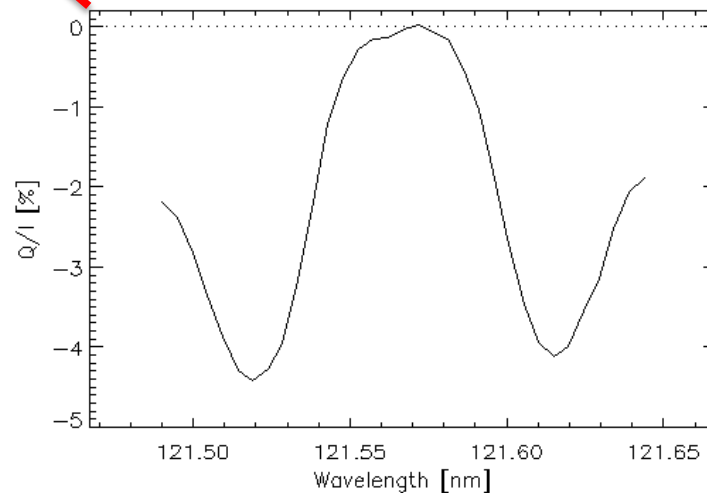


CLASP Initial Results



Further calibrations/investigations are required, but ...

- **A few %** of polarization in the wing, and **a few of 0.1 %** in the core.
- A clear **C-to-L variation** in the wing of Q/I.
- Small-scale structures along the slit.
- Q/I profile is essentially **consistent with the model prediction**.



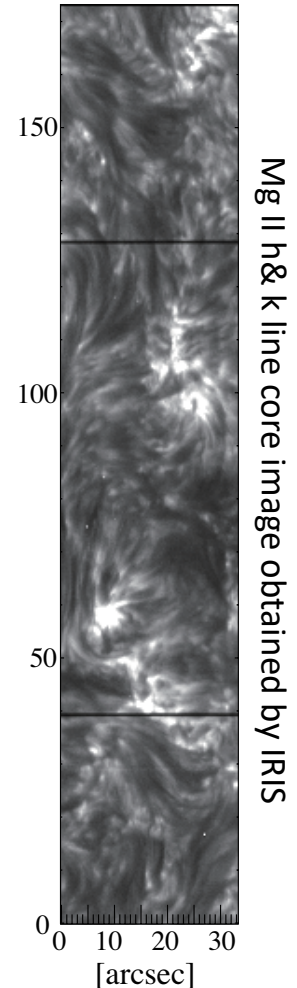
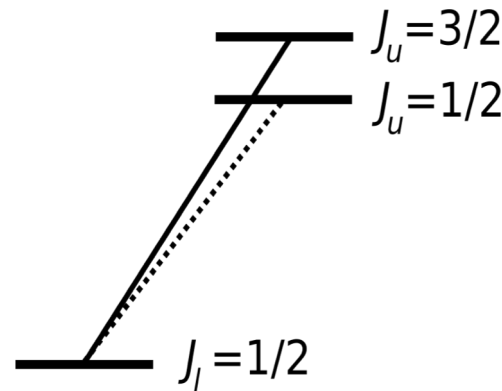
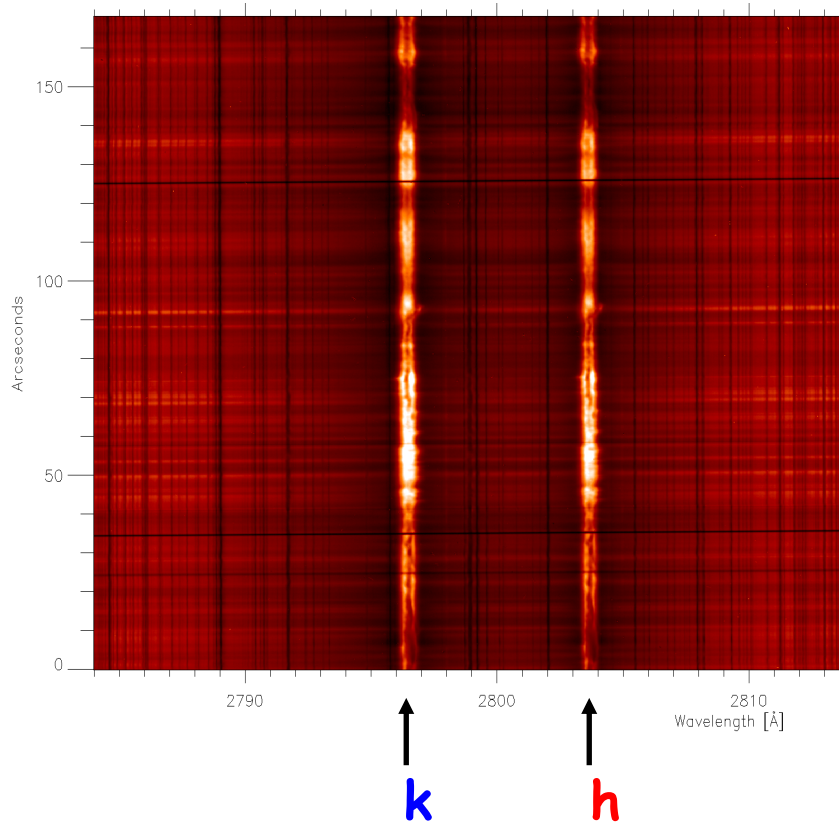


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What is next for CLASP?

CLASP 2 proposes to change the wavelength to Mg II h&k, another set of magnetically sensitive spectral lines in the UV at ~ 280 nm.

Observing target: QS and plage (if available)

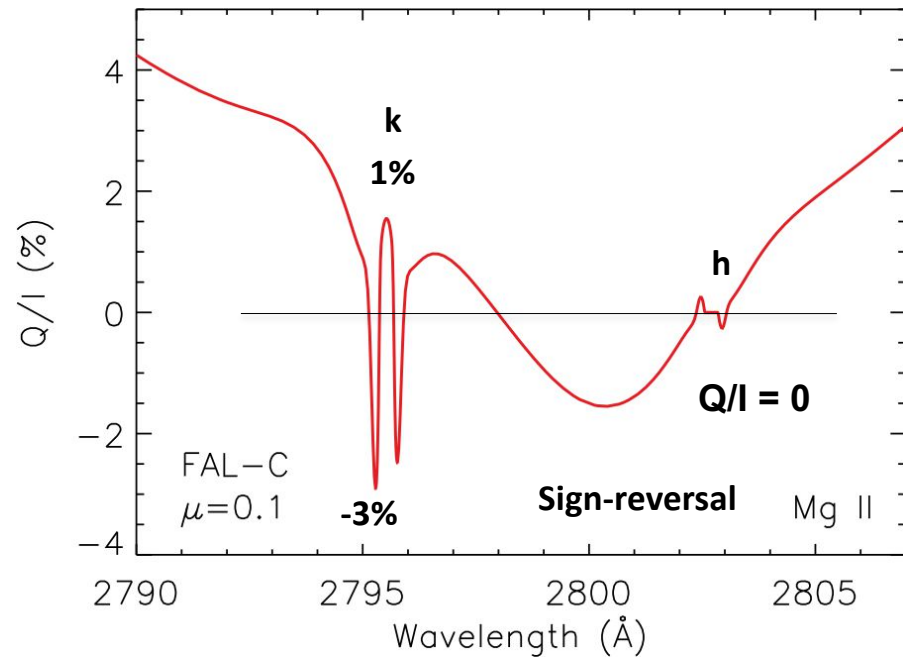




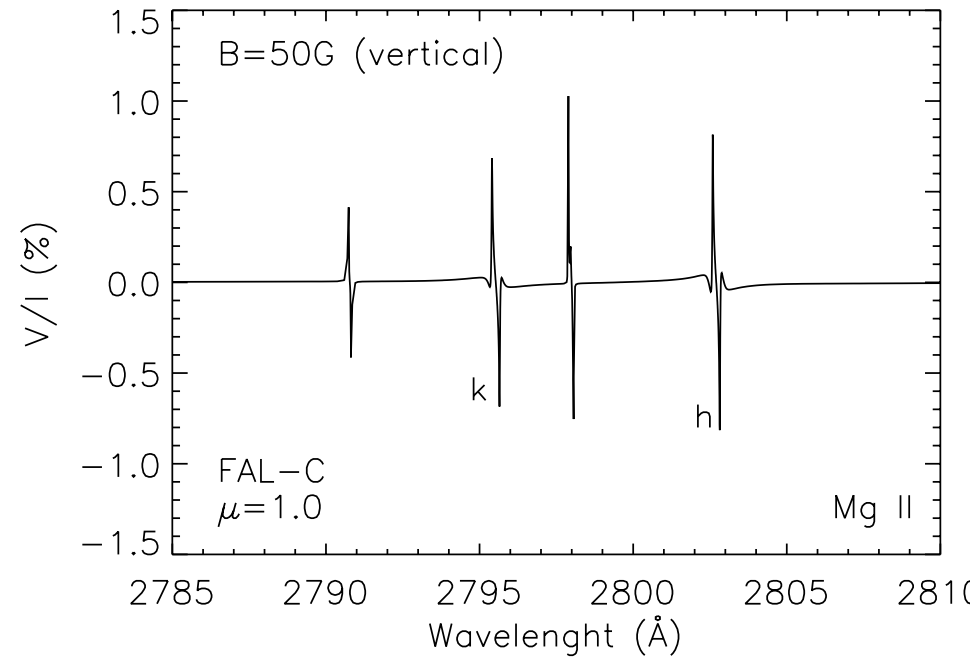
2

What is next for CLASP?

Linear polarization sensitive to scattering polarization and Hanle effect from 5-50 G.



Circular polarization sensitive to Zeeman effect for $B > 50$ G.

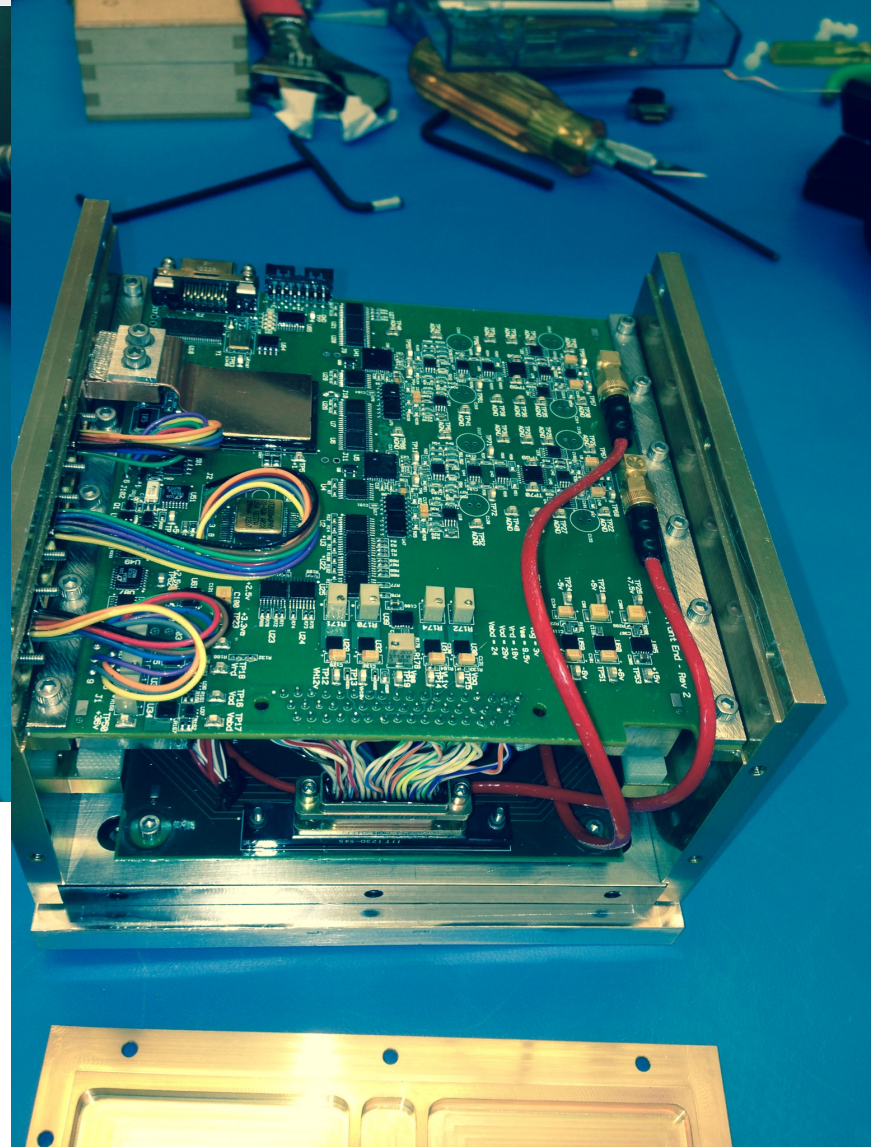
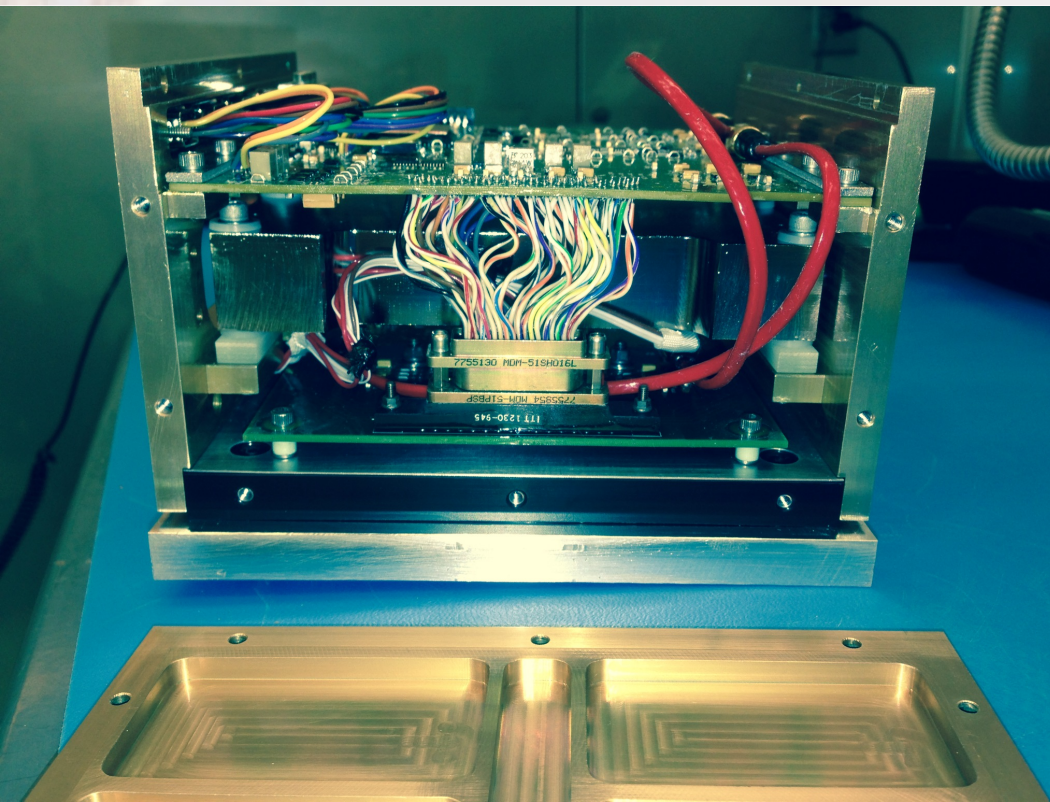


Will launch in Spring 2019.

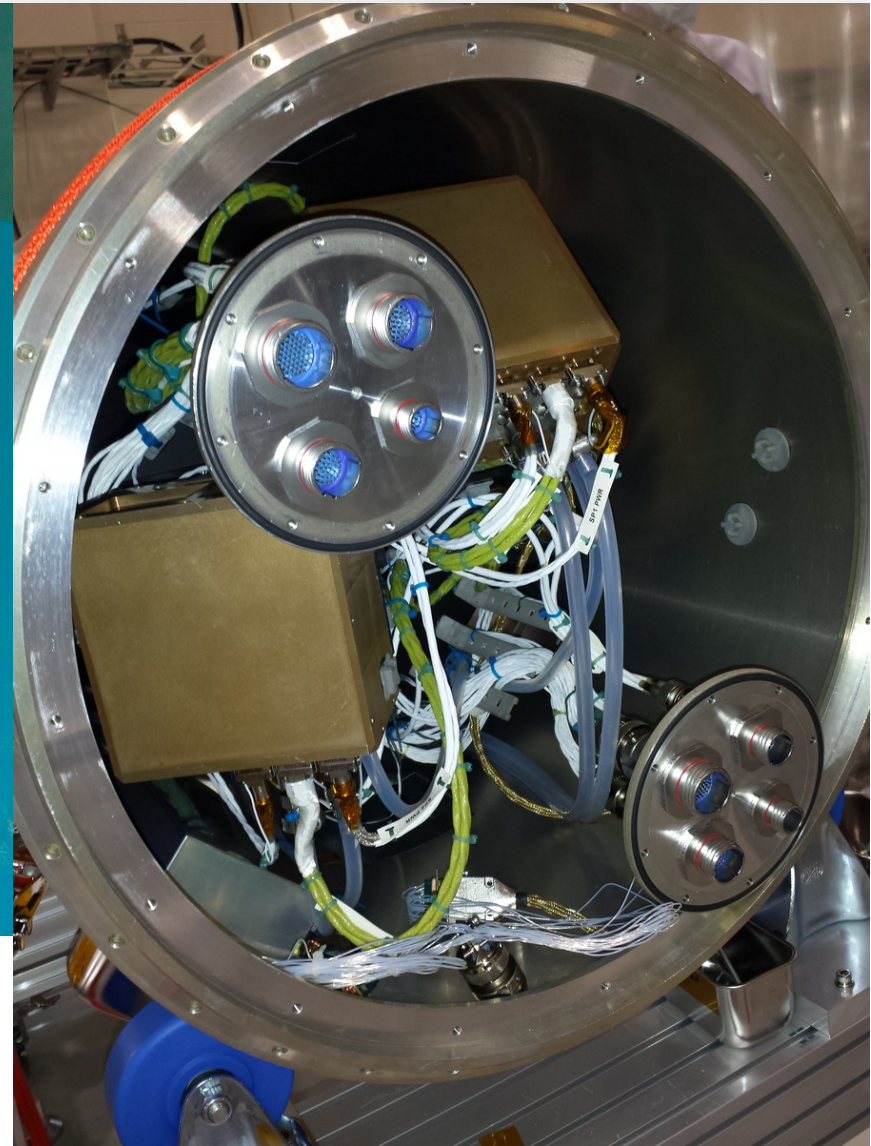
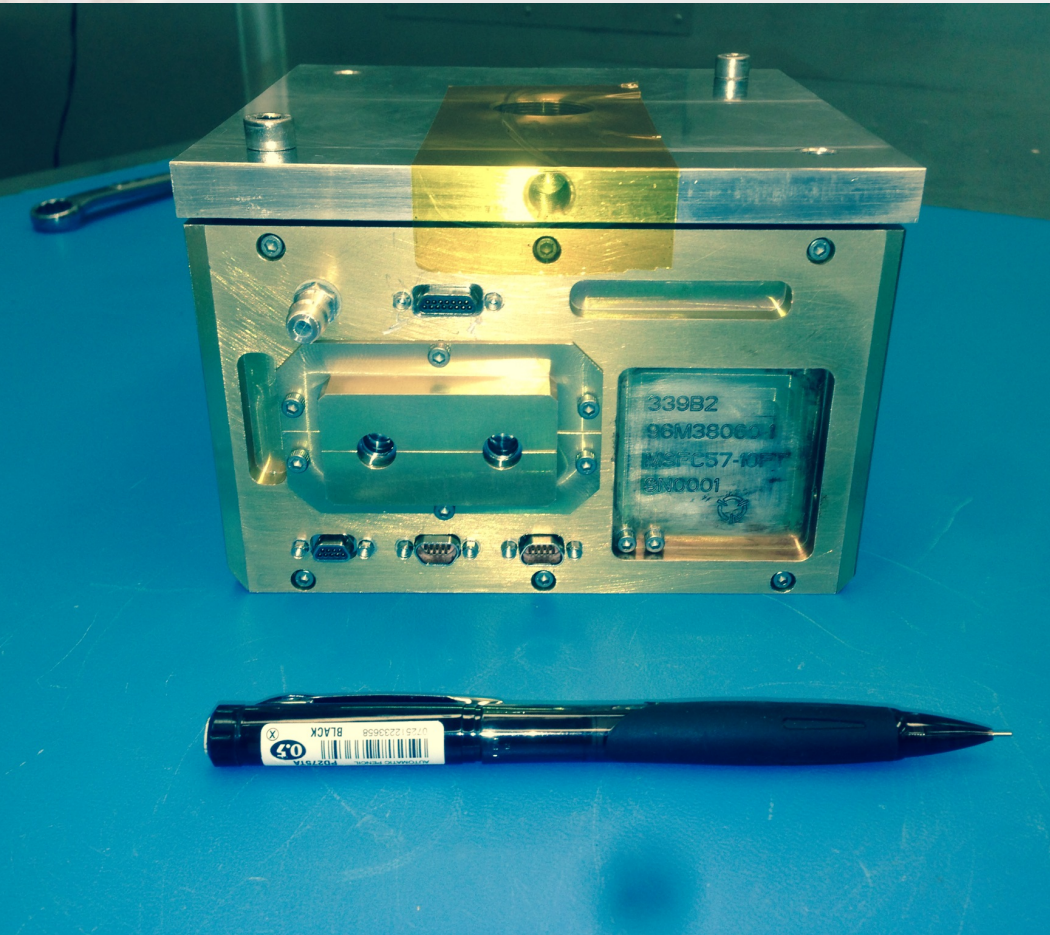
Low Noise Camera Development

- To achieve the 0.03% polarization accuracy required by CLASP, we required detectors with less than $25e^-$ total noise.
- We developed a 512x512 frame transfer camera at MSFC suitable for sub orbital instruments.
- 3 flight cameras were built (2 SP, 1 SJ)
- Each contain a back-thinned e2v CCD57-10 detector, coated with lumogen.
- Noise calculations from flight data demonstrate $<6e^-$ noise RMS noise in all cameras.

Low Noise Camera Development



Low Noise Camera Development

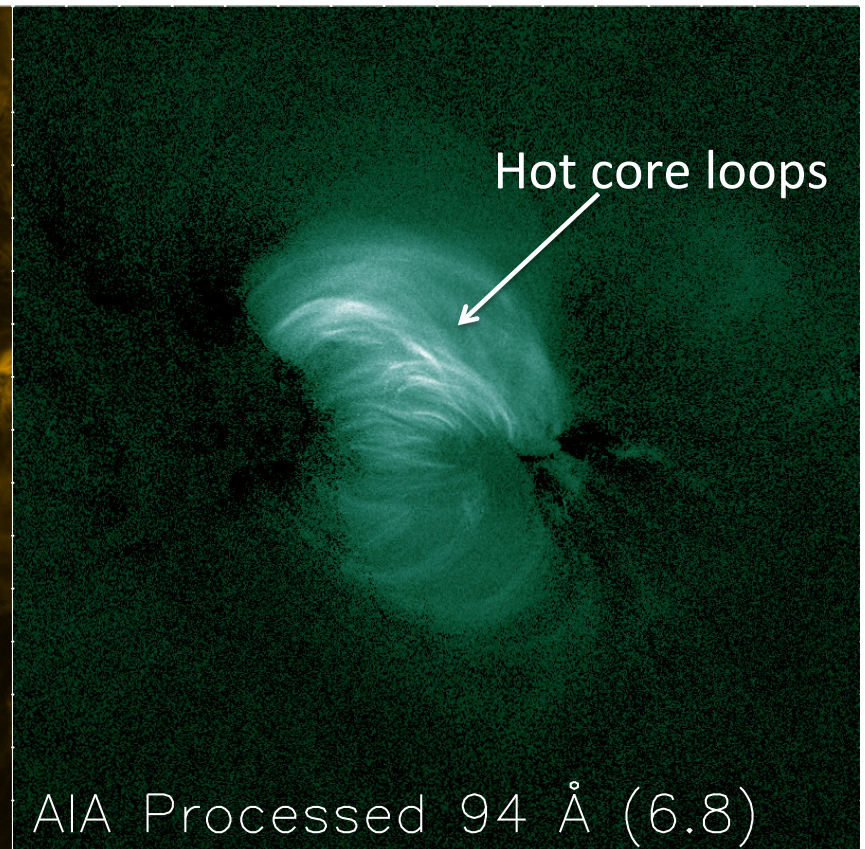
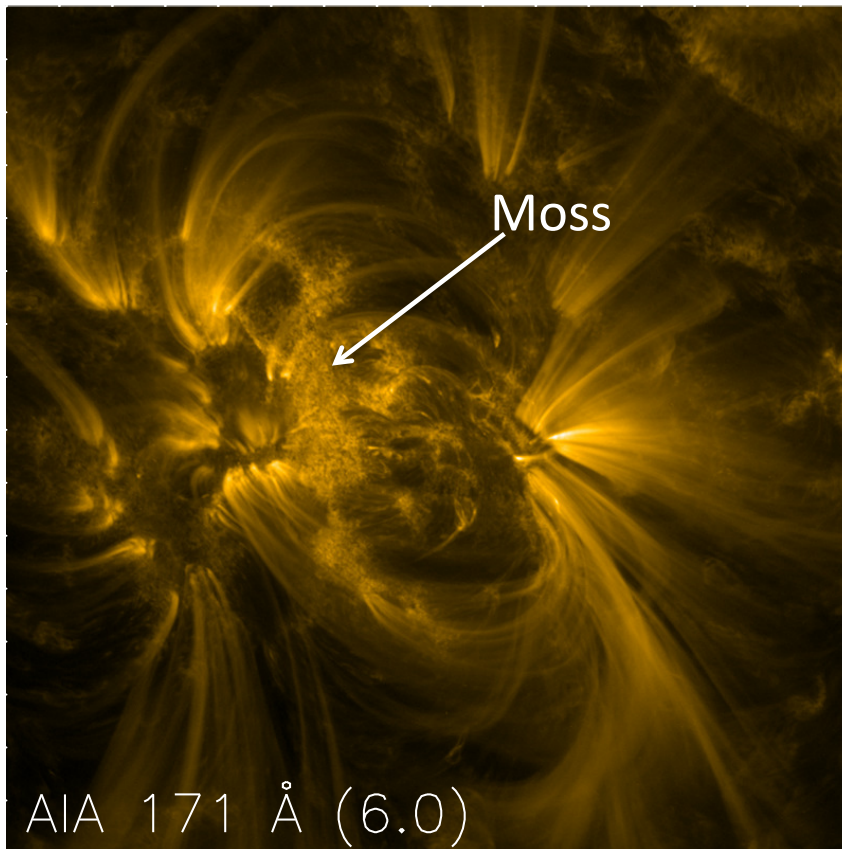


Low Noise Camera Development

- The design is currently being expanded for a 2kx2k CCD.
- Hi-C, MaGIXS, and ESIS (MSU sounding rocket) will make use of the new design.

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

The science goal of MaGIXS is to determine the frequency of heating in active region cores.



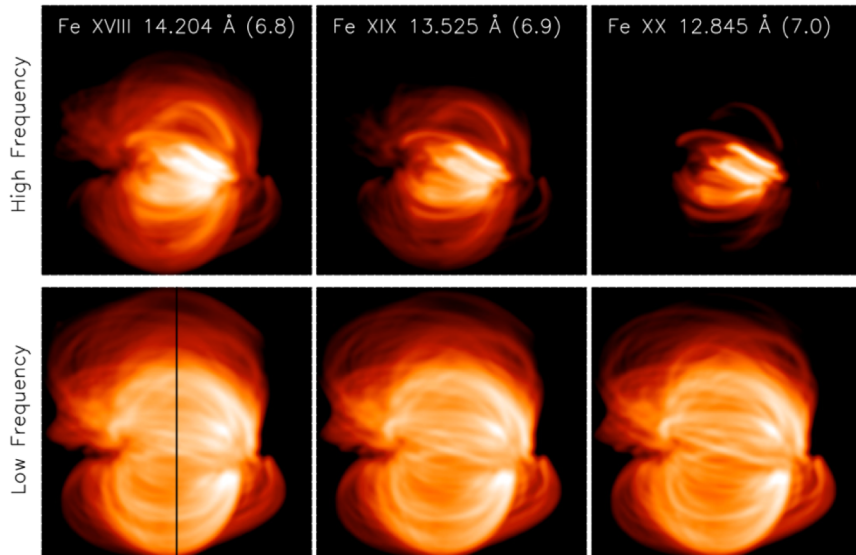
Is heating sporadic (nanoflares) or frequent (waves)?

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

MaGIXS will make four key observations to differentiate between sporadic and frequent heating.

- Relative amount of high temperature plasma
- Elemental abundances
- Temporal variability of high temperature plasma
- Likelihood of non-Maxwellian distributions

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Simulated active region core using 0-D EBTEL:

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

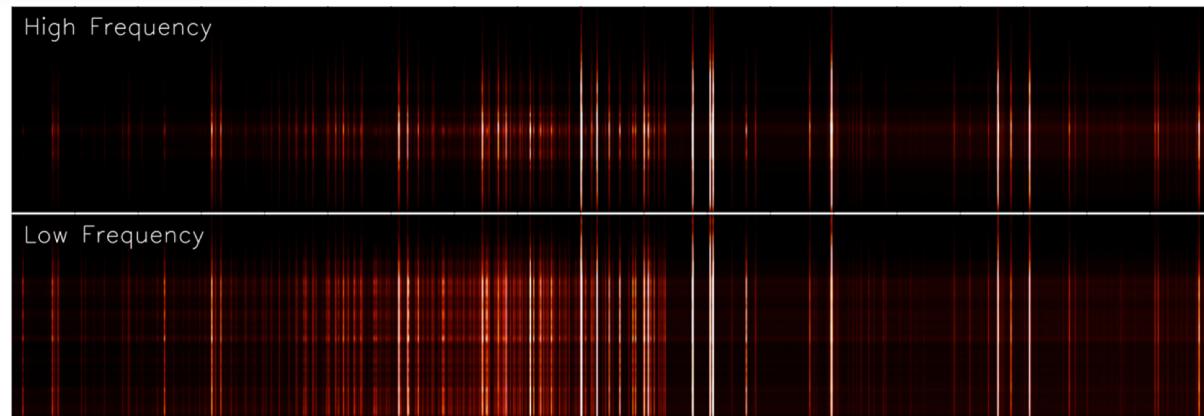
Expected emission quite different at higher temperature lines.

Simulated MaGIXS spectra

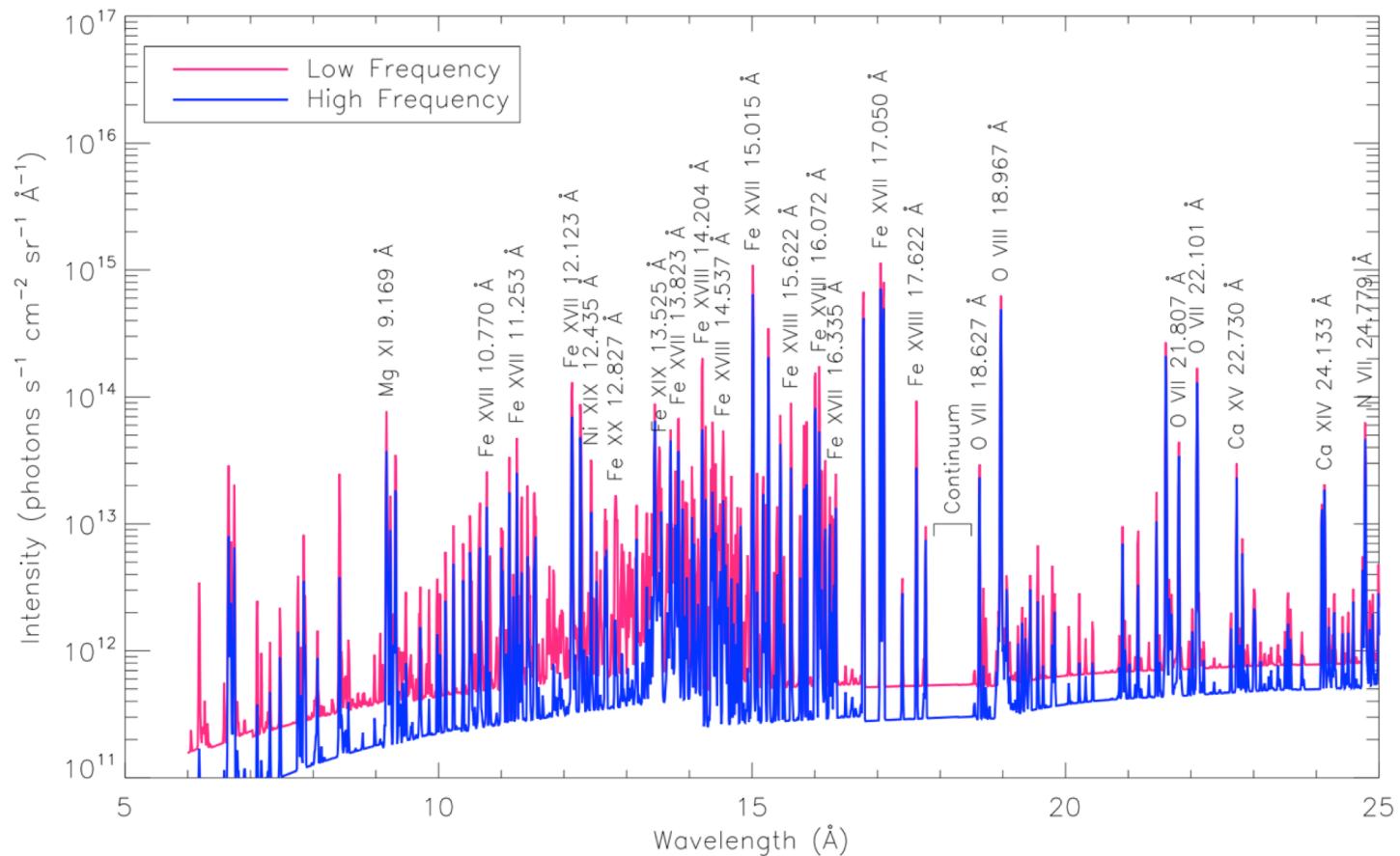
Biggest difference in Fe XX (12.845 Å).

Multiple high temperature spectra lines necessary for interpretation.

Fe XX 12.845 Å
Fe XIX 13.525 Å
Fe XVIII 14.204 Å
Fe XVII 15.015 Å
O VIII 18.696 Å
O VII 21.601 Å



Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



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

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

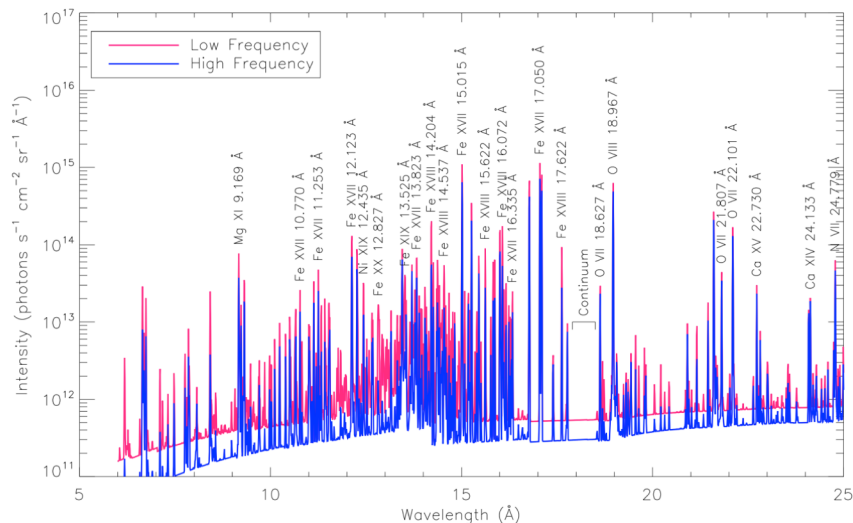
Trends in variability indicate that the FIP bias is proportional to the plasma's time of confinement.

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

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

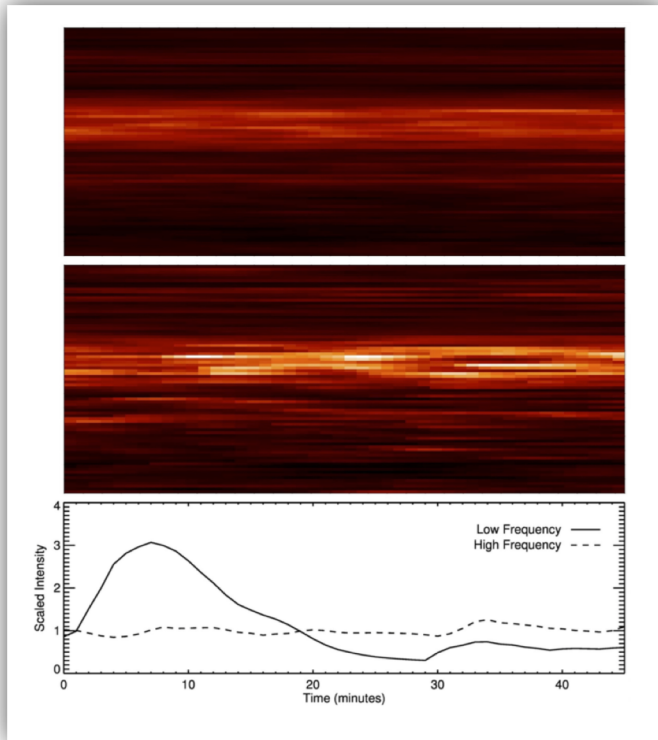
Spectral Line	Log Temperature
Mg XII 8.42 Å	6.9
Mg XI 9.16 Å	6.4
Ne X 12.13 Å	6.6
Ne IX 13.45 Å	6.2
Fe XVIII 14.21 Å	6.8
Fe XVII 15.01 Å	6.6
O VIII 18.97 Å	6.4
O VII 21.60 Å	6.3

Relative abundances largely independent of plasma temperature.



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

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



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).

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

Science Objectives

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.

Science Requirements

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)

Instrument Requirements

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

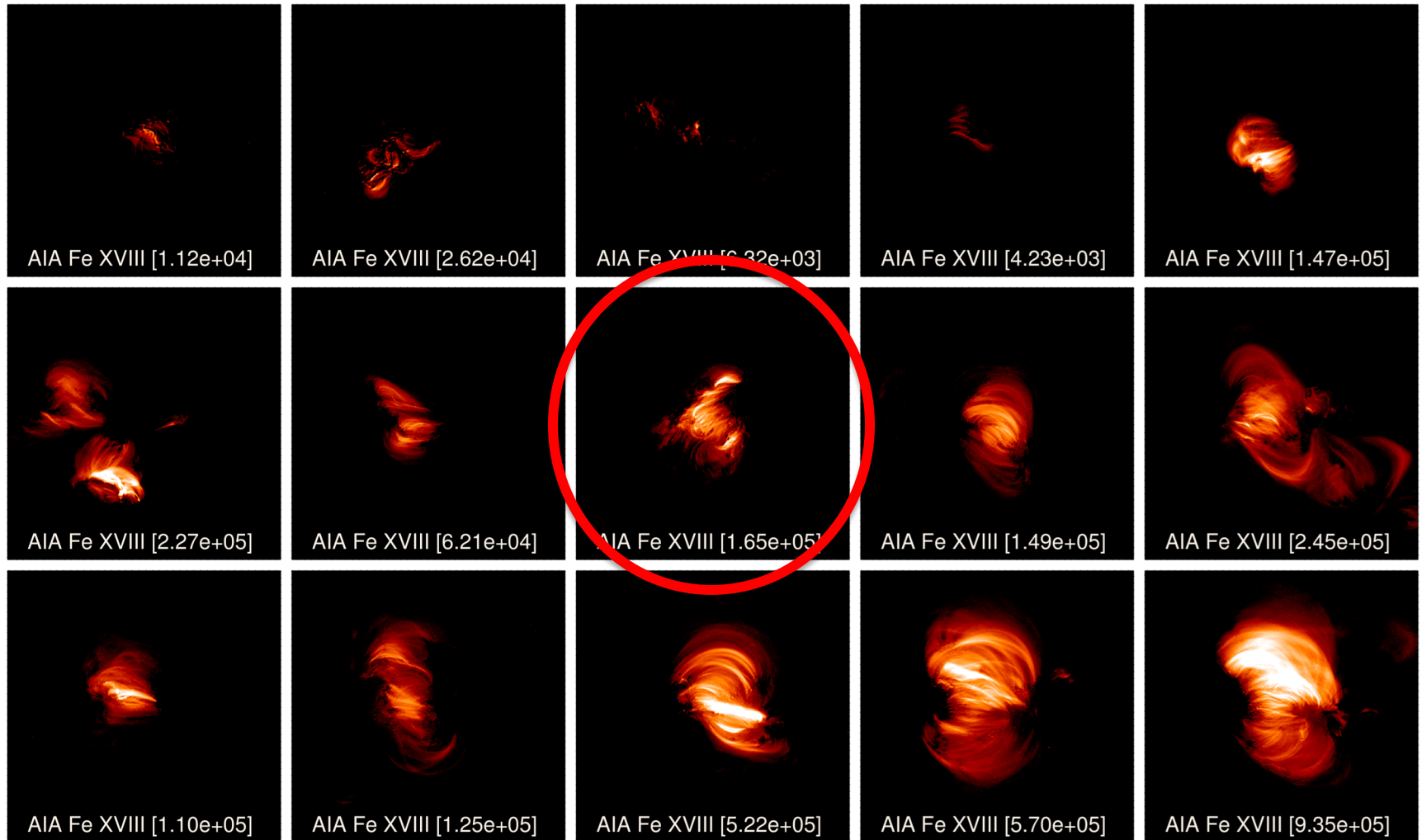
Slit jaw images to allow for co-alignment with other observatories

Supporting observation in space and ground based observatories

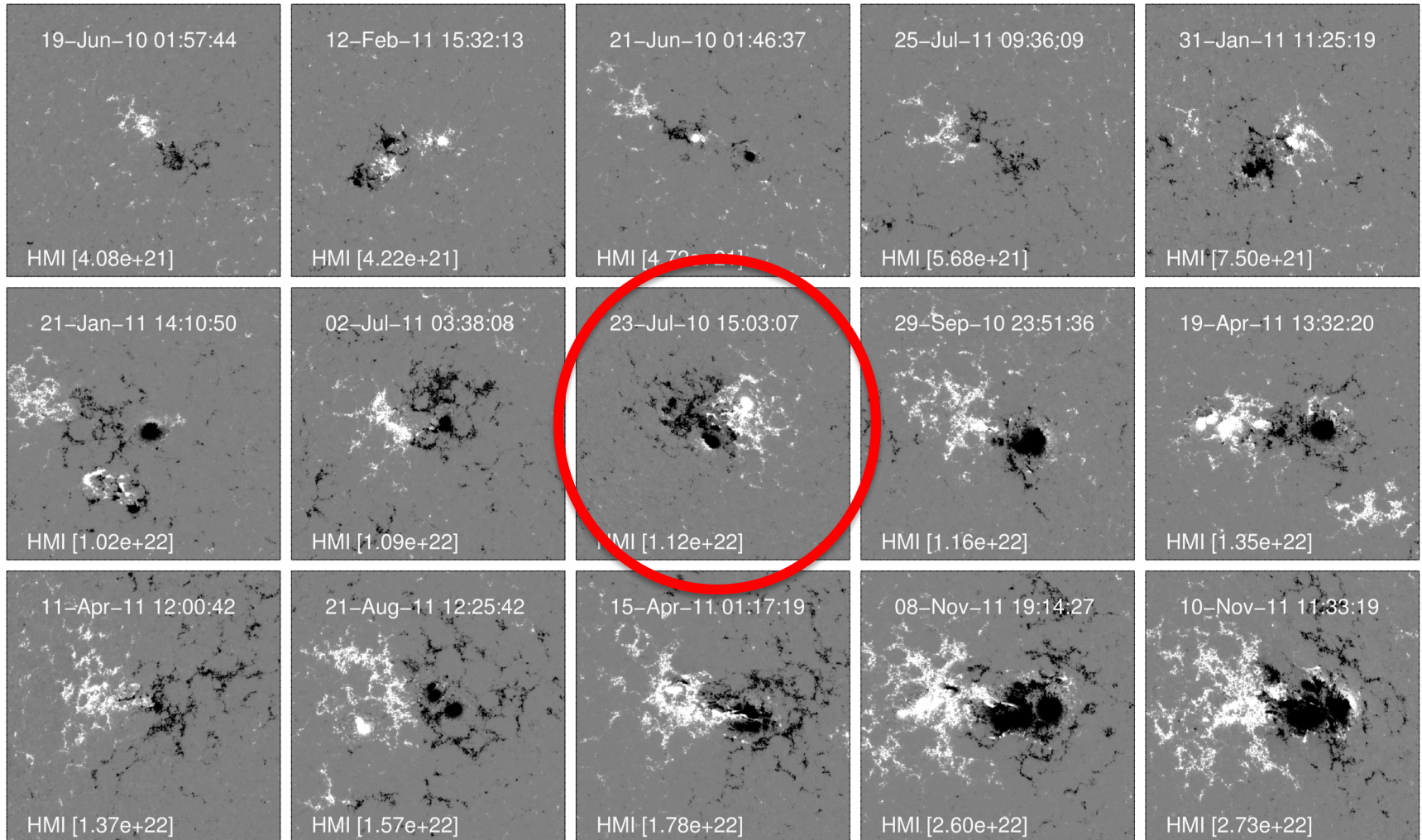
Camera read out < 5s.



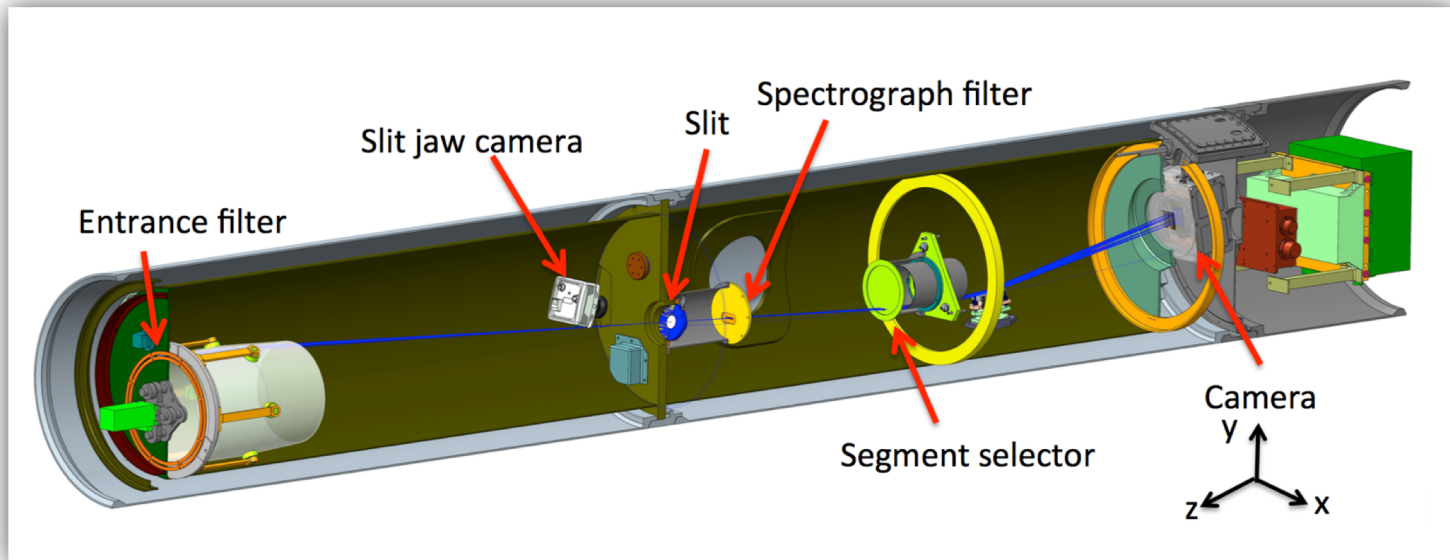
Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



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

Slit jaw imaging system for pointing and co-alignment

Detector : Low noise, 2kx1k frame transfer

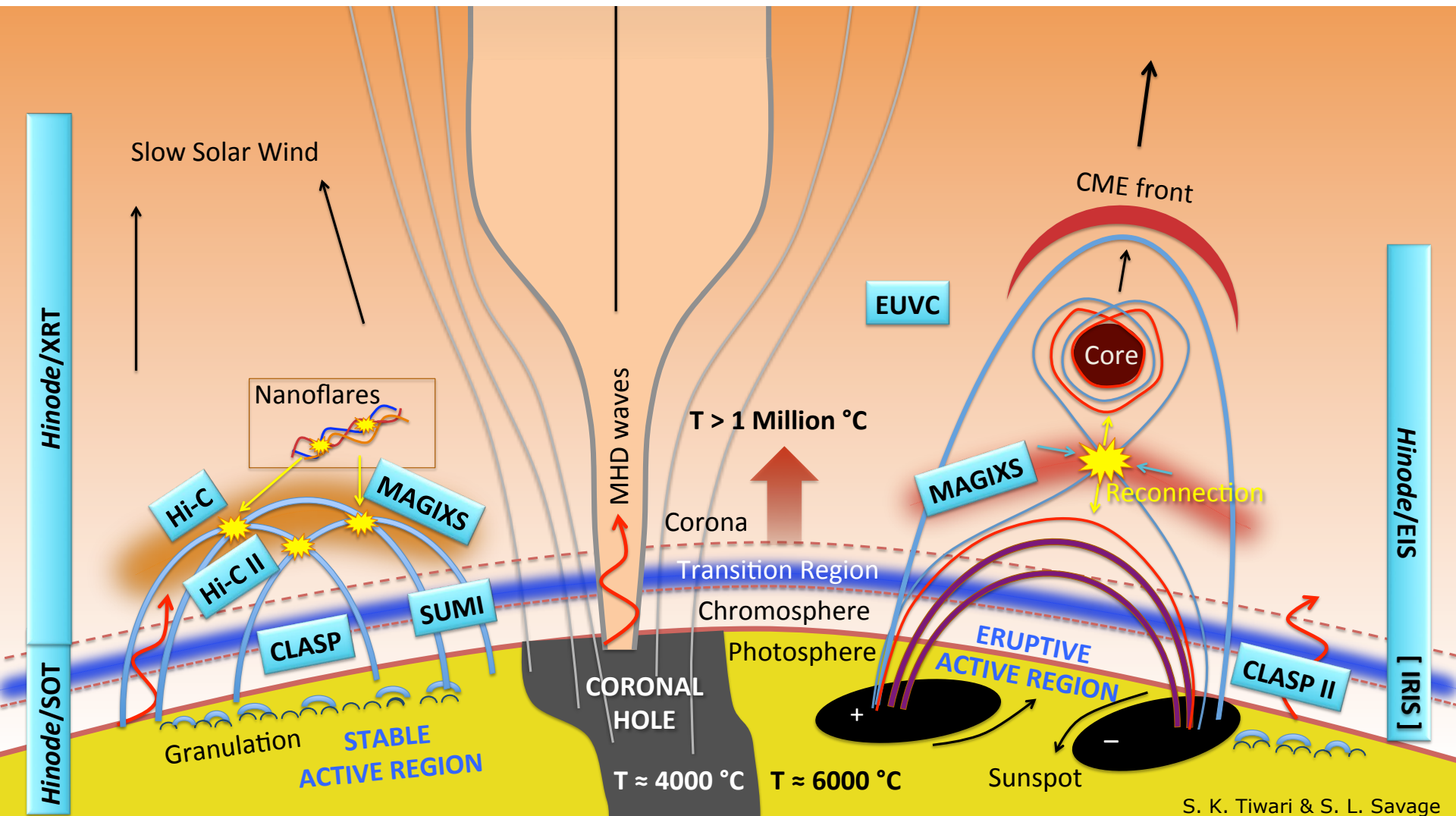
Spectrograph: Two matched parabolic mirrors + Grating

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

Grating: Blazed Planar Varied Line Space

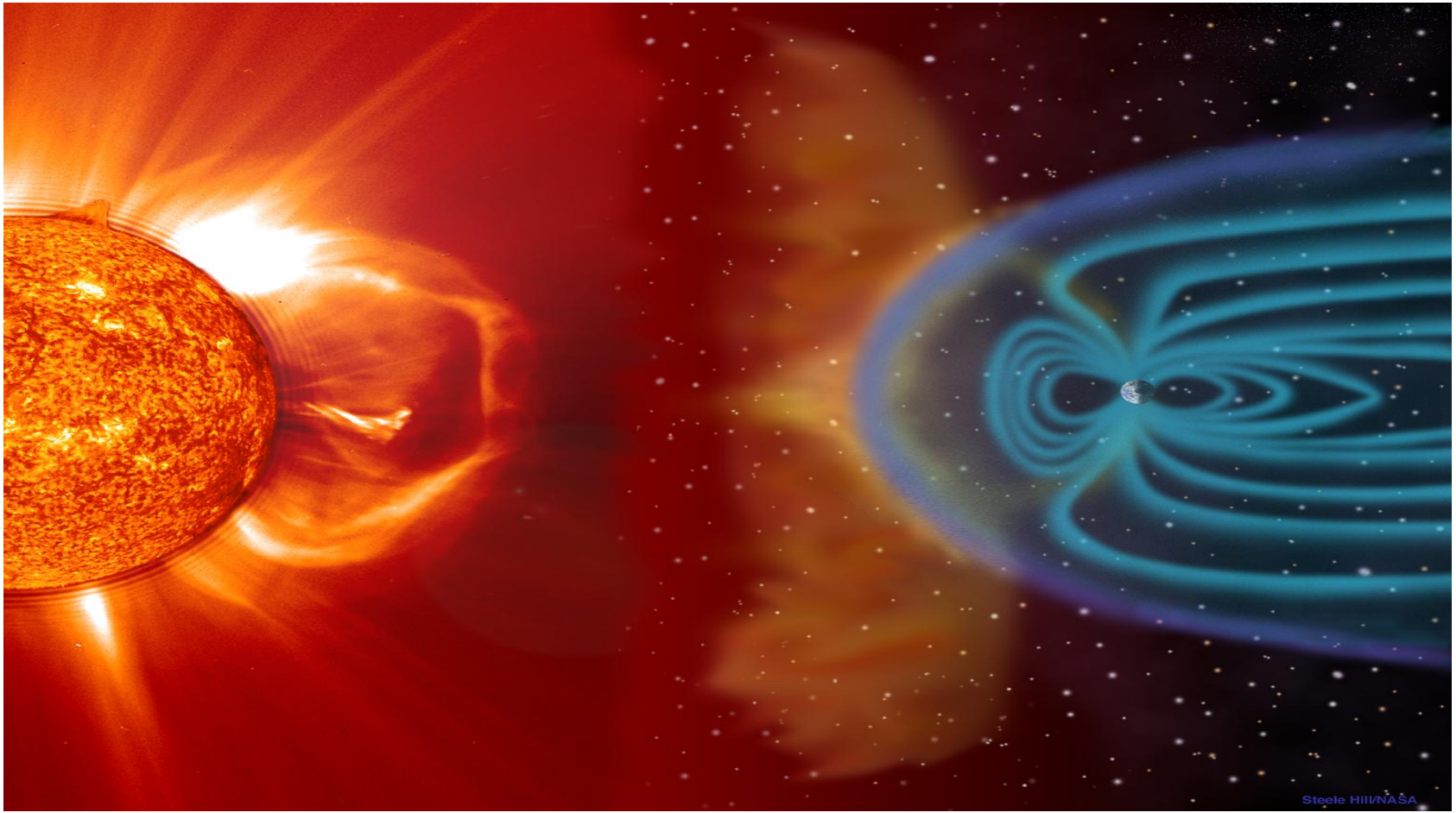
MaGIXS will be launched in summer 2018 or 2019.

Does this sound like fun?

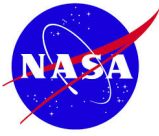


Heliophysics Research Opportunity for Undergraduates

**UAHuntsville/Center for Space Plasma and Aeronomic Research (CSPAR)
& NASA/Marshall Space Flight Center**



Heliophysics Research Opportunity for Undergraduates



10 Week program in Huntsville, Alabama.

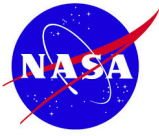
US Citizens

**Generous stipend, travel allowance,
housing, meal card, transportation &
support to American Geophysical Union
Annual Fall Meeting are provided.**

Applicant must be a US citizen or permanent resident,
and a full-time undergraduate student with 2.5 GPA or
better.

**Rising sophomores, women, and minorities are
encouraged to apply.**

Heliophysics Research Opportunity for Undergraduates



FOR OTHER RESEARCH OPPORTUNITIES:

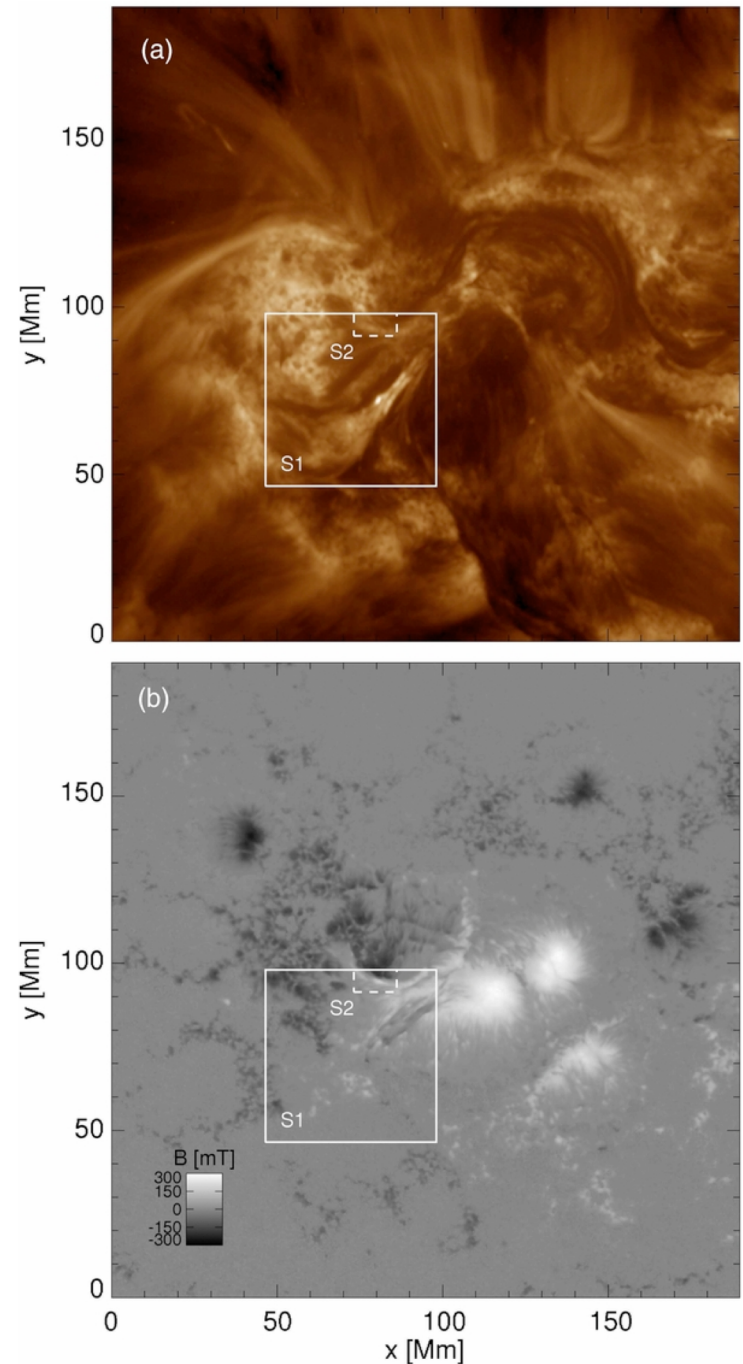
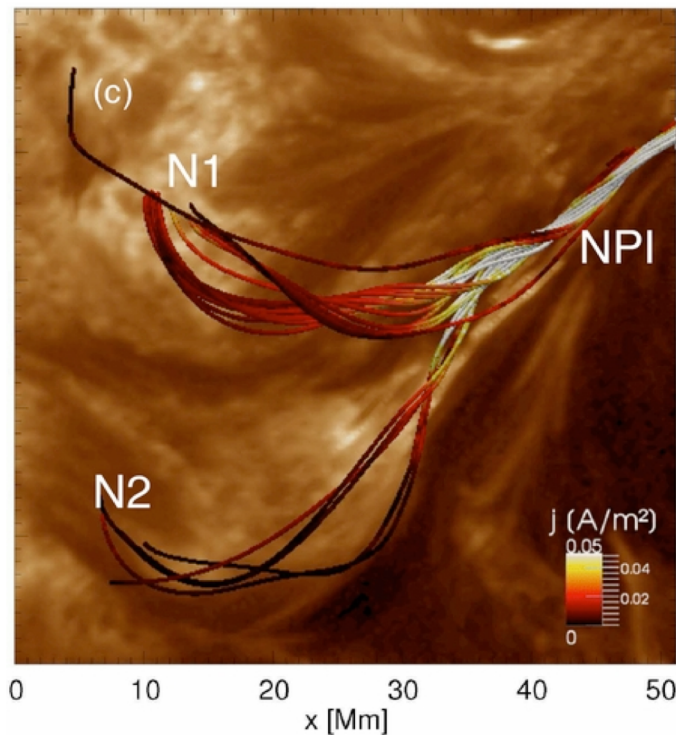
[HTTPS://WWW.NSF.GOV/CRSSPRGM/REU/REU_SEARCH.JSP](https://www.nsf.gov/crssprgm/reu/reu_search.jsp)

**NOTE MOST APPLICATIONS ARE DUE MID-JANUARY – LATE
FEBRUARY, START THINKING ABOUT NEXT SUMMER NOW!**

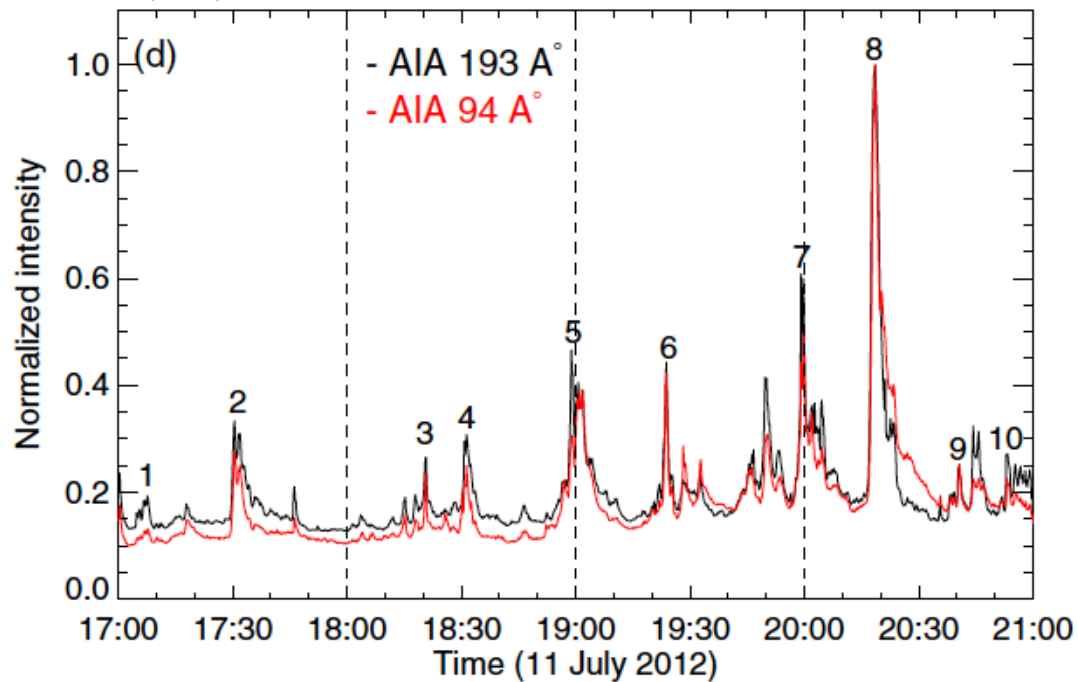
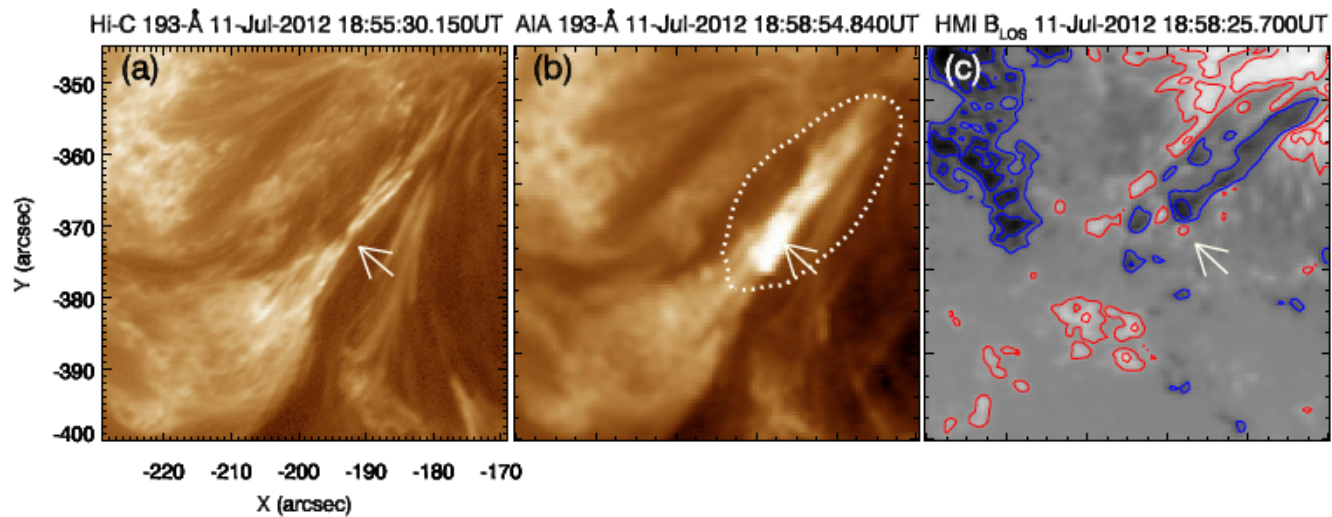
Modeling the braided field

NLFFF extrapolation confirms the braided structure, and free magnetic energy estimates in the given volume

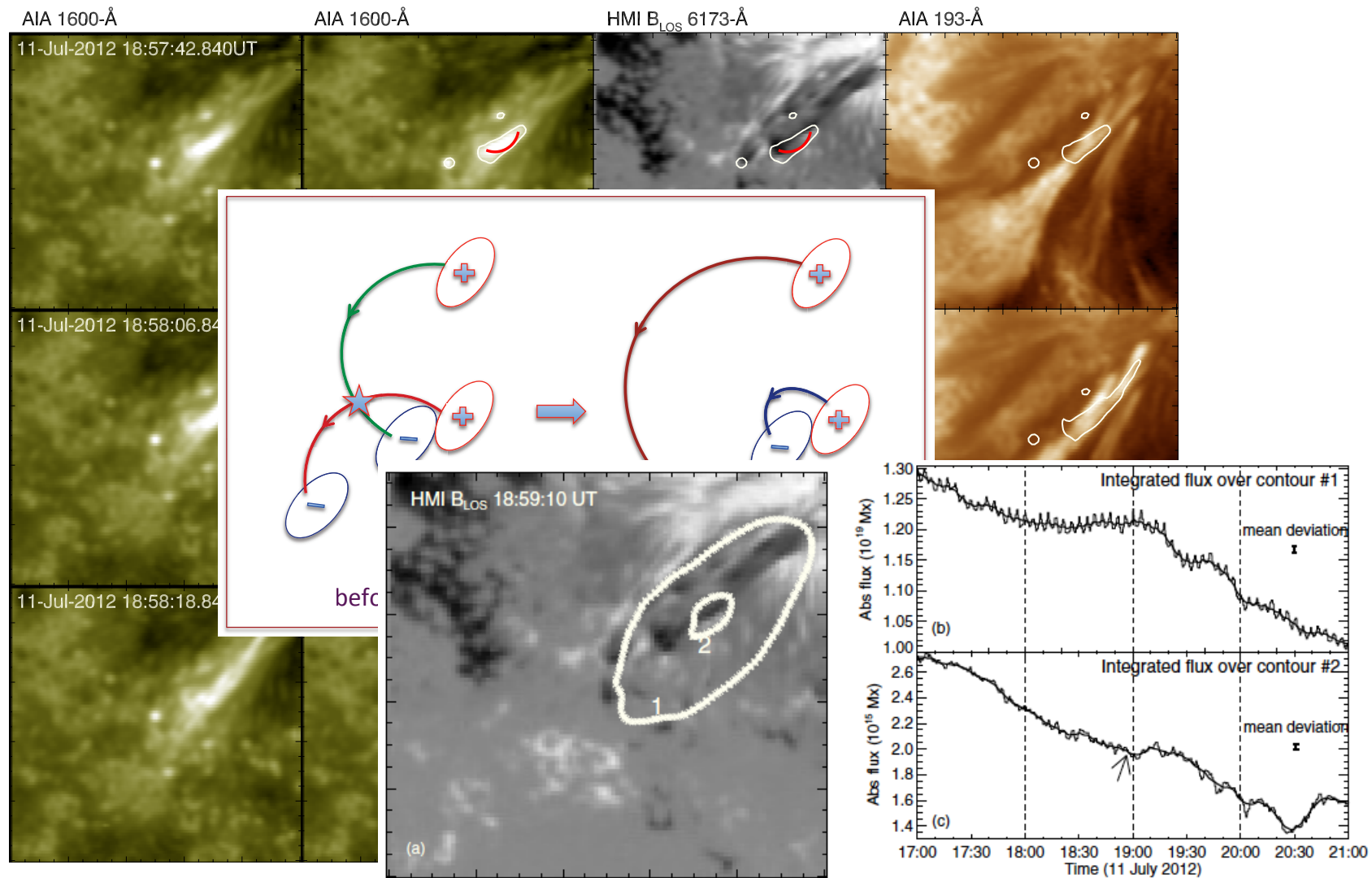
Thalmann, Tiwari & Wiegmann, 2014, ApJ



External triggering of subflares...

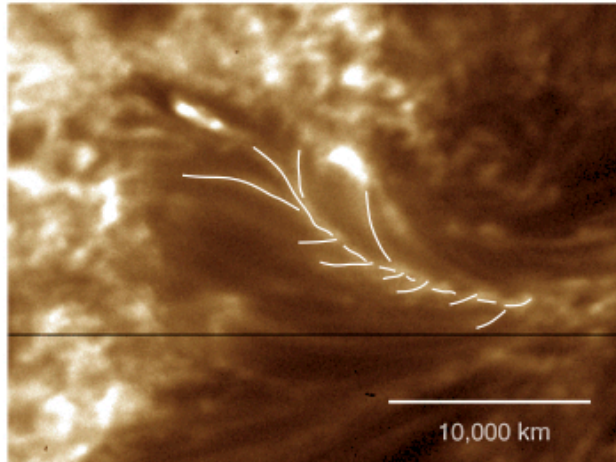


External triggering of subflares...

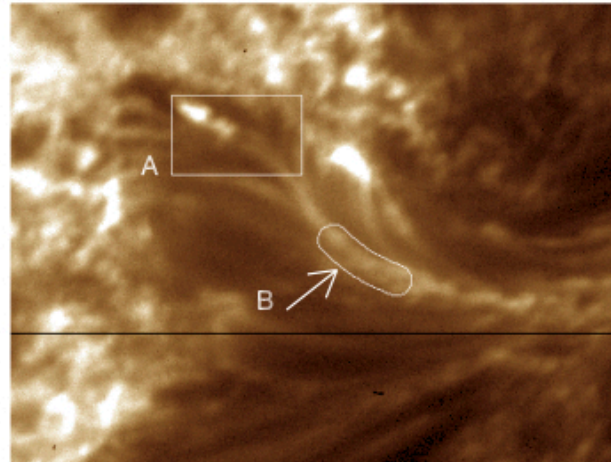


High-resolution Coronal Imager (Hi-C)

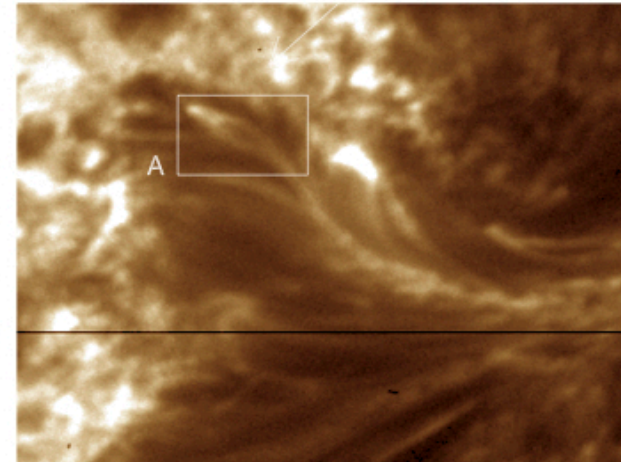
a Hi-C 193-Å: 18:53:28



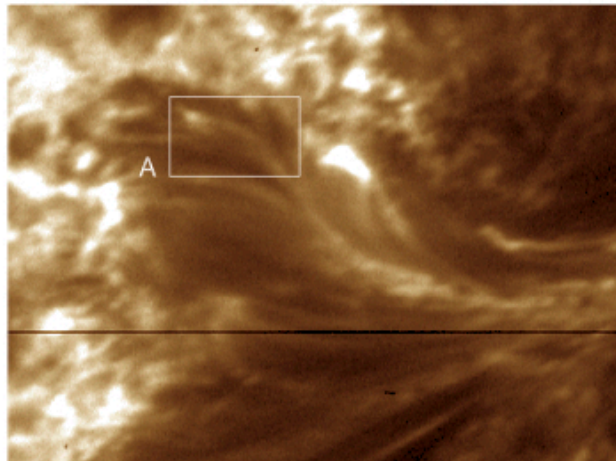
b Hi-C 193-Å: 18:53:45



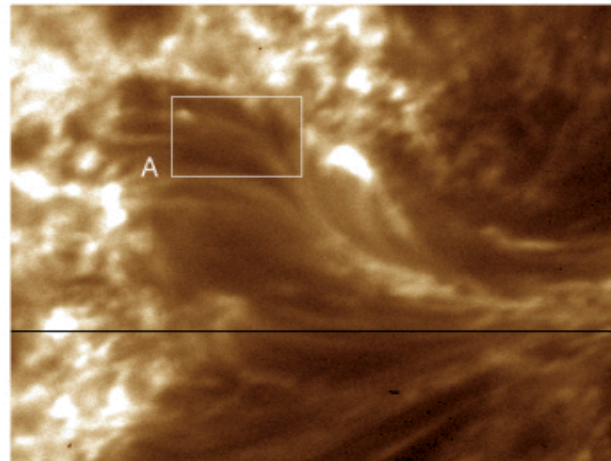
c Hi-C 193-Å: 18:54:13



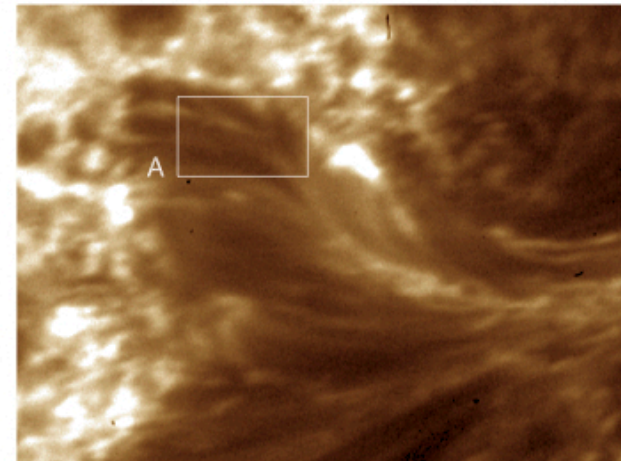
d Hi-C 193-Å: 18:54:41



e Hi-C 193-Å: 18:55:08



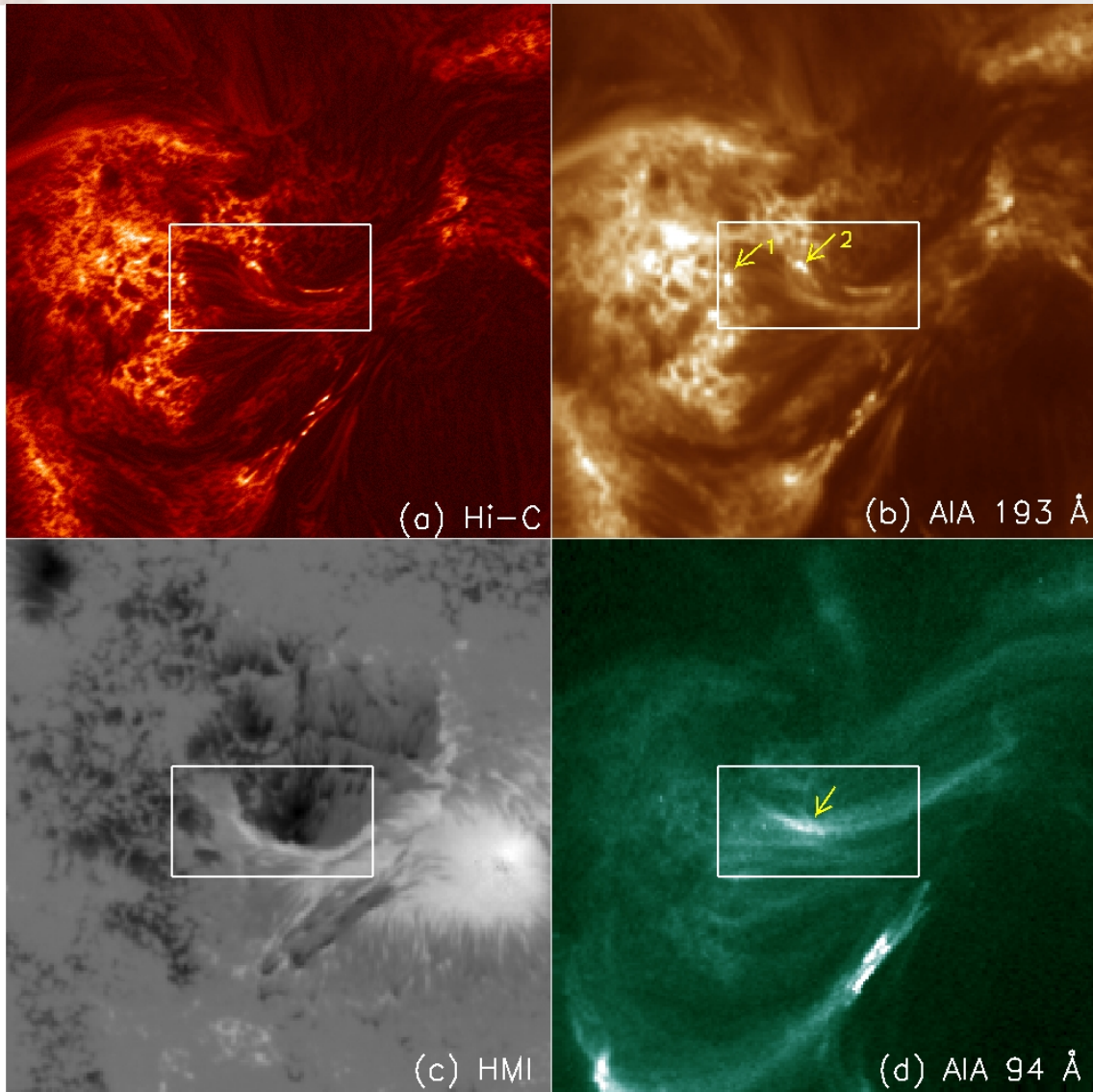
f Hi-C 193-Å: 18:55:36



Multiple strands join into this structure. It appears to unwind during Hi-C observations.

Cirtain et al, 2013, Nature

High-resolution Coronal Imager (Hi-C)



Brightenings in/near braided structure are associated with high temperature evolving loops.



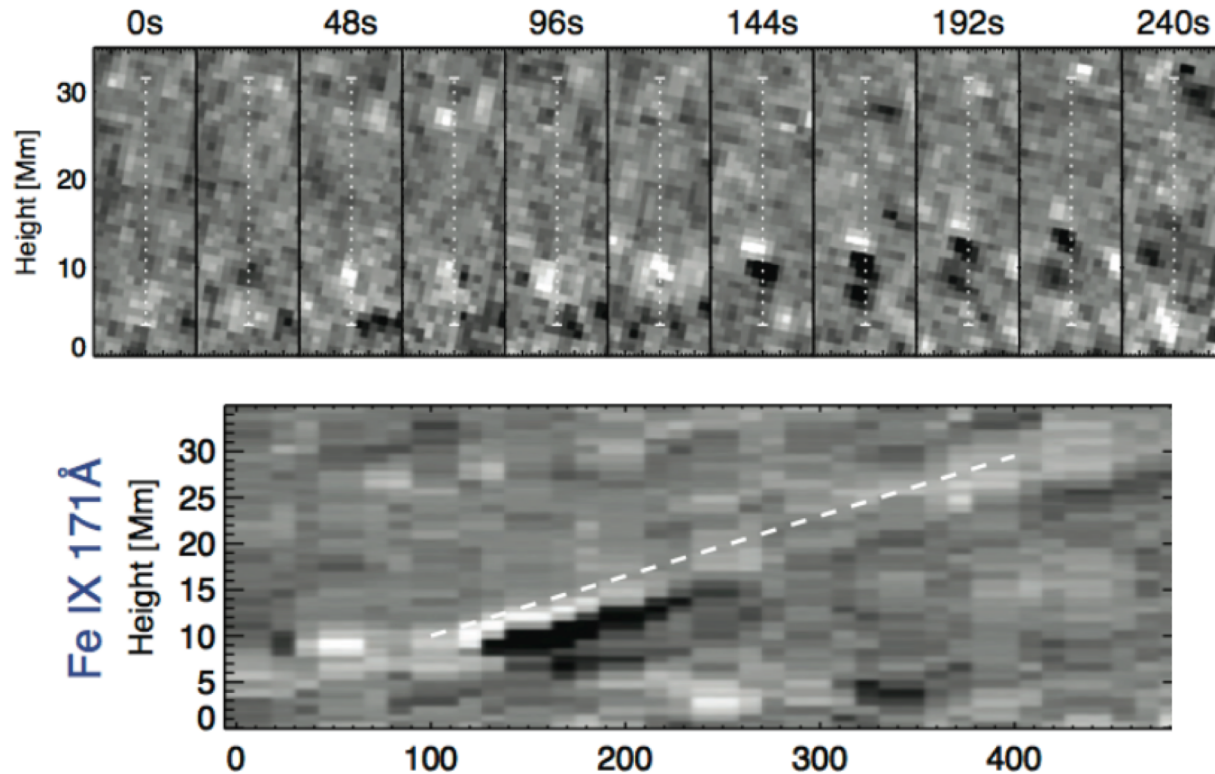
Hi-C II – Exploring the Chromospheric-Coronal Connection

IRIS has shown many chromospheric and TR structures do not reach coronal heights.

But there must be a “classic” TR to coronal structures. And some dynamic chromospheric phenomenon may feed the corona.

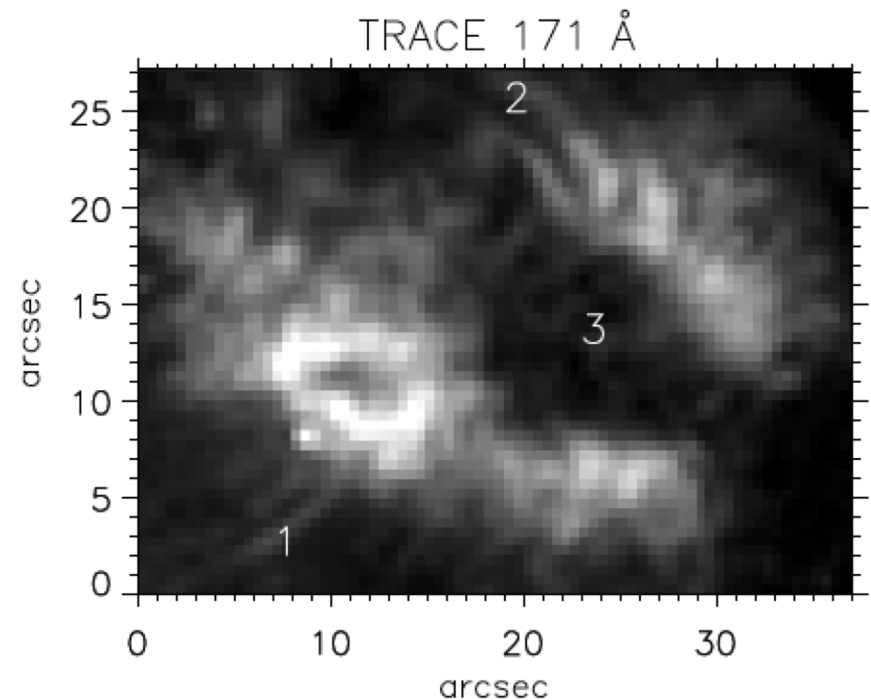
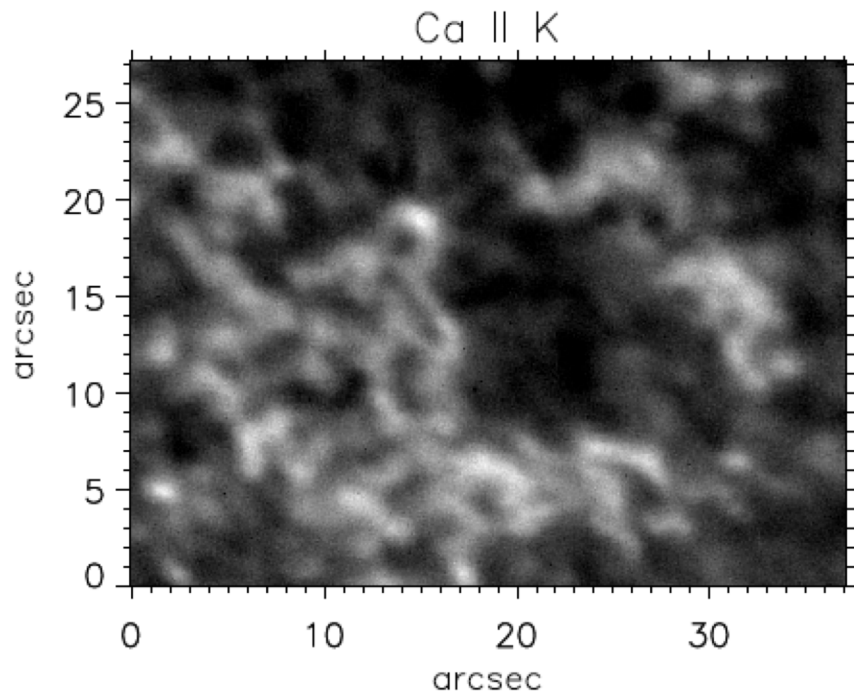
Hi-C II will look for the chromospheric-coronal connection in the two most obvious places, Type II spicules and hot core loops.

Hi-C II – Exploring the Chromospheric-Coronal Connection



Do Type II spicules result in coronal plasma?

Hi-C II – Exploring the Chromospheric-Coronal Connection



Can mass elements be traced through various TR temperatures?

De Pontieu et al, 2003

Hi-C 2

- Telescope design capable of $\sim 0.25''$ resolution at the solar corona,
- Multi-layer coatings for EUV observations in the 171Å passband,
- High sensitivity to EUV flux sufficient for a 5 s cadence,
- Pointing stability necessary to achieve resolution goal,
- Image readout and data storage capable of maintaining high-cadence observations, and
- Camera with low readout noise.
 - Camera for Flight #2 will feature an e2V 2Kx2K CCD with 12μm pixels
 - Using very similar board layout and electronics design as CLASP, HiC camera read noise expected not to exceed $8 \text{ e}^-/\text{pixel}$

