Science Missions with CubeSats Sure are Fun!

The Story of the MinXSS CubeSats

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& the MinXSS CubeSat Team

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MinXSS web site

http://lasp.colorado.edu/home/minxss/

Outline

Miniature X-ray Solar Spectrometer (MinXSS)

- Introduction
  - MinXSS mission highlights
- MinXSS CubeSat Technology
  - Enabling Technology and Advances
- MinXSS Science
  - Solar forcing in Earth's upper atmosphere
  - Solar flare energetics
  - Solar reference spectra and space weather
- Future Plans
  - MinXSS-3 (new DAXSS instrument), CUBIXSS, SunCET

CubeSats as Disruptive Technology

- NRC 2016 CubeSat Report, *Achieving Science with CubeSats: Thinking Inside the Box*, discusses how CubeSats are Disruptive Technology

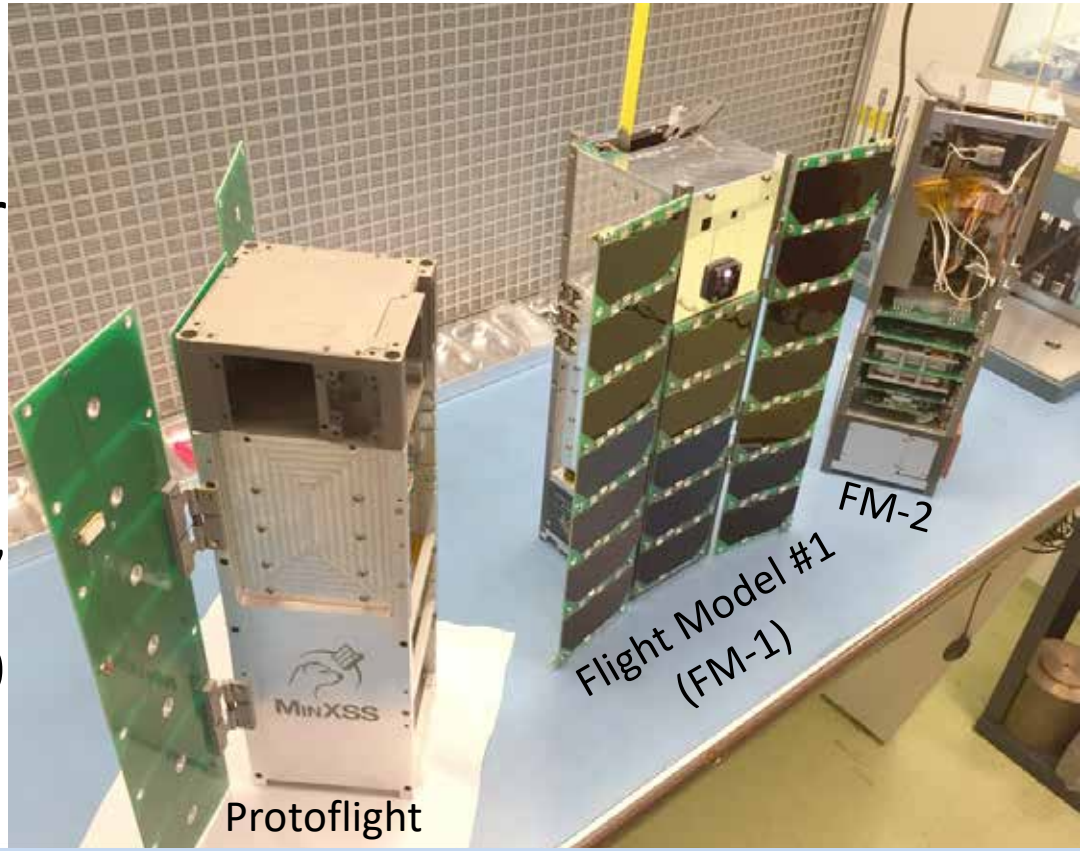
Disruptive Technology Characteristic	Application for CubeSats (vs Small Explorer standard)	Applied for Student Projects (some ingredients for Fun)
Poorer performance than current standard	Smaller size, less power, lower data rates	Encourages innovation to reduce size, power, data
Significantly cheaper than the status quo	Subsystem costs of few $K, low-cost rideshare launches	Affordable for development of a system in a year
Target underserved	Students, even high school	Source of many creative ideas
Performance improves rapidly and at low cost	100s are launched per year now, some at < $1M	Focus on payload as S/C subsystems can be bought
Introduced by a non-mainstream player	Cal Poly & Stanford defined CubeSat, new industry	Seed for new businesses after graduation
Advanced by an enabling technology	Many different satellite technologies available now	Excitement to develop new technology for CubeSats
Follows new business model	Small teams, high-risk	Class size of 10 is adequate

MinXSS Mission Background

- A University of Colorado (CU) graduate student project initiated a new CubeSat mission concept in 2012. It initially had focus on studying the far ultraviolet (FUV) emissions of the thermosphere (aurora).
- The data volume for FUV imaging was too large for UHF communication, so the focus changed in 2013 to studying the solar soft X-ray (SXR) emissions, which are key energy input for the ionosphere.
- This mission called the Miniature X-ray Solar Spectrometer (MinXSS) was proposed to NASA and selected in 2014.

MinXSS

- 3U CubeSat to study the solar soft X-ray (SXR) spectra
- Developed as CU student project and funded by NASA
- MinXSS-1 mission: 2016-2017
- MinXSS-2 mission: 2018-2019
- MinXSS-3: awaiting launch…



MinXSS Co-Is & PhD Students


Tom Woods


Andrew Jones


Rick Kohnert


Scott Palo


Amir Caspi

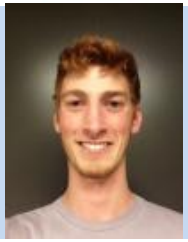

Stan Solomon


Phil Chamberlin


Harry Warren


James Mason PhD 4/16


Chris Moore PhD 12/17


Bennet Schwab


Robert Sewell

Students

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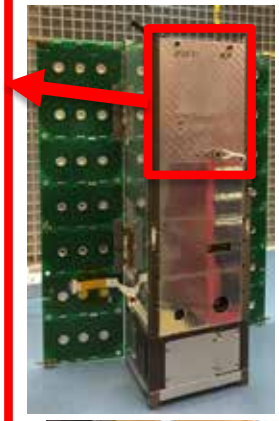
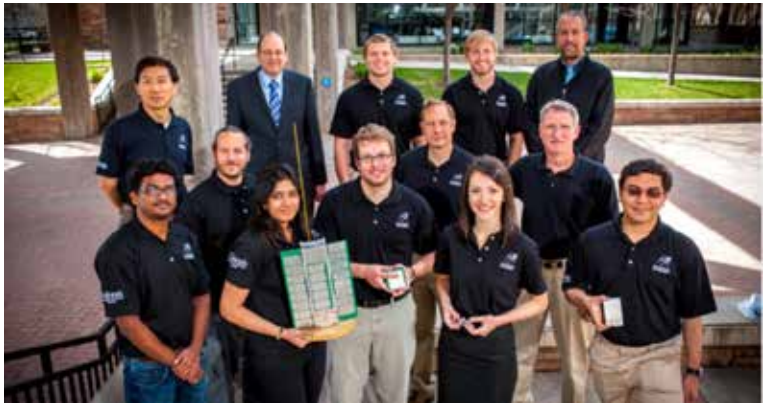
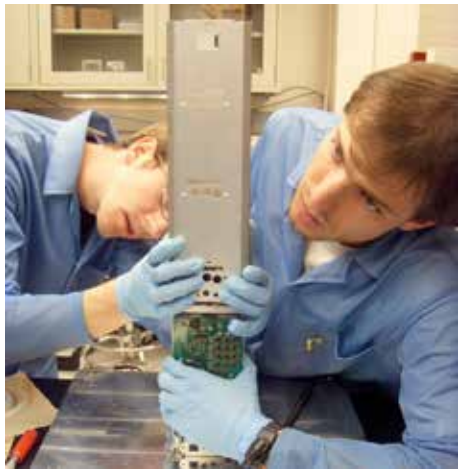




MinXSS-1 Mission Highlights

- MinXSS-1 was launched in December 2015 and deployed from the ISS in May 2016. It re-entered in May 2017.
- MinXSS is first CubeSat science mission for the NASA Science Directorate.
  - Many technology demonstration CubeSat missions had been flown by NASA.
  - NSF started science CubeSat missions in 2008. One of them is LASP's Colorado Student Space Weather Experiment (CSSWE, PI: Xinlin Li) that was launched in 2012 and provided strong heritage for MinXSS.

NSF's CCSWE CubeSat in 2011



Heritage from CSSWE
Student Project Structure
CubeSat System Engineering
CU/LASP UHF Ground Station
Spacecraft Subsystems
(EPS, CDH, COMM)

MinXSS CubeSat Prototype in 2014

MinXSS-1 Mission Highlights

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- MinXSS is first CubeSat Science mission for NASA Science Directorate.
  - ~30 technology demonstration CubeSat missions had been flown by NASA.
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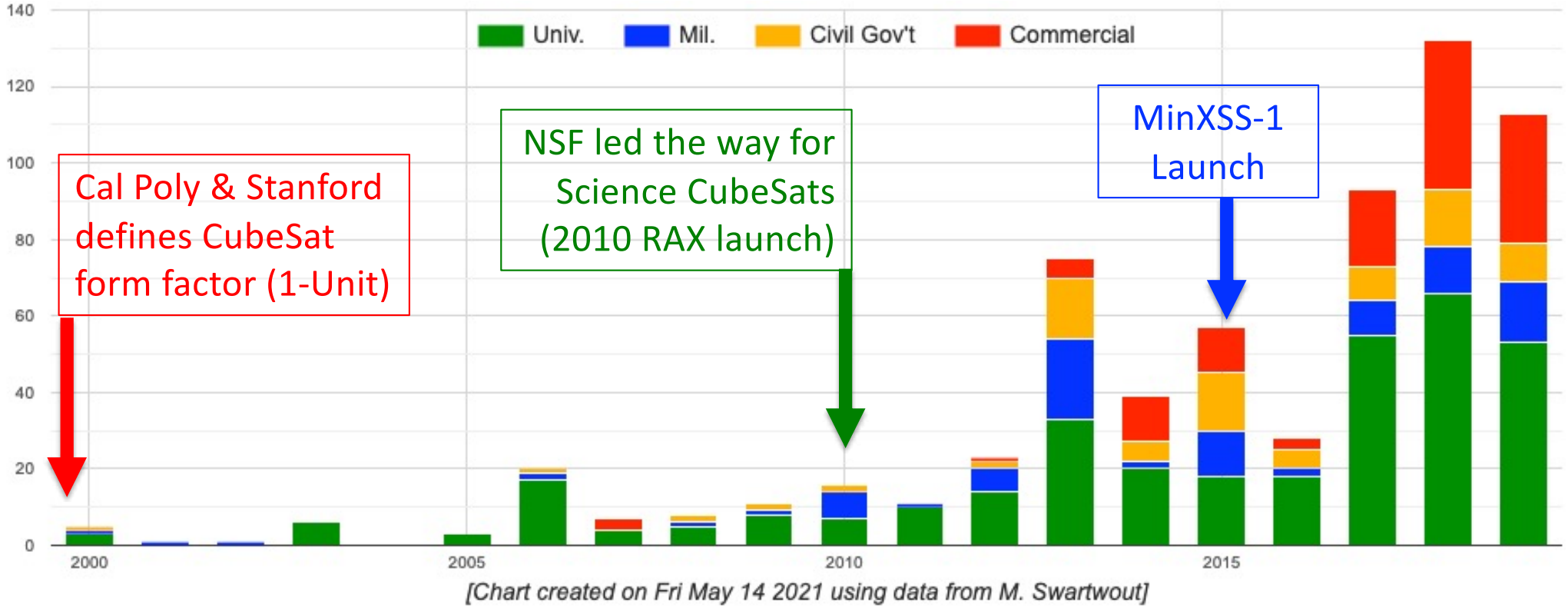

MinXSS-1 Launch & Deployment

- Launch: Dec 6, 2015 on Atlas-V as CRS OA-4
- ISS Dock: Cygnus docked with ISS on Dec 9
- ISS Deployment: May 16, 2016

NASA OA-4 Orbital ATK COMMERCIAL RESUPPLY SERVICES

MinXSS CubeSat

MinXSS-1 Launch & Deployment

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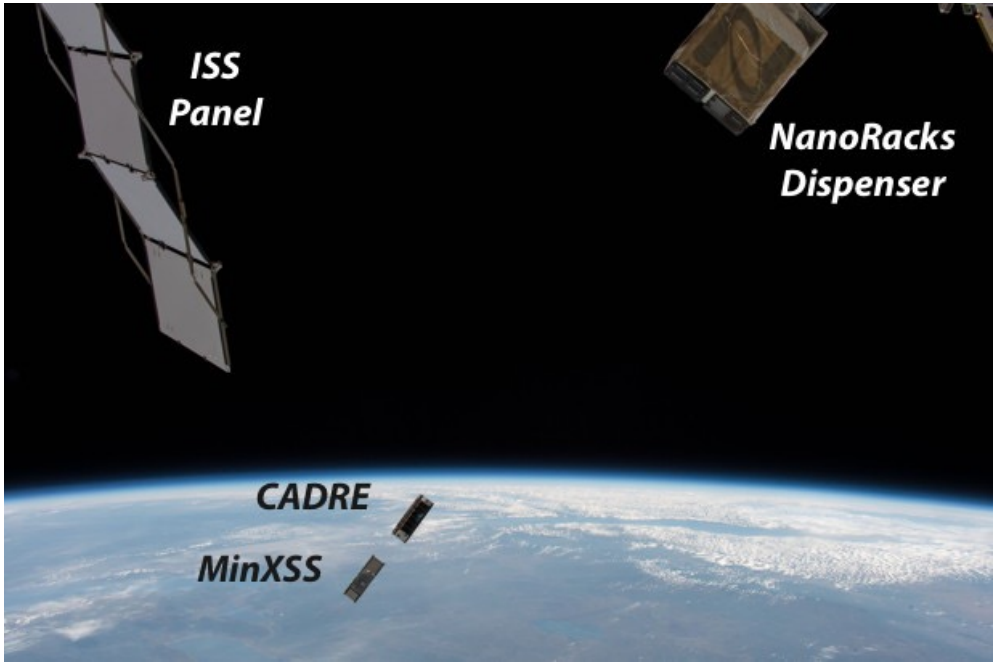
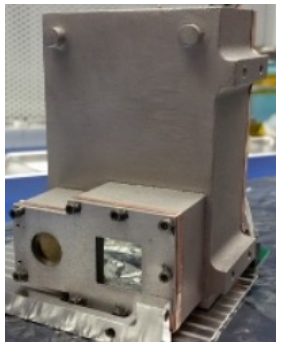


MinXSS Technology Highlights

- MinXSS-1 technology demonstration includes:
- Blue Canyon Technologies (BCT) Attitude Determination and Control System (ADCS)
  - Innovative ADCS in 0.5U size with star tracker and capability for 10-arcsec 3-axis control
  - MinXSS-1 flies first BCT XACT unit
- Amptek X123 X-ray Spectrometer
  - Advanced X-ray detector for the solar observations
- 3-D Printed (sintered) Metal Parts
  - Solar panel deployment hinges made with SS
  - Solar Position Sensor (SPS) housing made with Al

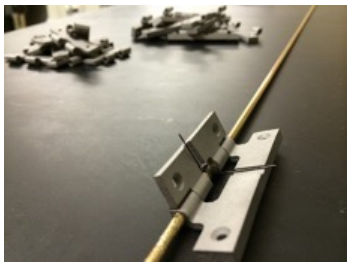
BCT XACT (0.5U)

Amptek X123 (0.2U)



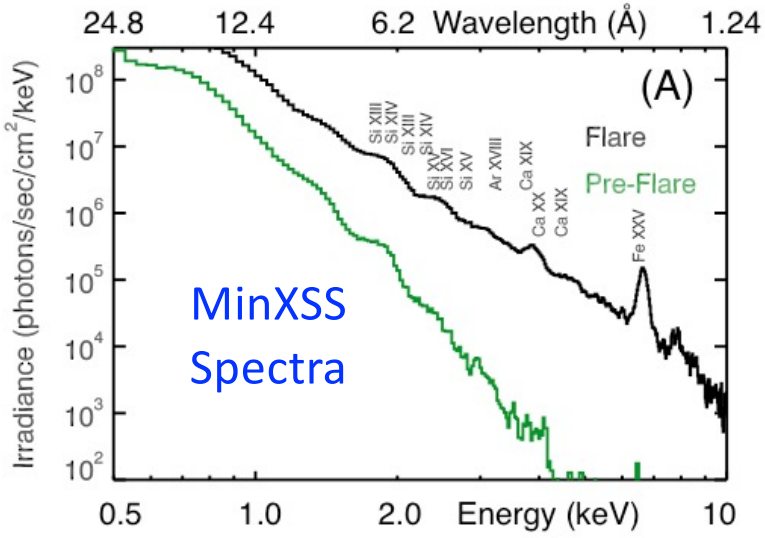
CU/LASP SPS Housing

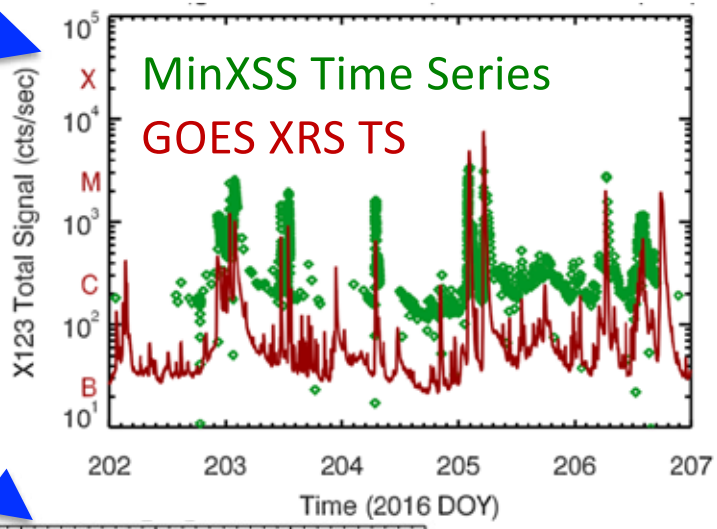
CU/LASP Deployment Hinge

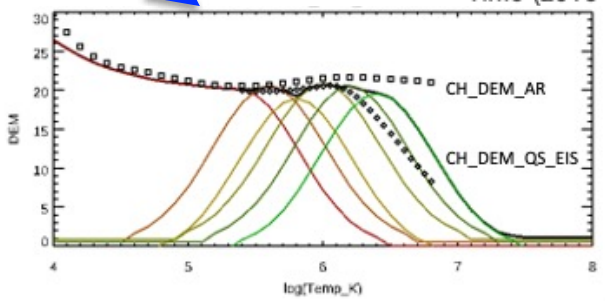


MinXSS Science Highlights

- MinXSS Mission Goals:
  - MinXSS-1: Understand the highly energetic solar flares in the soft X-ray (SXR) range and their impact on Earth's ionosphere and thermosphere
  - MinXSS-2 & -3: Understand the heating of active regions in the SXR range and solar forcing in ITM
- MinXSS has obtained solar SXR spectra for over 100 C-class and 8 M-class flares
- Analyses of those flare spectra reveal:
  - large enhancements of corona temperature
  - changes in the coronal elemental abundance
- MinXSS has provided new reference spectra for use in TIMED, SORCE, and SDO processing
- MinXSS provides calibration for GOES XRS





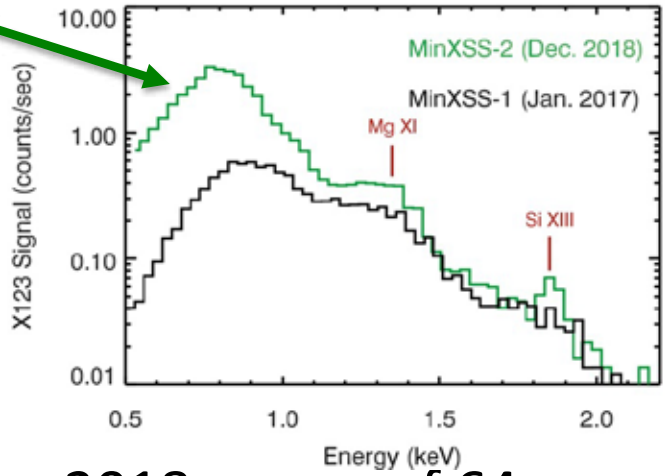


New AR DEM

MinXSS-1 awarded the 2016 Small-Sat Mission of the Year

MinXSS-2 Mission Highlights

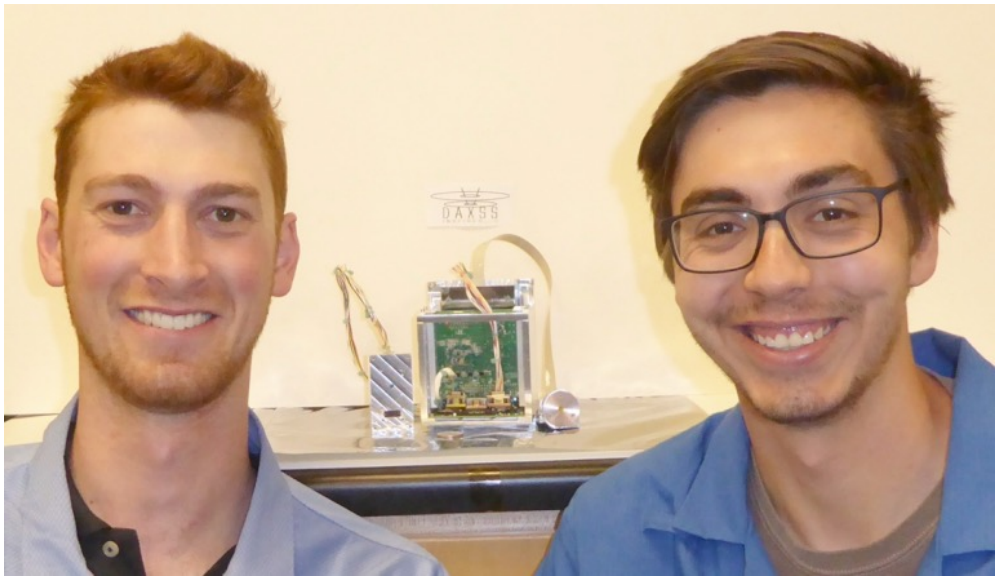
- Improvements over MinXSS-1 (Mason et al., *Adv Sp Res*, 2020)
  - Improved sensor: Amptek X123 SDD
  - Extra UHF ground station at UAF
  - Increased UHF rate to 19200 baud
  - Added heat sink for Li-1 radio
  - Added reset switch (uplink command)
  - Flight software improvements

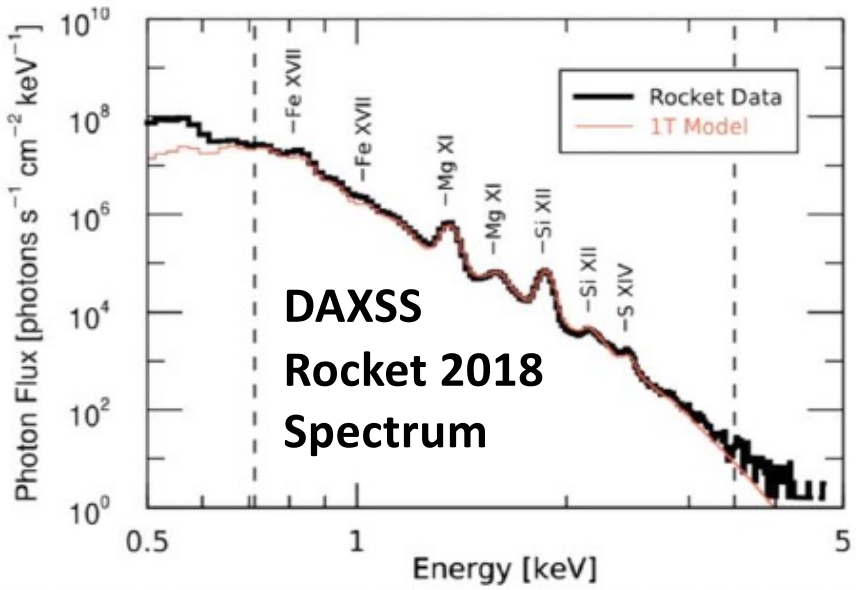


- MinXSS-2 was launched on 4 December 2018 as one of 64 small satellites on Spaceflight Industries SSO-A SmallSat Express (Falcon-9). MinXSS-2 was commissioned in 4 days.
- MinXSS-2 had SD-Card single event upset (SEU) on 7 January 2019. Resets have not been successful.
  - Lesson Learned: (1) Increase Watchdog Timer from few seconds to few minutes; (2) Use more robust rad-tolerant FLASH for SSO
- MinXSS-2 has provided one month of quiet Sun spectra

SP

DAXSS – Improved Spectrometer for "MinXSS-3"





- DAXSS = Dual-zone Aperture X-ray Solar Spectrometer
  - Amptek X123 SDD has higher energy resolution and larger dynamic range. DAXSS has innovative dual-zone aperture design to enhance the solar signal.
  - Flown in June 2018 to provide calibrations as part of SDO EVE underflight calibration rocket payload. Reference: Schwab & Sewell et al., *Ap J*, 2020.
- Grad students Bennet Schwab and Robert Sewell converted rocket instrument into satellite instrument in 3 months after MinXSS-2 anomaly. DAXSS is integrated onto InspireSat-1 as flight of opportunity. Due mostly to COVID, IS-1 launch has been delayed to NET August 2021.

Miniature X-ray Solar Spectrometer

MinXSS CubeSat

MinXSS Technology

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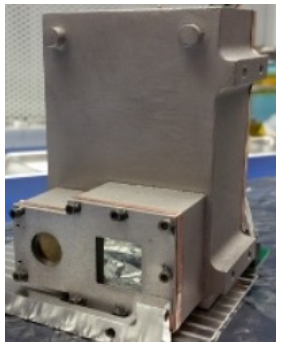
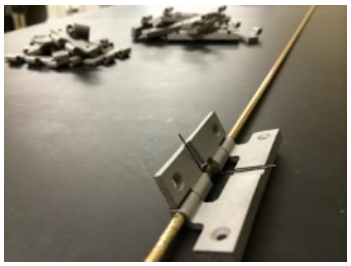


CU/LASP SPS Housing

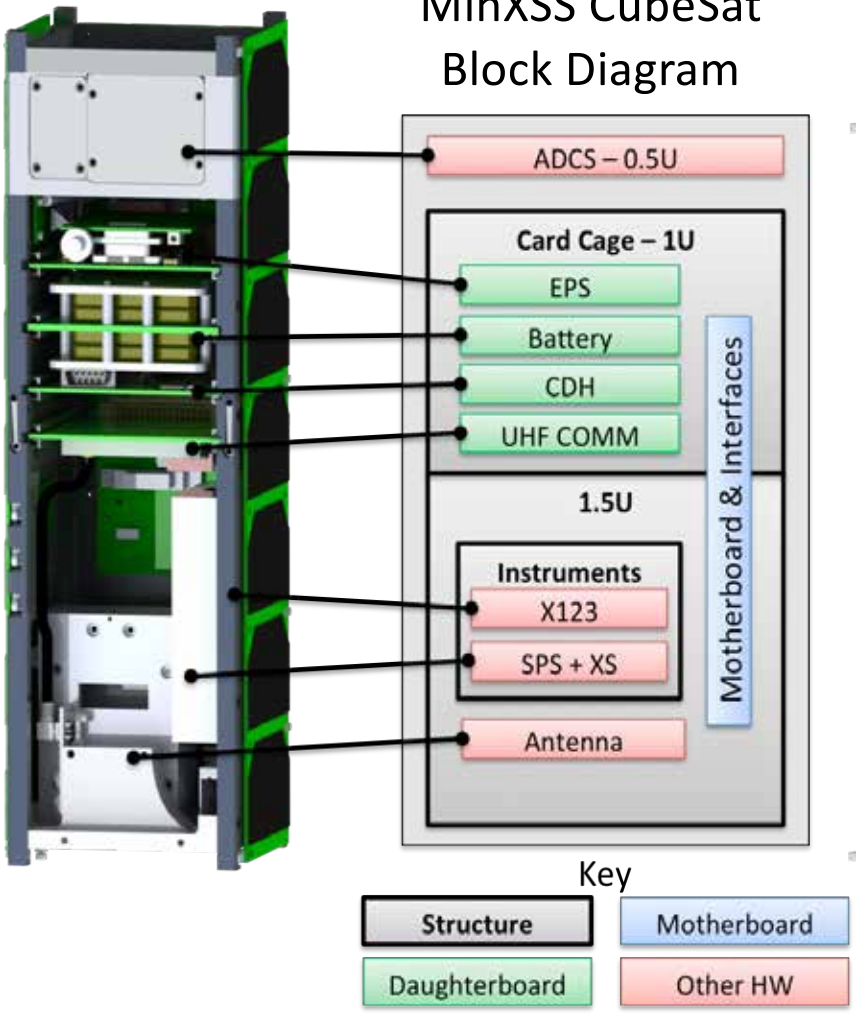
CU/LASP Deployment Hinge



Spacecraft 6 Ps

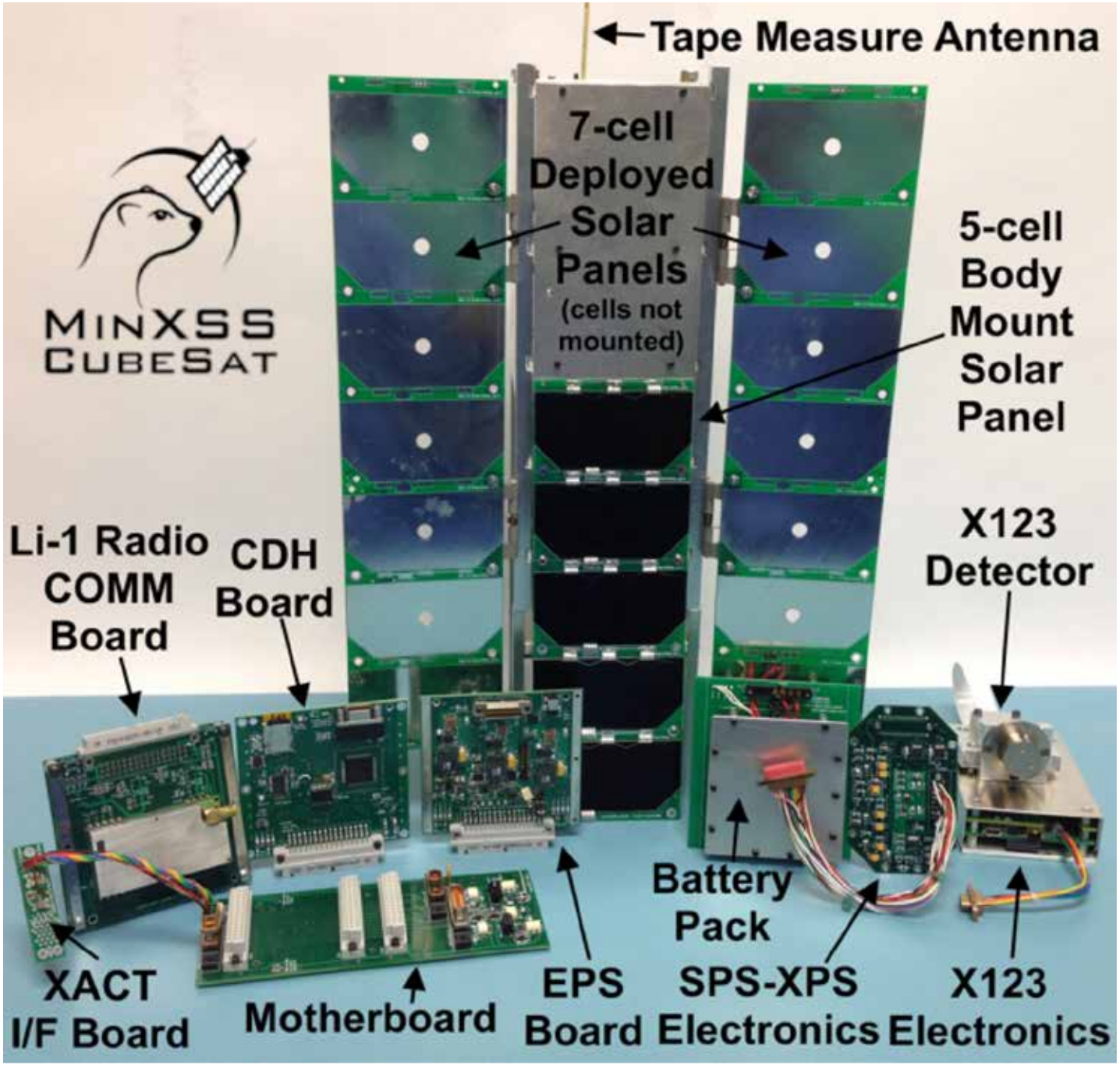
- **P**ayload
  - instrument
- **P**ointing
  - attitude control
- **P**hone
  - communication, radio
- **P**ower
  - solar cells, battery, voltage regulation
- **P**rocessor
  - command & data telemetry
- **P**ropulsion
  - navigation

MinXSS CubeSat Block Diagram



NASA Ames: Small Satellite Technology State of the Art (2018)
https://www.nasa.gov/centers/ames/engineering/state-of-the-art

MinXSS Exploded View of Subsystems



Volume
3U
Mass
3.51 kg
Power
Avg. 8.3W
Peak 25W

Acronyms: Command & Data Handling (CDH), Electrical Power System (EPS) with **AzurSpace solar cells** and **sparkfun Li-poly battery**, Communications (COMM, **AstroDev Li-1 UHF Radio**), **Attitude Determination & Control System (ADCS, BCT XACT),** Solar Position Sensor (SPS), X-ray Sensor (XS), **X123 is Amptek X-ray spectrometer**.

BLUE = Purchased

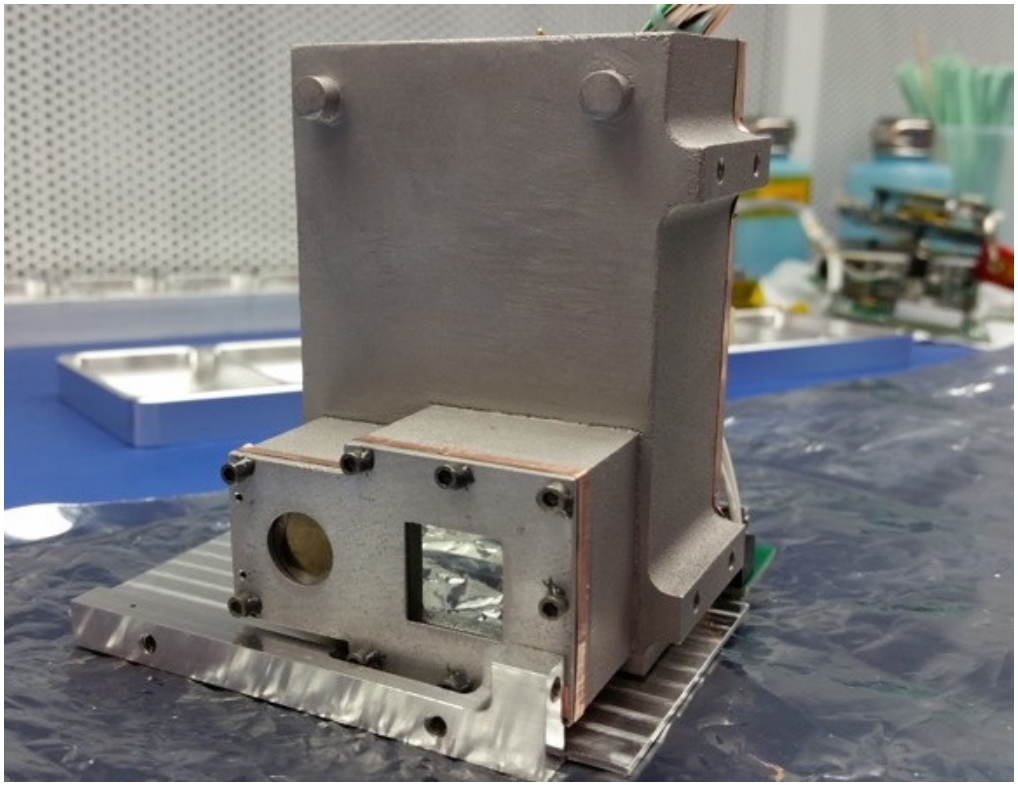
BLACK = Student Built

Science Instruments: X123 & SPS-XP

X-ray Spectrometer
(primary instrument)

Amptek X123-SDD

Solar Position Sensor & X-ray Photometer



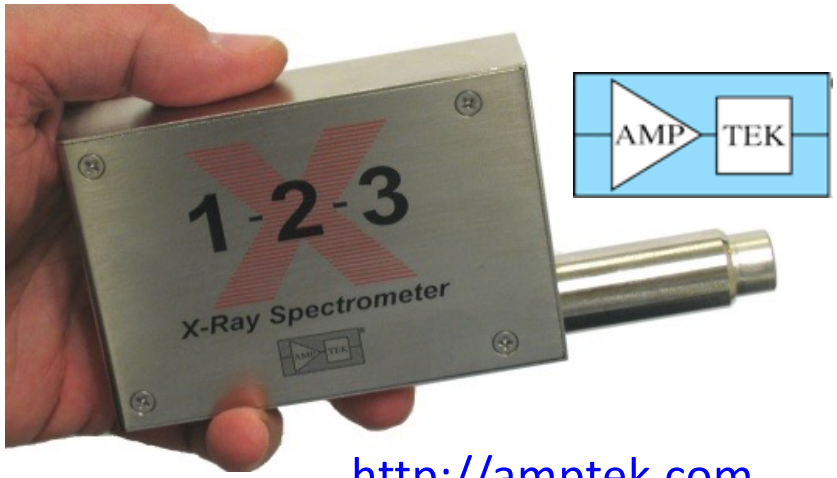
GOES-R XRS PCB with ASIC & Diodes

Student-built SPS-XP Power Board

Student-designed Housing: **3D Printed**

Enabling Technology for MinXSS

- Amptek miniature X-ray spectrometer
  - X123: 0.2U, 0.2kg, 2.5W
  - Energy range of 0.5-30 keV with 0.15 keV resolution



http://amptek.com

- Blue Canyon Technologies (BCT) Attitude Determination and Control System (ADCS)
  - XACT: 0.5U, 1kg, 2W
  - In-flight performance of 10 arc-sec stability

BCT XACT 0.5U
Star Tracker
Coarse Sun Sensor
Magnetometer
Reaction Wheels
Torque Rods

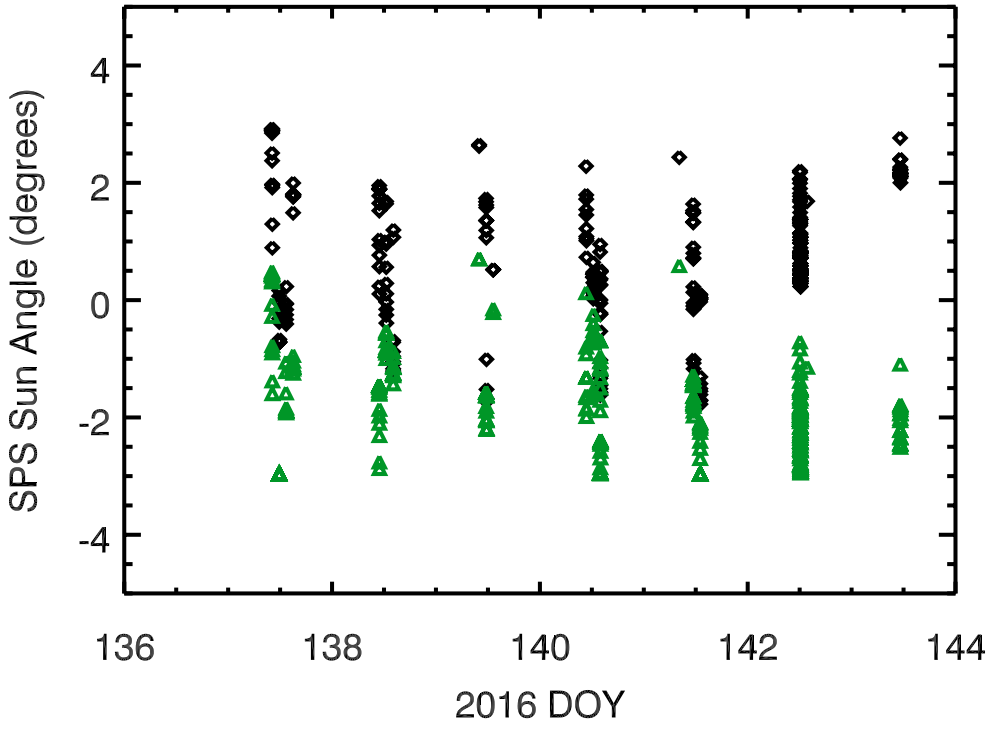
http://bluecanyontech.com

MinXSS-1 SPS Validates XACT Performance

- Coarse solar pointing is used in Safe mode to provide solar illumination for the solar panels
- Fine solar pointing is used in Science mode for most of the mission
- XACT performance is published in Mason et al., *J. Small Sat.*, 2017

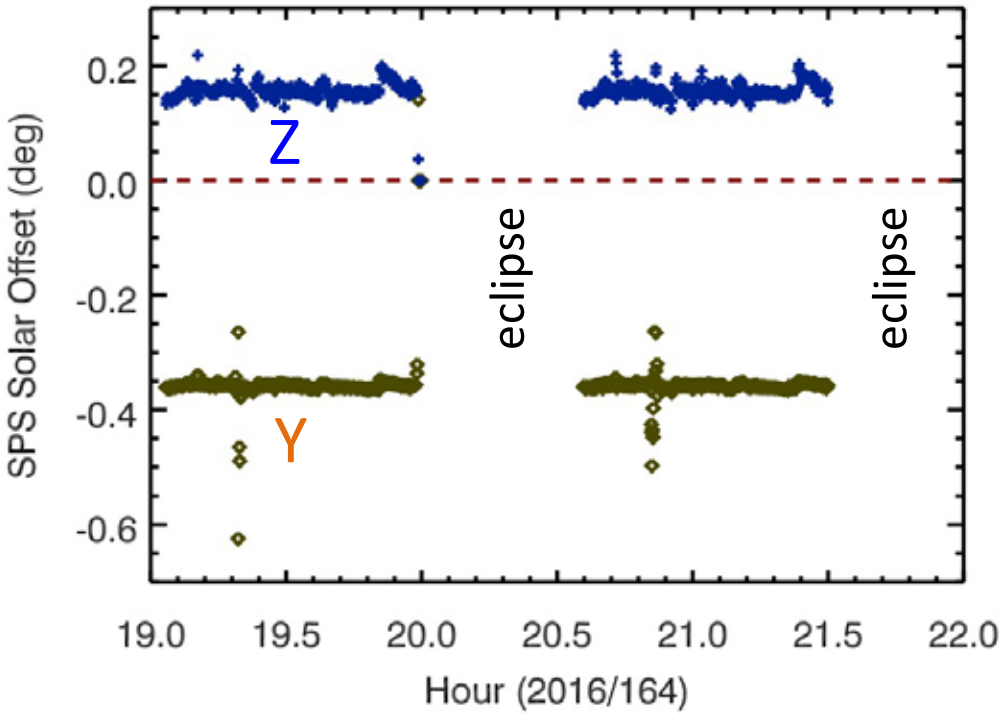
XACT Sun Point (**safe**) goal is 10° from Sun.

SPS validates MinXSS-1 is < 3° from Sun.



XACT Fine Ref (**science**) goal is 12 arc-sec.

SPS validates pointing is 10 arc-sec (1-σ)



Mechanical tolerance acceptable for instrument-ADCS alignment because of large 6° FOV for the instruments.

Ground Stations for MinXSS

CU's CubeSat UHF antenna is located on LASP's roof.

Extra MinXSS-2 UHF Ground Station was installed at UAF GI in 2017

Jim White's Ground Station in Parker, CO

International HAM Radio Operators

Miniature X-ray Solar Spectrometer

MinXSS
CubeSat

MinXSS Science Results

MinXSS Science Highlights

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- MinXSS has obtained solar SXR spectra for over 100 C-class and 8 M-class flares
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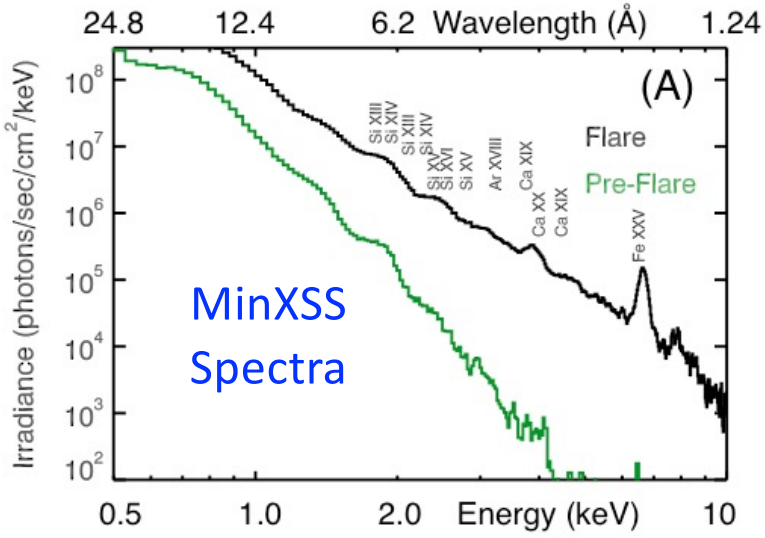
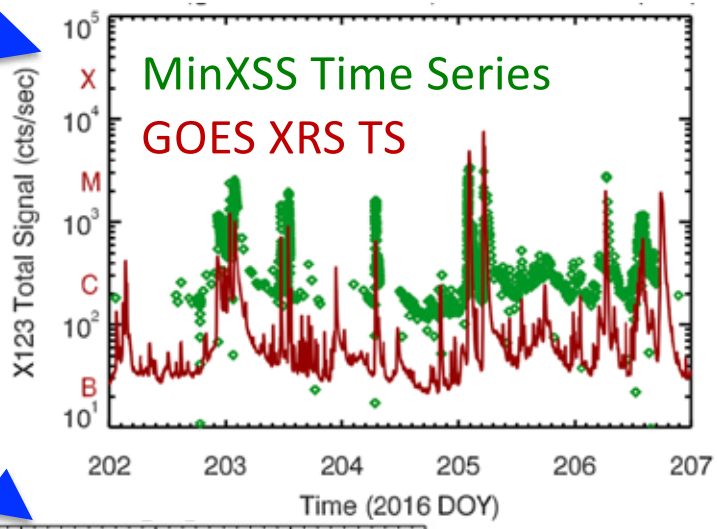
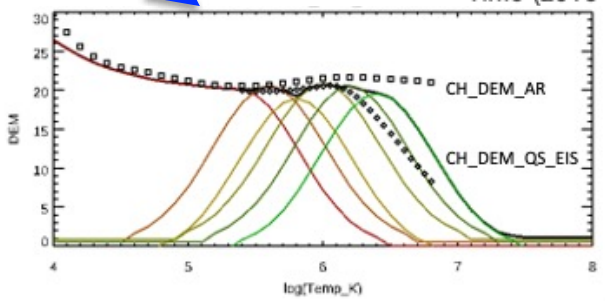




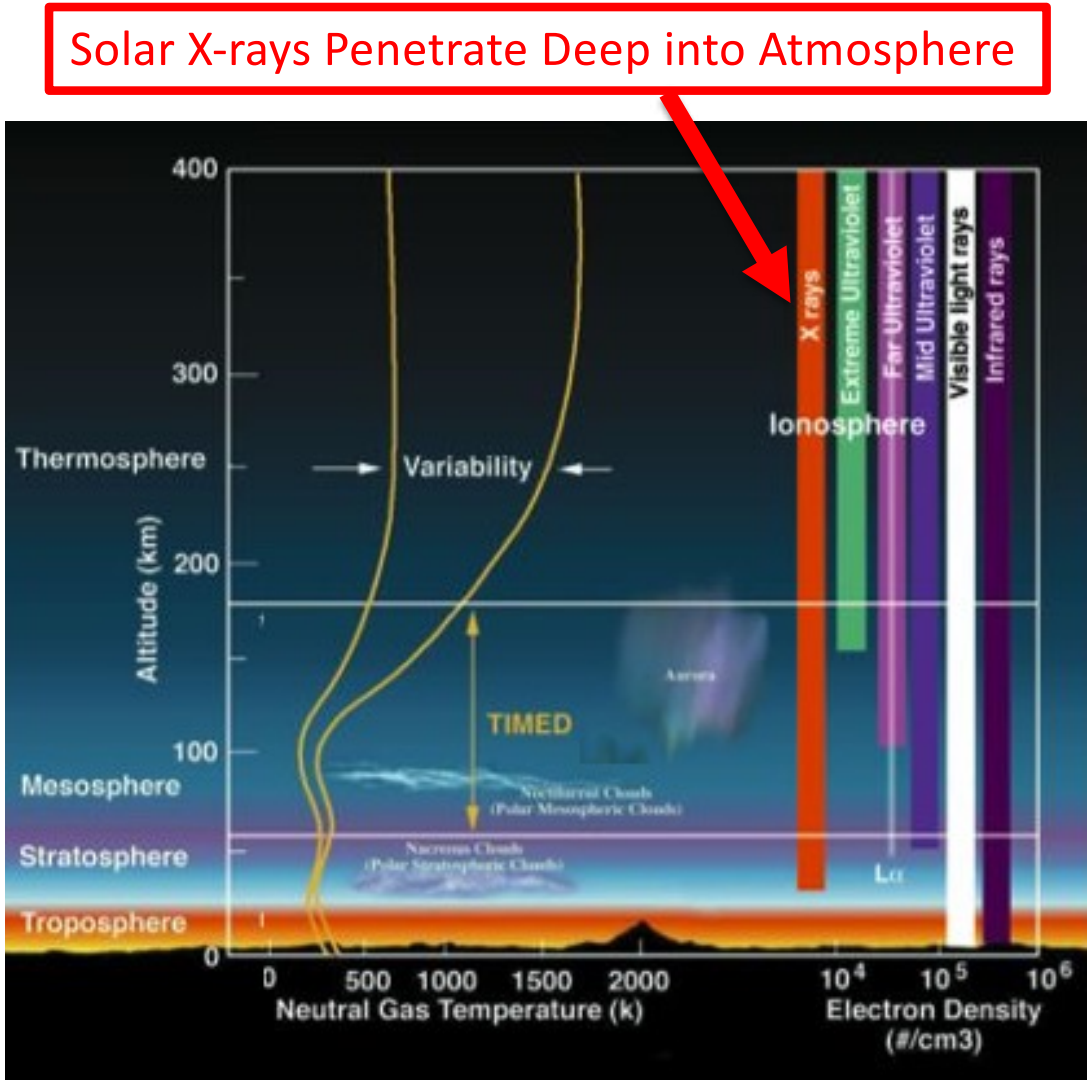


New AR DEM

Motivation for MinXSS: Close the Gaps in Understanding the Solar Input for Earth's Atmosphere

- Solar extreme ultraviolet (EUV) and X-ray radiation, energetic particles, and Joule heating are the primary energy inputs for the ionosphere and thermosphere.

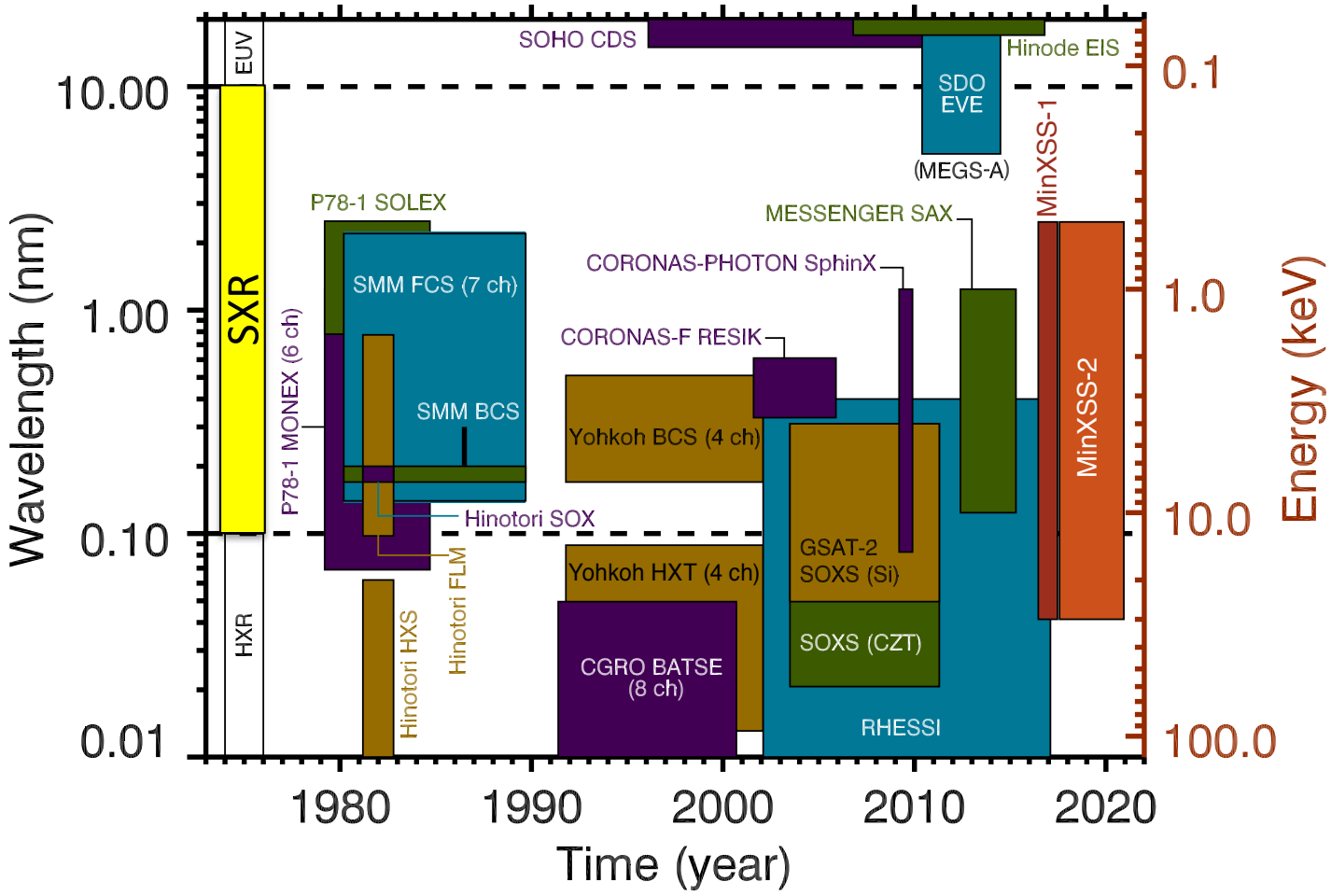
- MinXSS is a mission to study the solar soft X-ray (SXR) spectra and its influence on the ionosphere E region.



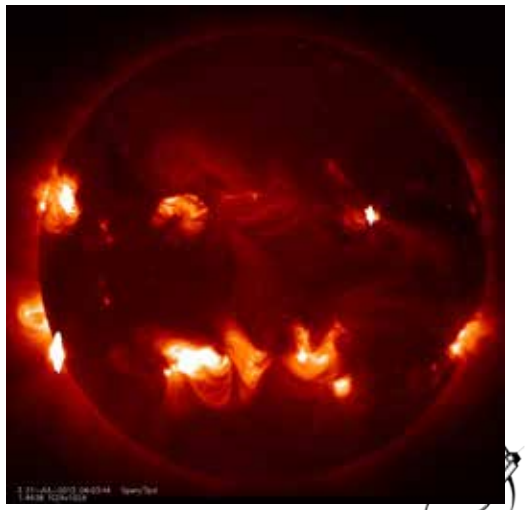
Graphics from JHU-APL TIMED project

Progress has been Hampered for Decades because of λ Gaps in Solar SXR Spectra

- Most solar SXR measurements are broad band (not shown).
- The problematic spectral gap has been 0.4-17 nm (0.07-3 keV).

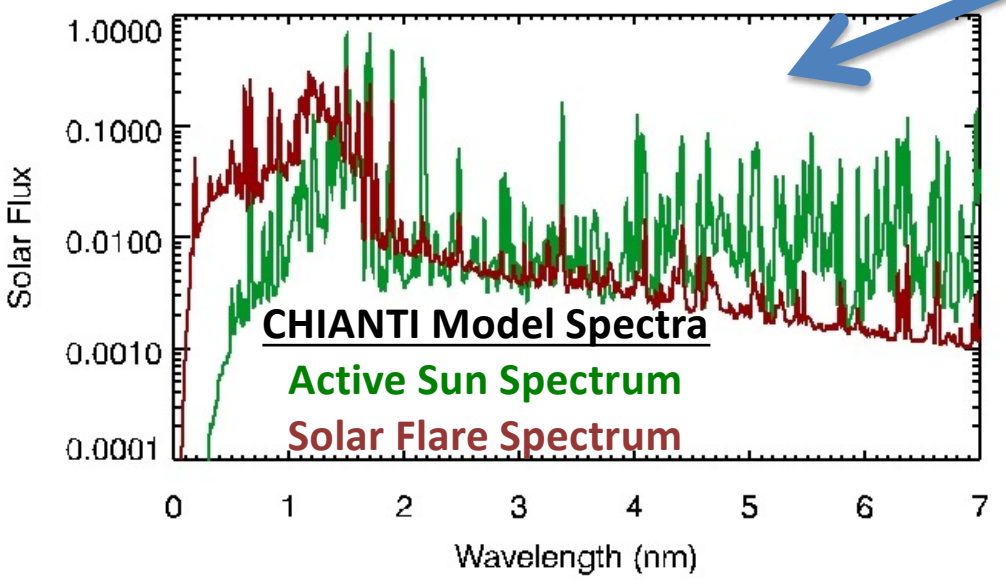


Spectral Gap In SXR



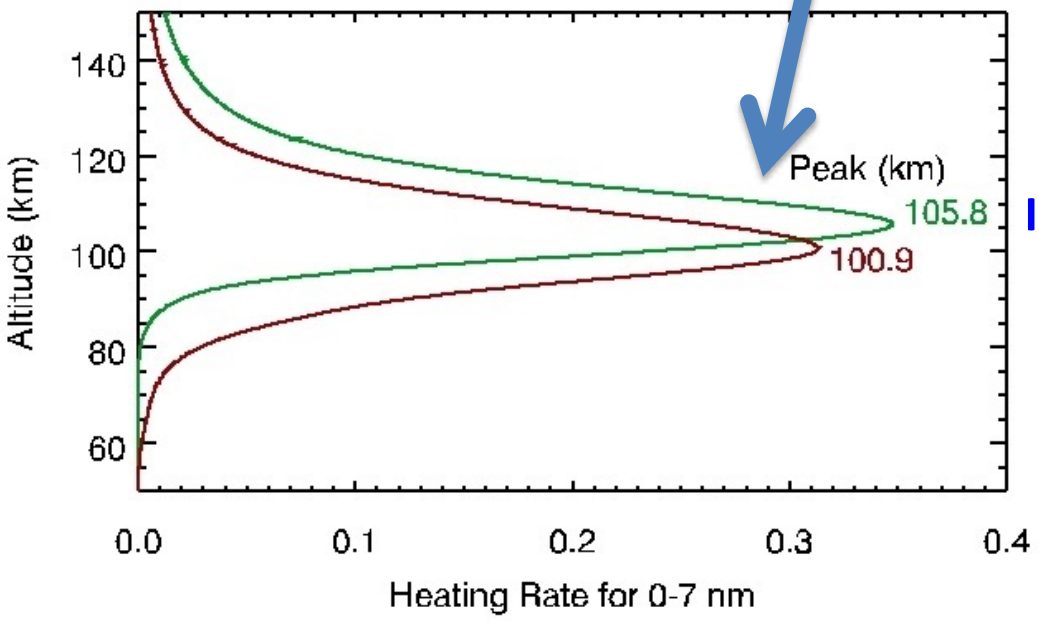
The Sun in X-rays (Hinode XRT)

Unknown Spectral Distribution is Major Challenge from Decades of Measuring the Solar SXR in Broad Bands



- Same amount of irradiance in the soft x-ray (SXR: 0.1-10 nm) can have very different spectral distributions
- Earth's atmospheric cross sections are steep in the 0-10 nm range
- Consequently, the solar SXR radiation can be deposited into different layers of the atmosphere

MinXSS Co-I Stan Solomon is improving ionosphere modeling with new SXR spectra.



Thermosphere
Ionosphere F Layer

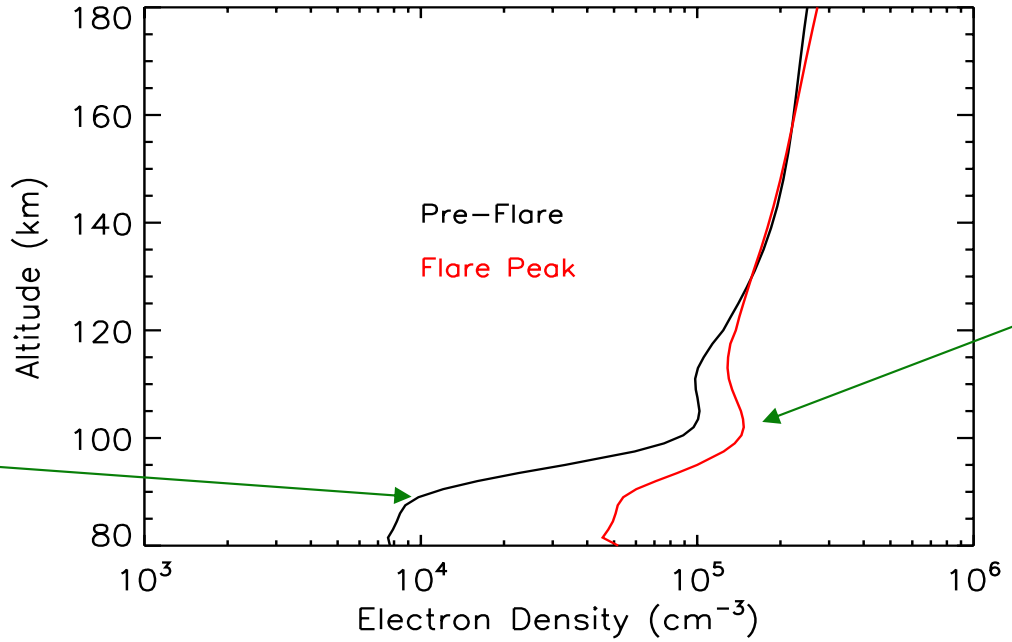
Ionosphere E Layer

Ionosphere D Layer
Mesosphere

Stratosphere

Ionosphere & Thermosphere have Large Response (factor of 2-5) from Solar Flare (M5)

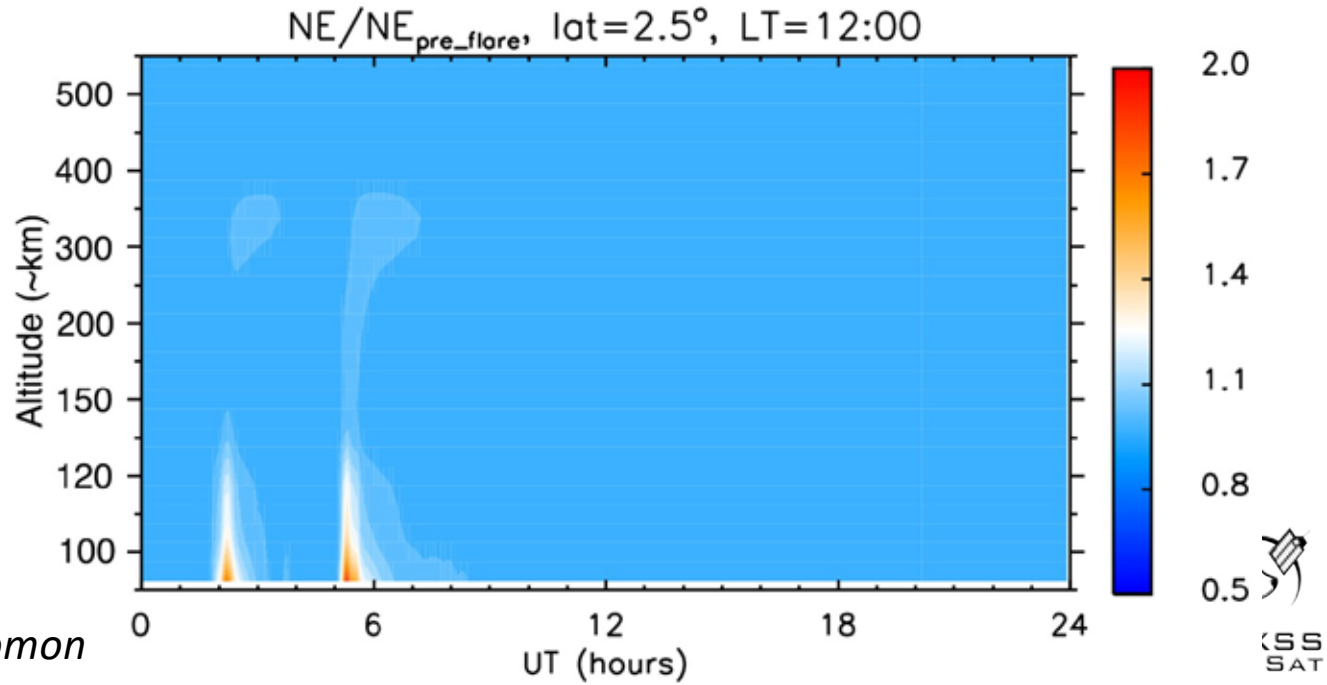
Electron density profiles calculated using the Global Airglow (GLOW) model near the sub-solar point



D-region is enhanced

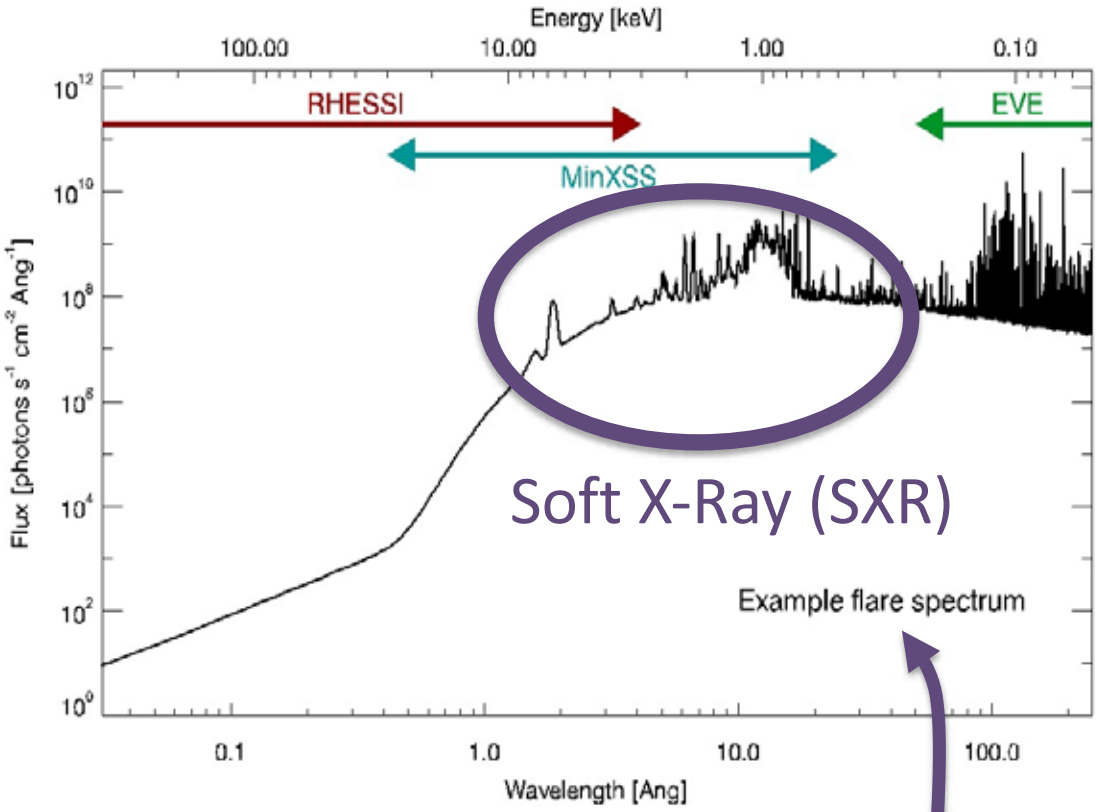
E-region enhanced and lower in altitude

Time-dependent Electron density change calculated globally using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)

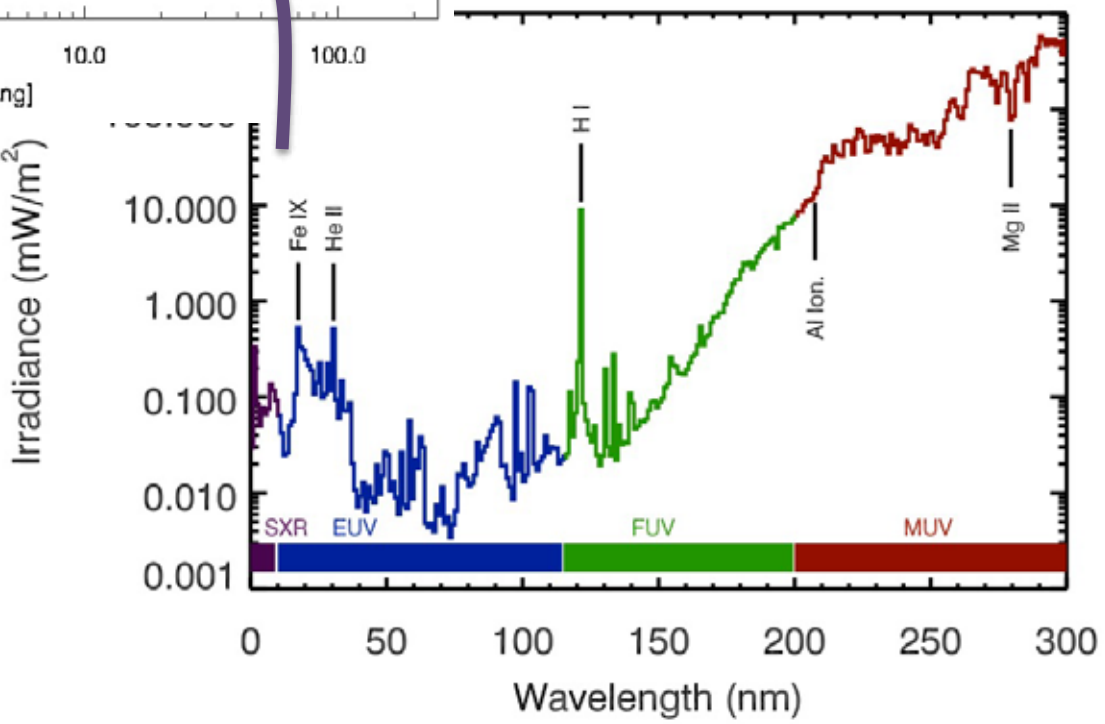


From Stan Solomon

Science Motivation: Measure Flare Spectra

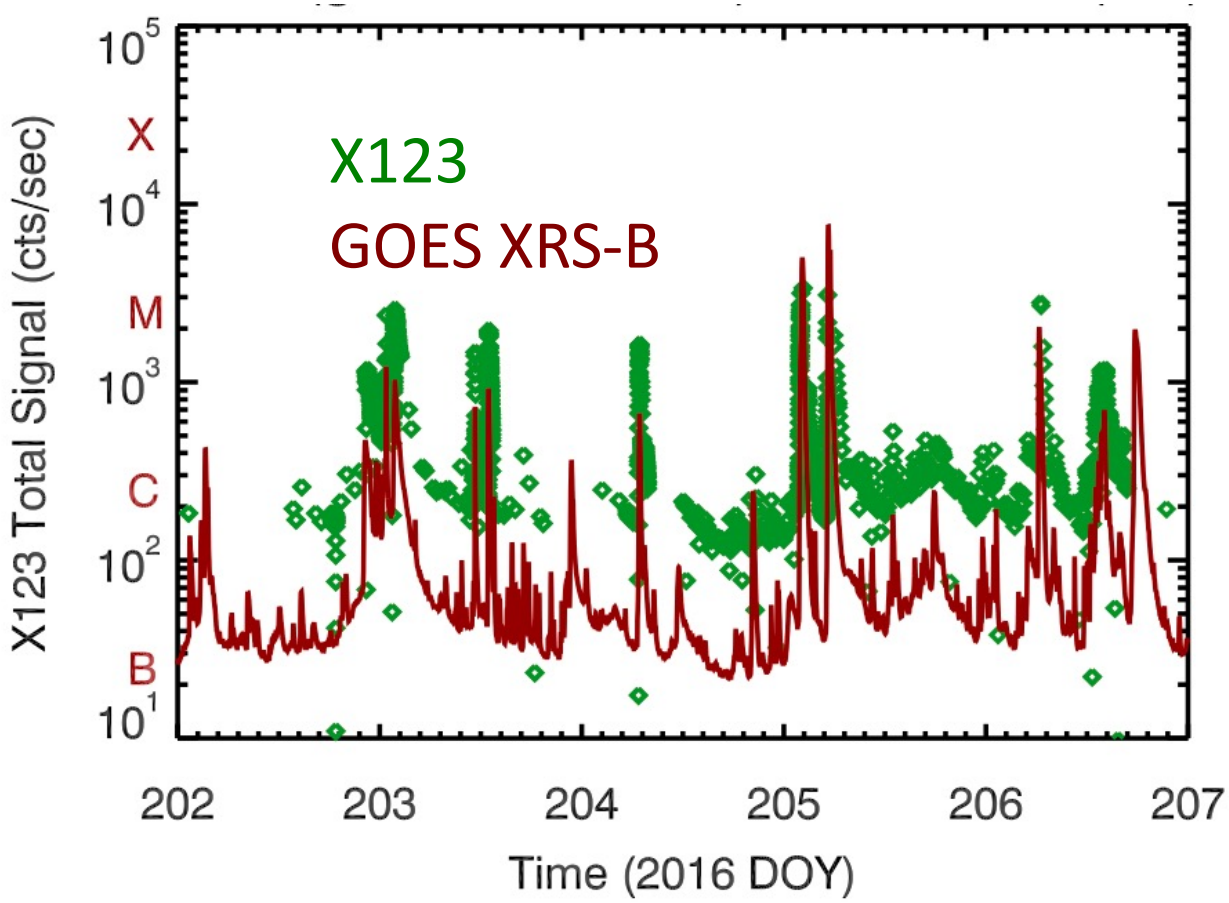


Largest flare enhancements are expected near 1-2 nm (10-20 Å) from solar models, but this part of the SXR spectrum has not been measured well during flare events. [Rodgers *et al.*, *JGR*, 2006]



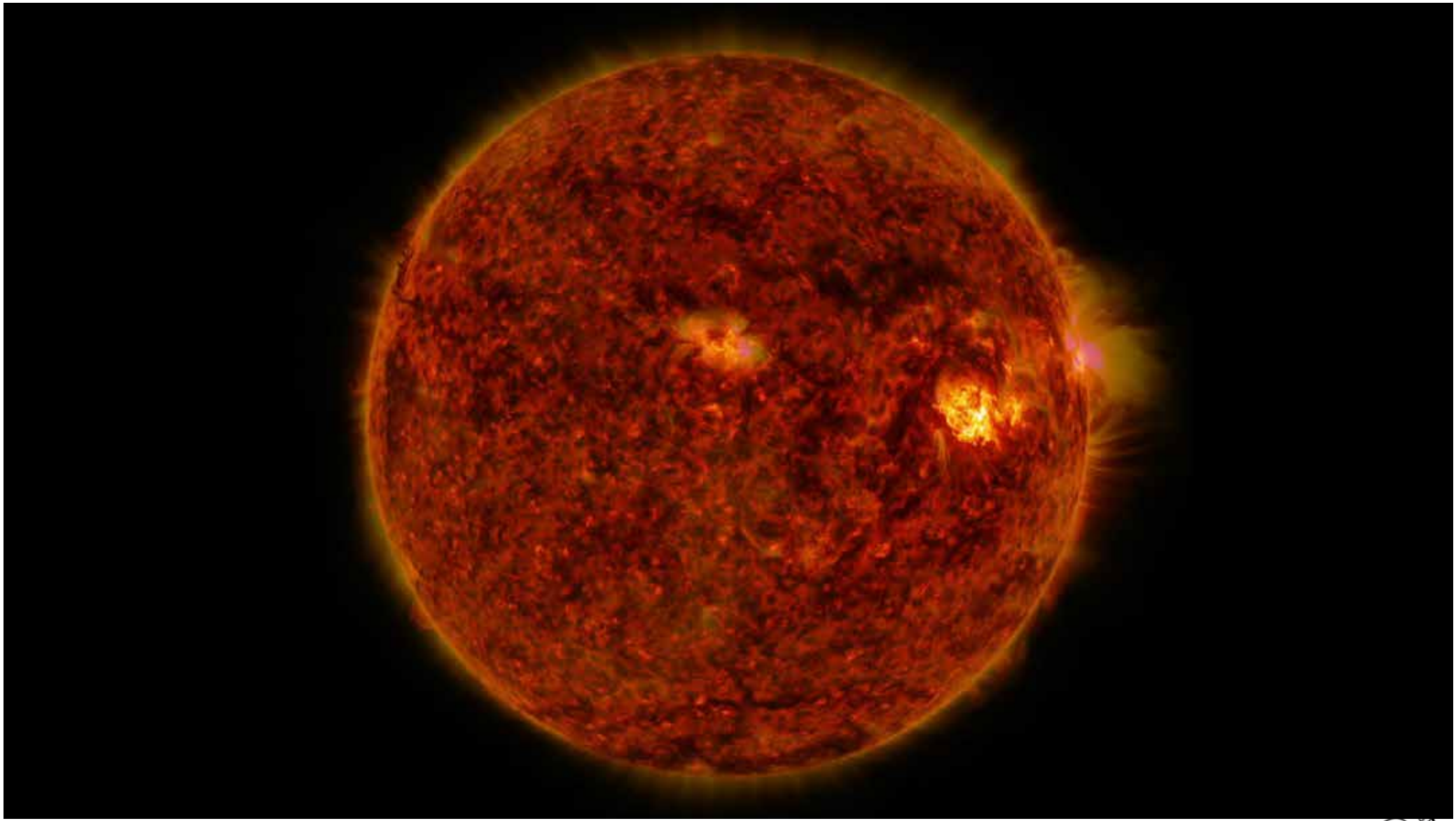
MinXSS-1 Has Observed > 100 Flares

- MinXSS-1 has observed over 100 C-class and 8 M-class flares between May 2016 and May 2017.
- Most intense solar activity is in July 2016 and April 2017.



Example flare spectrum for M1 flare on July 21

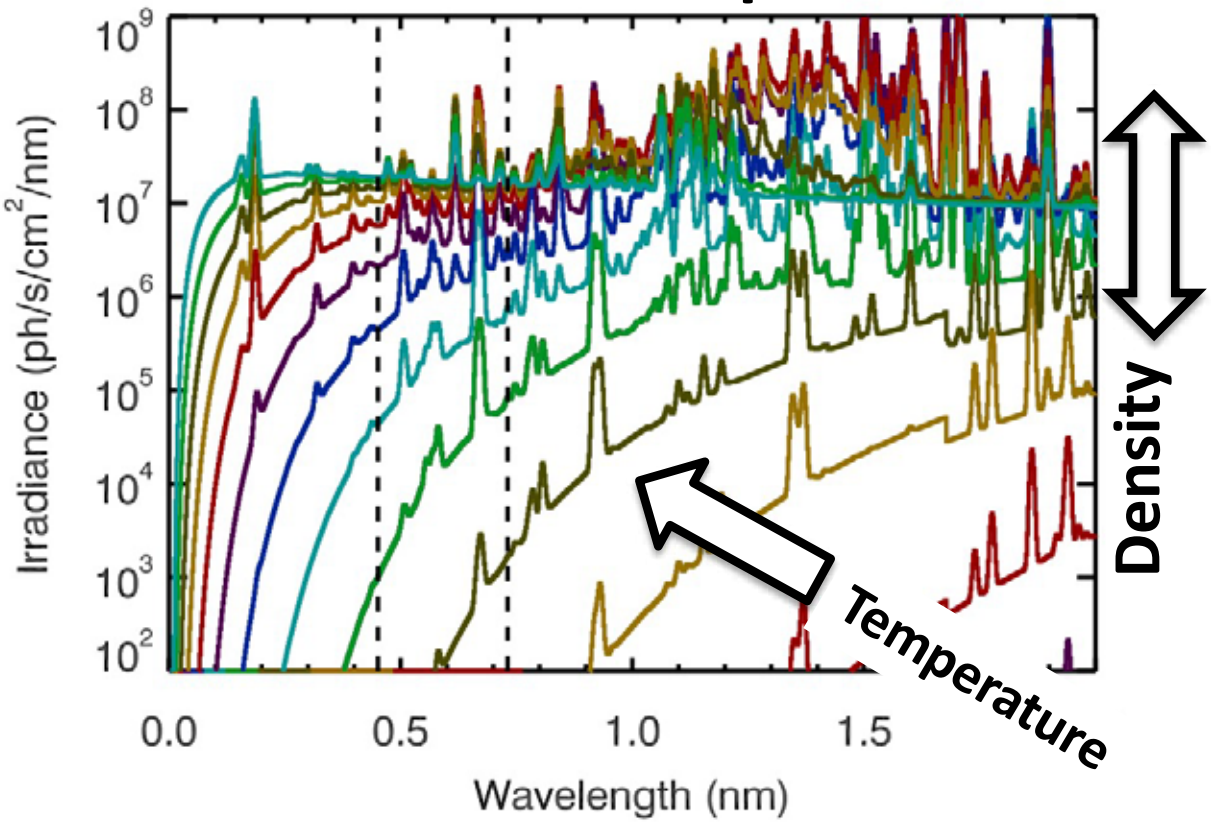
– GSFC movie for this flare uses SDO AIA 193 Å images



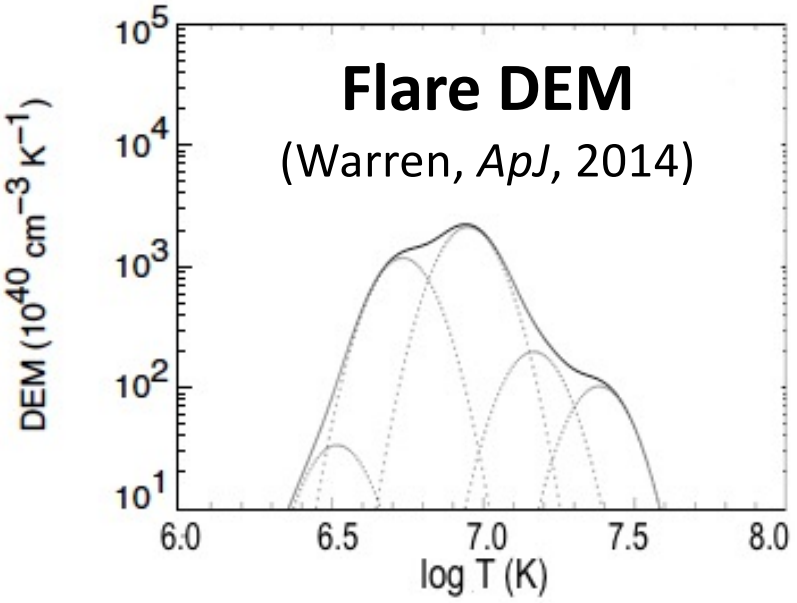
SXR Spectra are Highly Dependent on Temperature

- Solar SXR spectra includes hot plasma Bremstrahlung continuum & emission lines
  - CHIANTI atomic database used for spectral model

Isothermal Spectra



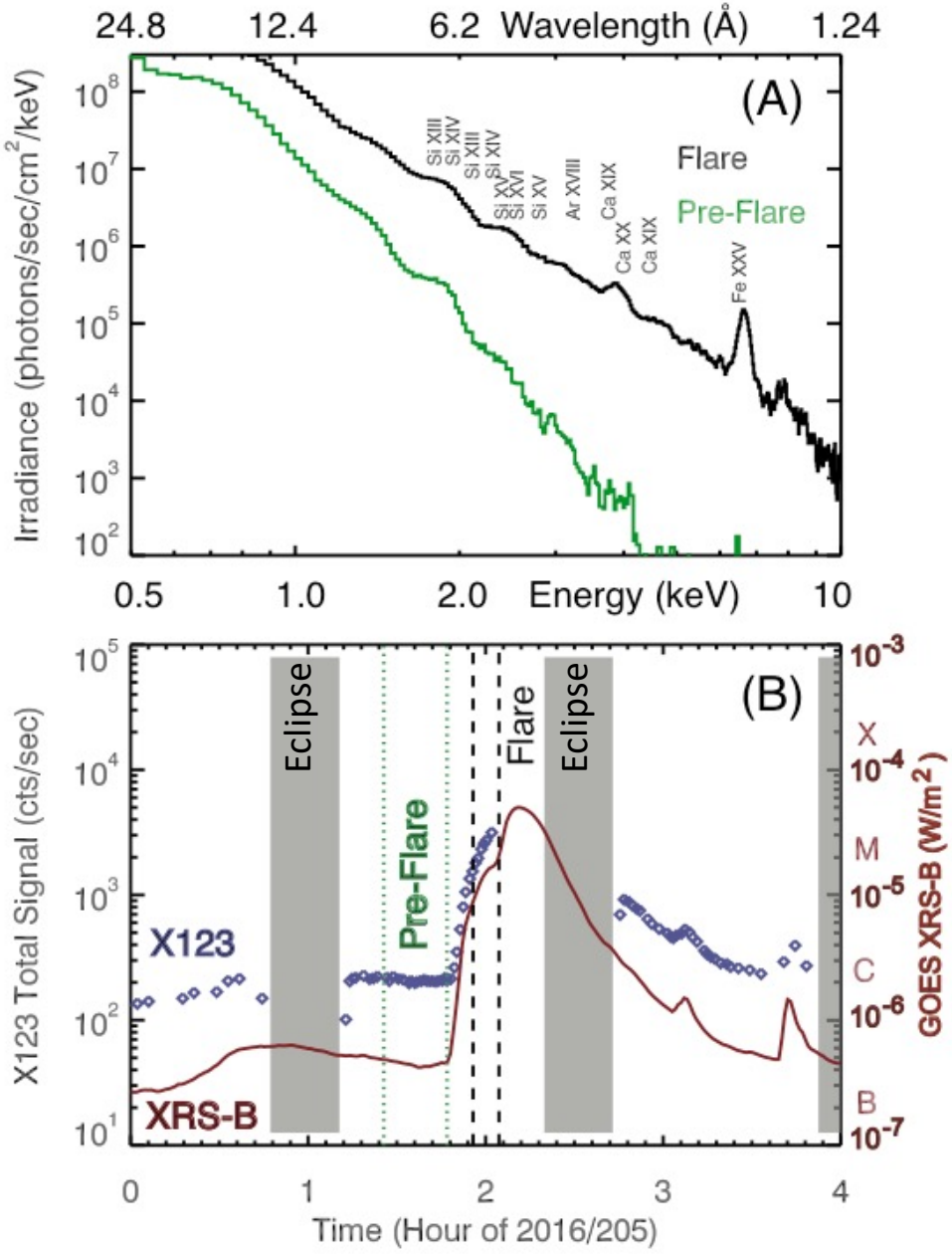
Differential Emission Measure (DEM) works well for SXR optically-thin spectra



Example MinXSS Flare Observation: M5 flare

- **M5.0 flare on 23-Jul-2016**
  - SXR irradiance increases during this flare by a factor of 4-200 relative to the pre-flare level
  - Emission includes Bremsstrahlung continuum along with many hot coronal lines

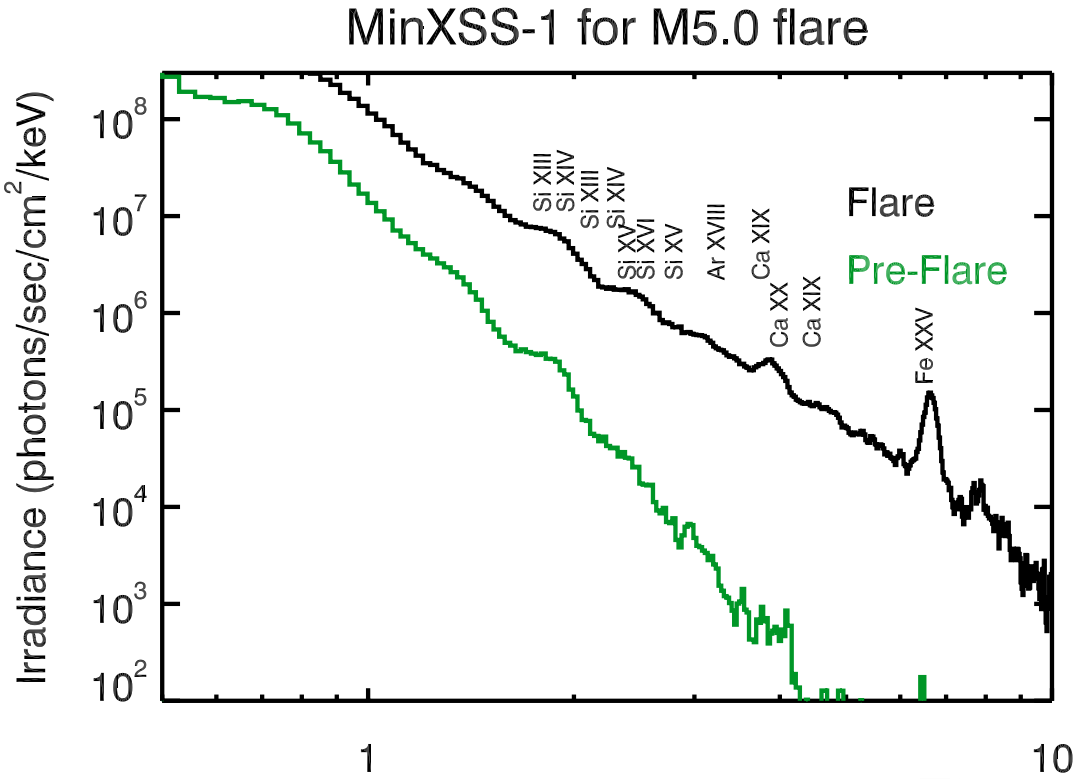
- MinXSS X123 data have 10-sec cadence but with data gaps during orbit eclipse periods

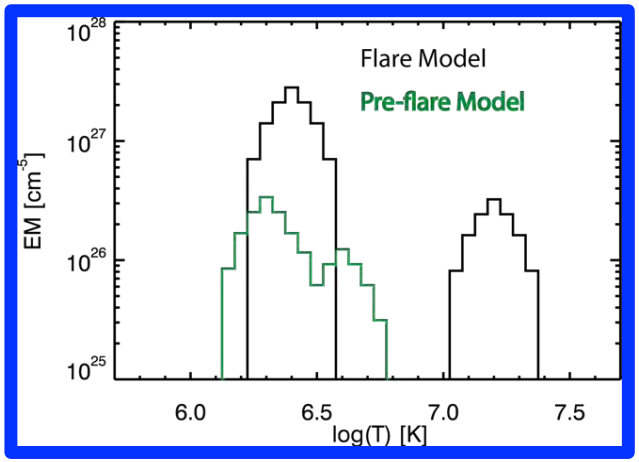


Figures from Woods *et al*. (*ApJ*, 2016)

Solar SXR Spectra provides Plasma Diagnostics

- **Plasma Diagnostics**
  - **Temperature**
    - Harder spectra (e.g. flare) have hotter temperatures
      - Pre-flare: 2-4 MK
      - Flare: 2-15 MK
    - Multiple temperature components can be derived with SXR spectra
  - Low First Ionization Potential (low-FIP) ions like Fe, Ca, and Si provide indication of **composition**
    - Pre-flare: coronal (2.1)
    - Flare: photospheric (1.2)



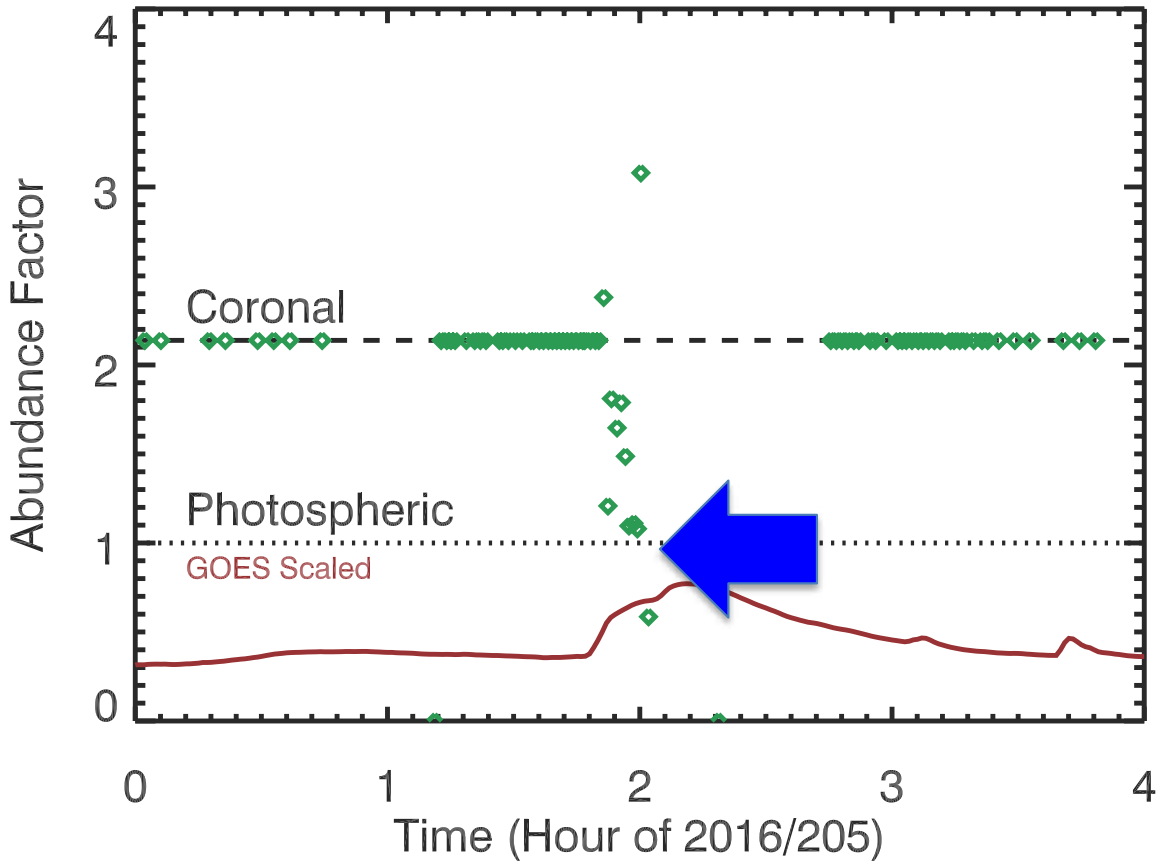


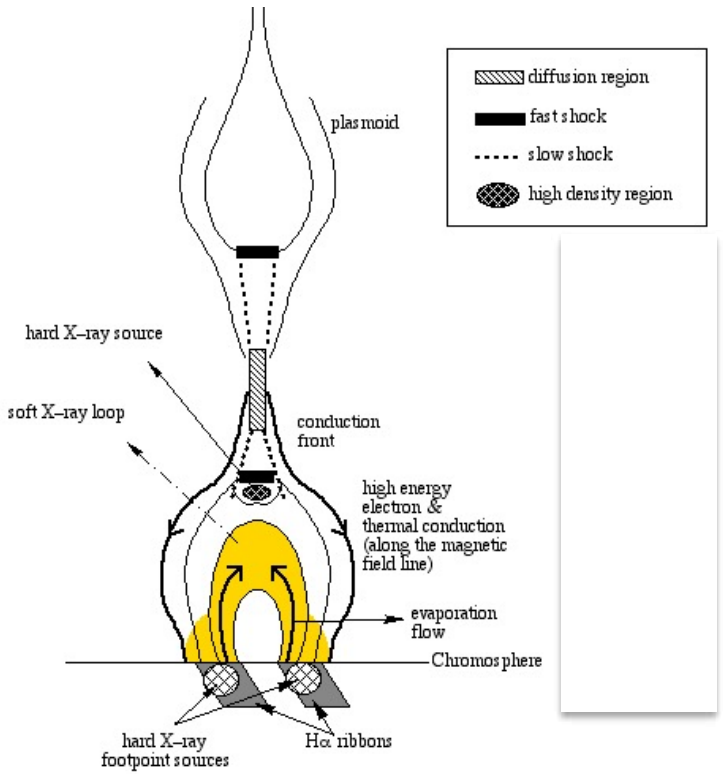
Two-temperature model fits for MinXSS spectra

Figure from Woods *et al*. (*ApJ*, 2016)

Abundance Results with MinXSS Data

- The abundance factor changes from coronal level of about 2 to a photospheric level near 1 during the M5 flare
  - This implies chromosphere contribution to the corona after the flare begins
  - This is consistent with standard flare concept with magnetic reconnection in the corona and energetic particles then evaporating the chromosphere below

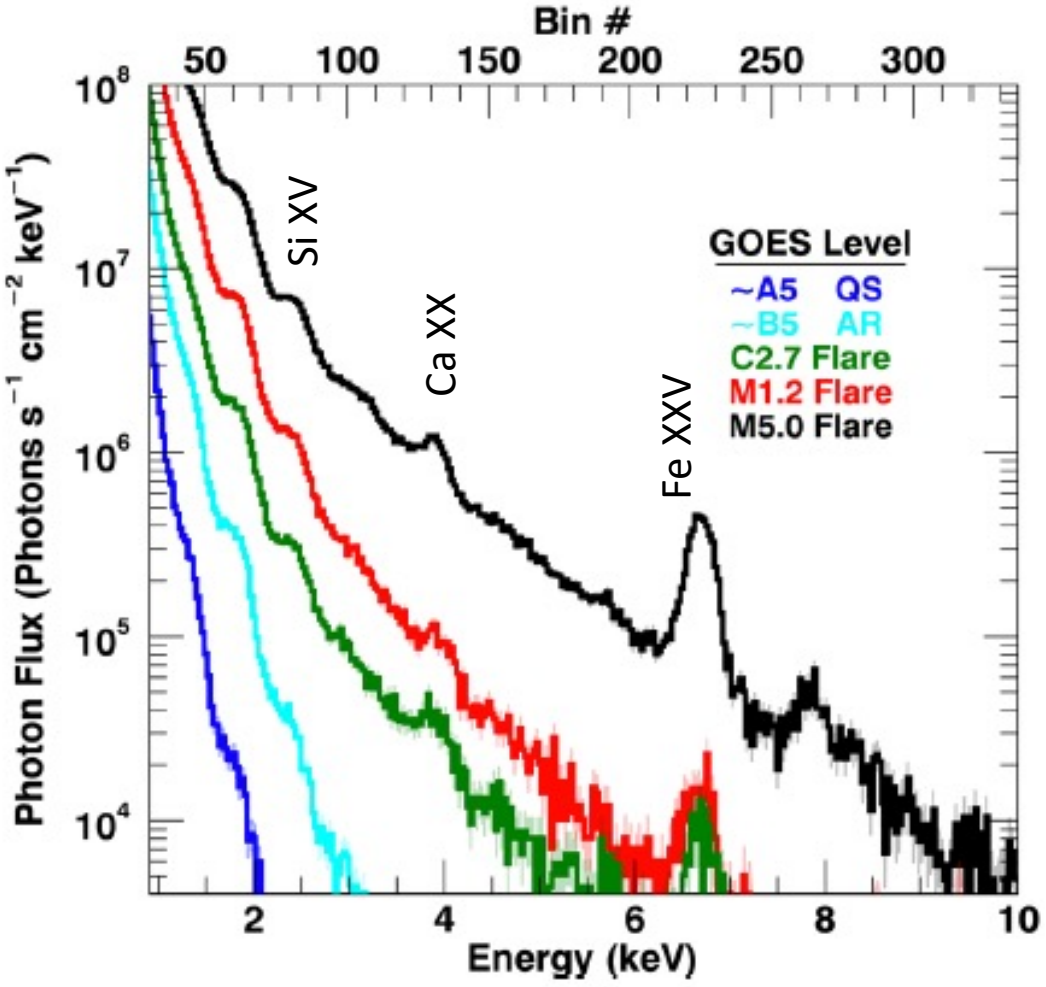




Standard Flare Model from Montana State

MinXSS Spectra at Different Levels of Solar Activity

- Results are from Moore et al., *Solar Phys*, 2018
- FIP bias decreases from **pre-flare value of 2-3** to 1-1.4 during flare
  - FIP bias: 1-2=Photosphere, **2-4=Corona**



GOES Level	Temp #1 MK	Temp #2 MK	Pre-flare Bias	Flare FIP Bias
A5 -QS 7/1/16	1.17	2.43	**3.48**	N/A
C2.7 7/8/16	4.28	14.9	**2.89**	1.41
M1.2 7/21/16	4.05	13.0	**2.17**	1.41
M5.0 7/23/16	4.86	19.7	**2.21**	0.98

New Solar Reference Spectrum – Active Region

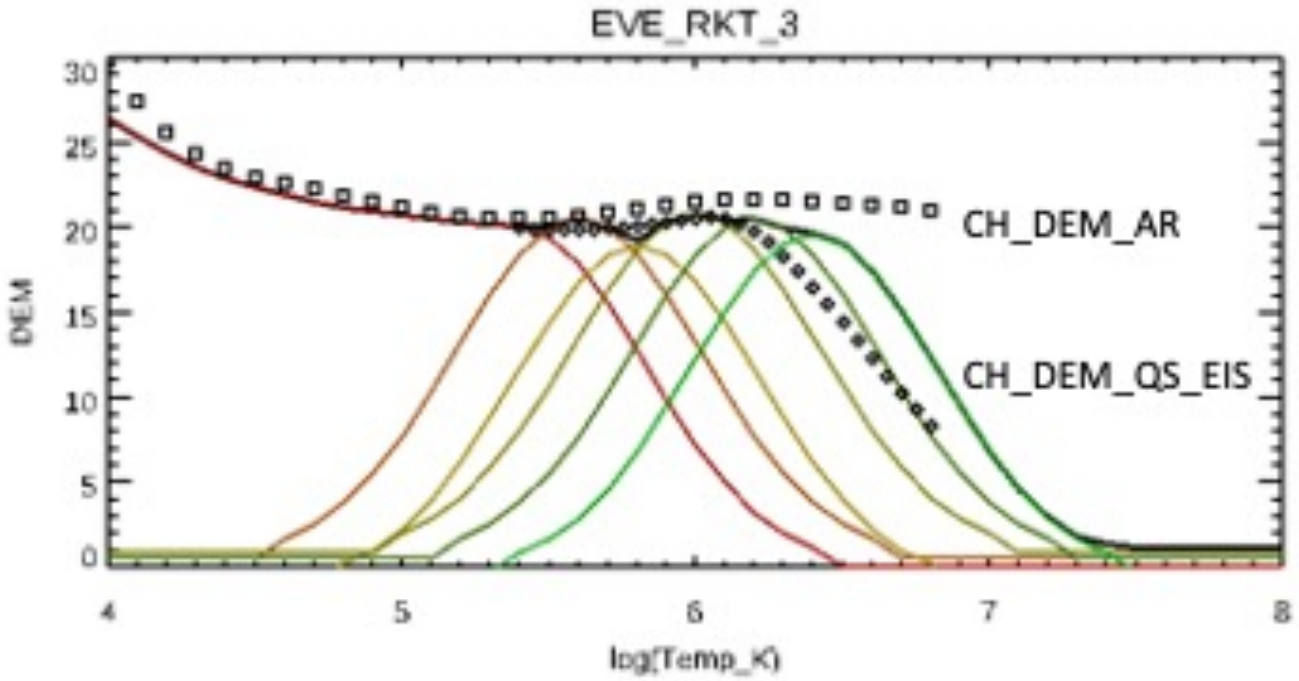
- Differential Emission Measure (DEM) is a multi-temperature analysis of plasma emissions. It is commonly used for optically-thin plasma emissions, such as for the corona.
- A DEM is derived using measured SXR and EUV spectra, then this DEM is used with the CHIANTI database to model the solar spectrum over the full SXR and EUV ranges.

Derived DEM (black line) is sum of each DEM component at different temperatures.

INPUT:

- rocket DAXSS (MinXSS-3) solar SXR spectra
- SDO EVE solar EUV spectra

Similar to Warren (2014) DEM analysis.



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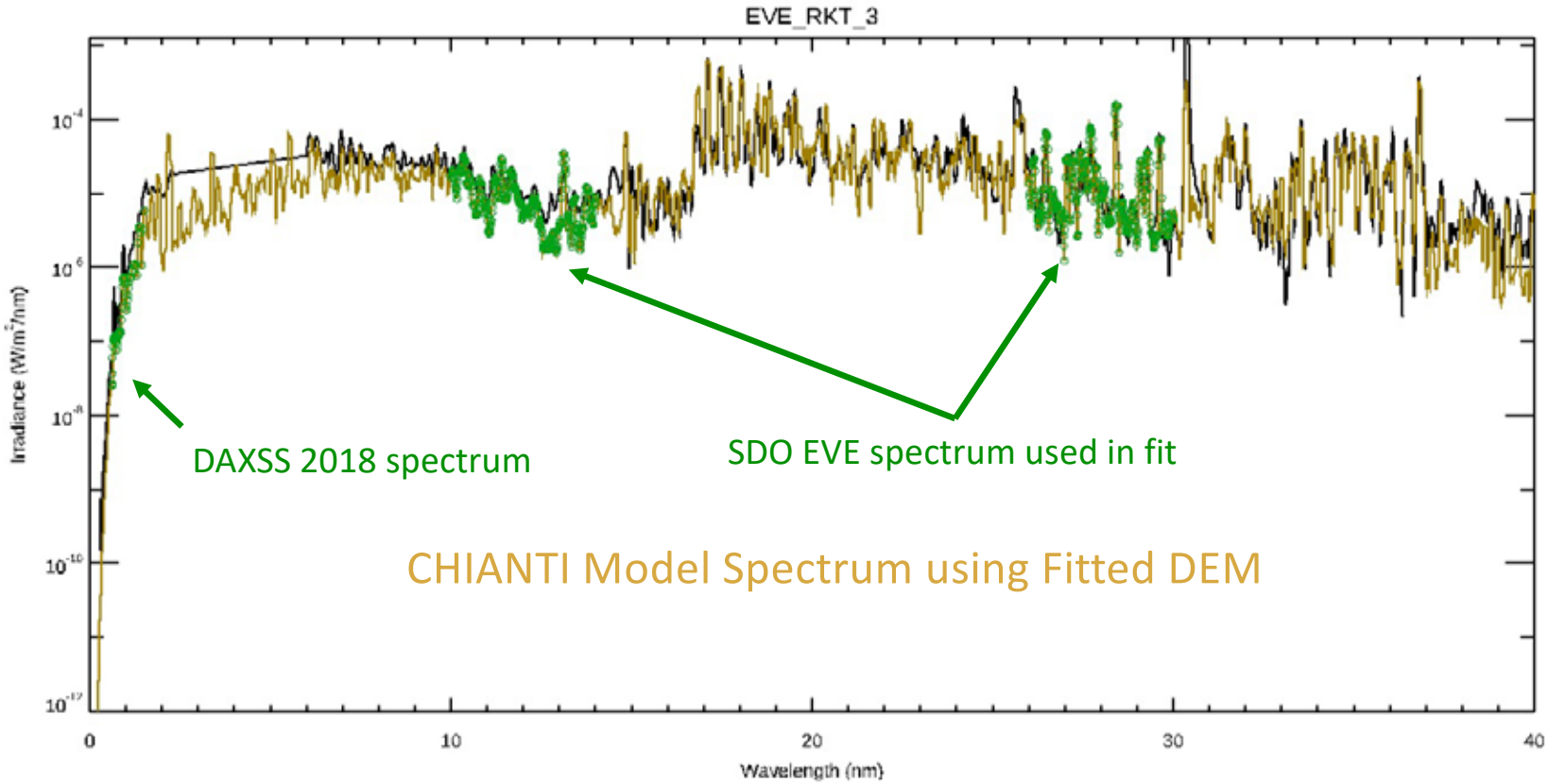
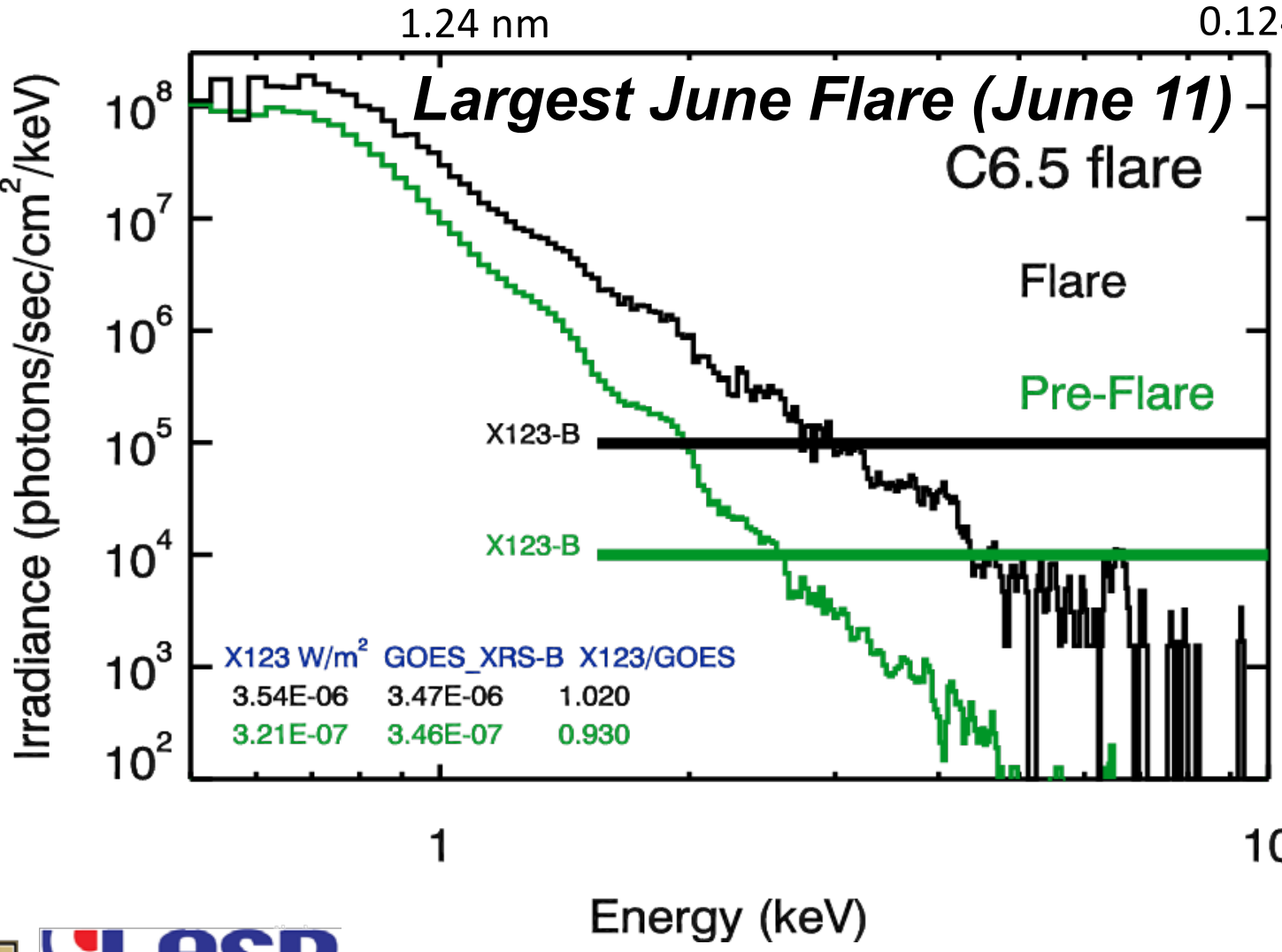


MinXSS Contribution for Space Weather

- GOES X-Ray Sensor (XRS) has been reference for X-ray flare detection and flare classification since the 1970s.
- MinXSS X123 can provide a spectral calibration for GOES XRS



GOES XRS-B 1-8 Å band is divided by 0.7 (or x 1.42)
[NOAA's calibration correction]

New GOES-16 and -17 XRS does not need calibration correction.

MinXSS Contribution for Space Weather

- The X123 integrated band over 1-8 Å is lower than the GOES-15 XRS-B for lower levels. This difference is related to the GOES-15 XRS-B background level and choice of reference spectrum for the GOES XRS data processing algorithm.

MinXSS X123 validates the GOES XRS calibration.

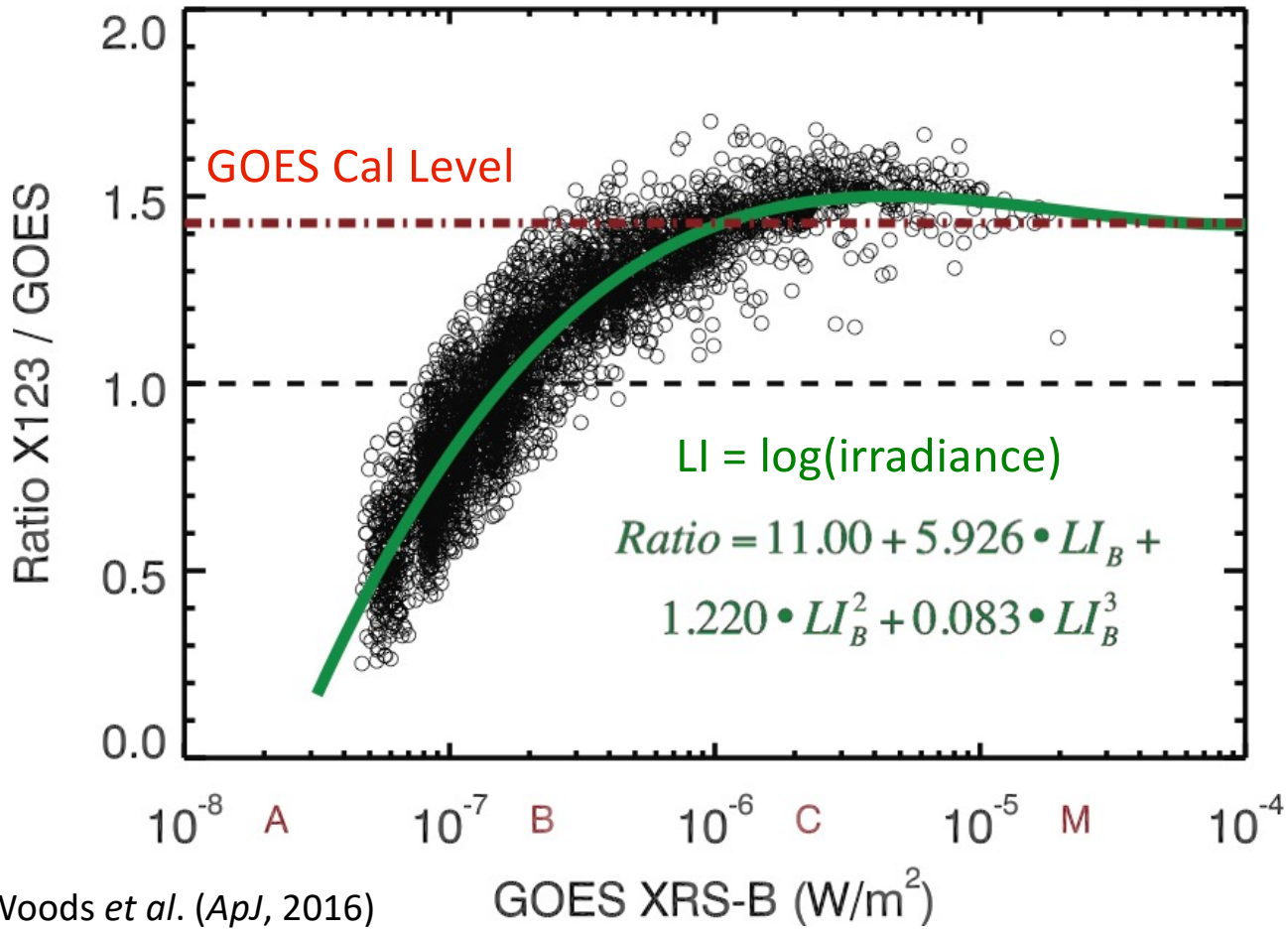


Figure from Woods *et al*. (*ApJ*, 2016)

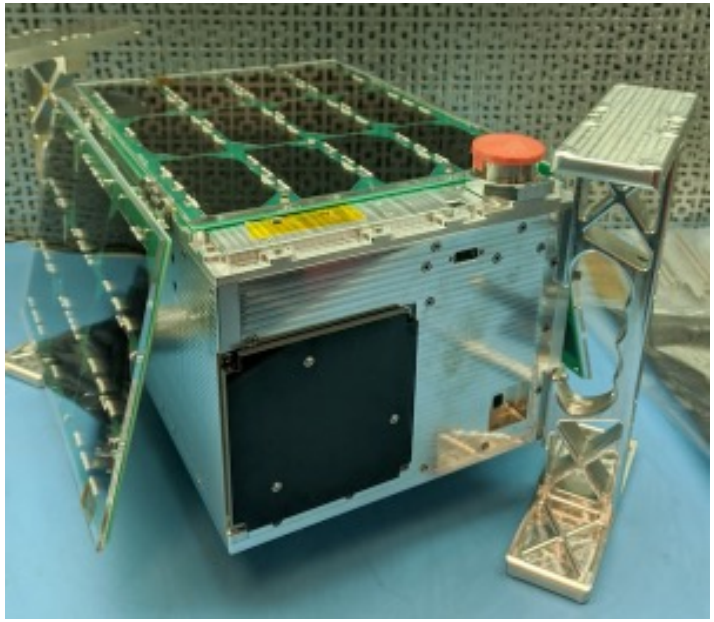
Miniature X-ray Solar Spectrometer

MinXSS CubeSat

Future Plans

More Solar Science CubeSats Planned

- "MinXSS-3" – awaiting launch
  - InspireSat-1 is on ESPA-like ring with rideshare on PSLV C-52 (PI: Amal Chandran)
  - Expected to overlap with India's Chandrayaan-2 Solar X-ray Monitor (similar to X123)
- CUBIXSS – completed Phase A
  - 6U CubeSat to study flare energetics with SXR imager and spectrometer (PI: Amir Caspi)
- SunCET – completed Phase A
  - 6U CubeSat to study Coronal Mass Ejections (CMEs) with EUV wide-FOV imager (PI: James Mason)



InspireSat-1
Launch is NET August 2021

Summary

- MinXSS has been very exciting and successful project
  - MinXSS has demonstrated key technology (e.g., BCT XACT, X123).
  - MinXSS has provided higher resolution and calibrated solar soft X-ray (SXR) spectra and helped to fill the SXR gap.
  - MinXSS has provided new results on flare energetics and revealed differences of coronal heating processes.
  - MinXSS has provided new reference spectra important for modeling Earth's atmosphere and calibration for GOES XRS.
- Key Reference Papers about MinXSS:
  - MinXSS-1 Overview: Mason et al., *J Spacecraft Rockets*, 2016
  - MinXSS-2 and Lessons Learned: Mason et al., *Adv Sp Res*, 2020
  - Calibration Paper: Moore et al., *SPIE 9905*, 2017
  - Solar Science Overview: Moore et al., *Solar Phys*, 2018
  - MinXSS-1 First Light Paper: Woods et al., *Ap J Lett*, 2016
  - DAXSS Instrument (MinXSS-3): Schwab & Sewell et al., *Ap J*, 2020

MinXSS web site

http://lasp.colorado.edu/home/minxss/