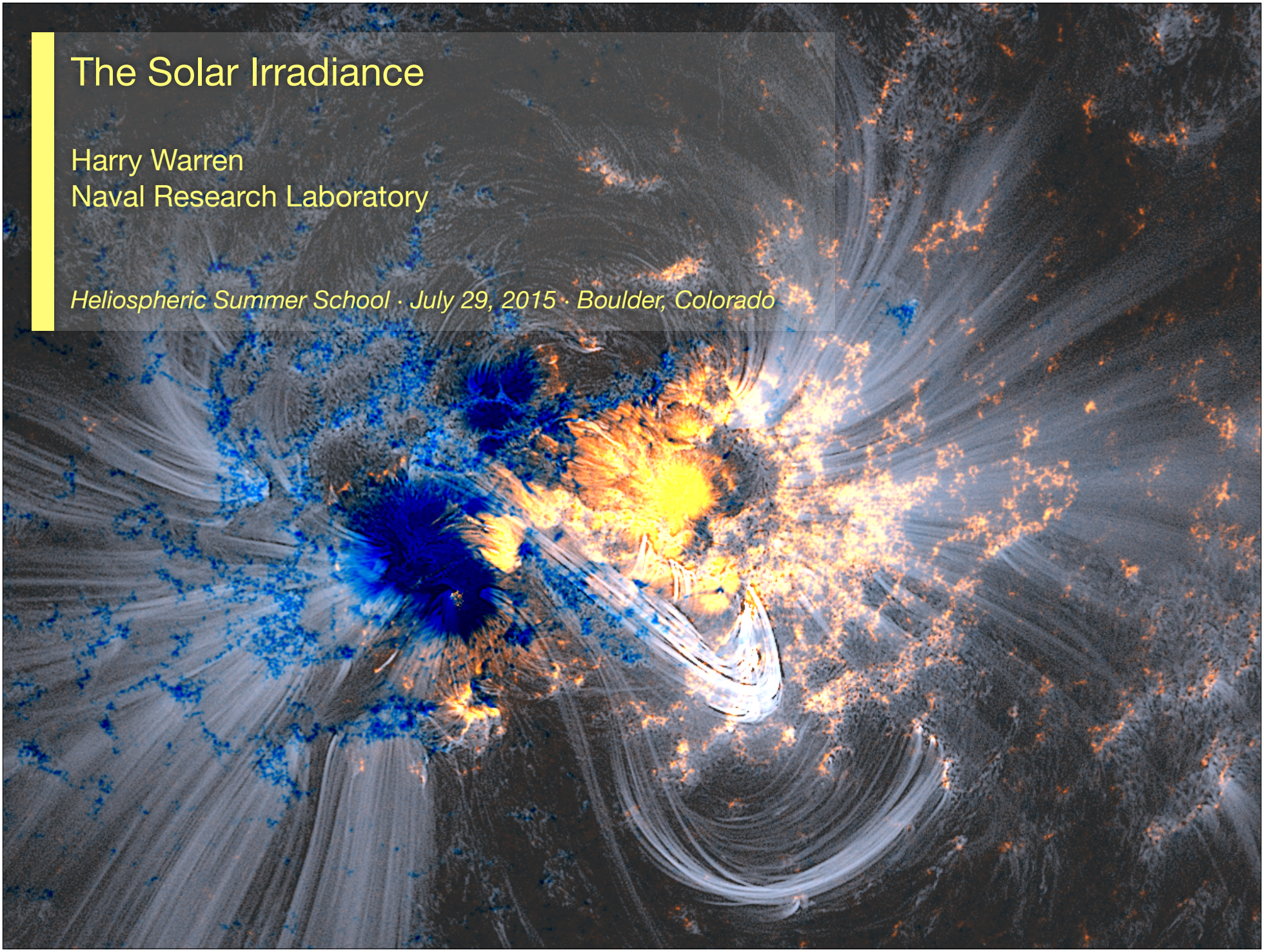
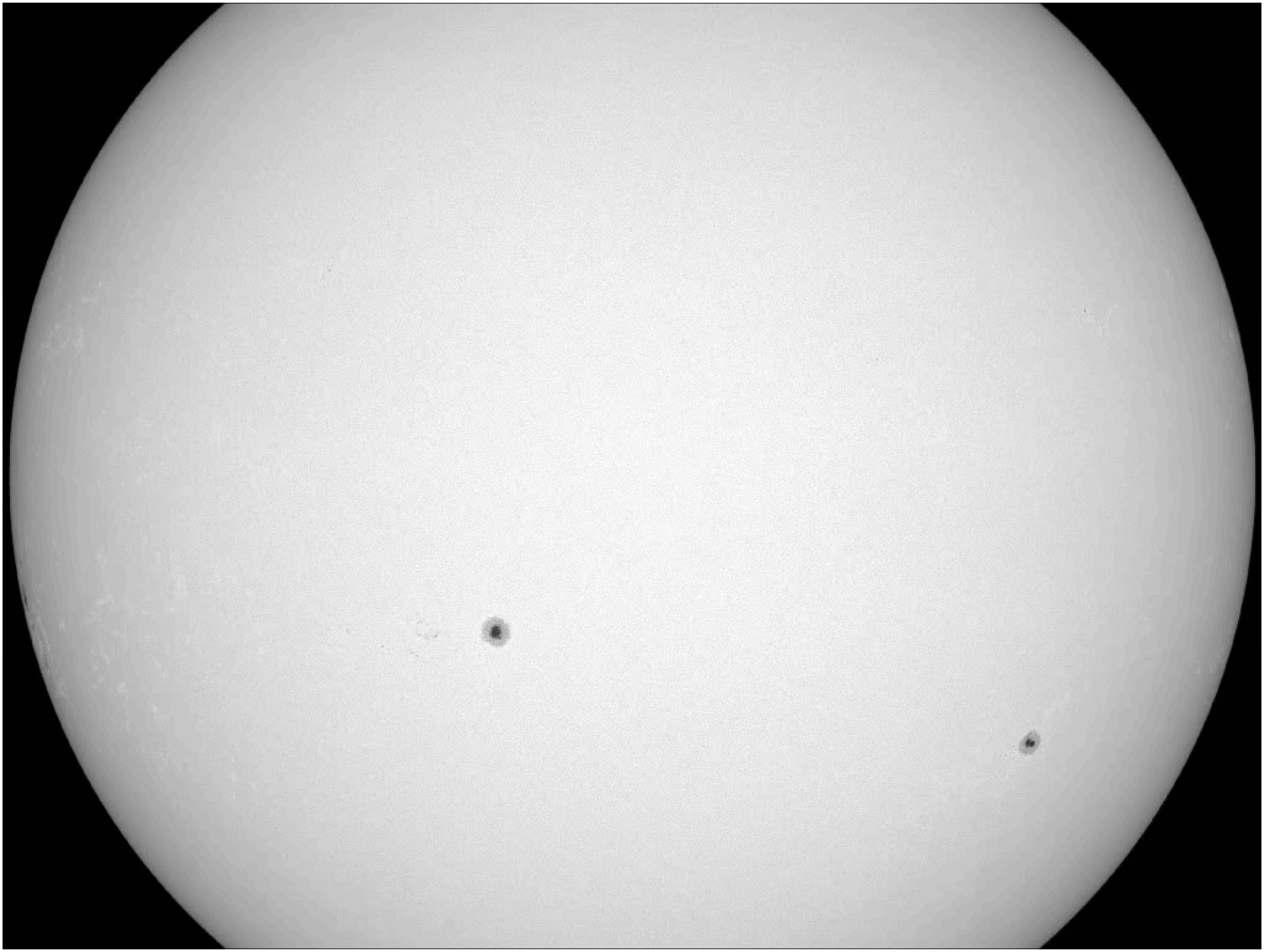
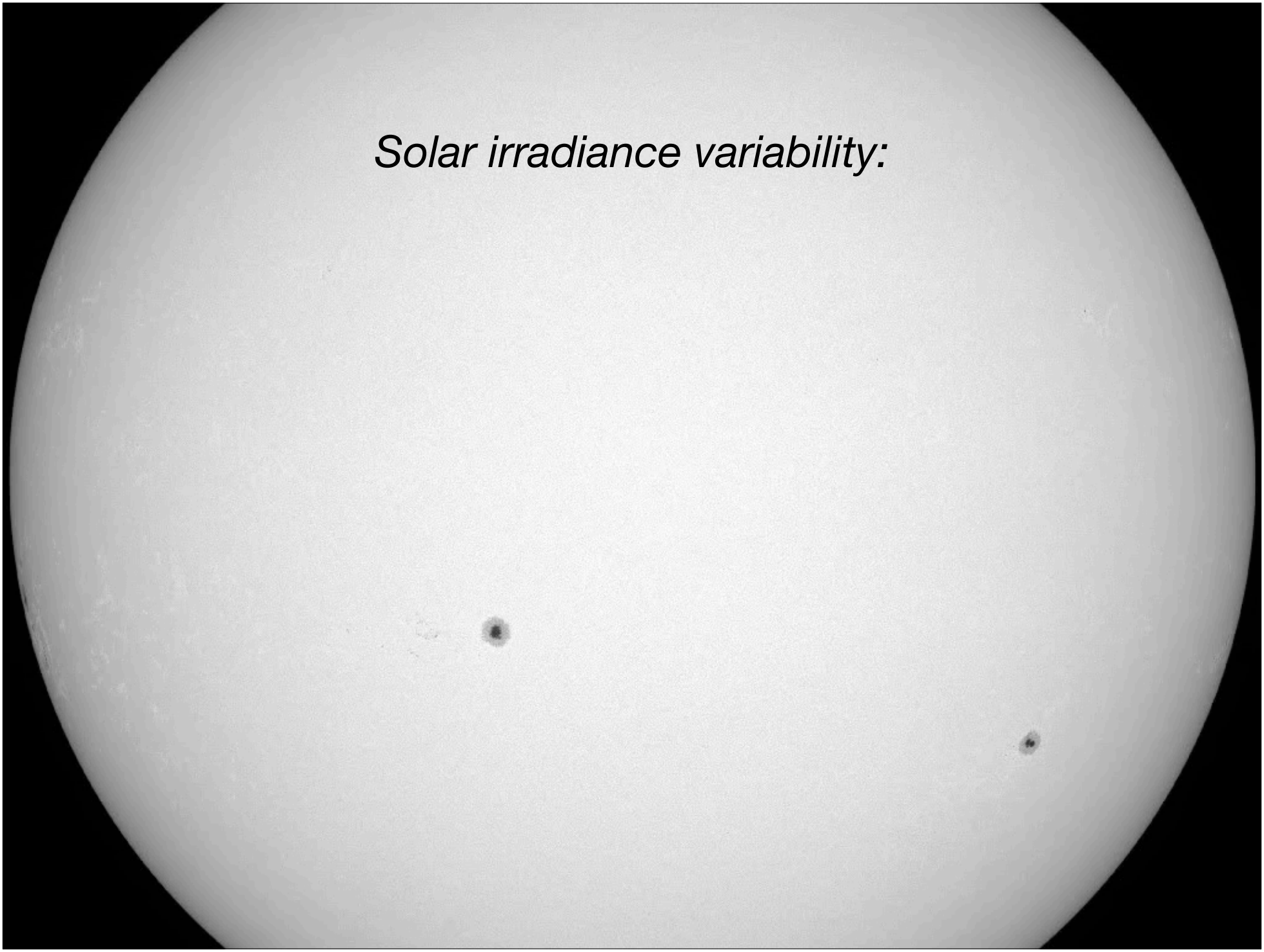
The Solar Irradiance

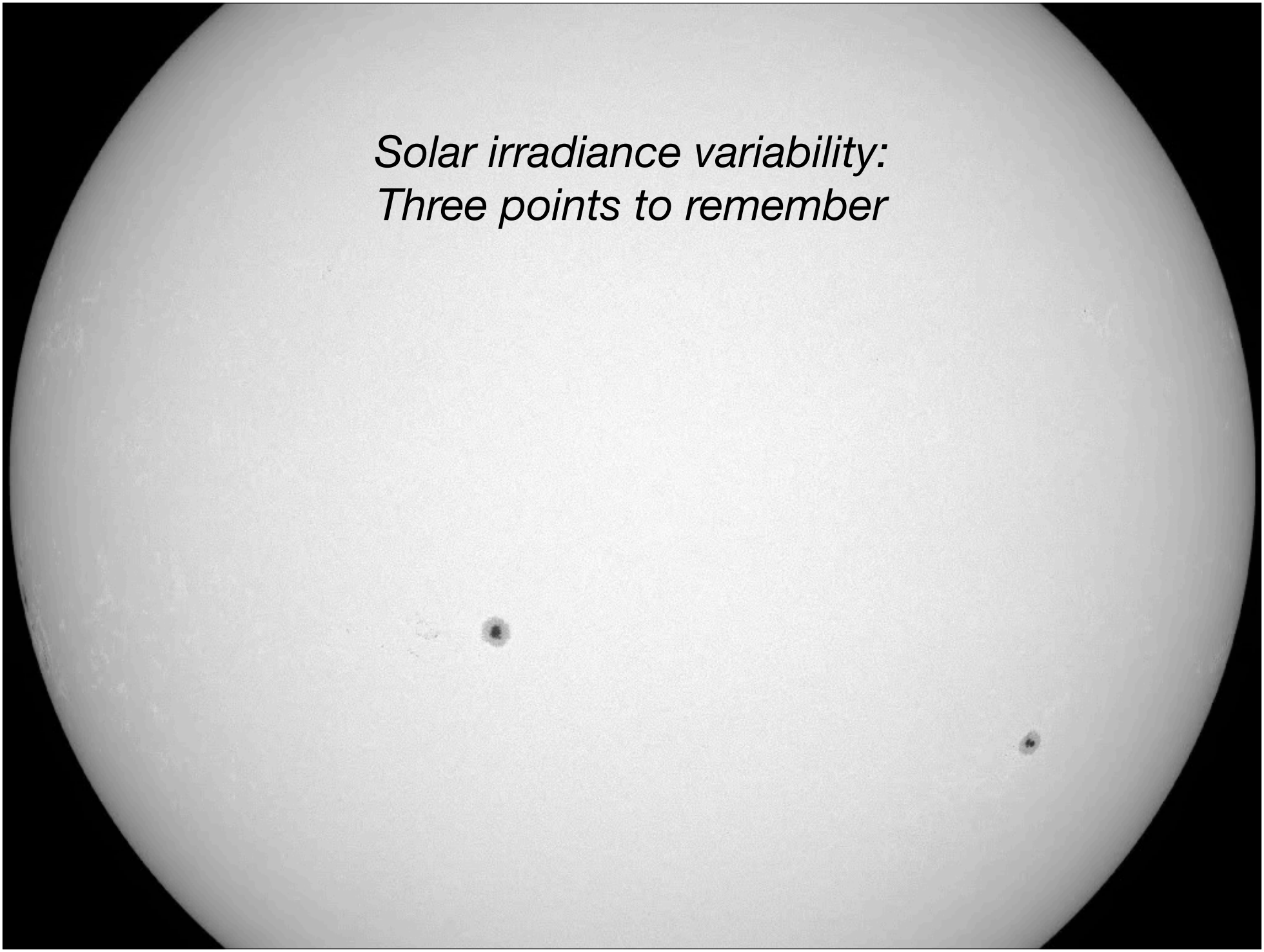
Harry Warren
Naval Research Laboratory

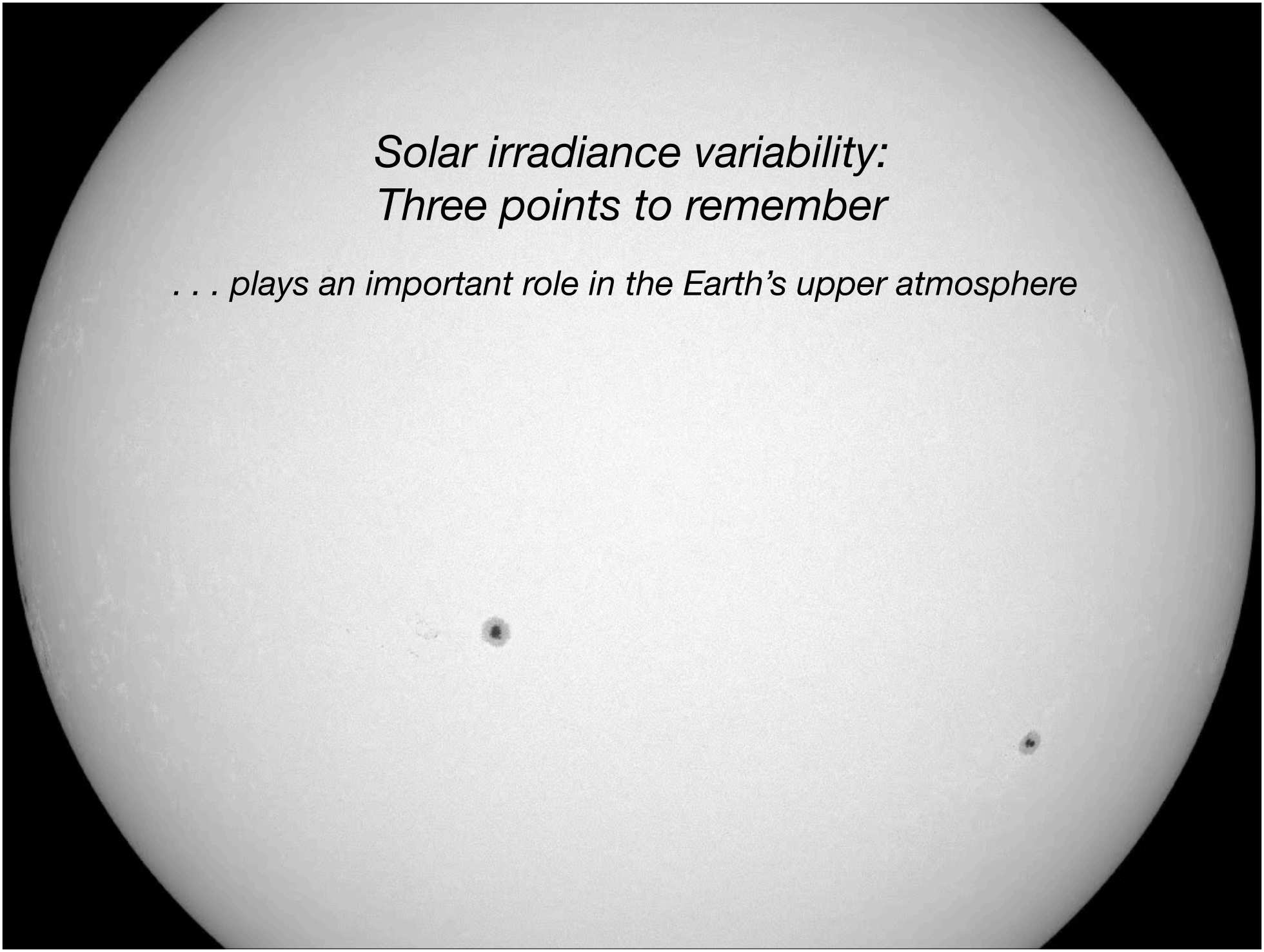
Heliospheric Summer School · July 29, 2015 · Boulder, Colorado

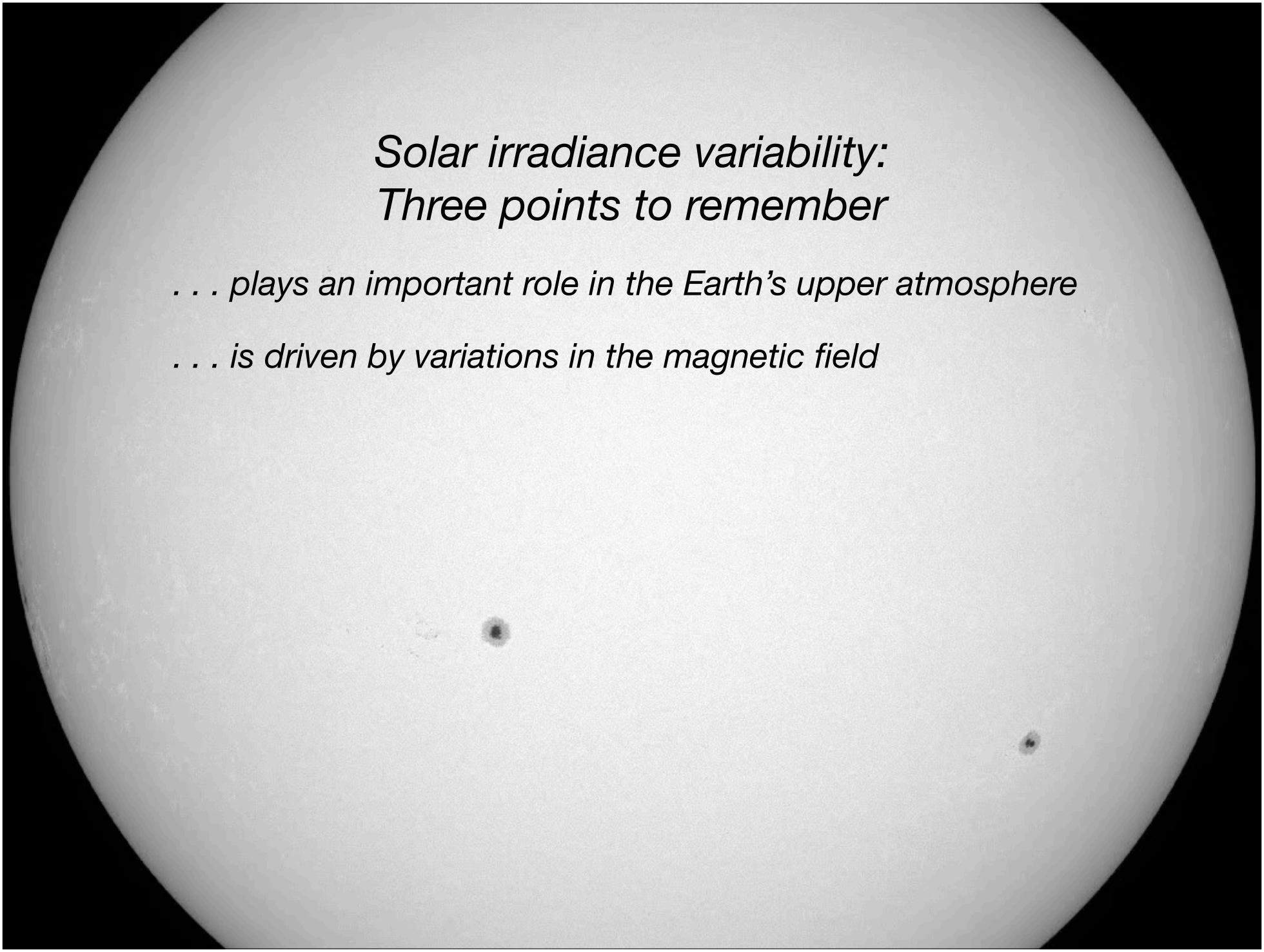





Solar irradiance variability:


Solar irradiance variability:
Three points to remember

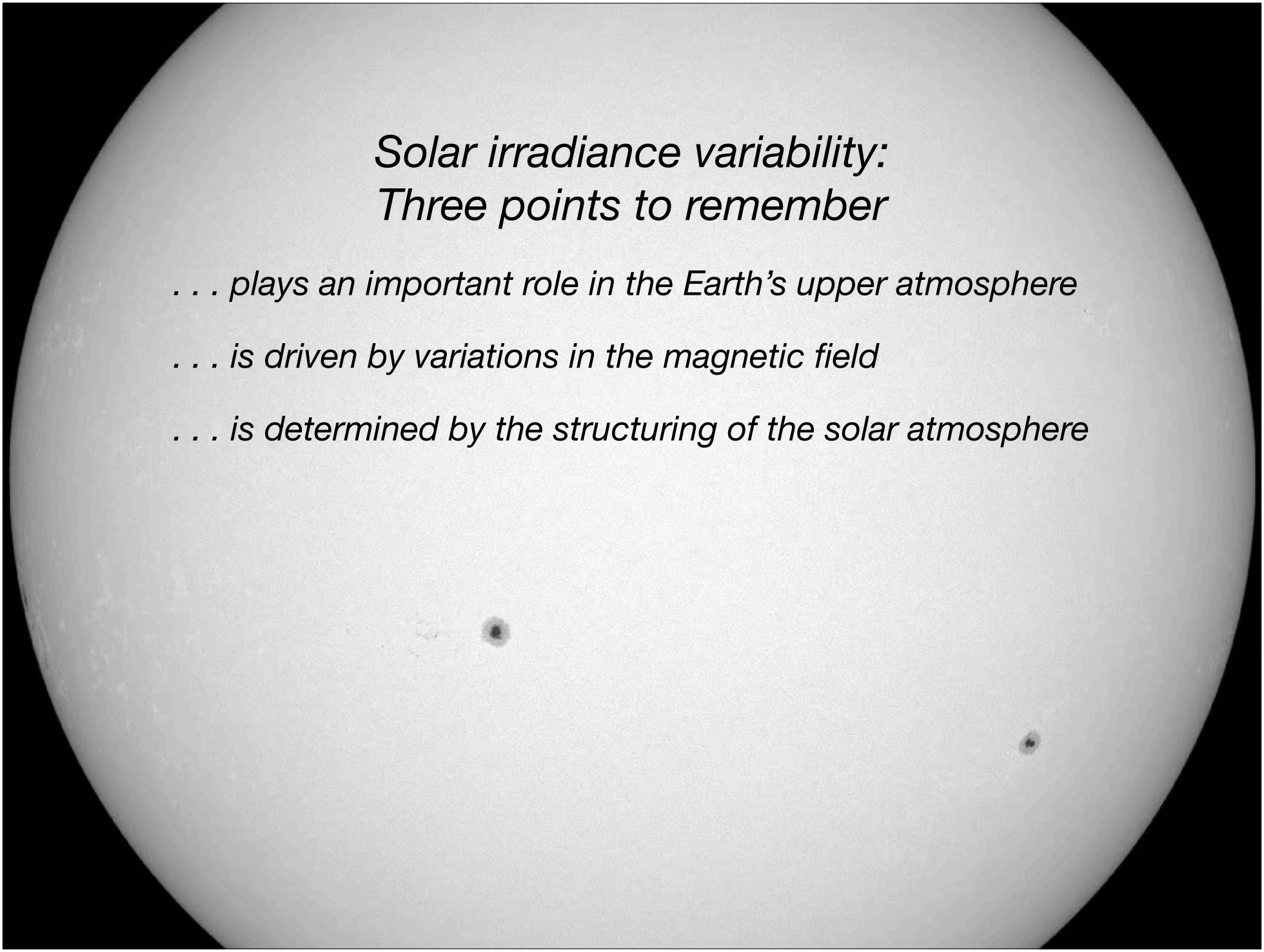

Solar irradiance variability:
Three points to remember
. . . plays an important role in the Earth's upper atmosphere



Solar irradiance variability: Three points to remember

. . . plays an important role in the Earth's upper atmosphere

. . . is driven by variations in the magnetic field

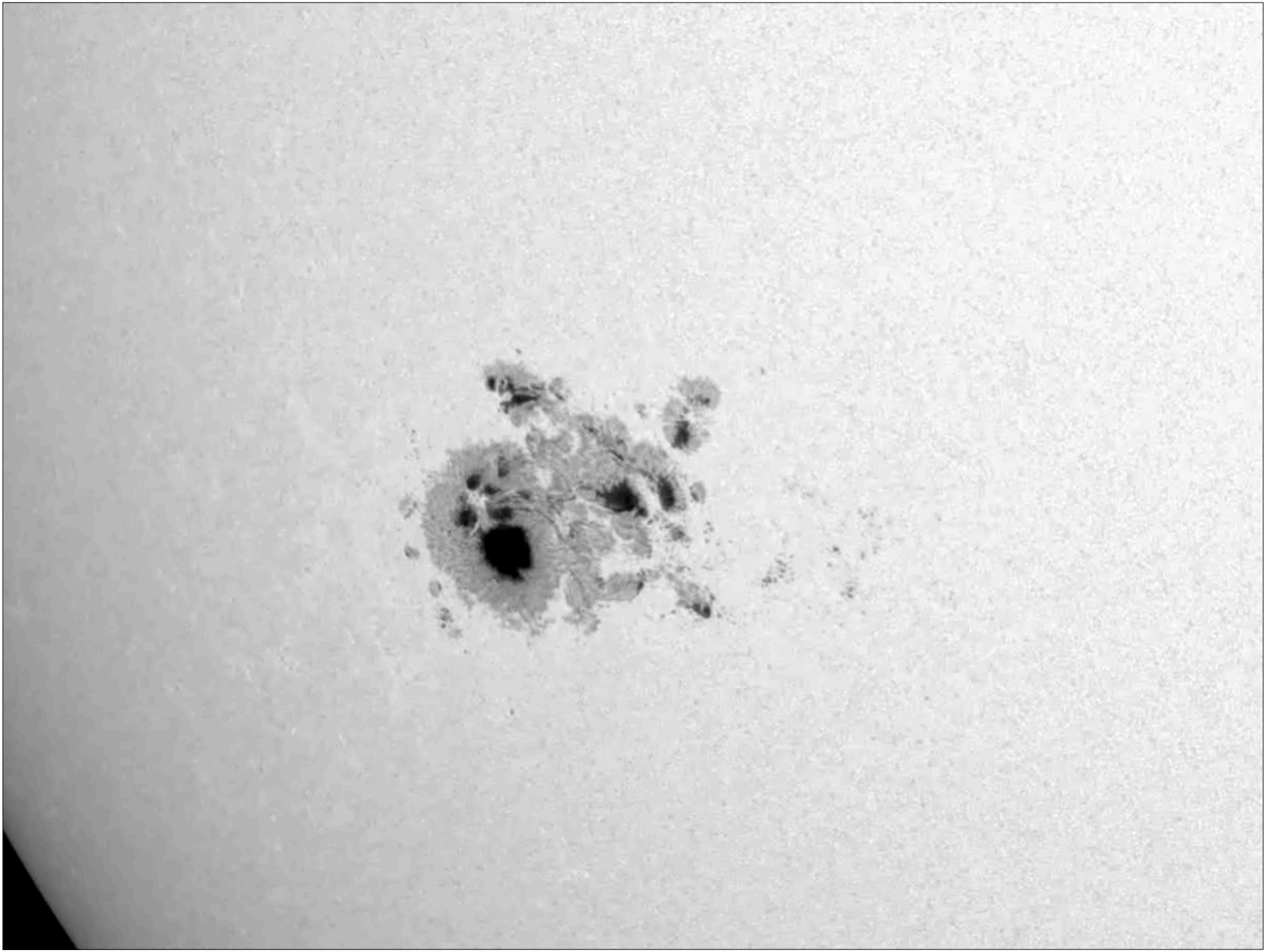


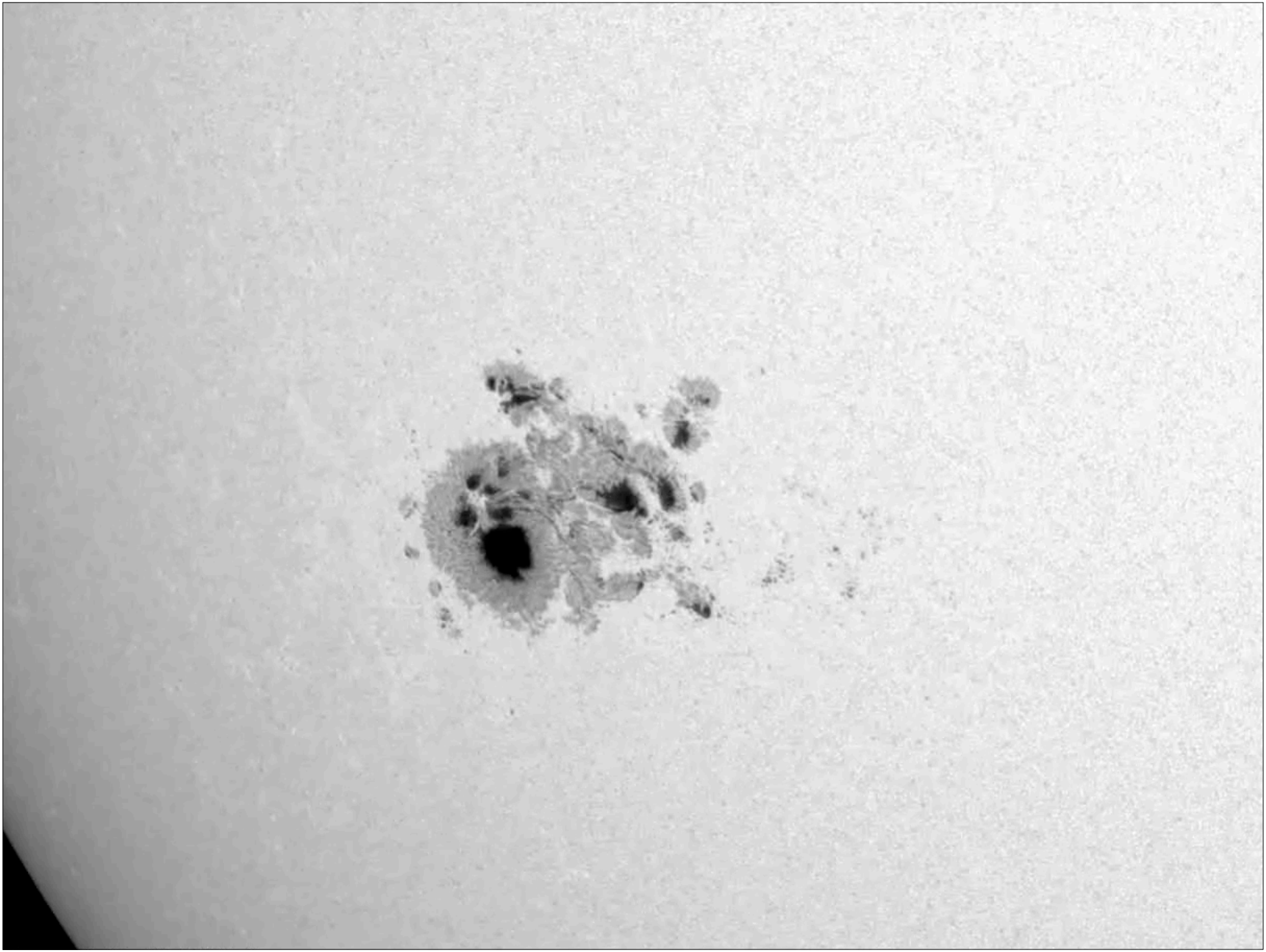
Solar irradiance variability: Three points to remember

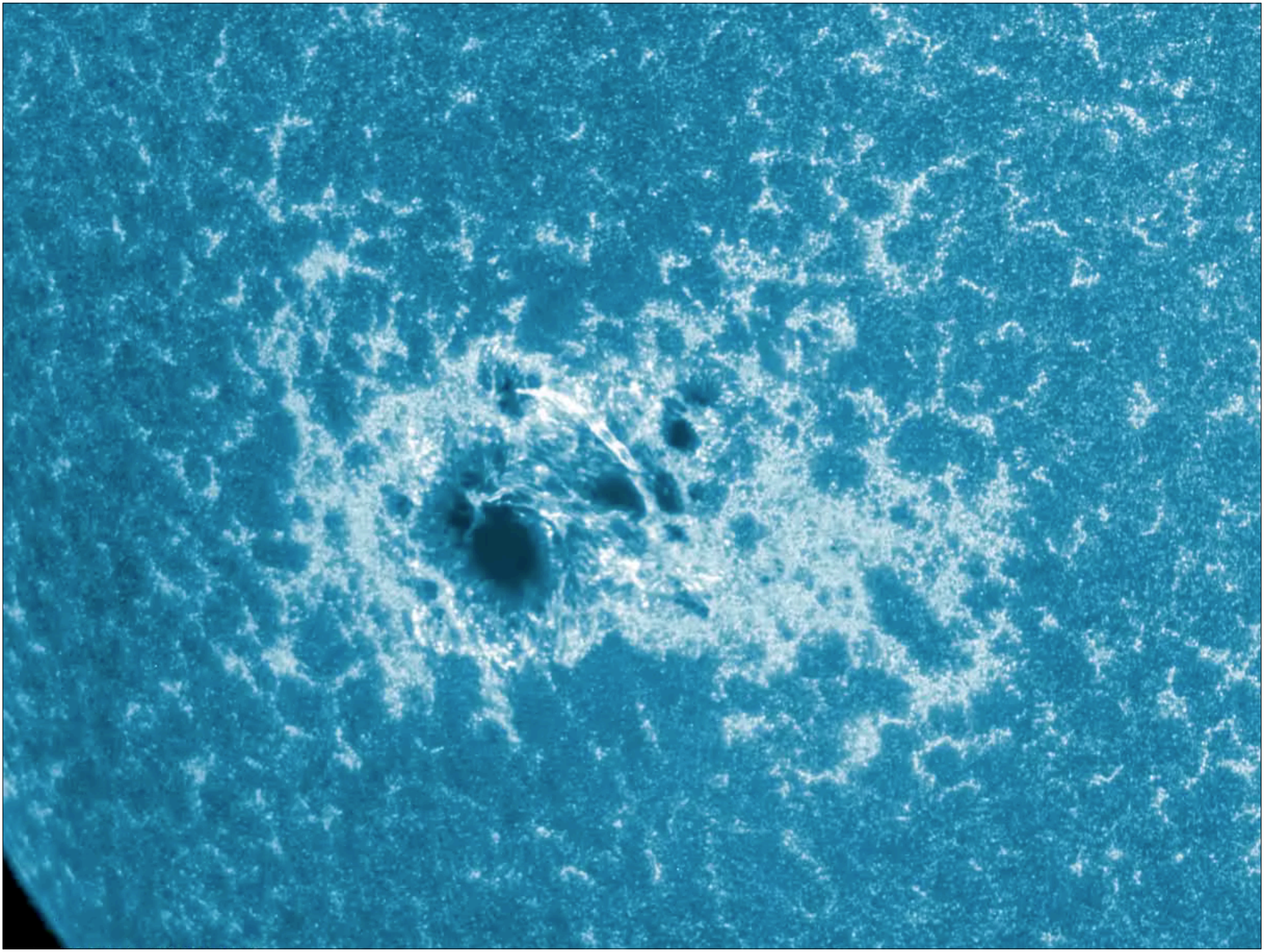
. . . plays an important role in the Earth's upper atmosphere

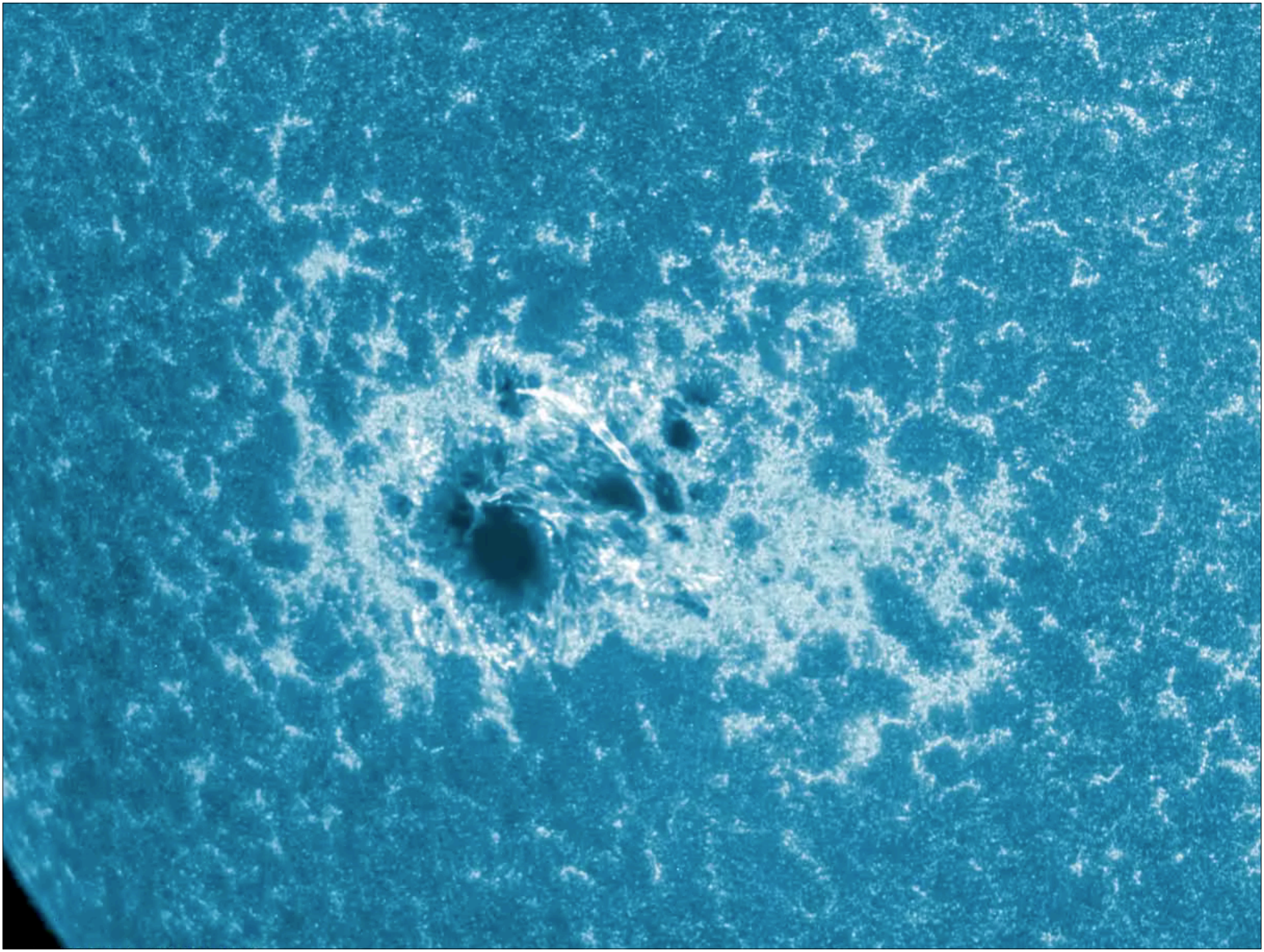
. . . is driven by variations in the magnetic field

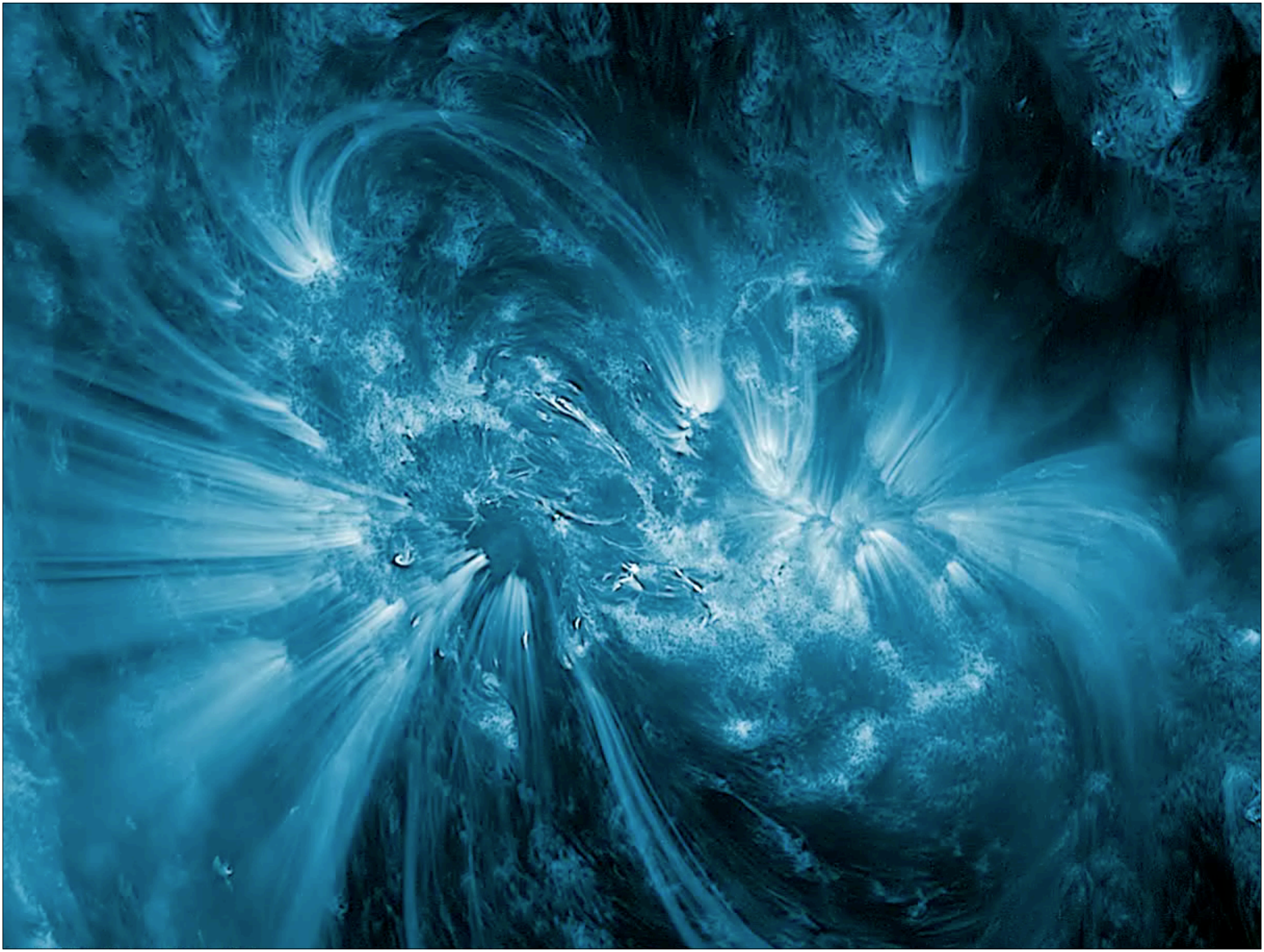
. . . is determined by the structuring of the solar atmosphere

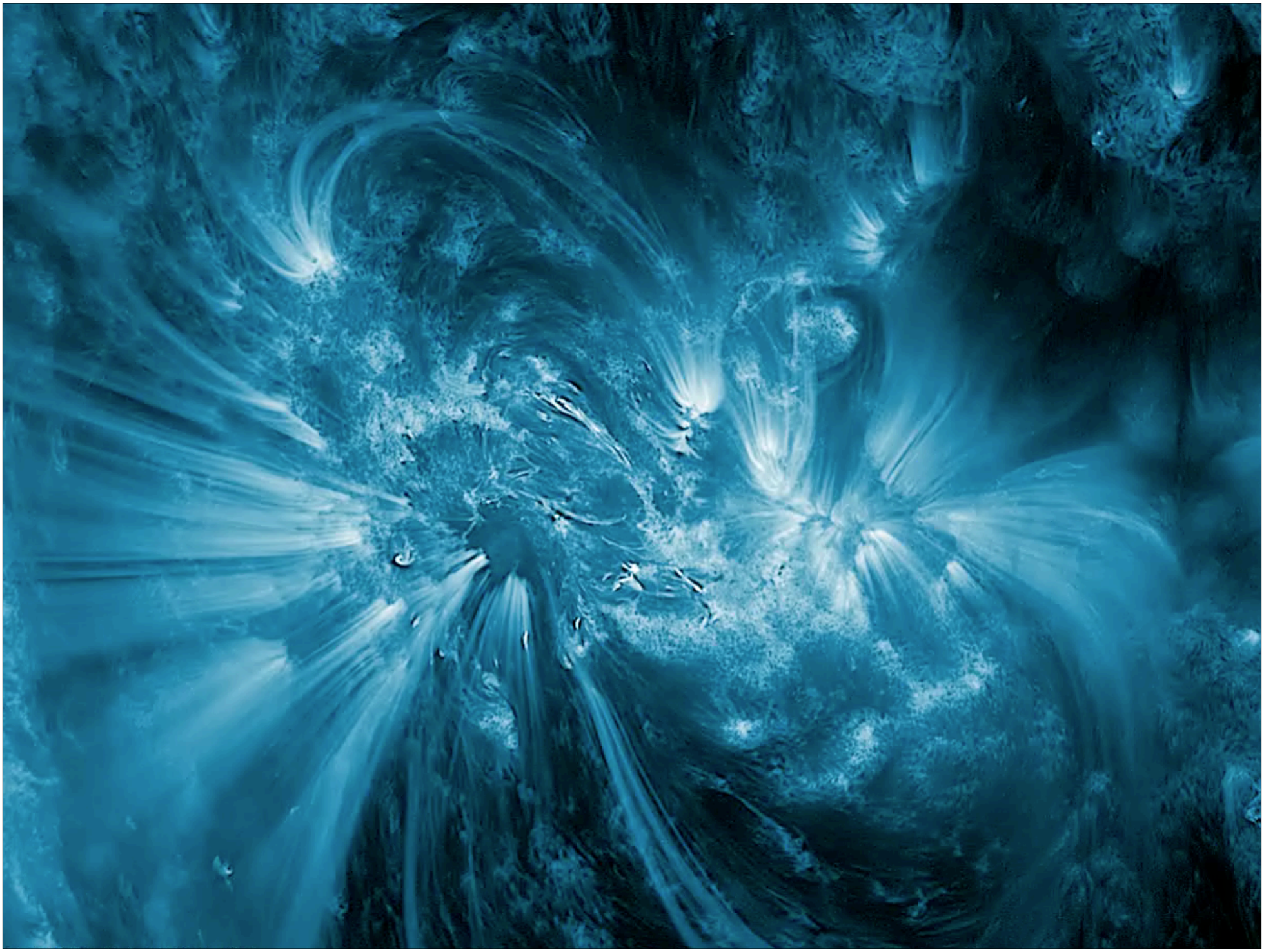


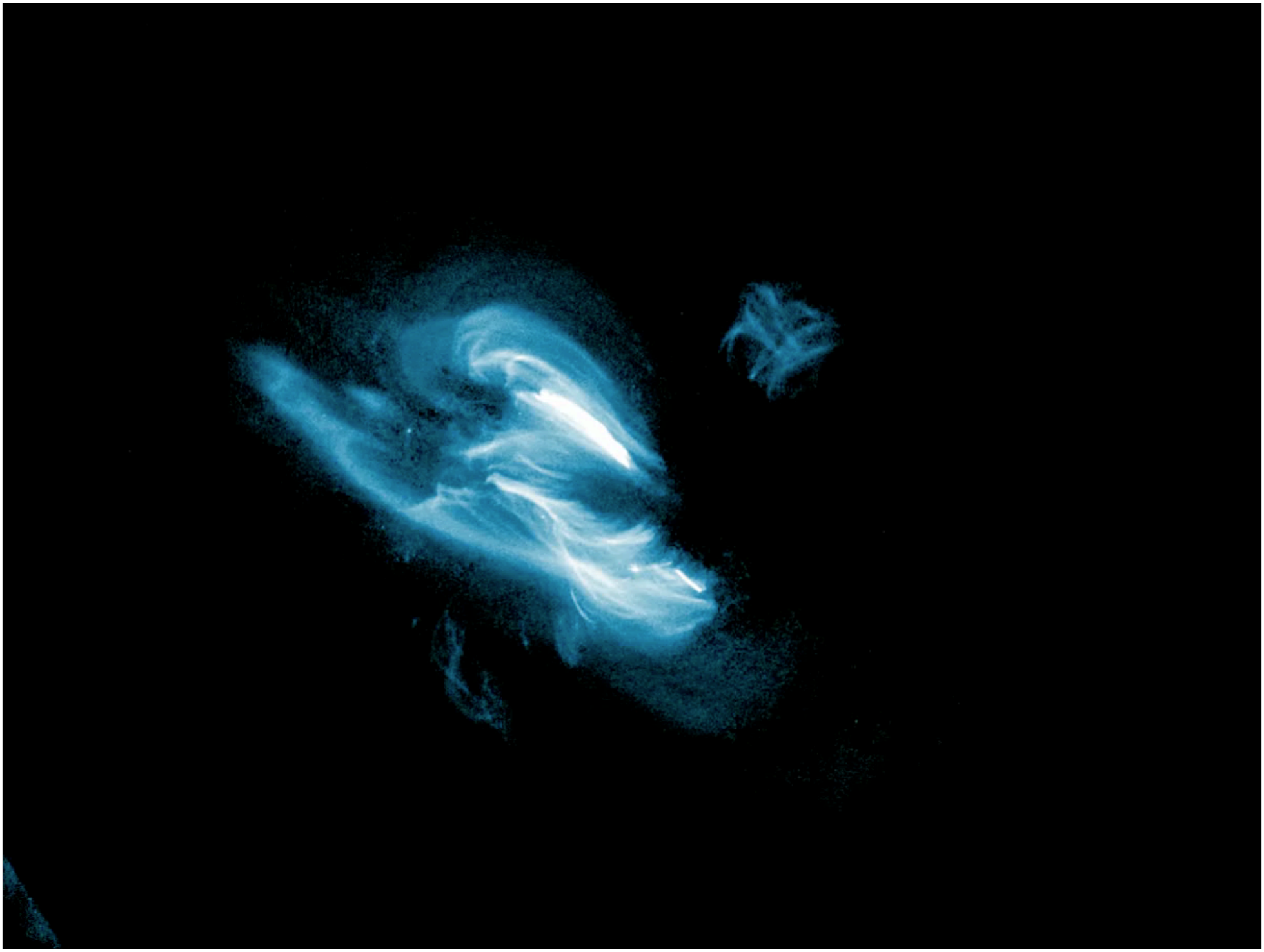


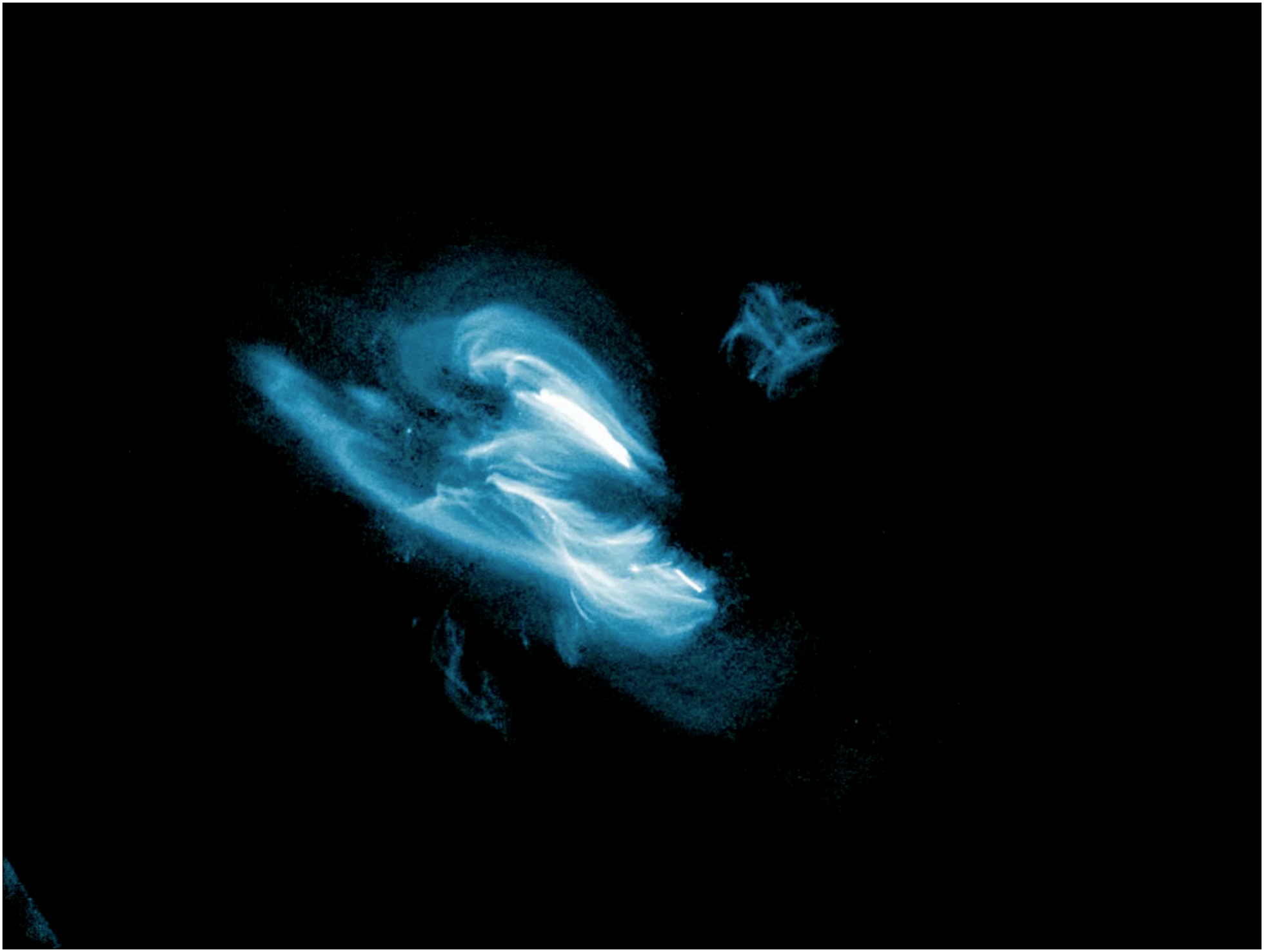


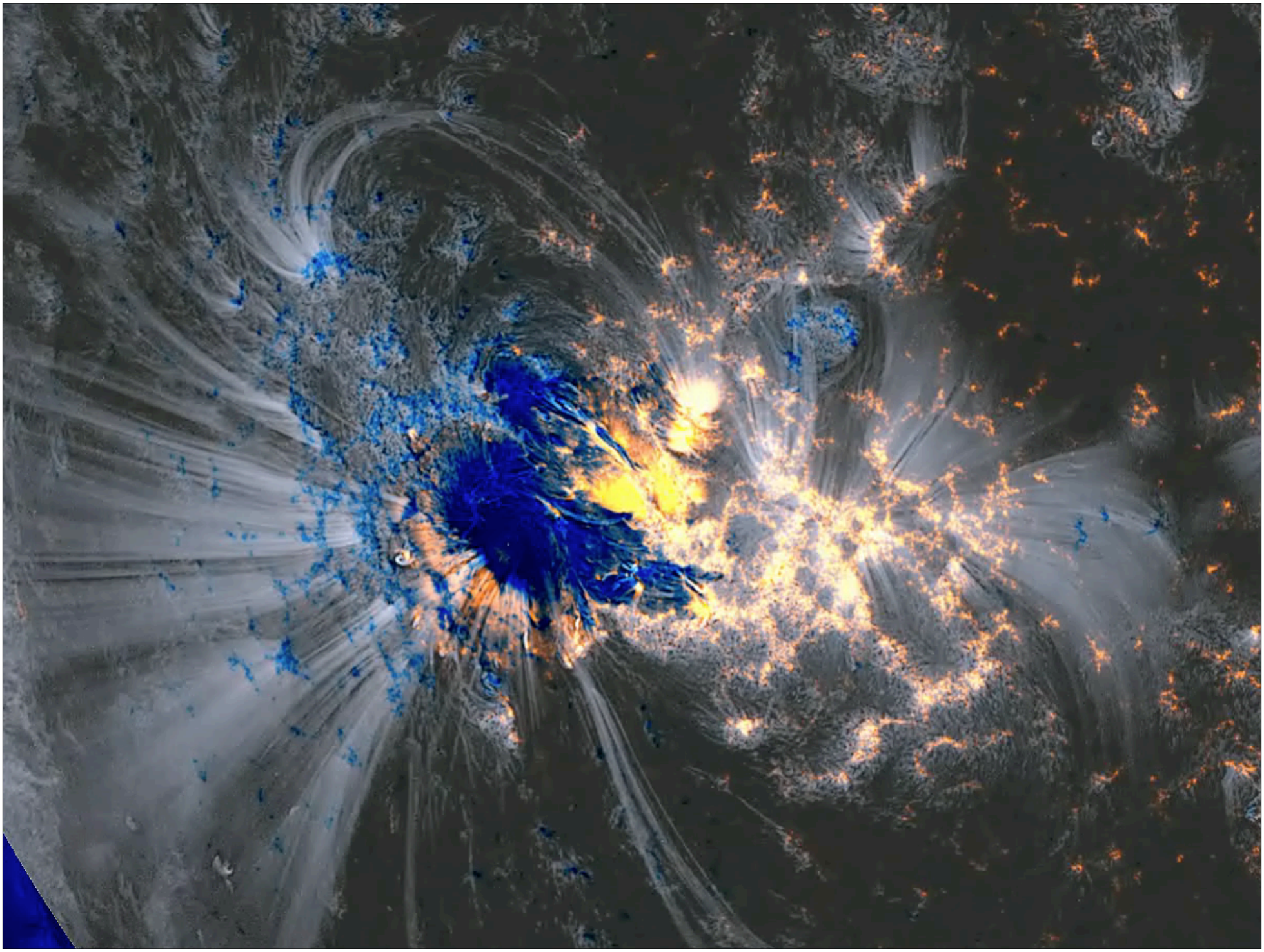


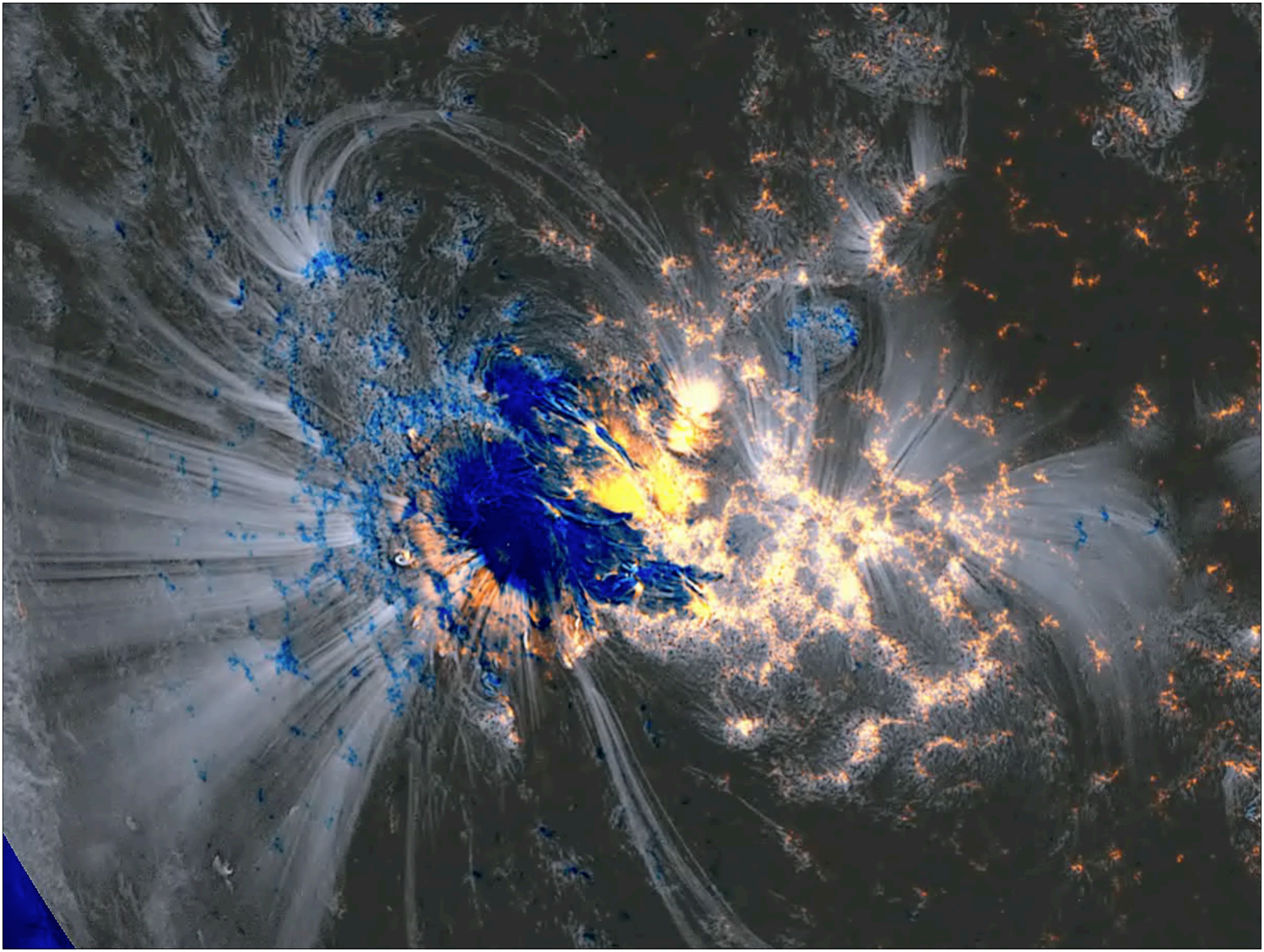




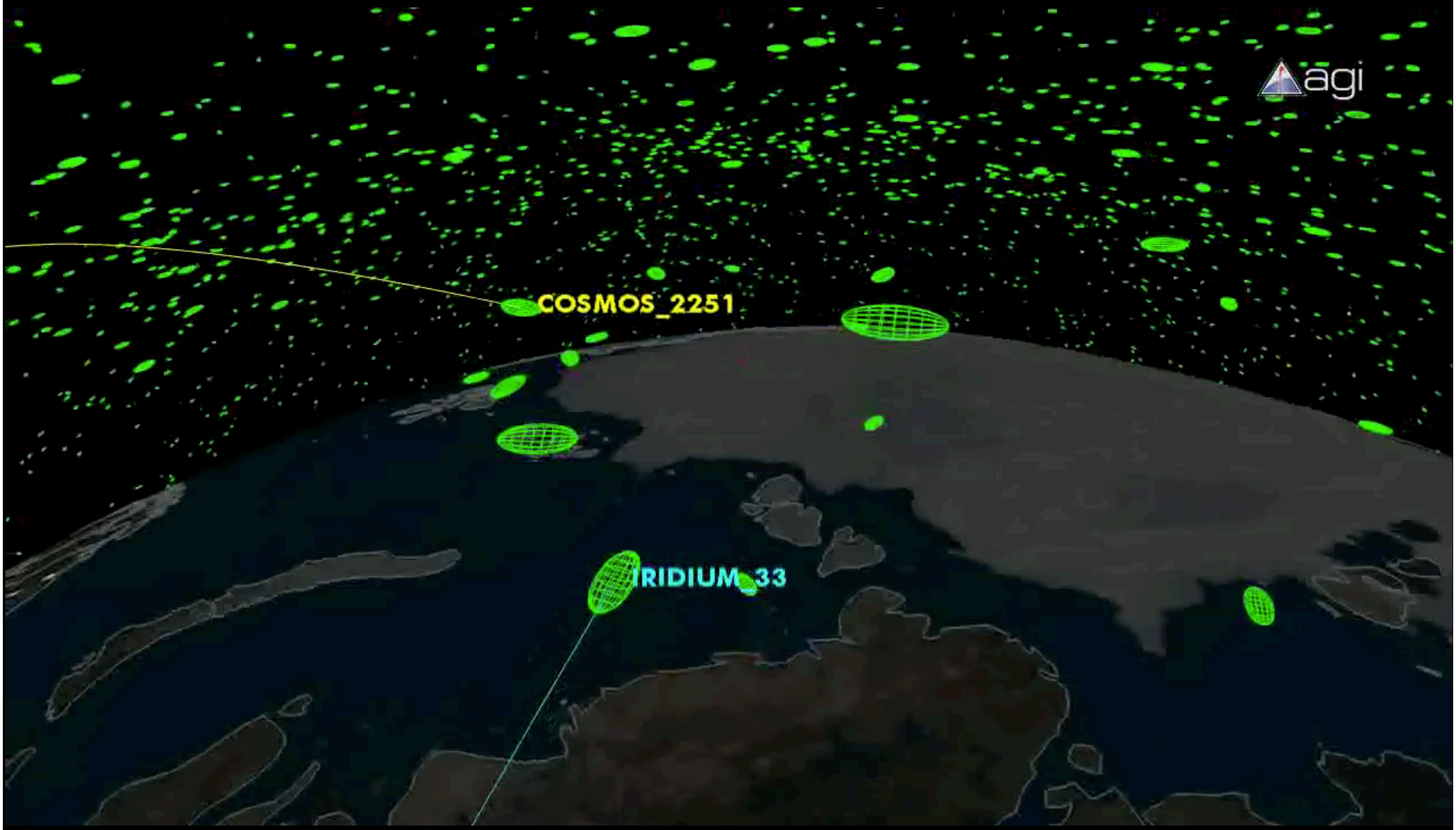








An Application: The Orbital Debris Problem



Video courtesy of Analytical Graphics, Inc. www.agi.com

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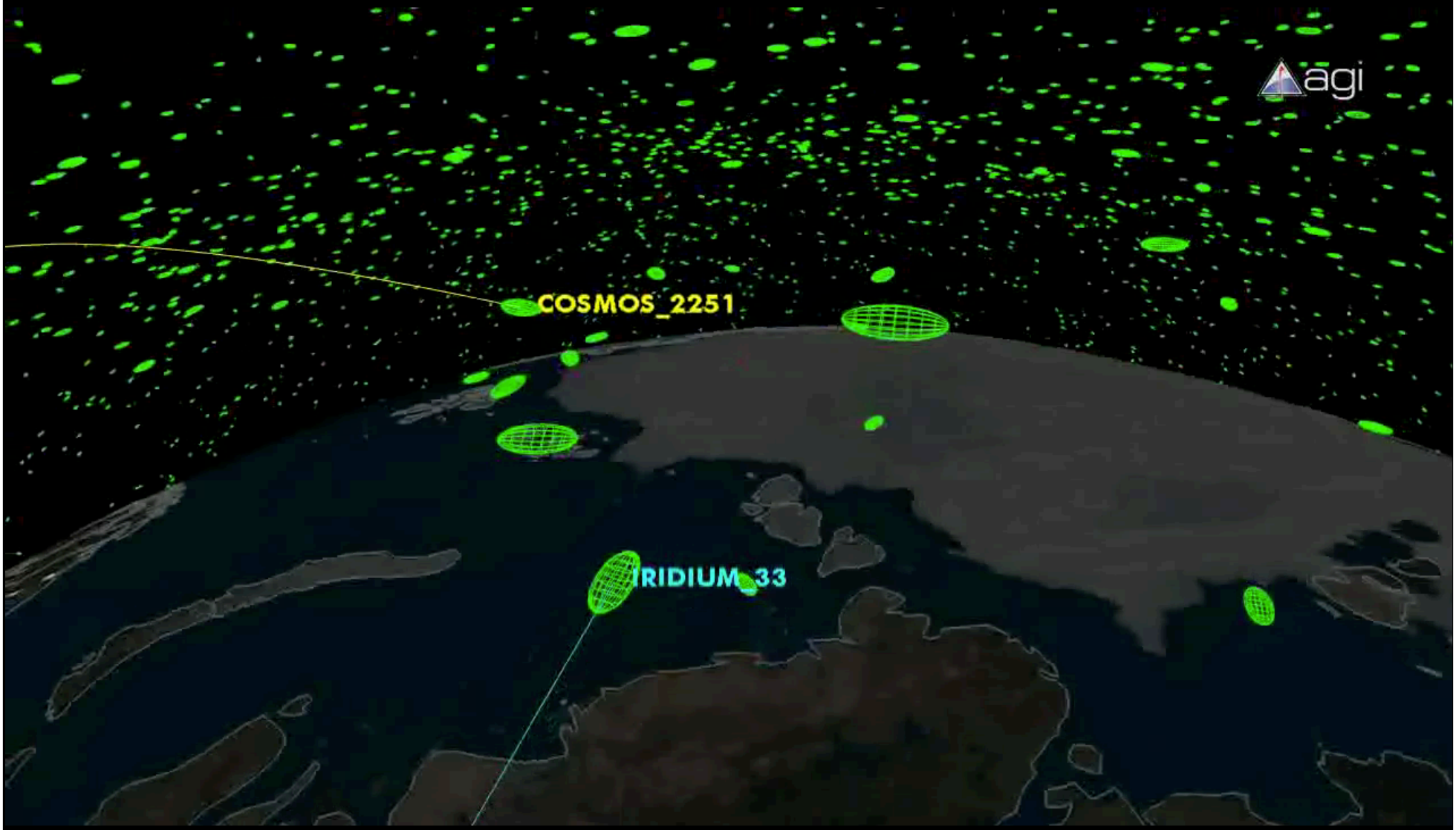


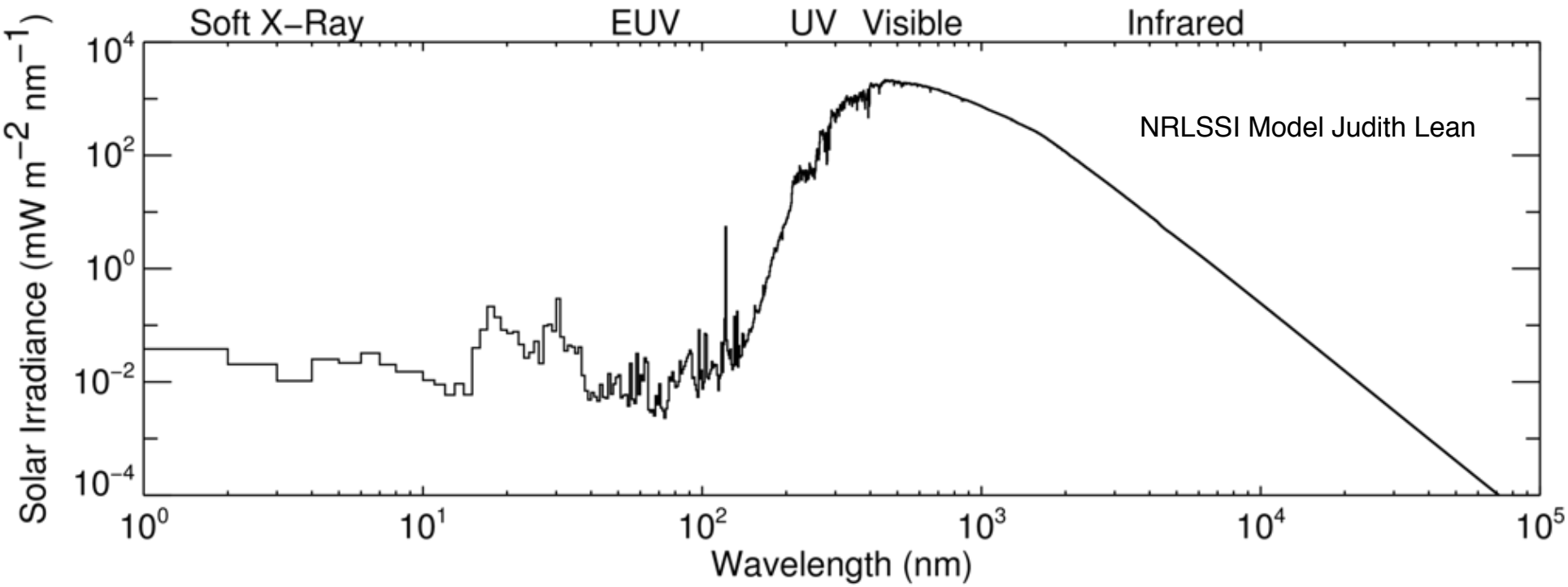
Video courtesy of Analytical Graphics, Inc. www.agi.com

Outline

- Total Solar Irradiance
  - Measurements
  - Application to climate change
- Solar Spectral Irradiance
  - The Solar Atmosphere
    - Soft X-rays
    - Extreme Ultraviolet
    - Ultraviolet
    - Visible/Infrared
  - Overview of observations
  - Application to satellite drag

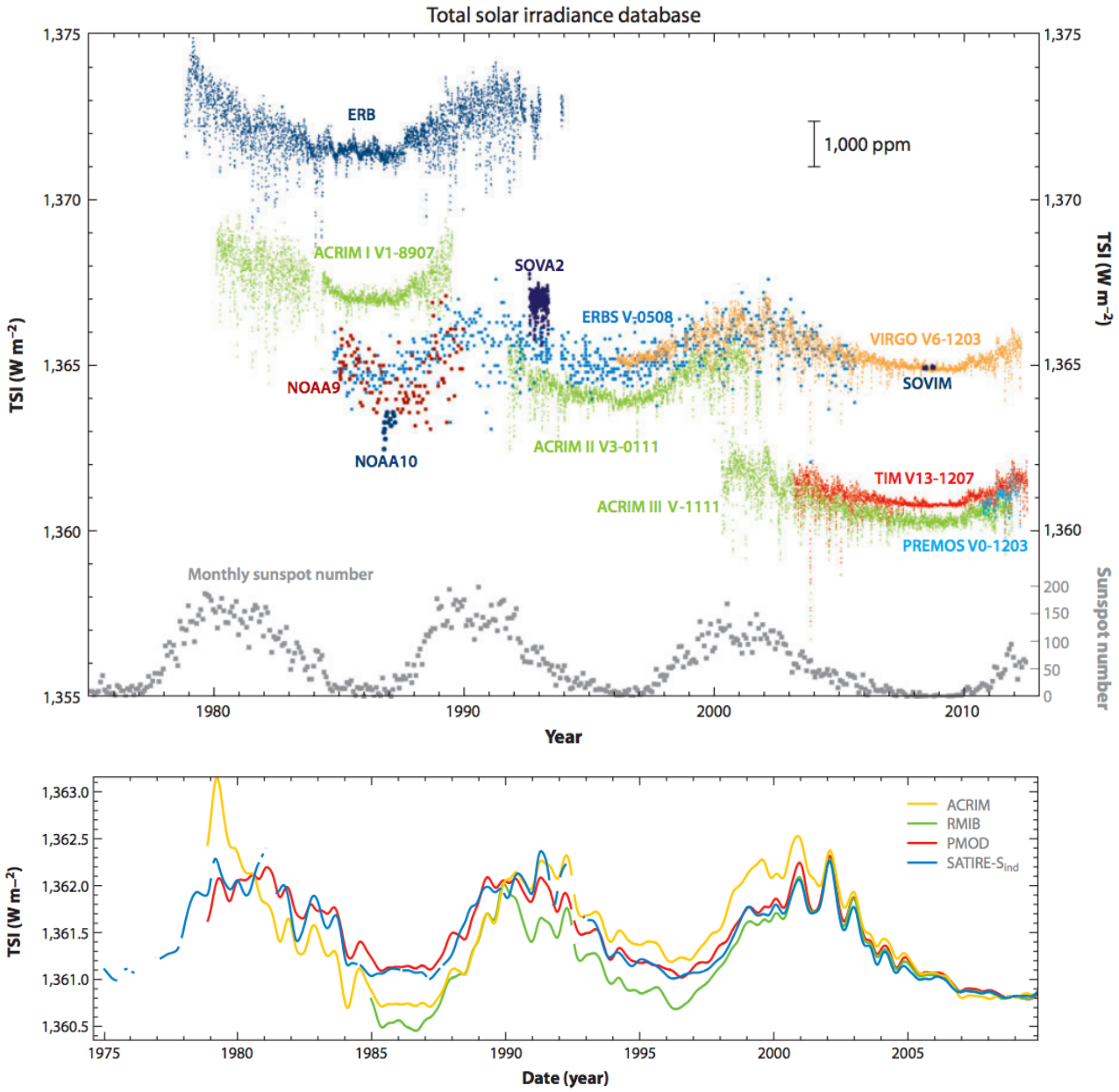
- Common proxies for solar activity
- Proxy irradiance models
- A quick note on regression
  - Training/Test/Validation
  - Gaussian Process Regression
- The magnetic flux as a proxy
- Forecasting solar activity
  - Autoregression
  - Magnetic flux transport
- Emission processes
  - Optically thin line emission
- Semi-empirical models
  - Differential emission measure
- My 2 cents on useful tools and skills

Overview of the Solar Spectral Irradiance



Total Solar Irradiance: The Sun's radiated power integrated over all wavelengths

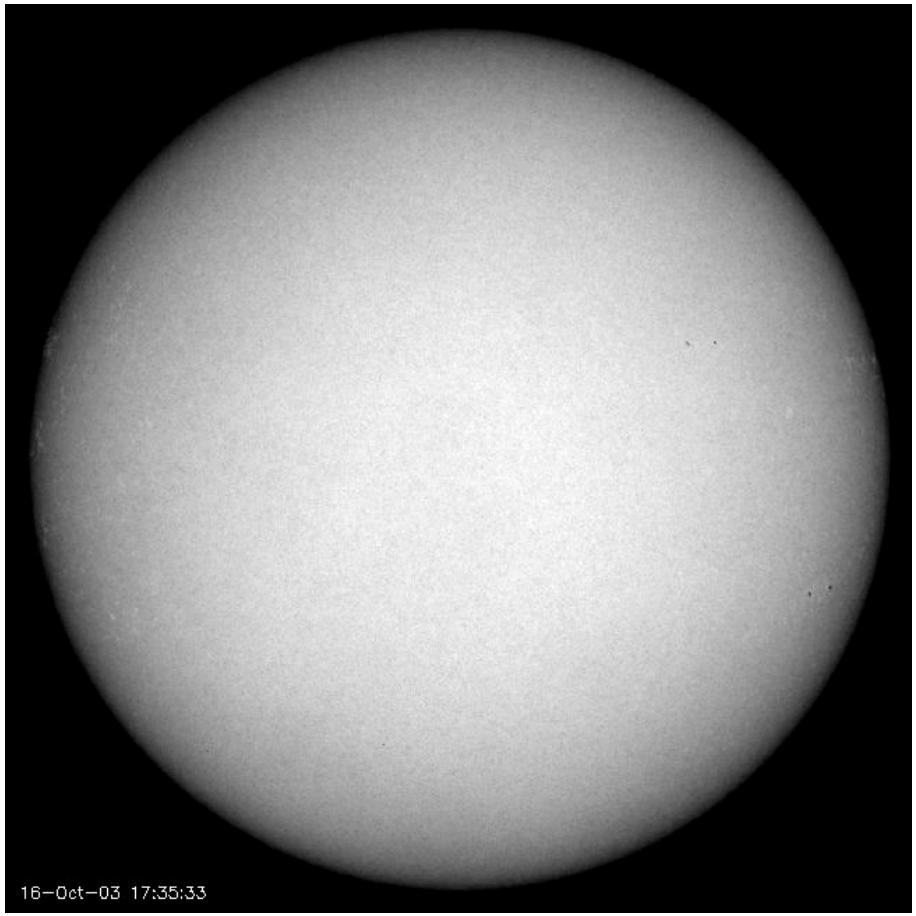
The Total Solar Irradiance: Measurements and Composites



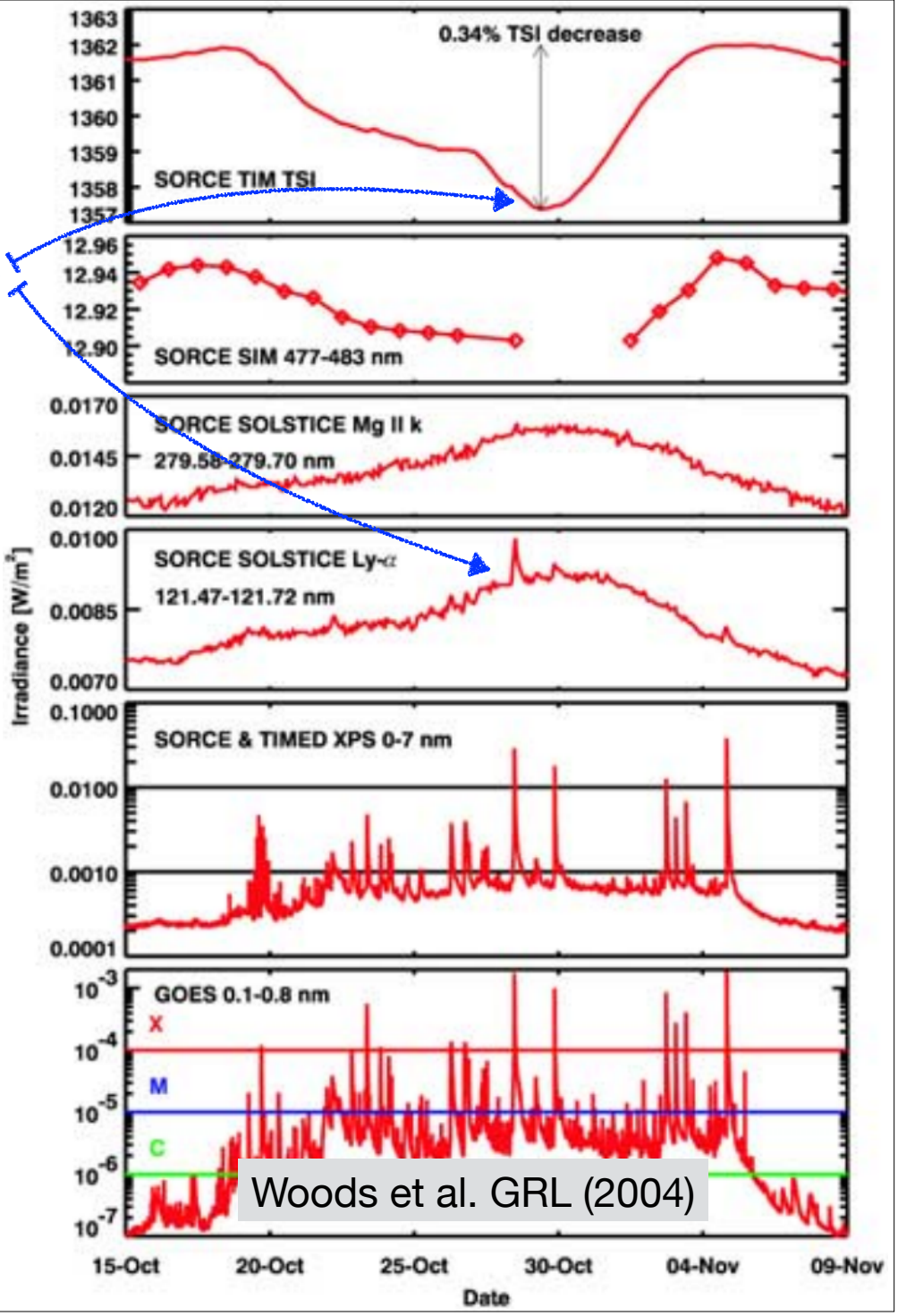
Solanki, Krivova, & Haigh, Annual Reviews, 2013

TSI Variations During a Period of Very High Solar Activity

TSI is often anti-correlated with solar activity



MDI/SoHO
October - November 2003



Woods et al. GRL (2004)

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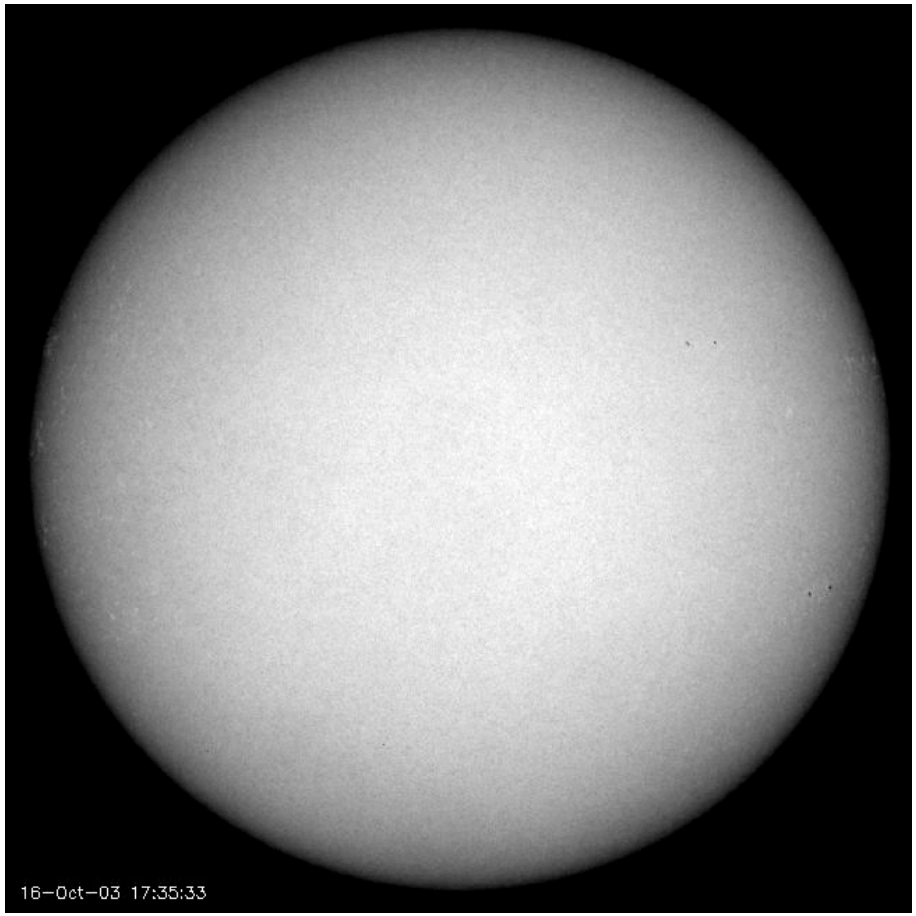

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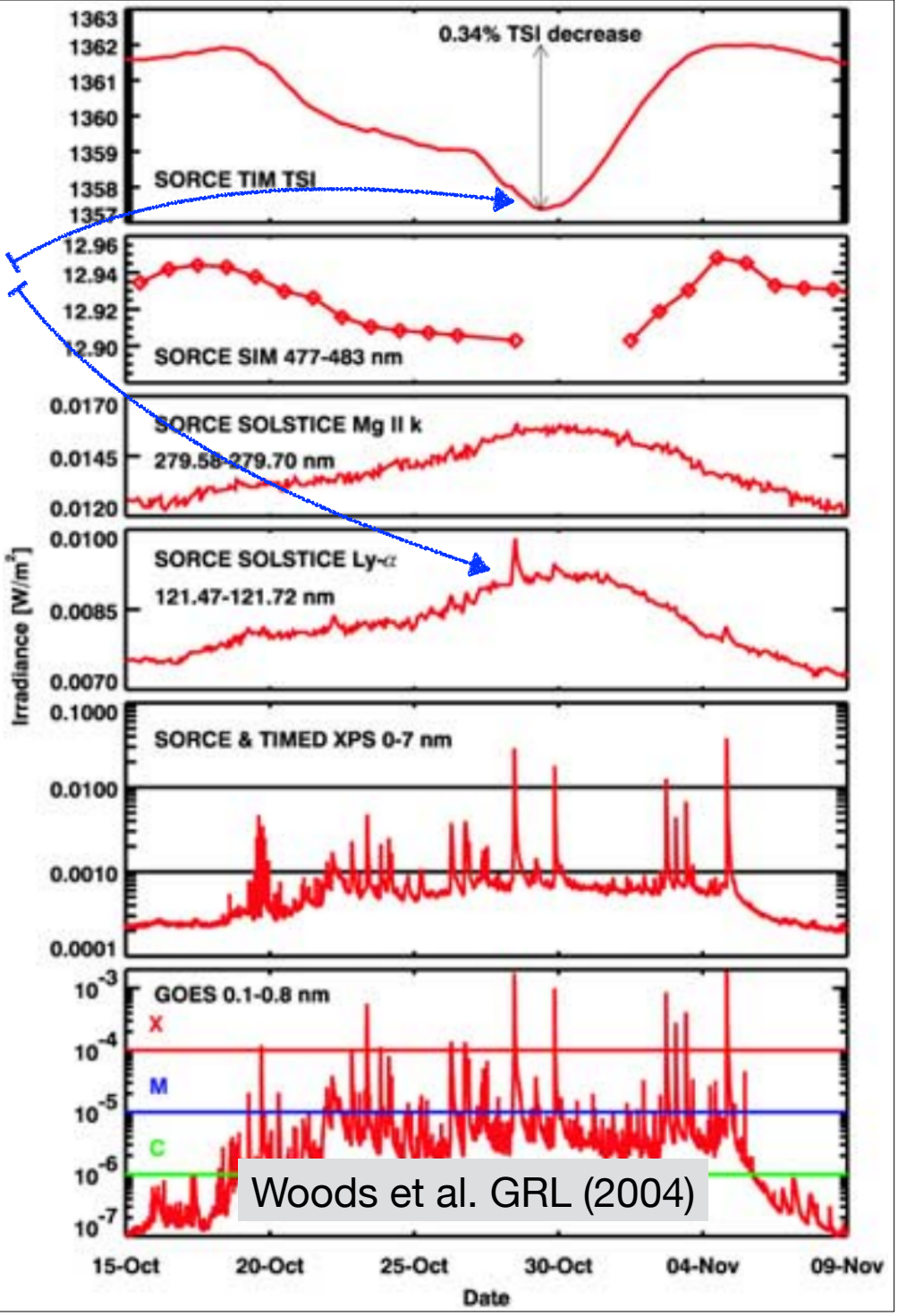
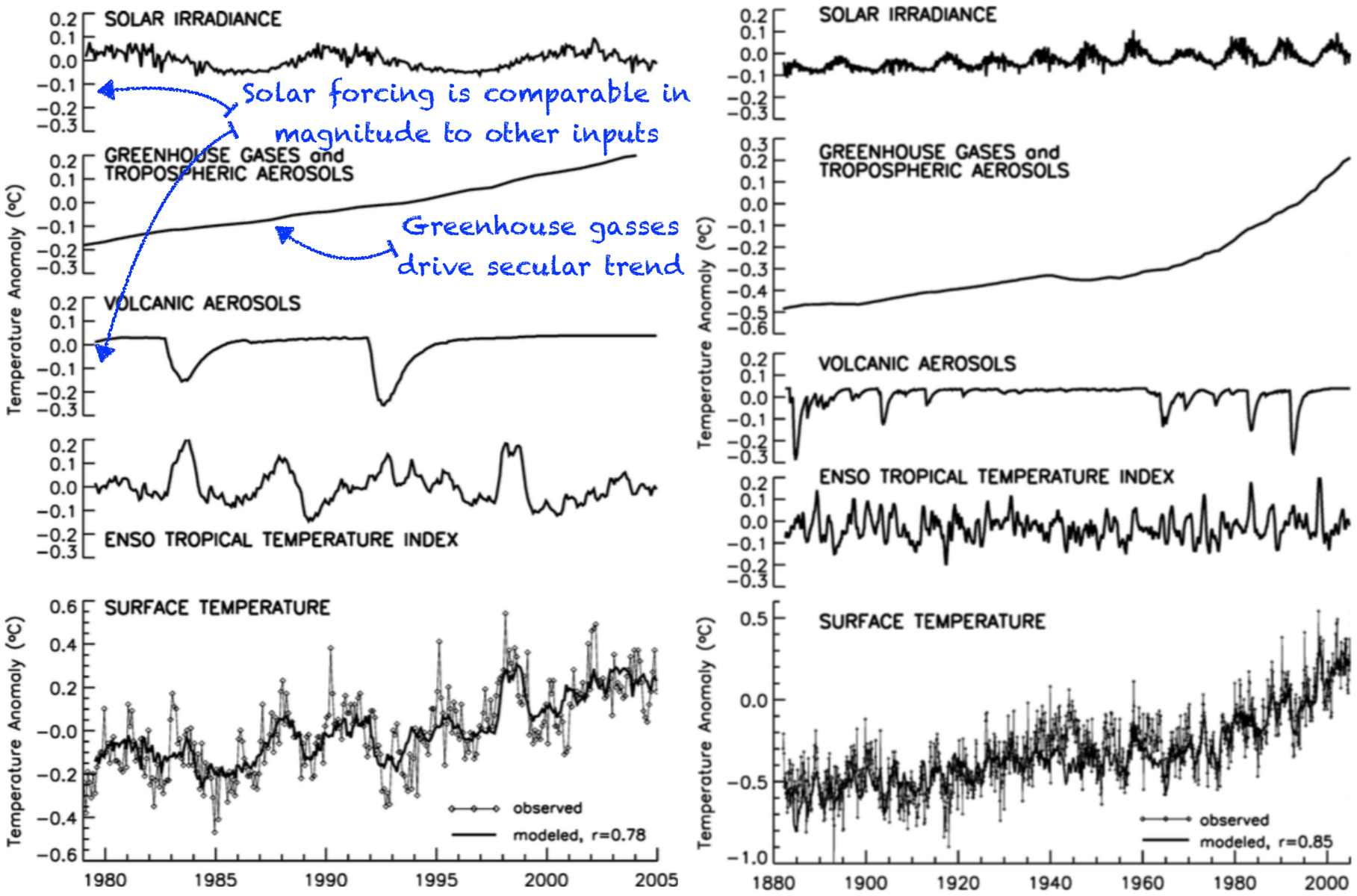


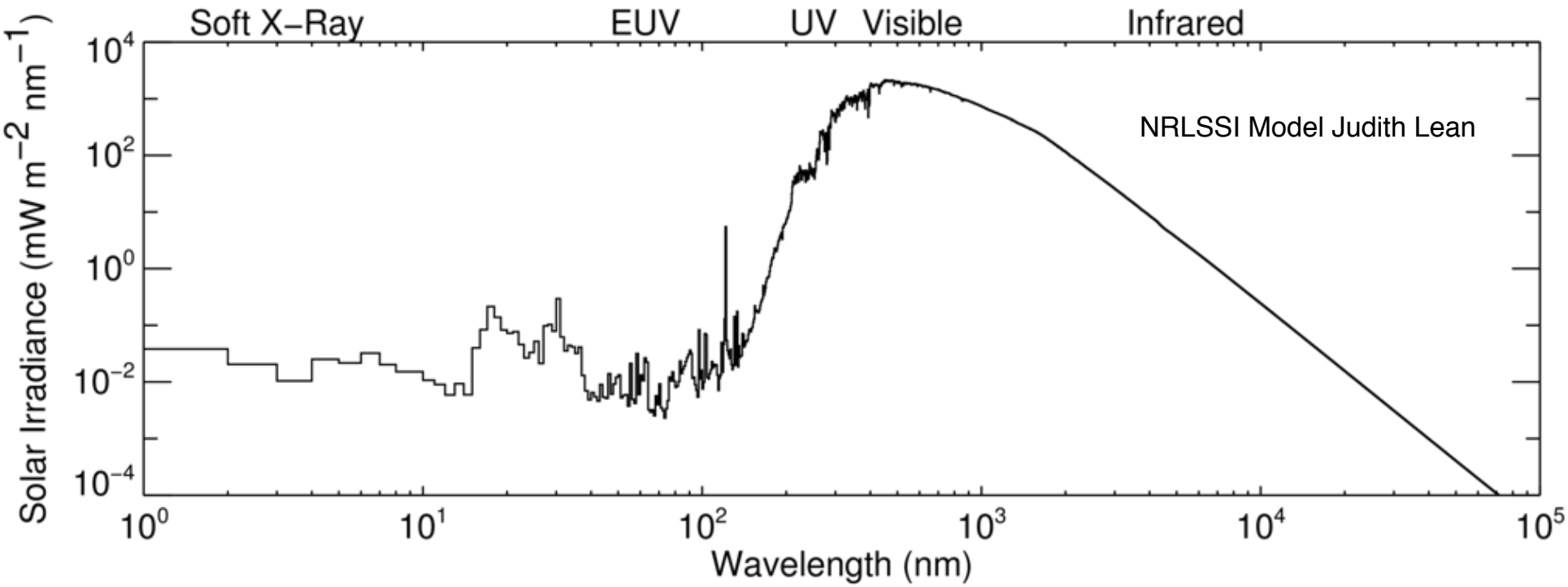
Woods et al. GRL (2004)

The Total Solar Irradiance: Application to Climate Change

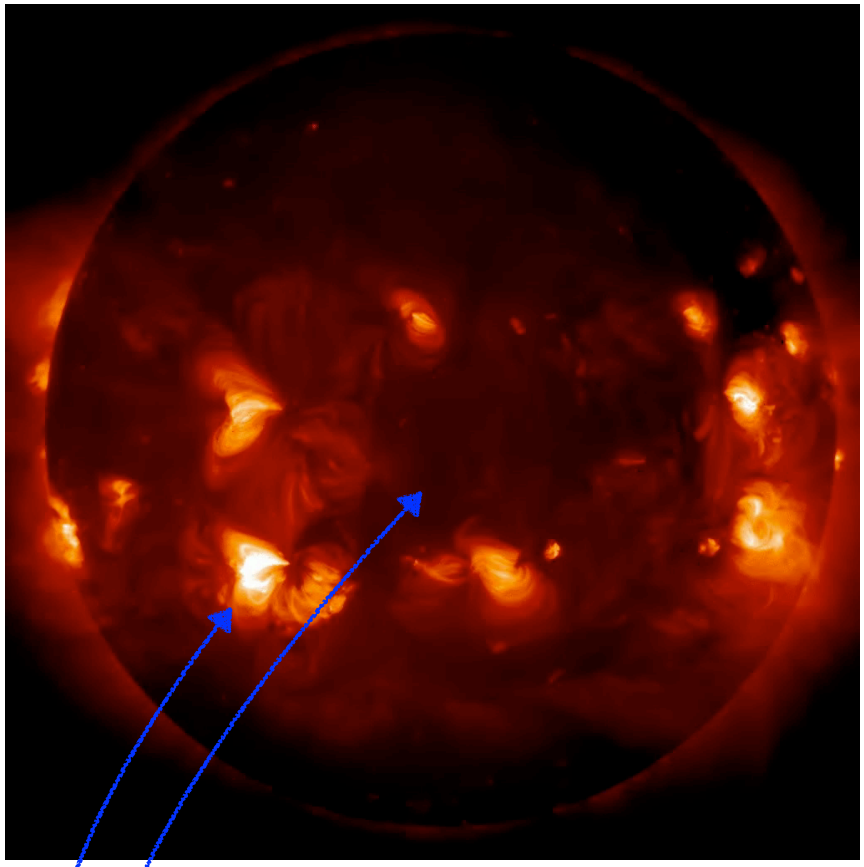


Lean, Solar Physics (2005)

Overview of the Solar Spectral Irradiance



Soft X-Rays: < 50 Å

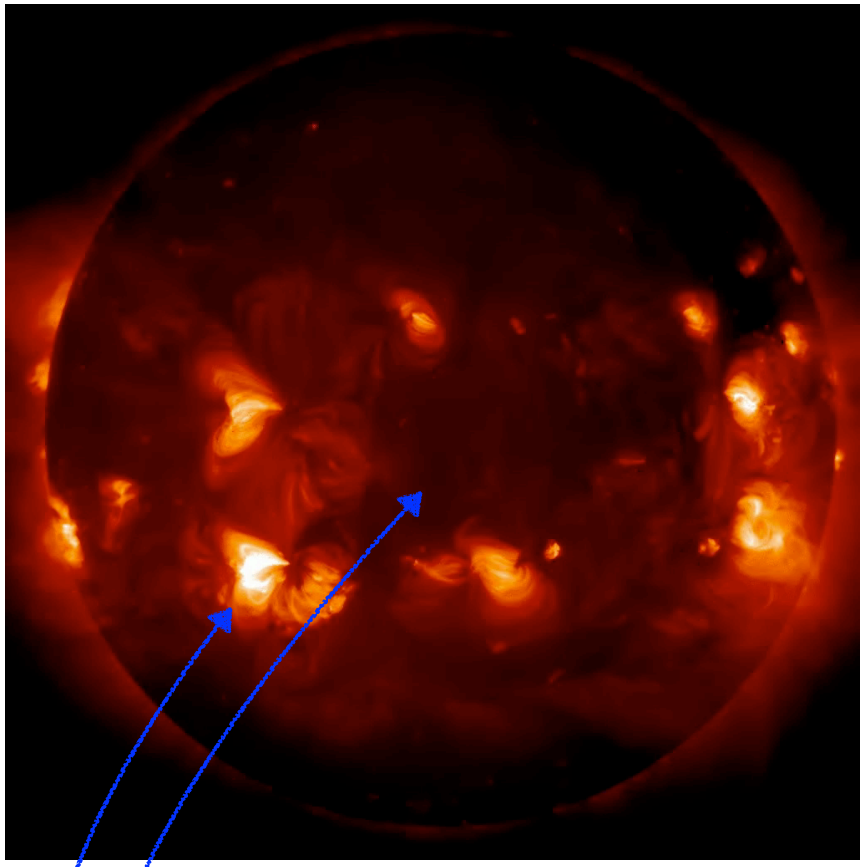


XRT/Hinode
September – November 2014

Very high contrast between quiet and active Sun

- Generally formed at high temperatures (> 2MK)
- Very high contrast between quiet and active sun ⇾ strong variation over solar rotation and solar cycle
- Flares contribute significantly to variability
- Optically thin
- Limited measurements

Soft X-Rays: < 50 Å



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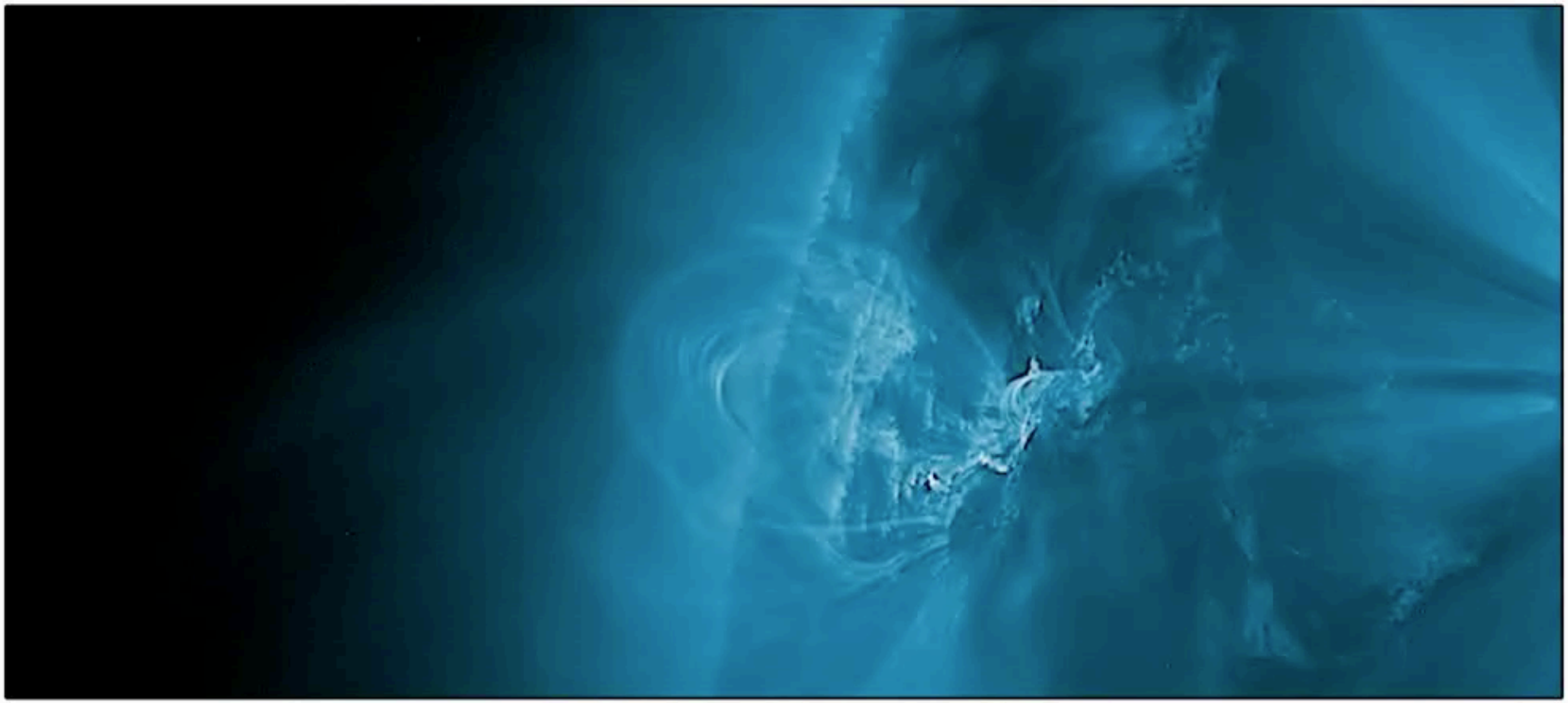
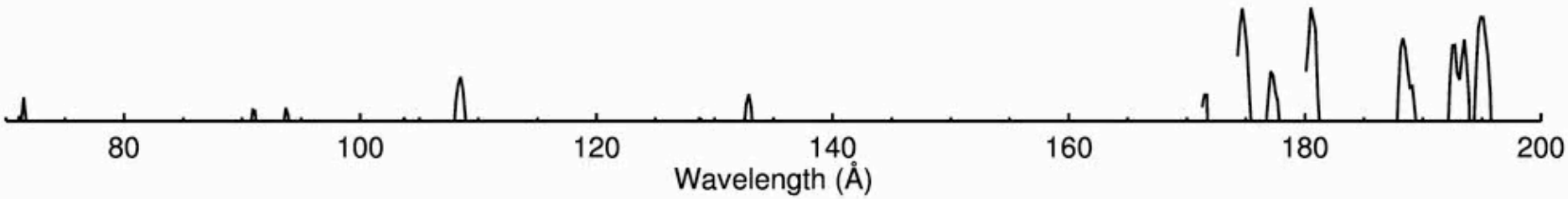
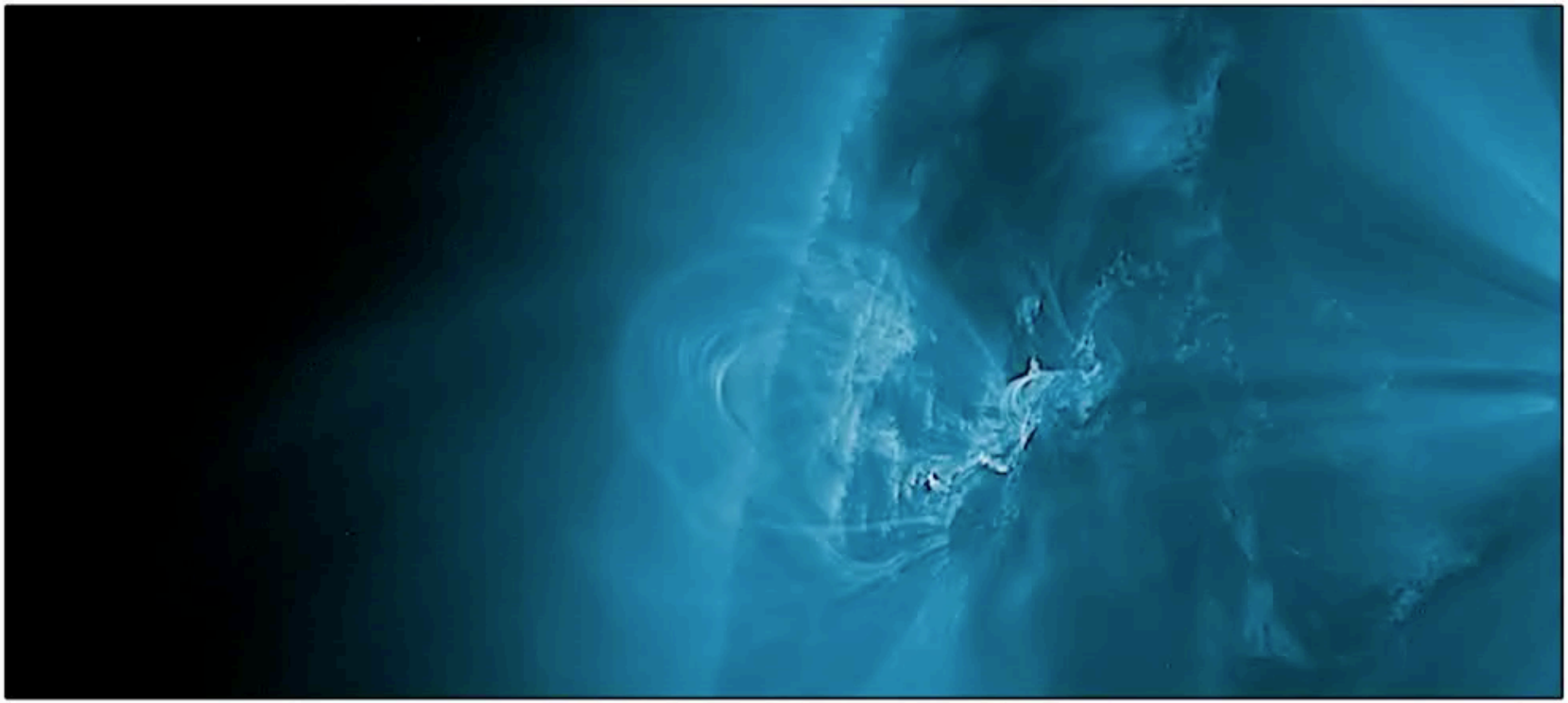
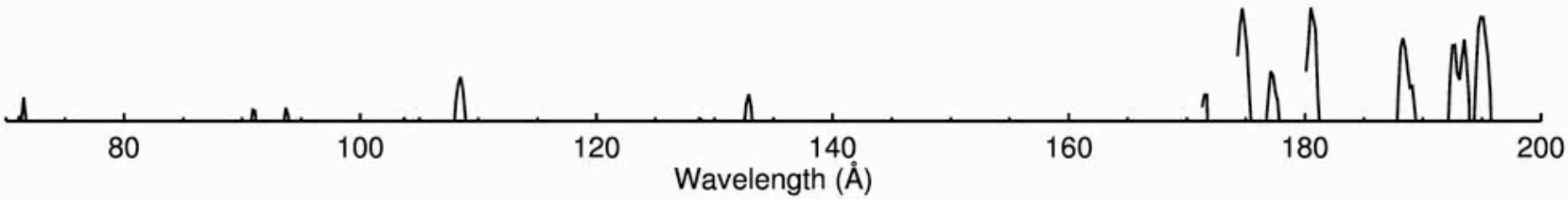


EVE/SDO Flare Irradiance

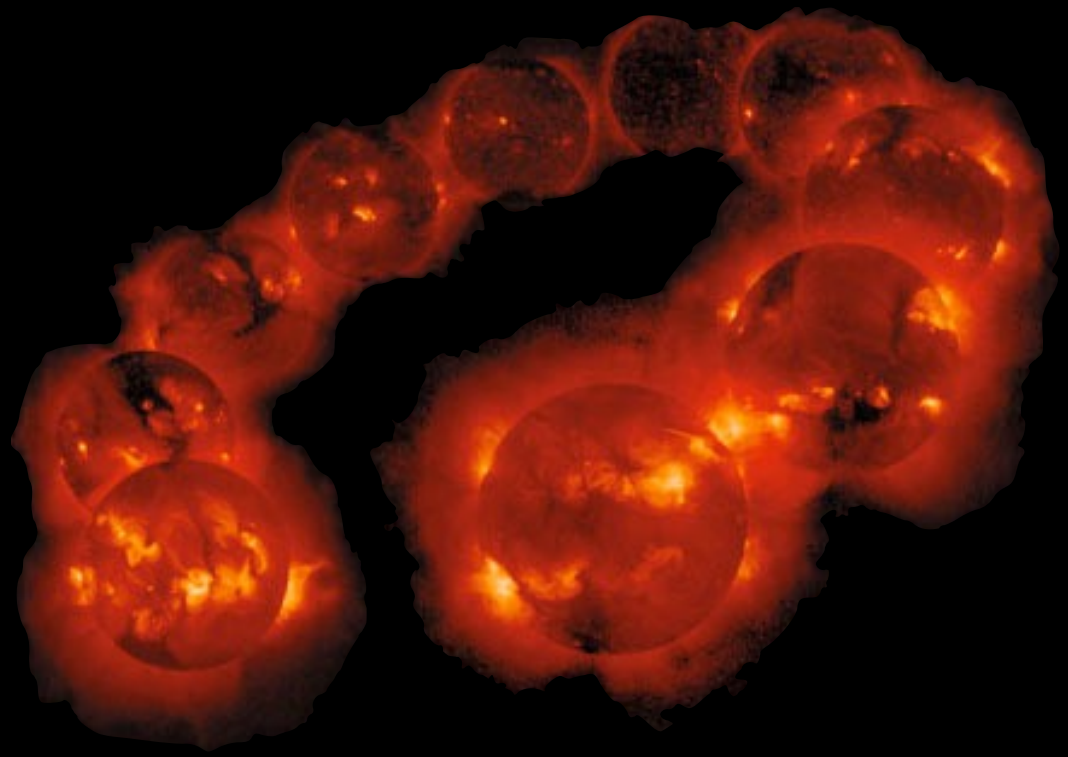




EVE/SDO Flare Irradiance



SXT/Yohkoh Images Over a Solar Cycle



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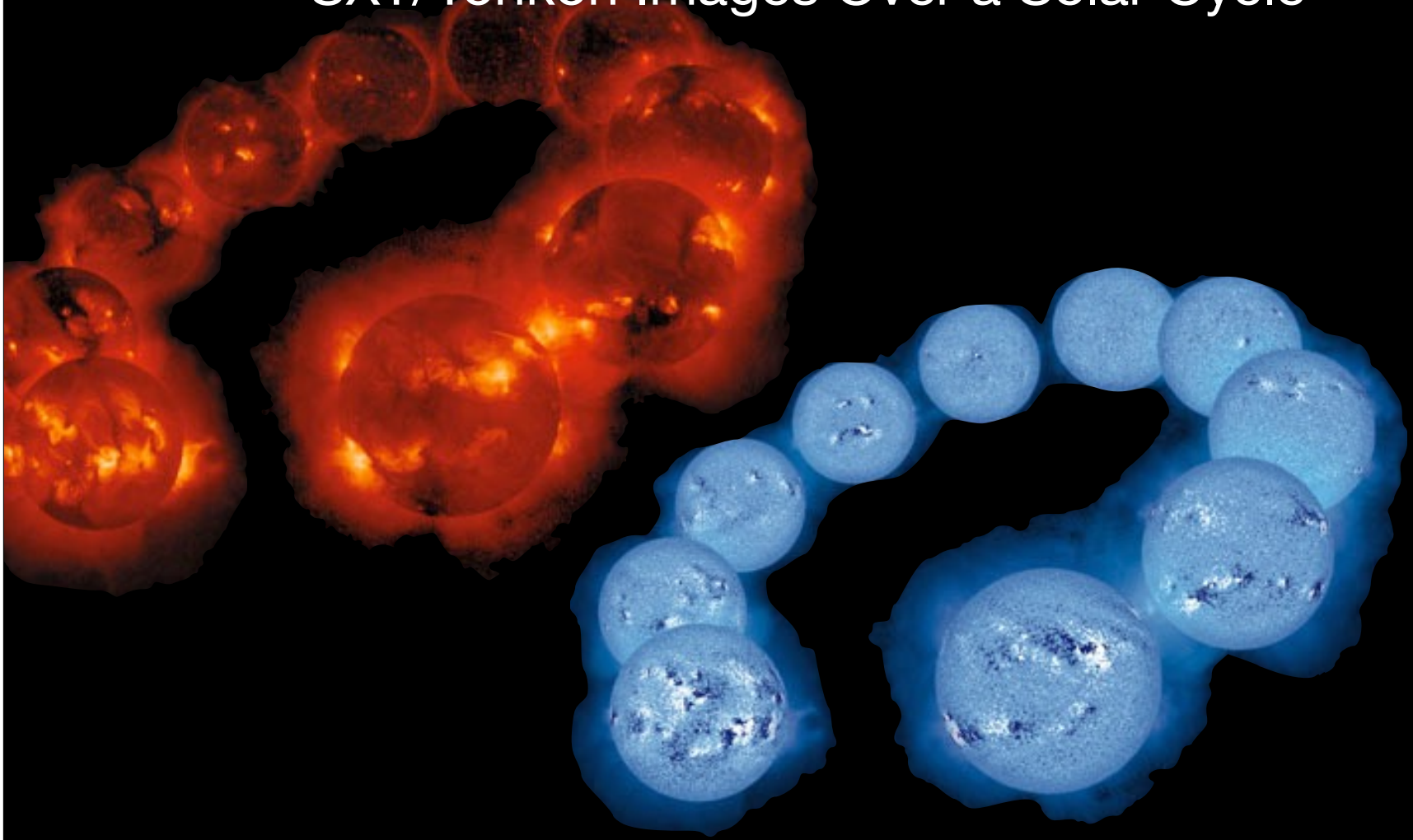
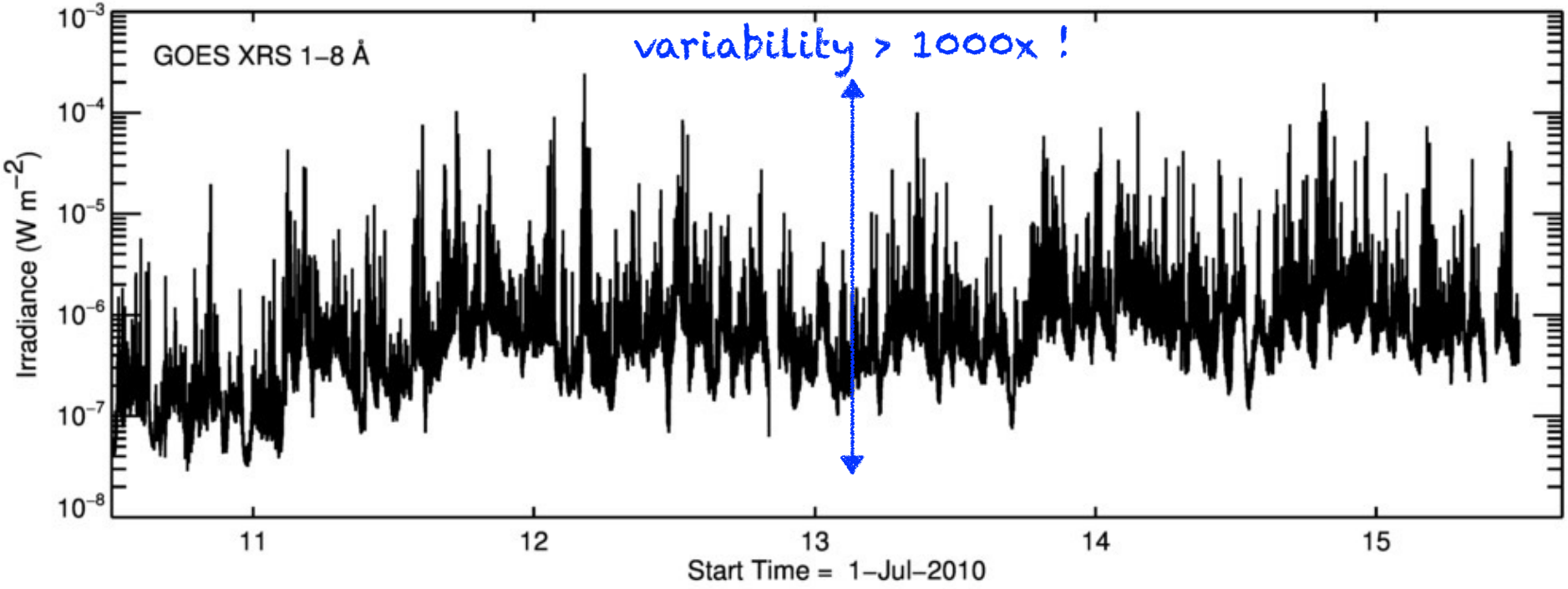


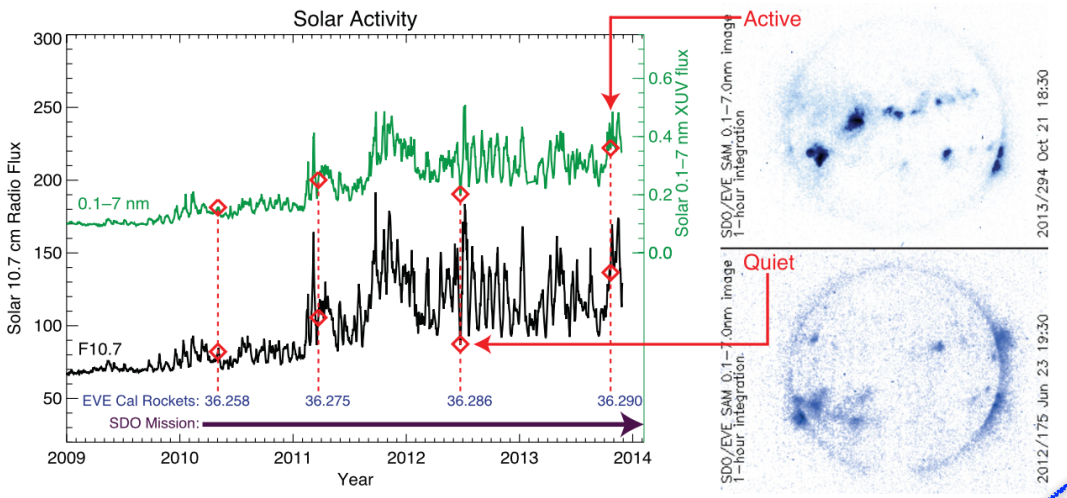
Example SXR Irradiance Solar Cycle Time Series
Daily XRS/GOES 1 – 8 Å

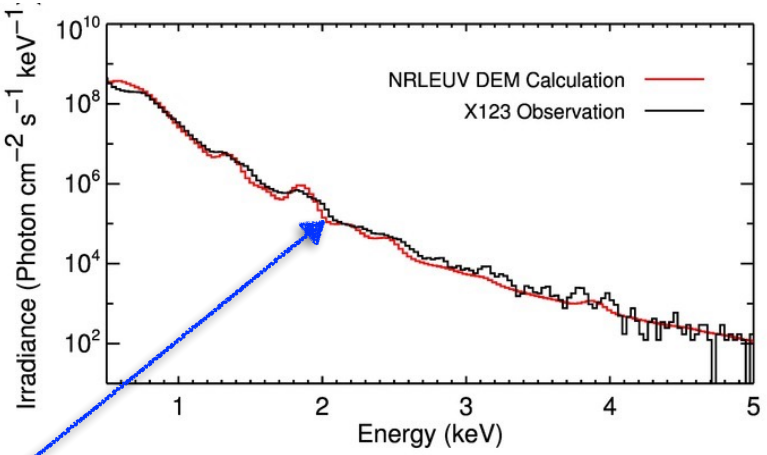


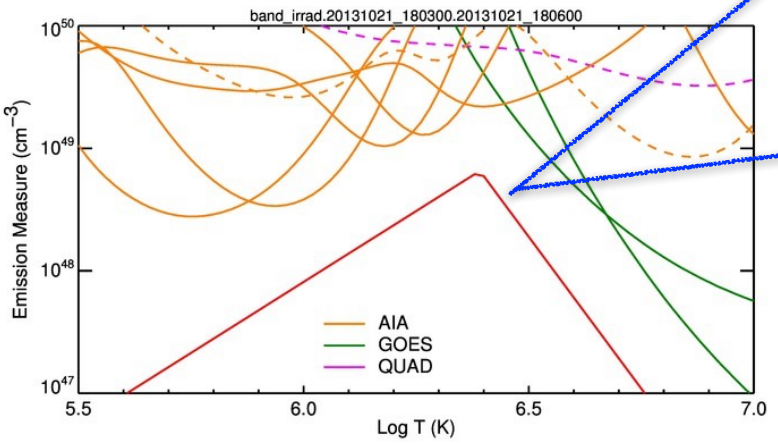
No continuous, spectral irradiance measurements that completely cover < 50 Å

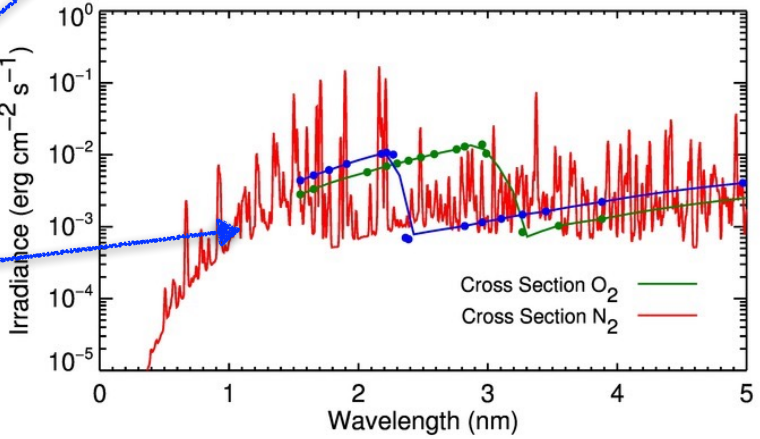
Example SXR Irradiance Spectrum
New Observations from X123

Caspi, Woods, & Warren (2015)





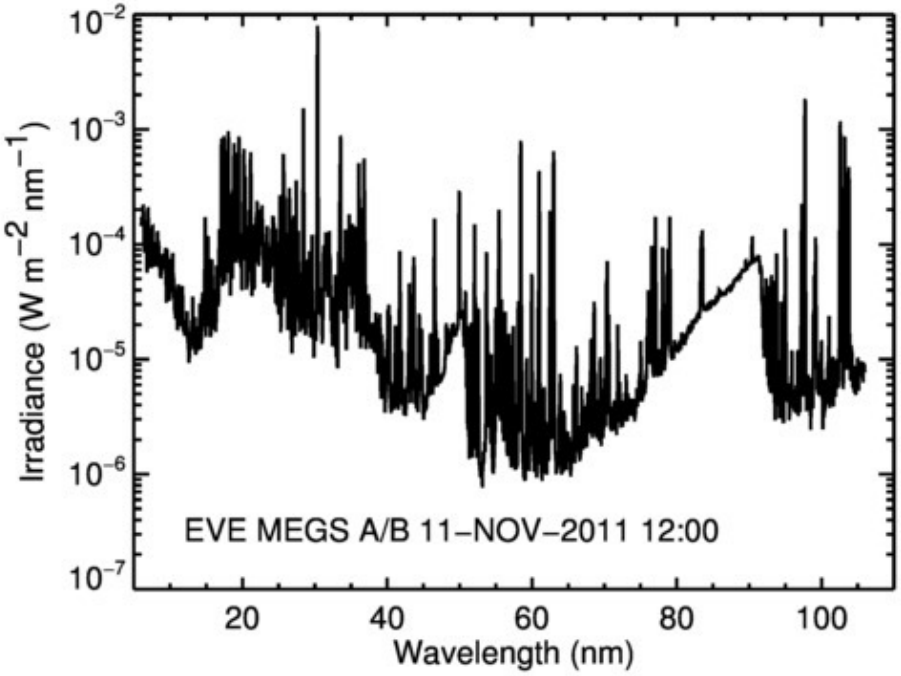




infer spectra from emission measure model?

MinXSS: LASP CubeSat
X123 SXR Detector
2015 launch

Extreme Ultraviolet: 50 – 1200 Å

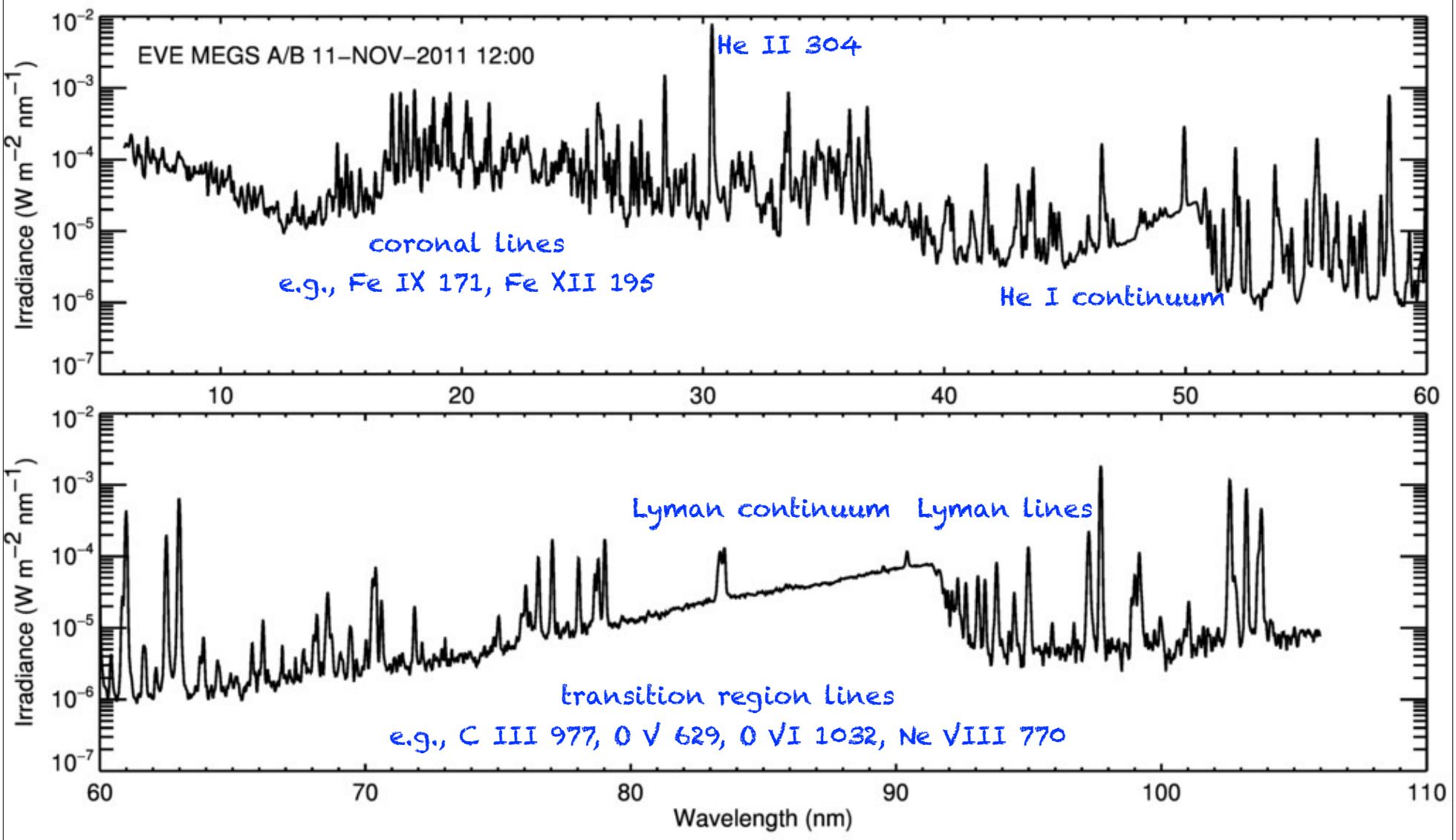


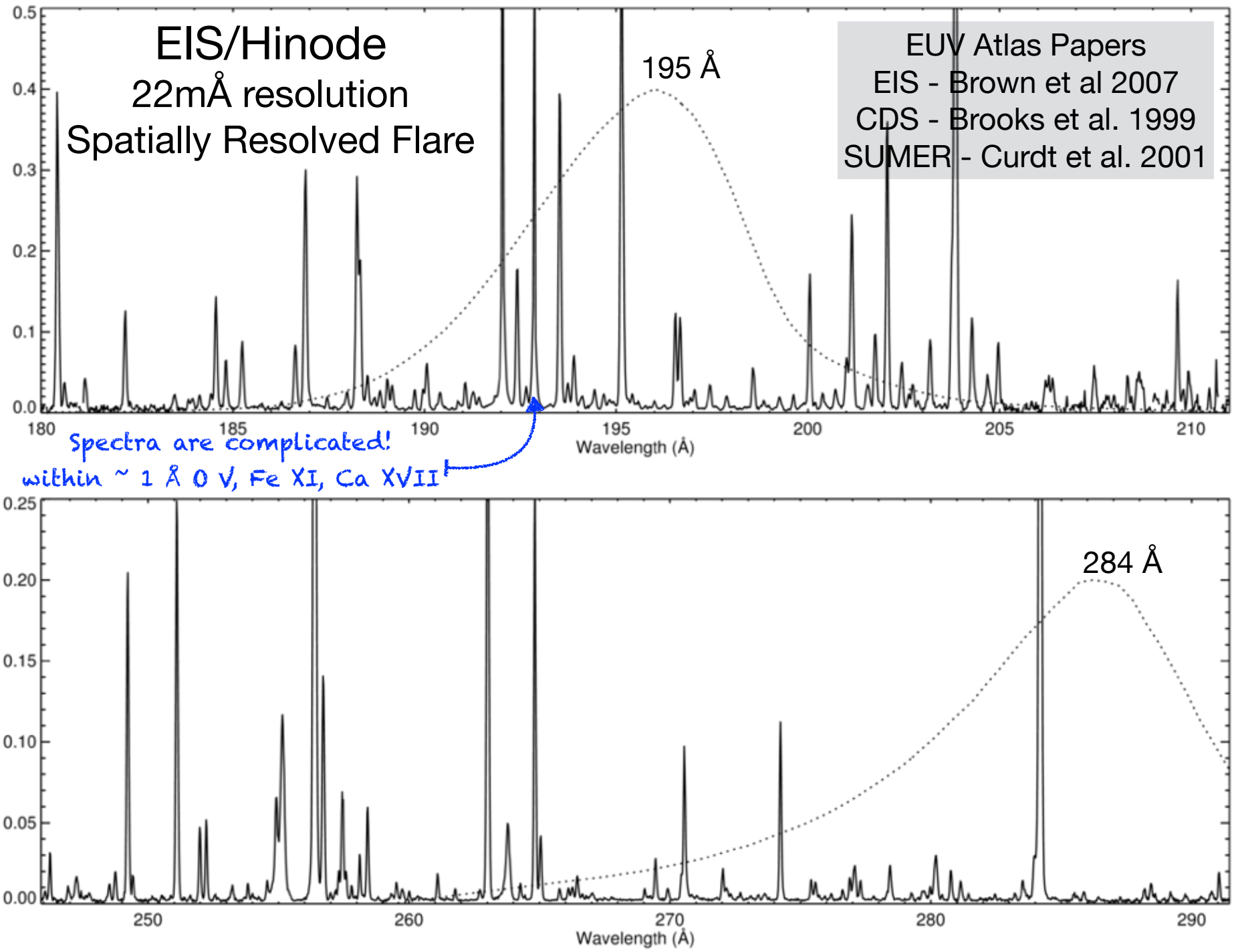
EVE/SDO EUV Spectral Irradiance

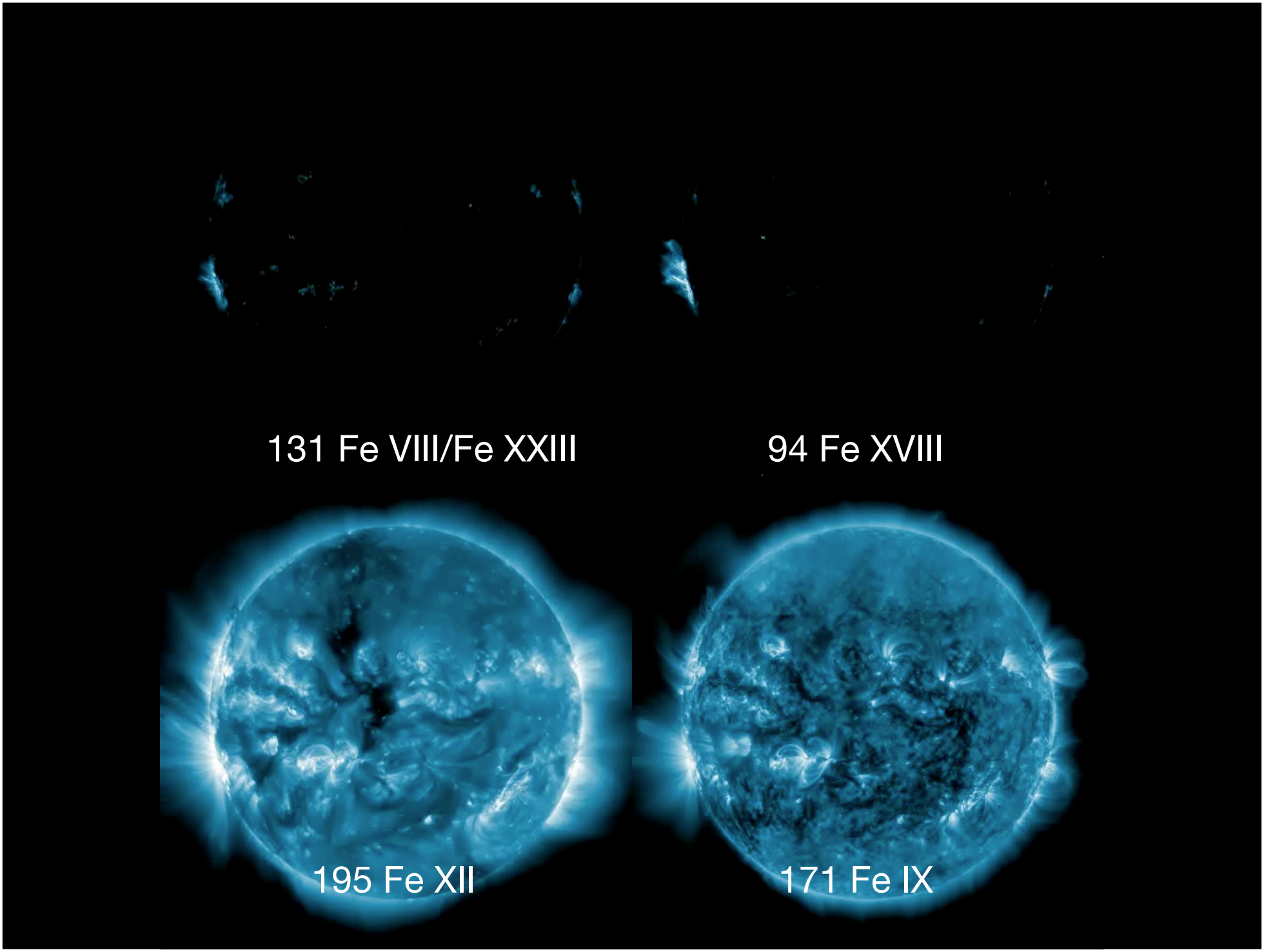
1 Å spectral resolution
10s cadence
50-1050 Å coverage
2010 - present

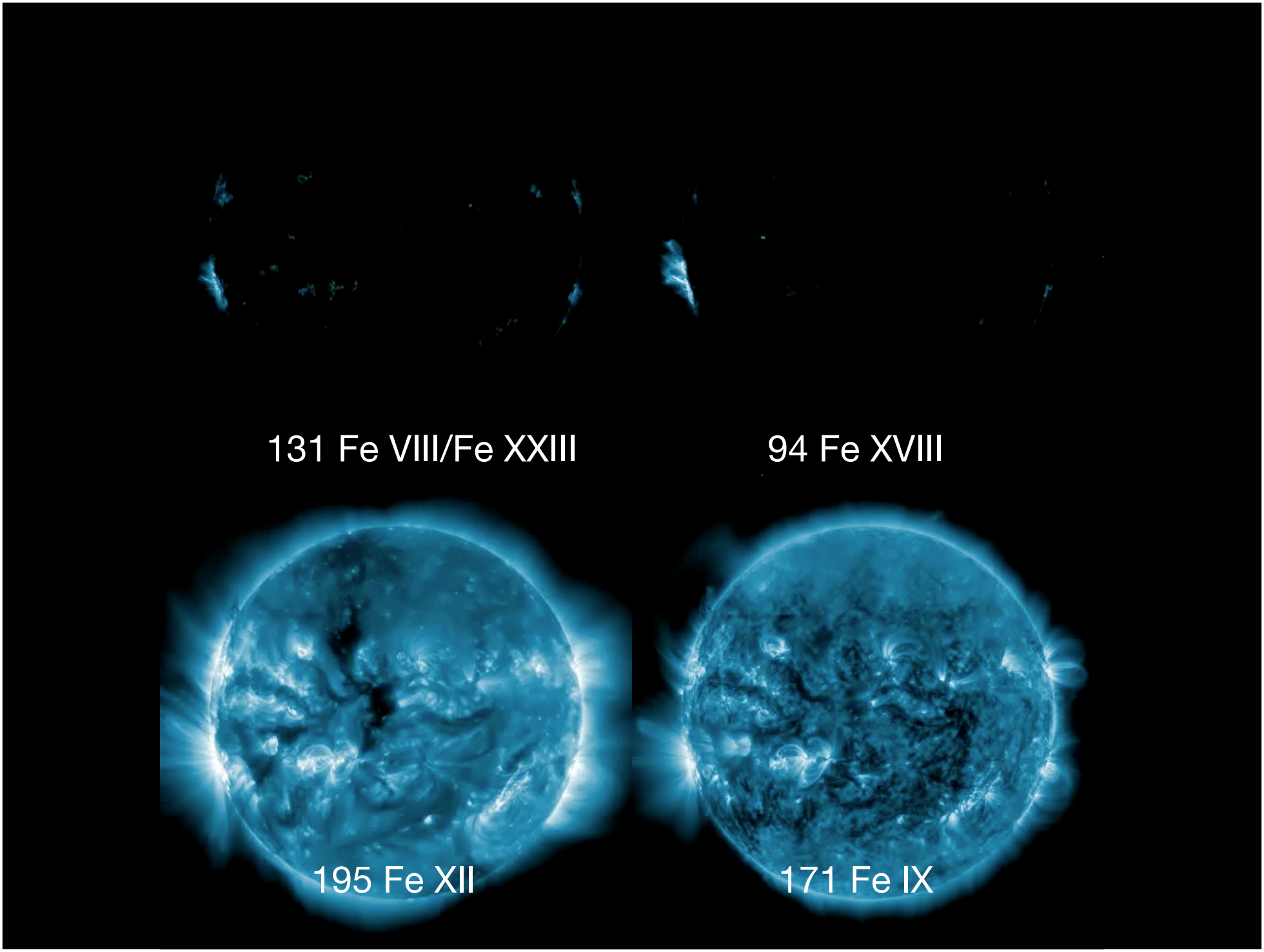
- Formed at chromospheric, transition region, coronal, and flare temperatures
- Optically thin and thick lines and continuua
- Moderate contrast between quiet and active sun ⇾ moderate variation over solar rotation and solar cycle
- Many measurements

EUV: 50 – 1200 Å: EVE/SDO Irradiance Spectrum




EIS/Hinode
22mÅ resolution
Spatially Resolved Flare
195 Å
EUV Atlas Papers
EIS - Brown et al 2007
CDS - Brooks et al. 1999
SUMER - Curdt et al. 2001
Spectra are complicated!
within ~ 1 Å O V, Fe XI, Ca XVII
284 Å
Wavelength (Å)
Wavelength (Å)


131 Fe VIII/Fe XXIII
94 Fe XVIII
195 Fe XII
171 Fe IX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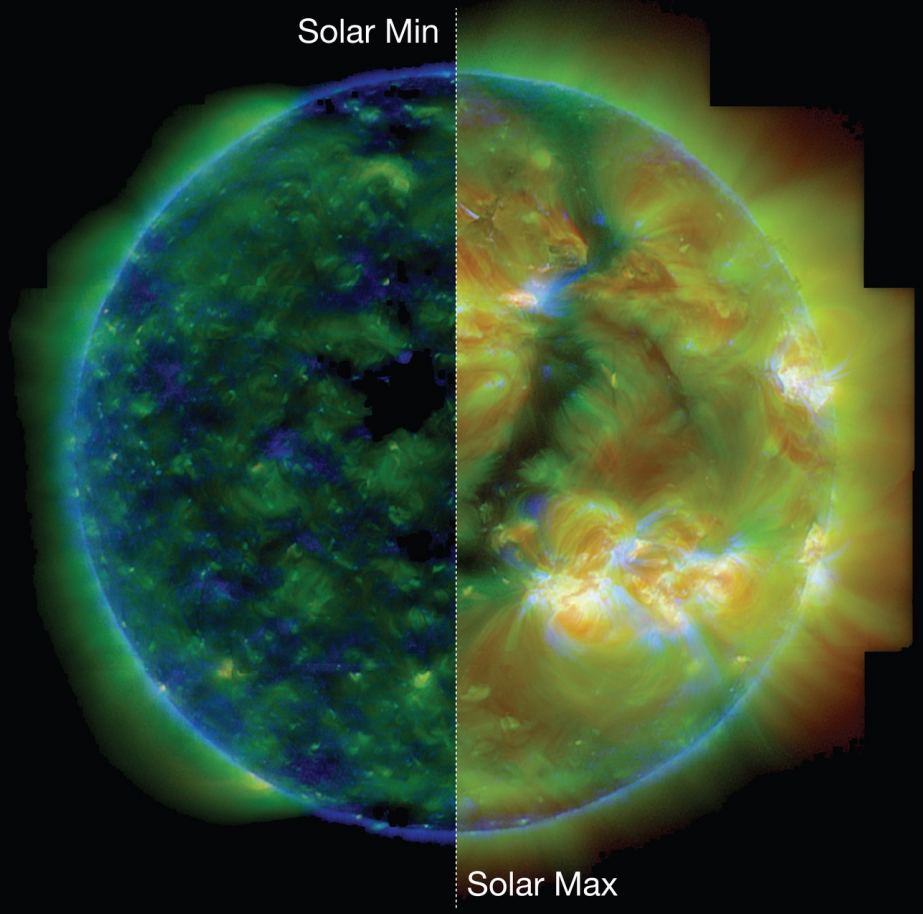
The Extreme Ultraviolet Imaging Spectrometer on Hinode

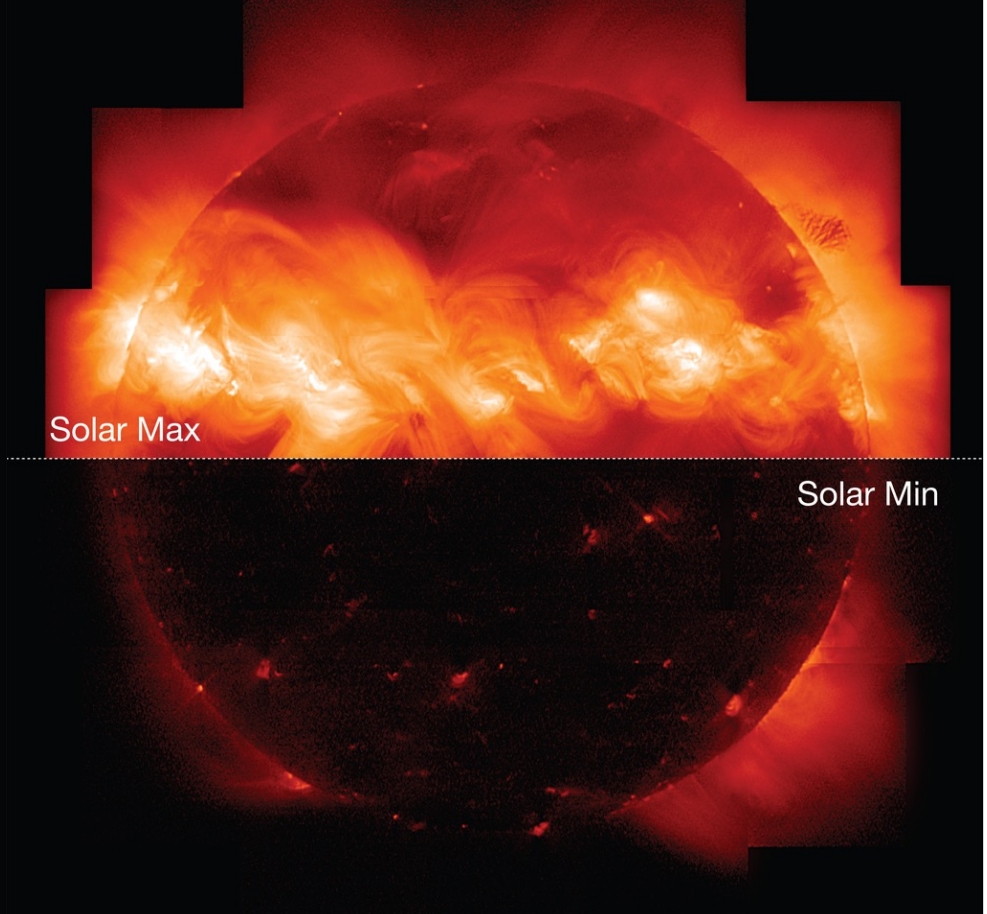


Si VII 275.37 Å
Fe XII 195.12 Å
Fe XV 284.16 Å

Science & Technology Facilities Council

Poster Prepared by the Naval Research Laboratory for the EIS Team

The Extreme Ultraviolet Imaging Spectrometer on Hinode



Fe XV 284.16 Å

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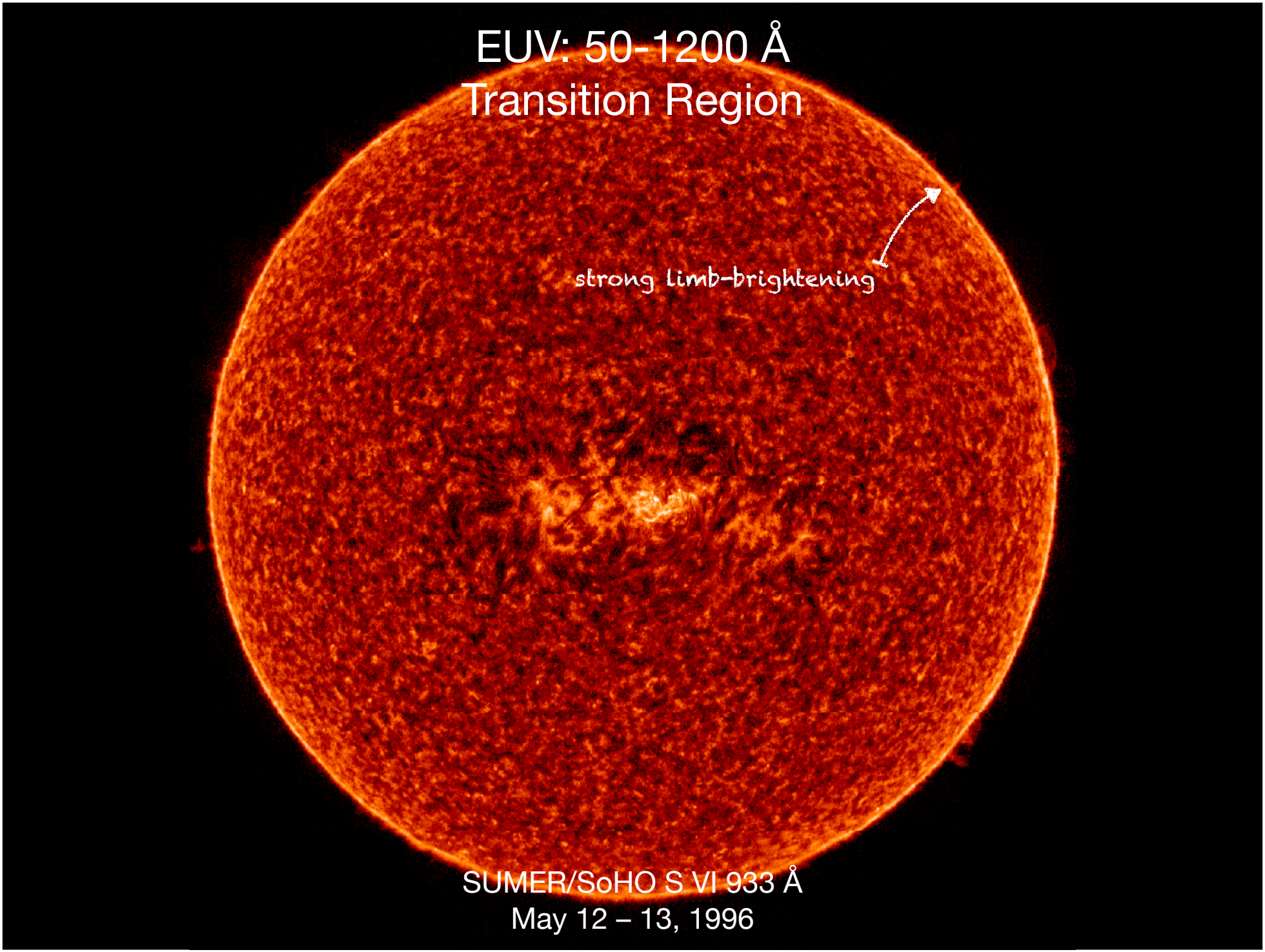
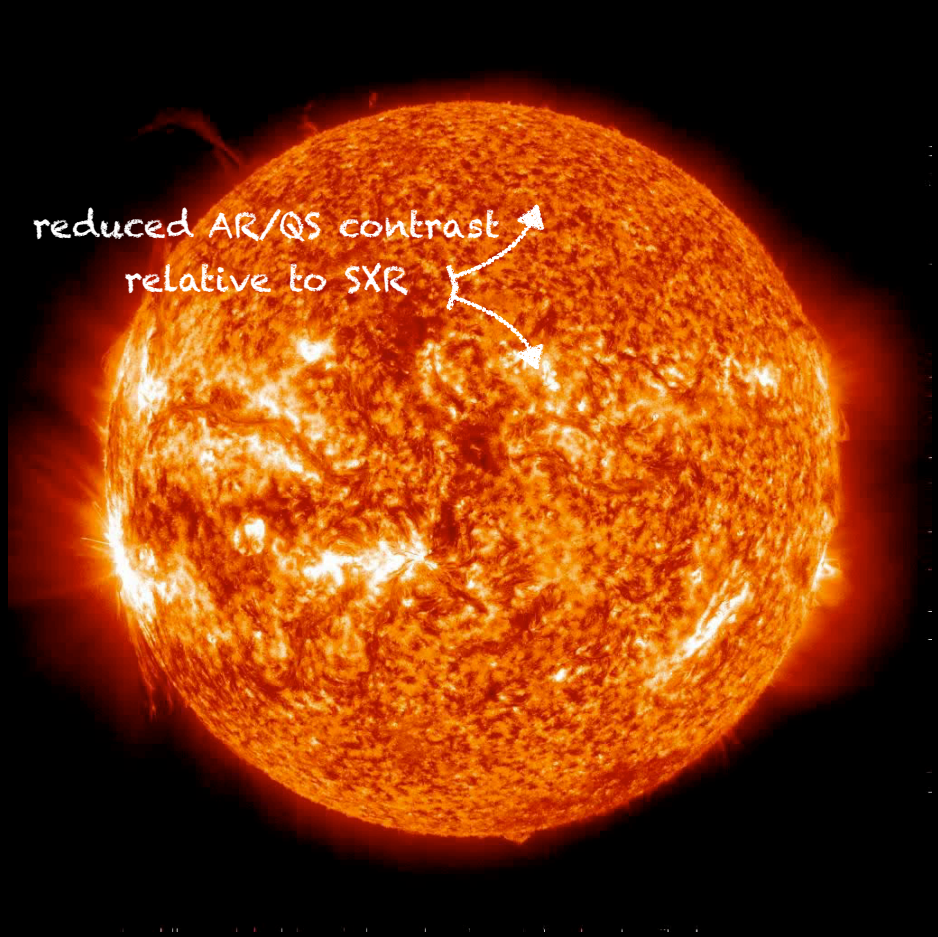
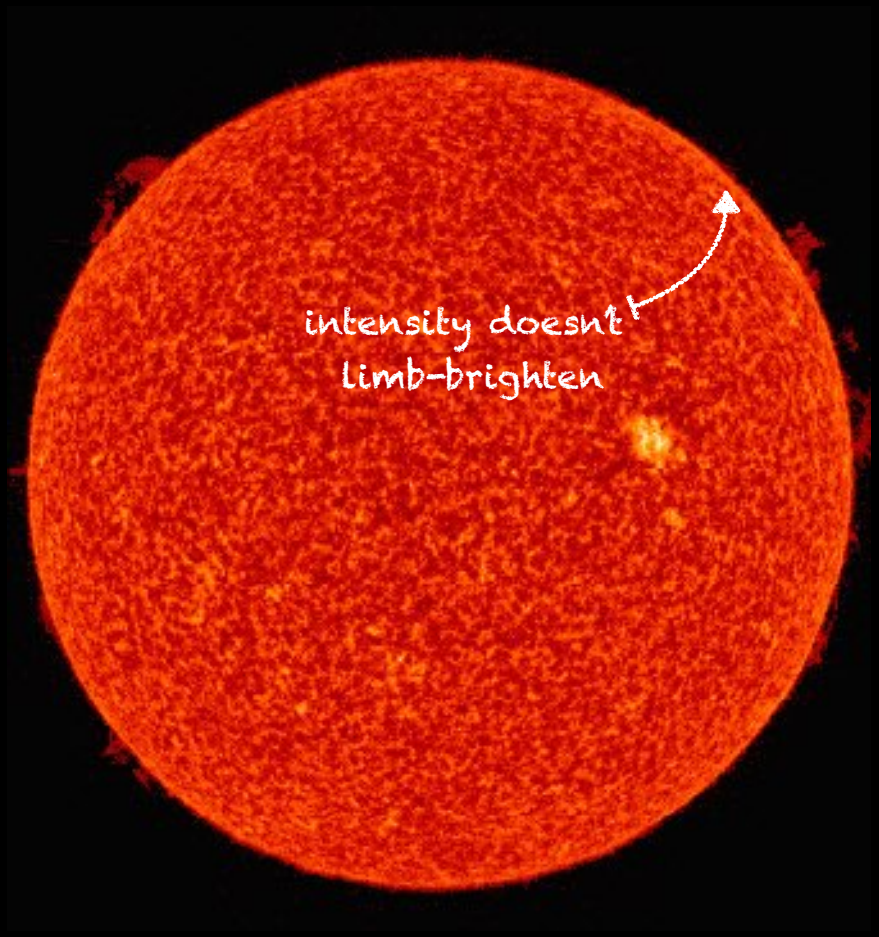

EUV: 50-1200 Å
Transition Region
strong limb-brightening
SUMER/SoHO S VI 933 Å
May 12 – 13, 1996

EUV: 50 – 1200 Å
Chromosphere

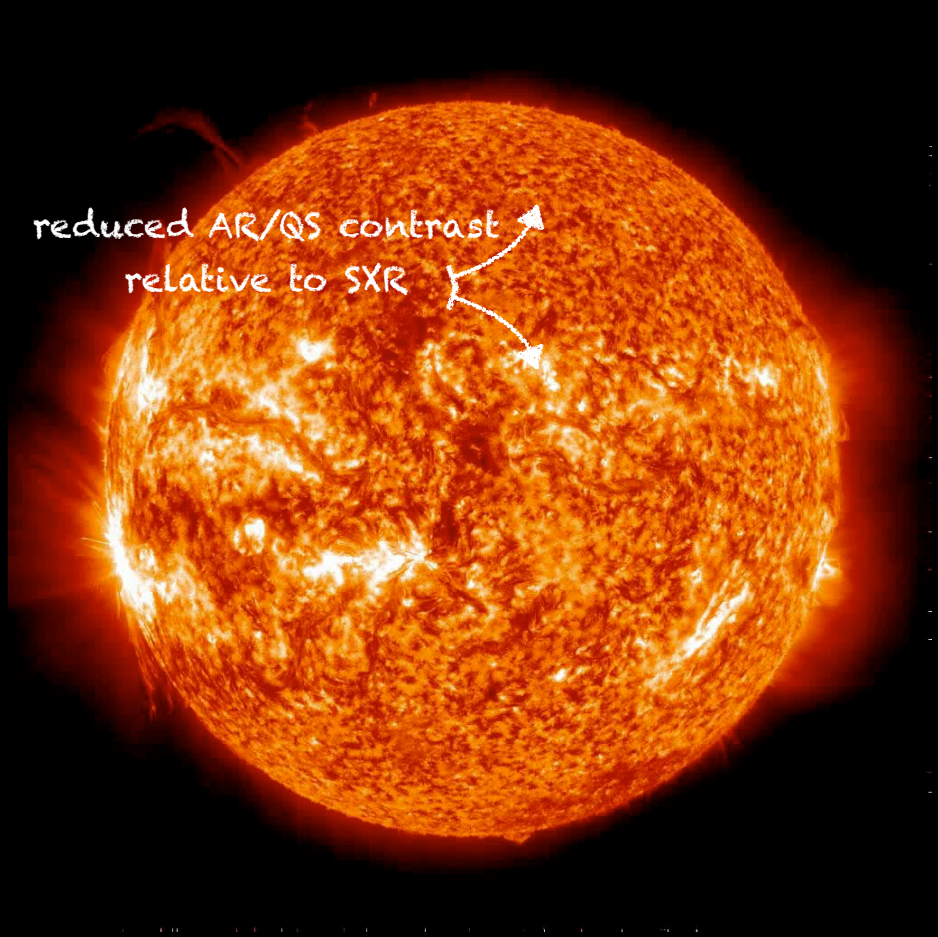


AIA/SDO He II 304 Å
October 2014



SUMER/SoHO Lyman ε 937 Å
August 11 – 12, 1996

EUV: 50 – 1200 Å
Chromosphere



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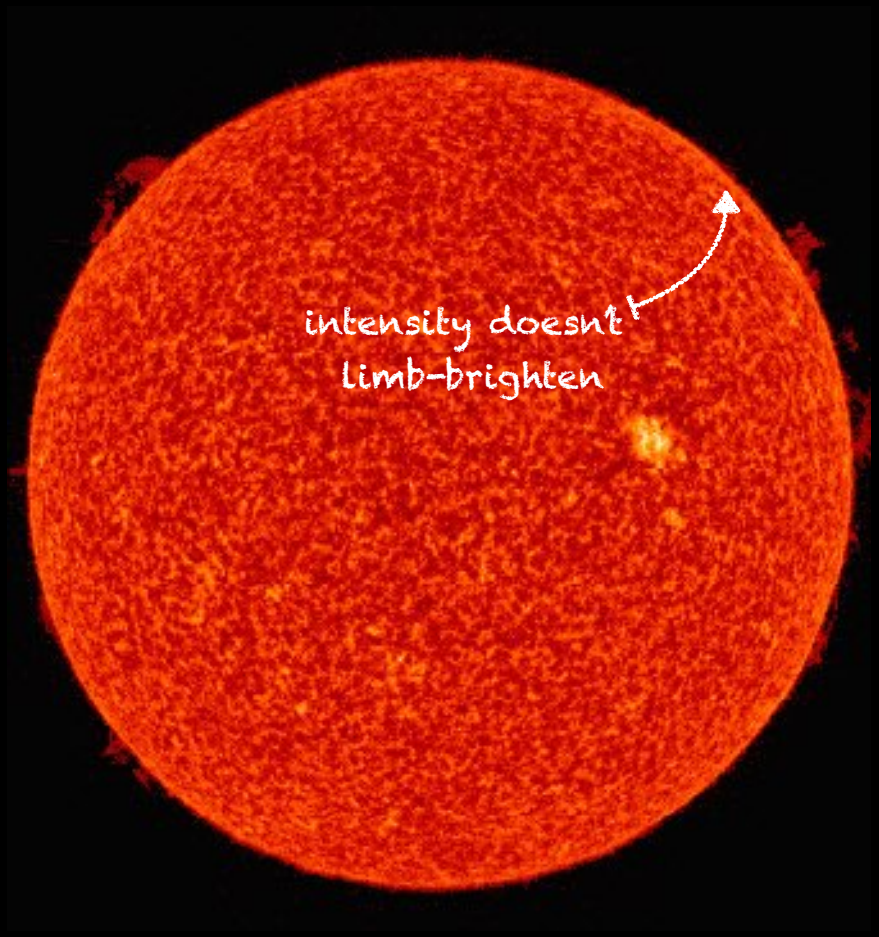
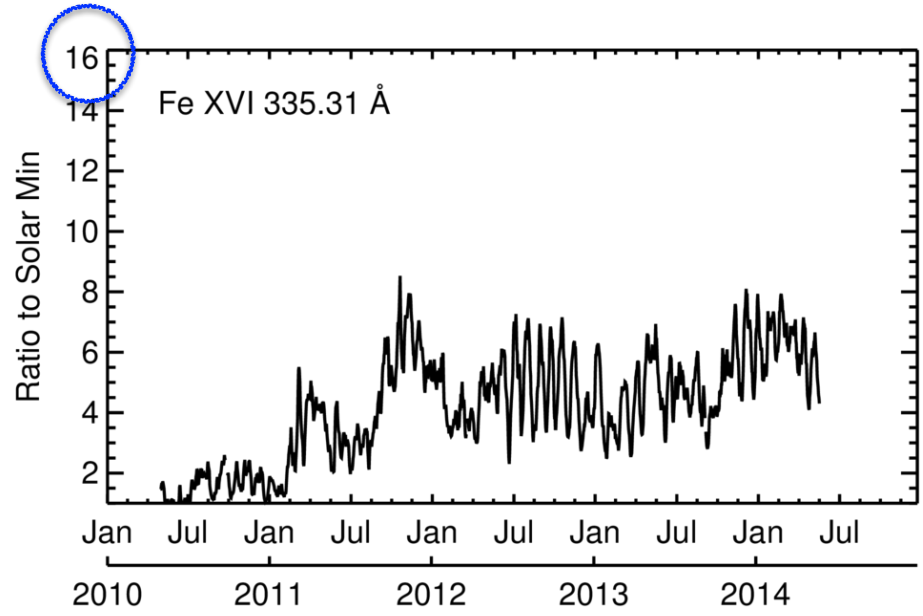
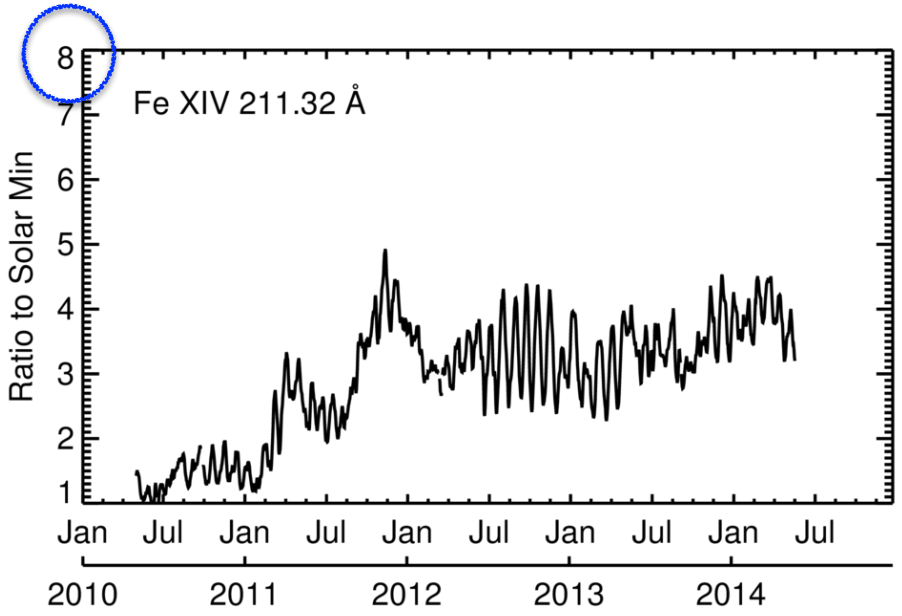
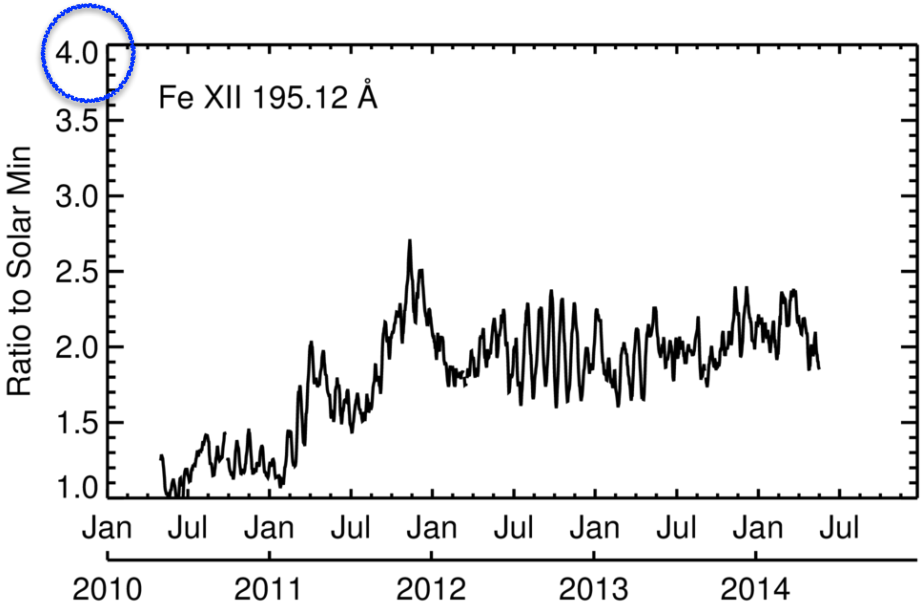


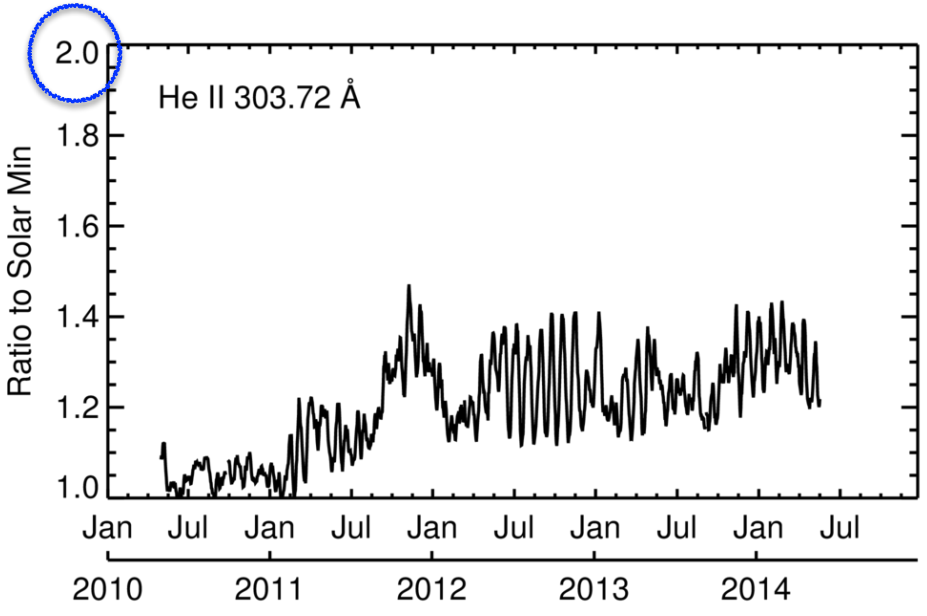
SUMER/SoHO Lyman ε 937 Å
August 11 – 12, 1996

Example EVE/SDO EUV Irradiance Time Series

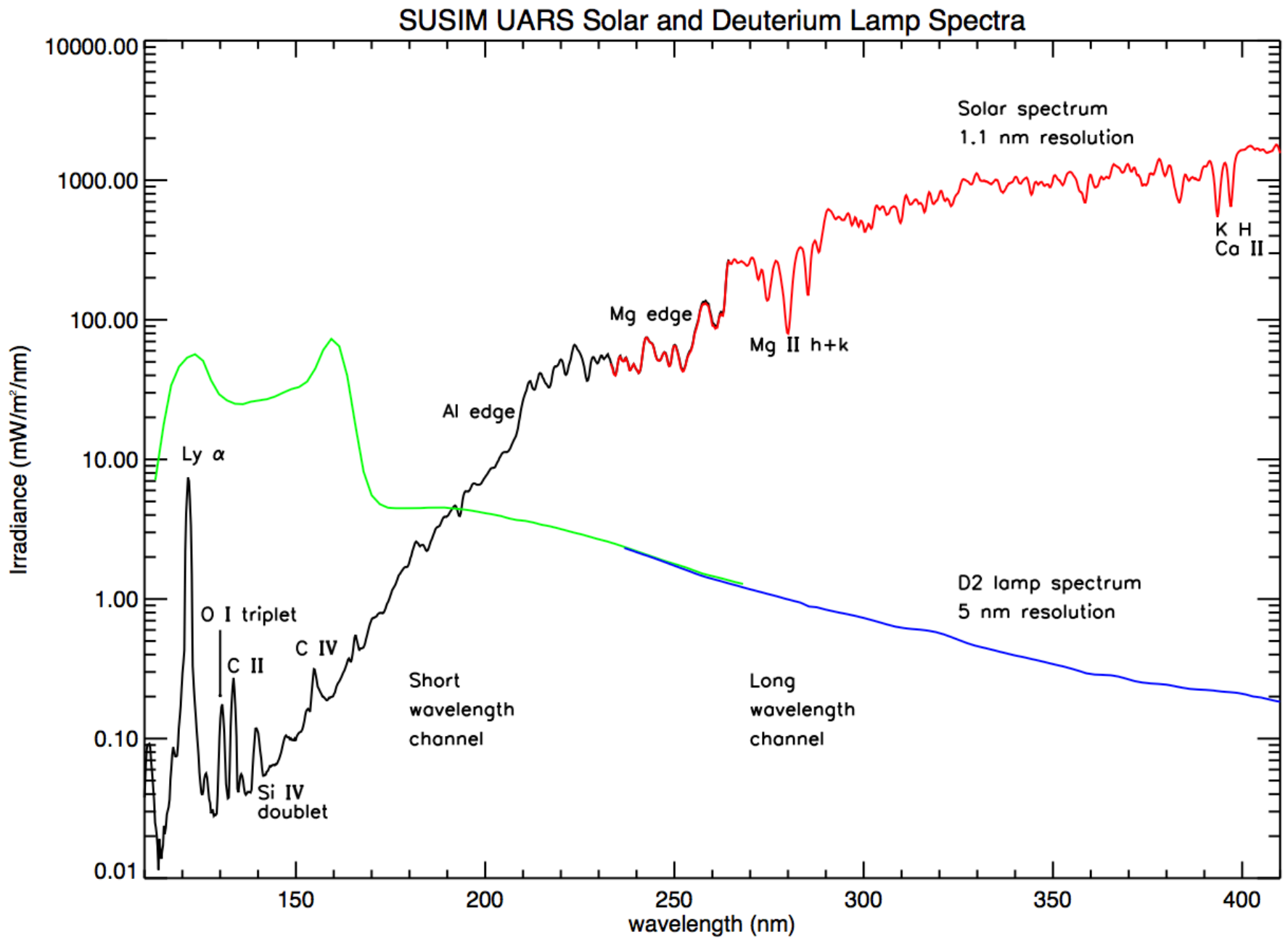


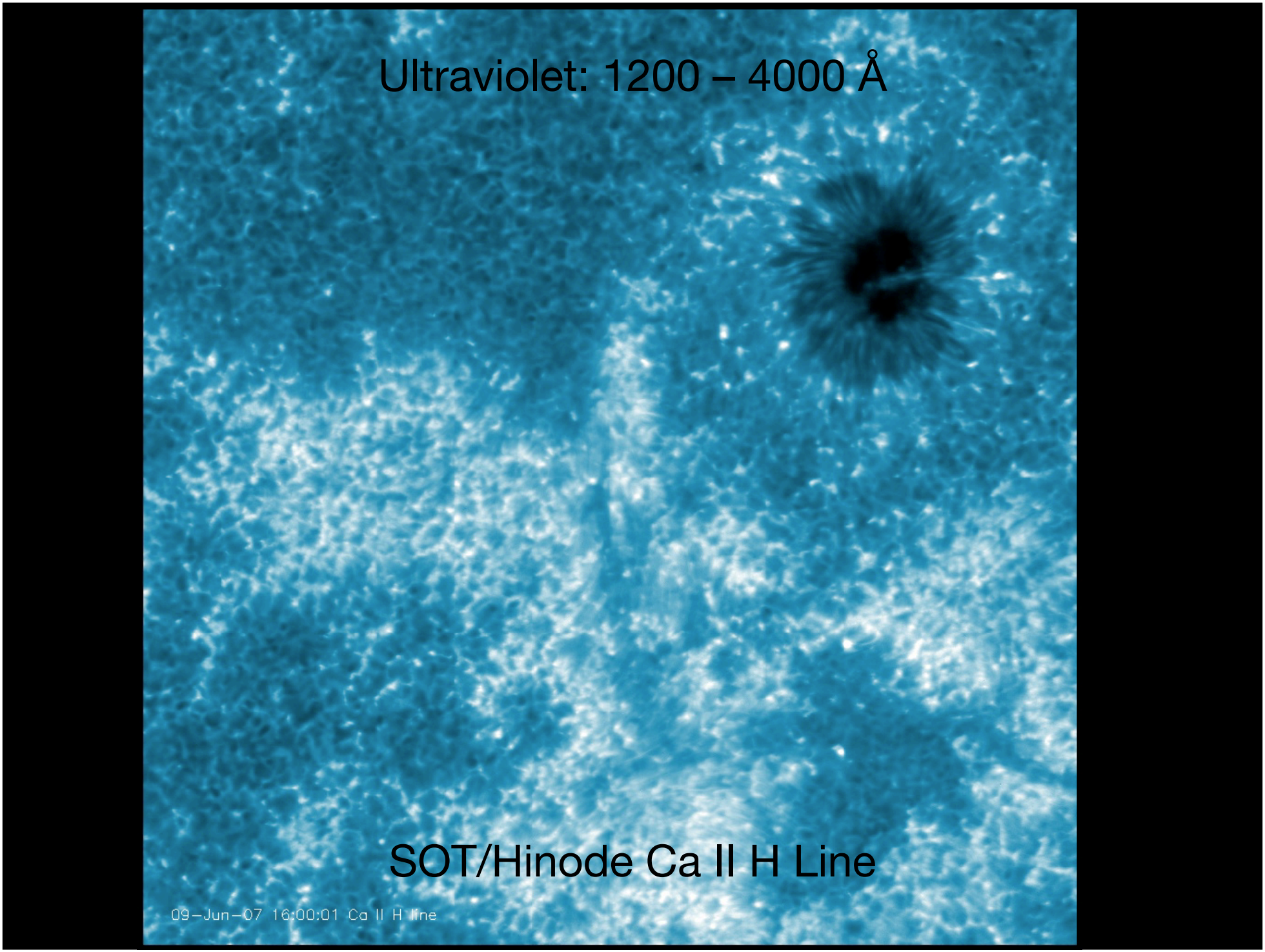


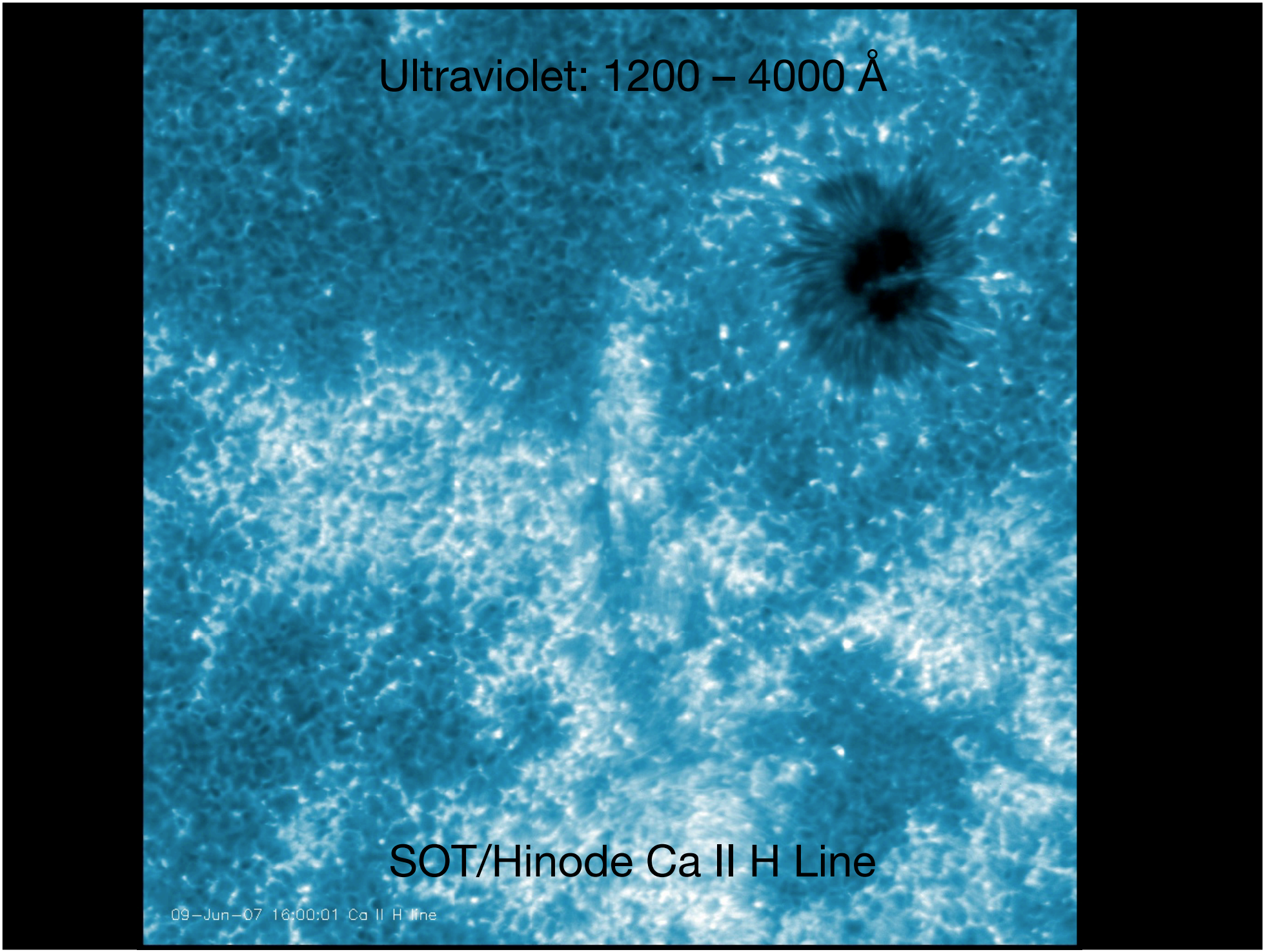




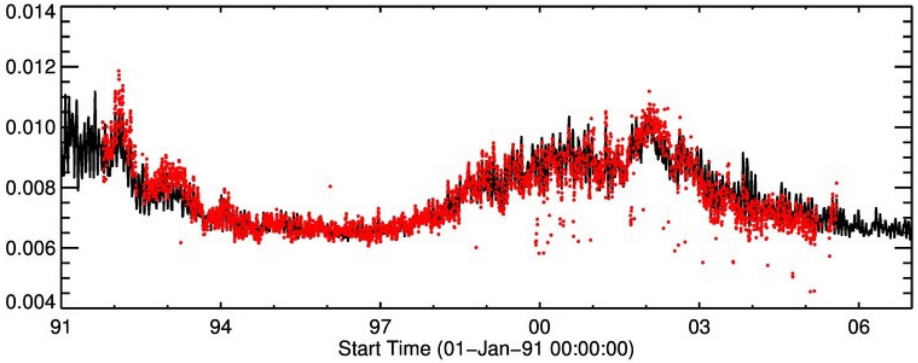
Example Ultraviolet Spectrum: 1200 – 4000 Å

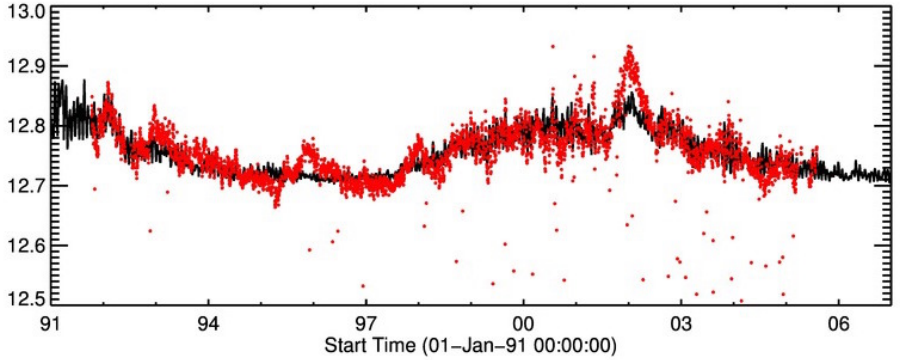


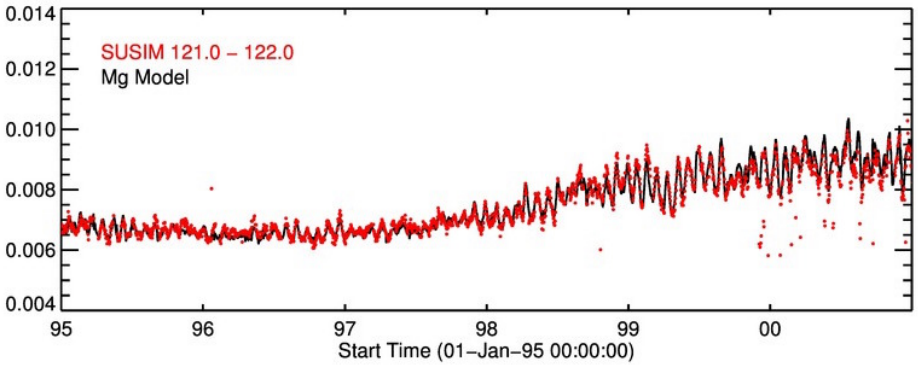

Ultraviolet: 1200 – 4000 Å
SOT/Hinode Ca II H Line
09-Jun-07 16:00:01 Ca II H line

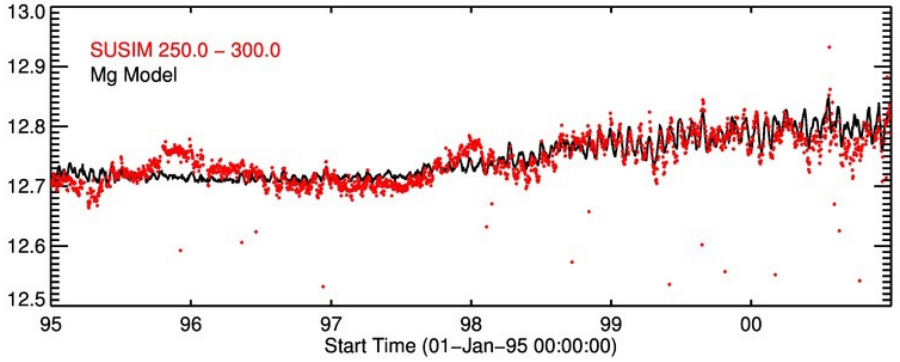

Ultraviolet: 1200 – 4000 Å
SOT/Hinode Ca II H Line
09-Jun-07 16:00:01 Ca II H line

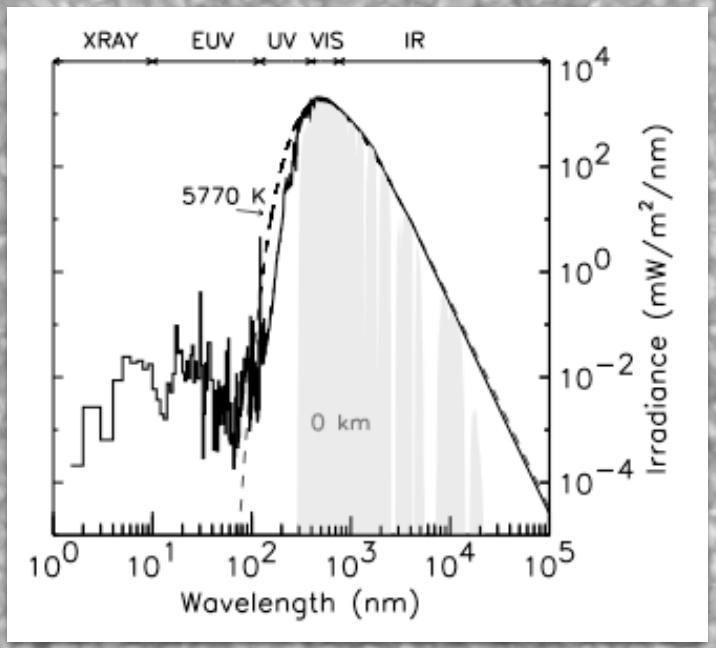
Example UV Irradiance Time Series
SUSIM/UARS



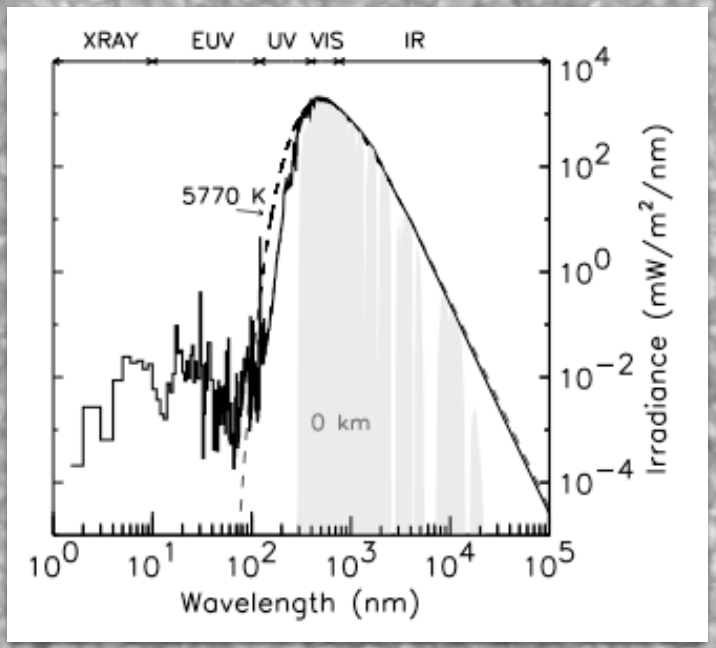








Visible Spectrum:
5770 K Blackbody



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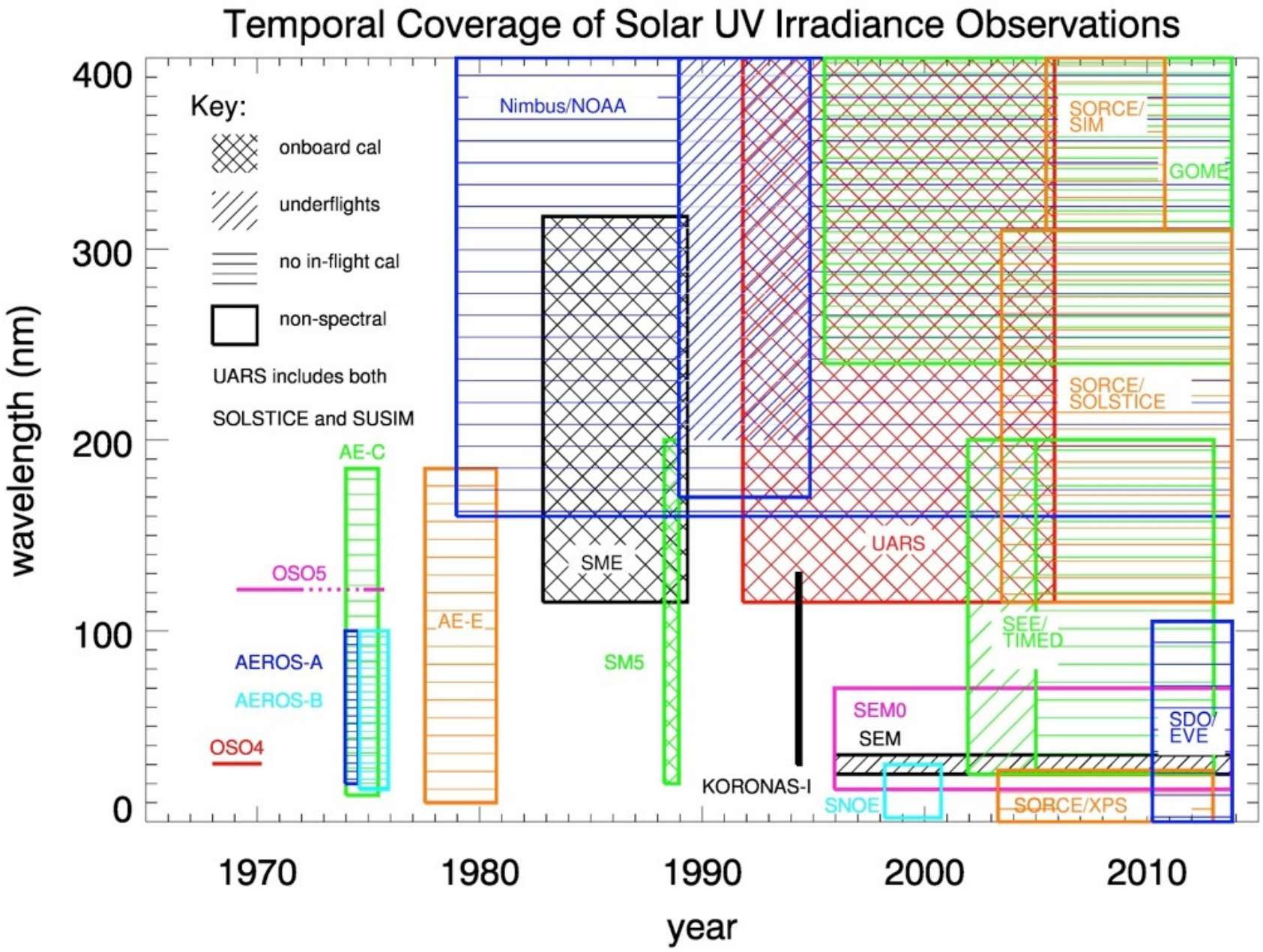


Jeff Morrill NRL/NASA HQ

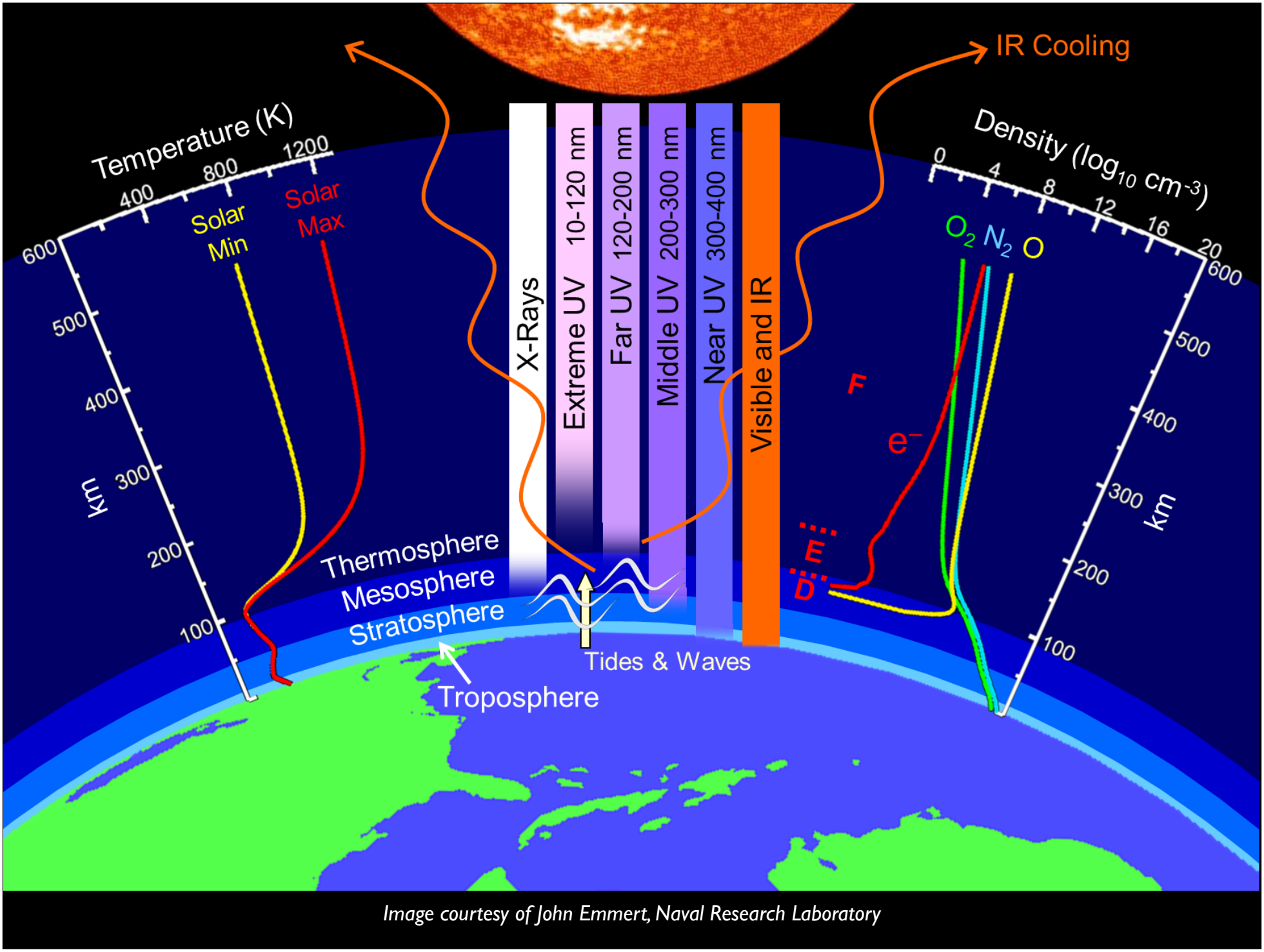
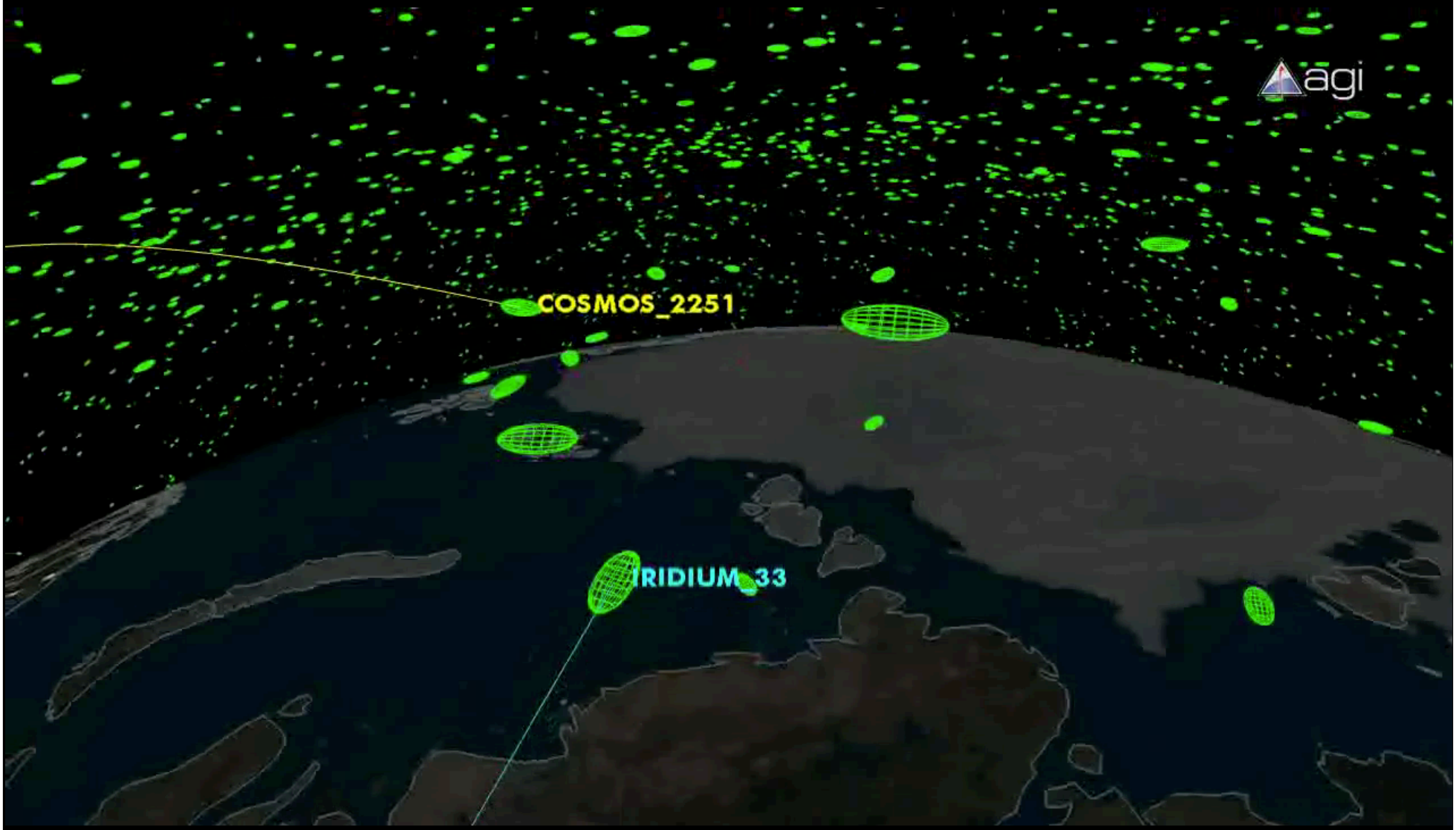


Image courtesy of John Emmert, Naval Research Laboratory

An Application: The Orbital Debris Problem



Video courtesy of Analytical Graphics, Inc. www.agi.com

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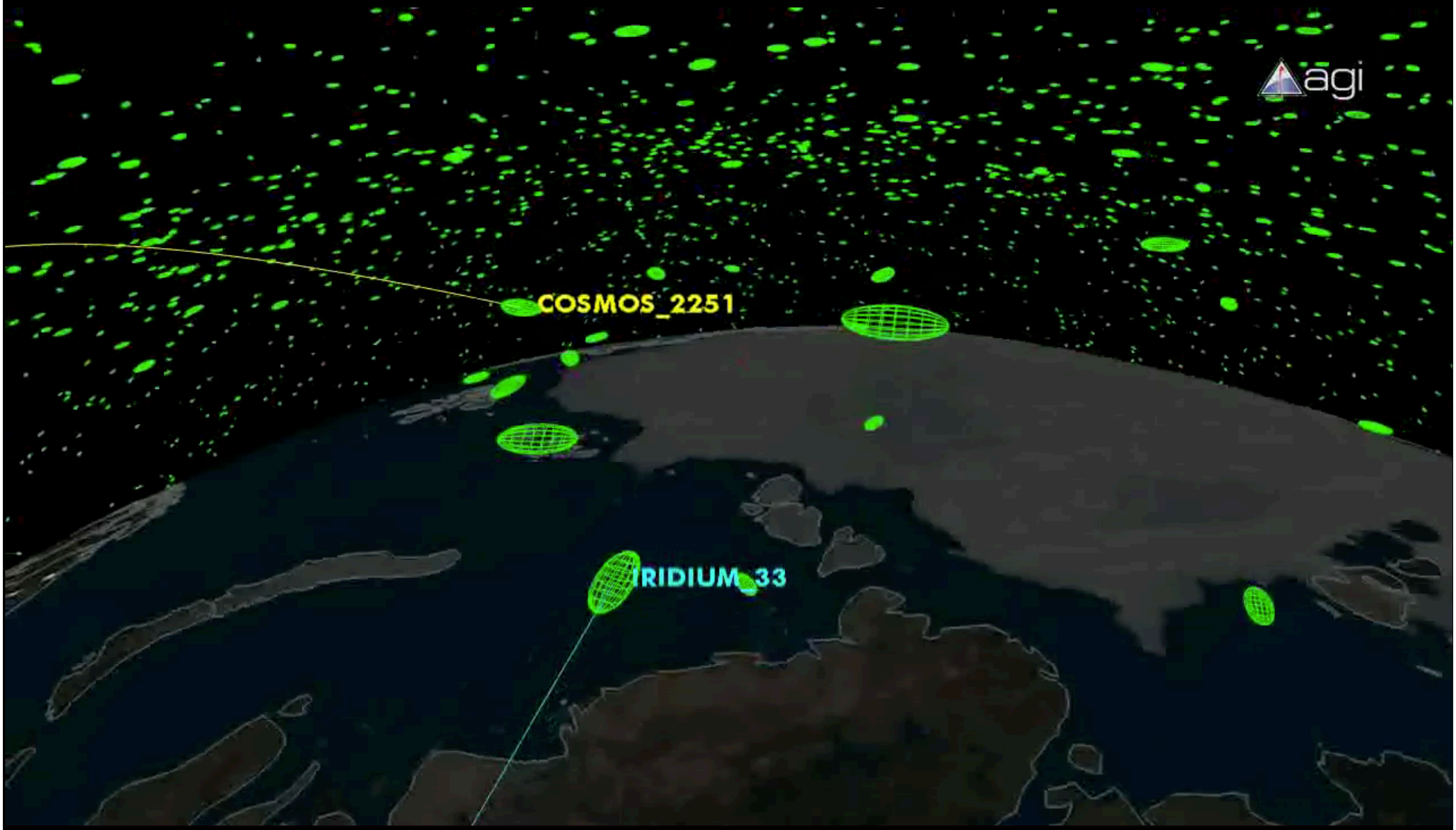

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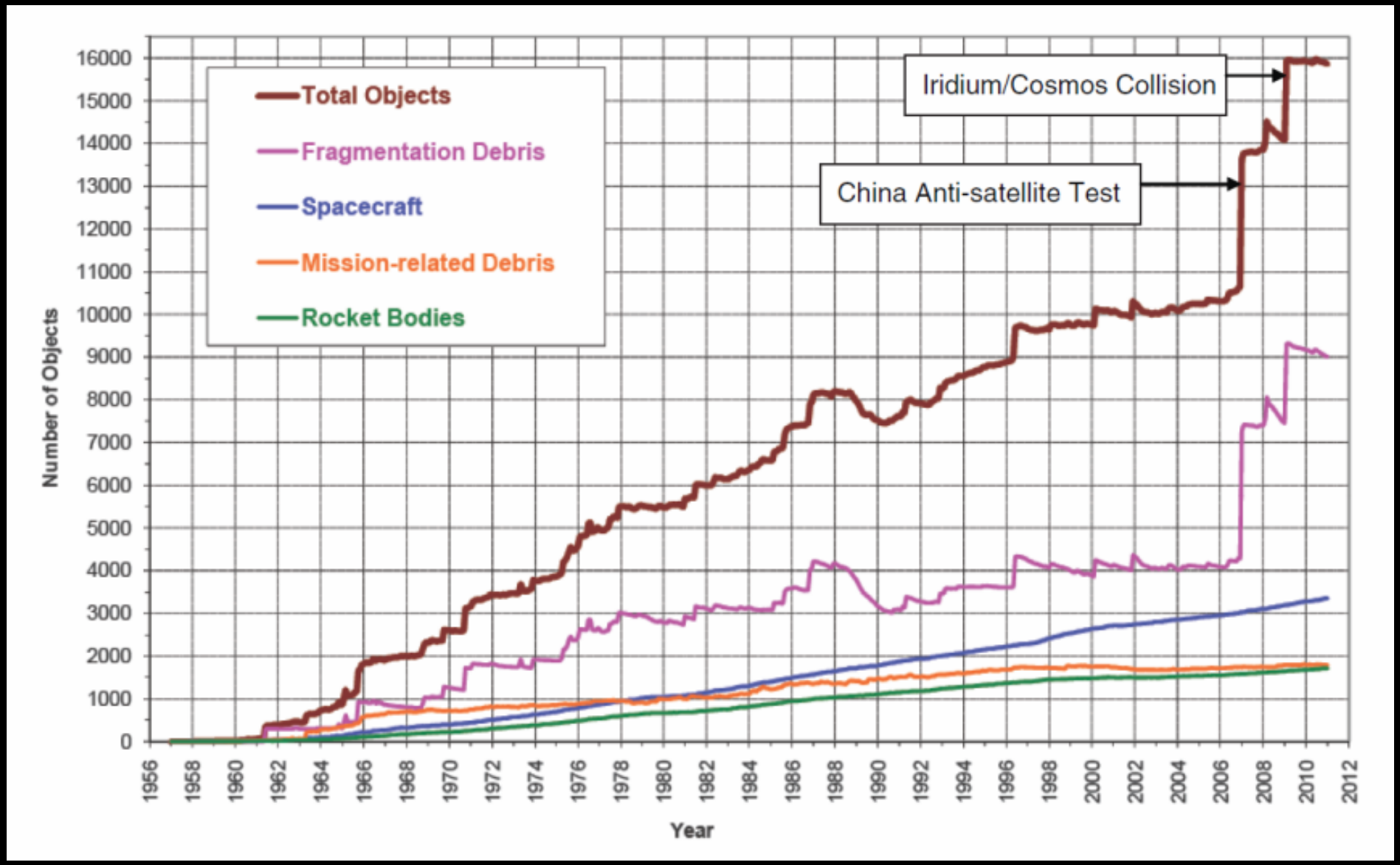
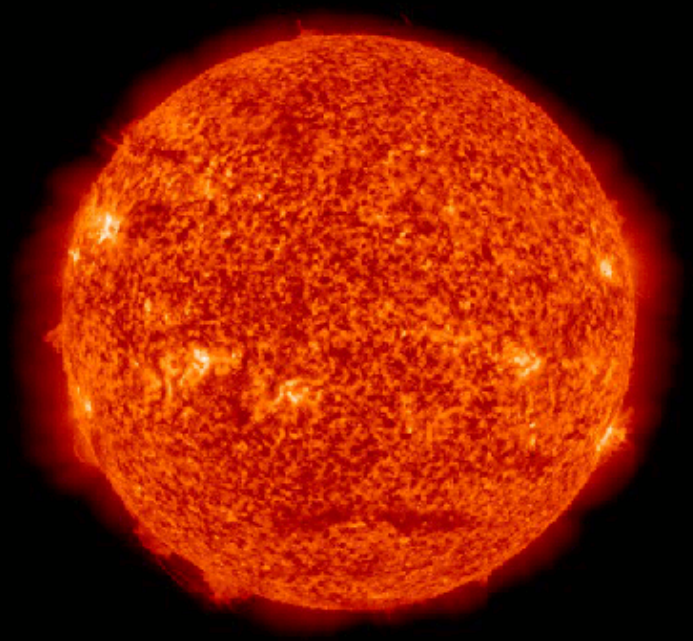
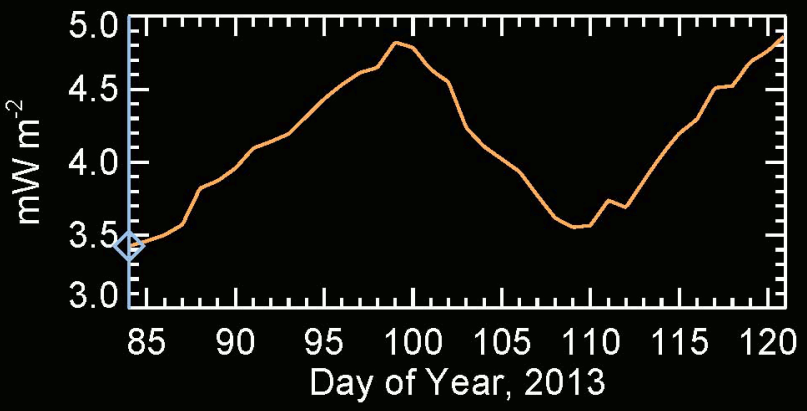


Solar EUV Irradiance Variations

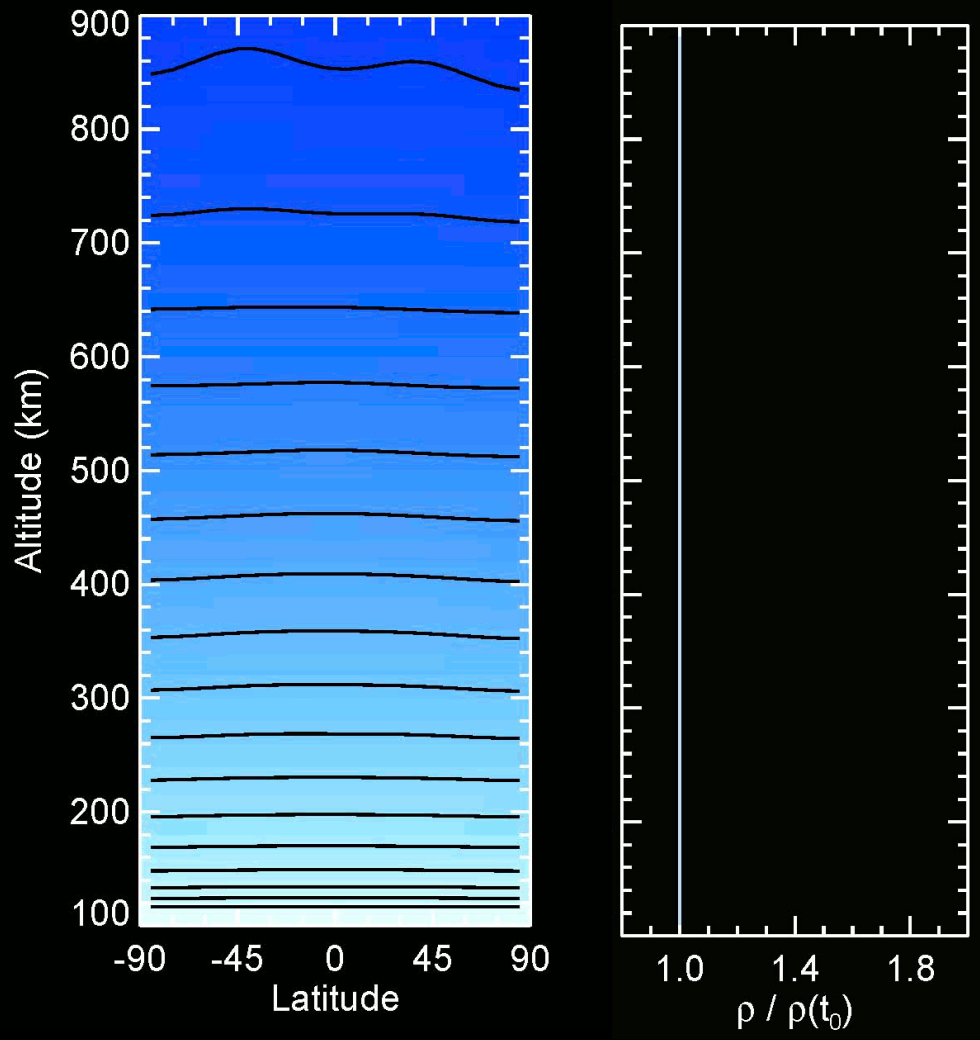
SDO/AIA 30.4 nm



0-103 nm Irradiance (TIMED/SEE)



Thermospheric Density Response NRLMSISE



John Emmert, NRL

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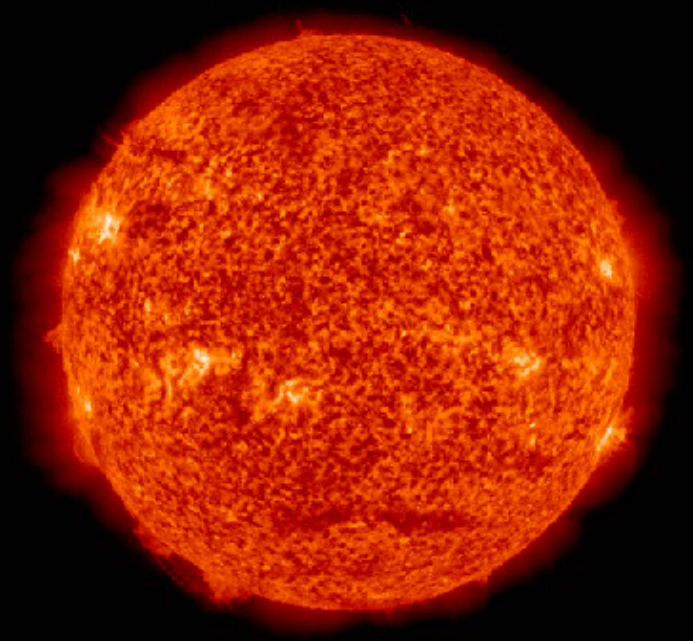

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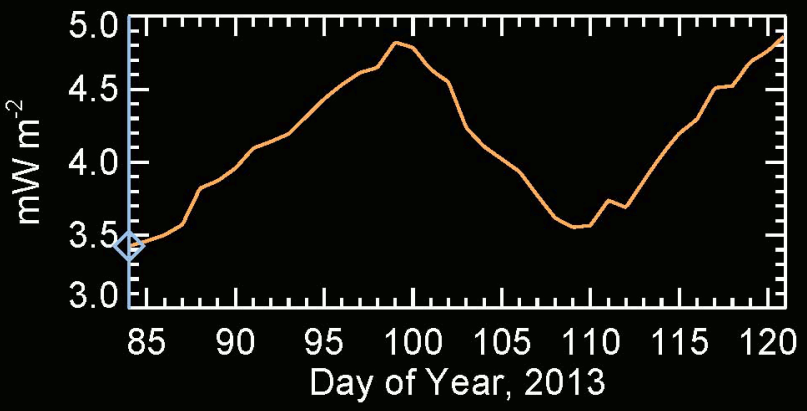

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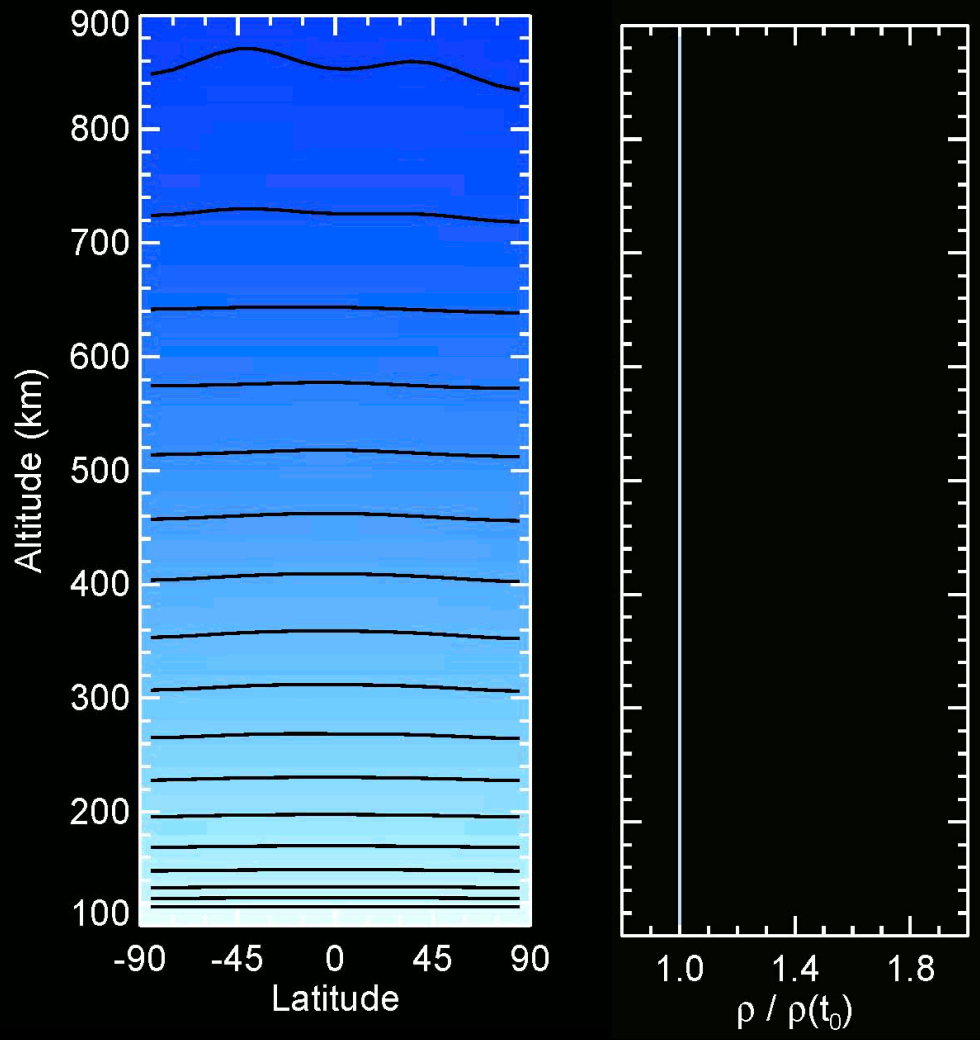
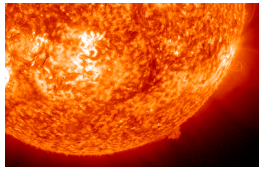
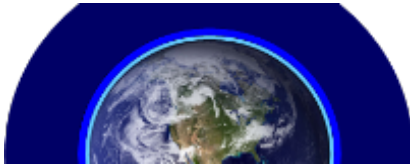


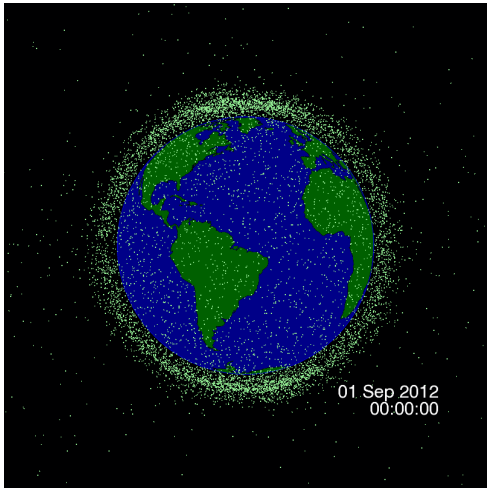
John Emmert, NRL

Connections Among Space Environment Components

Photons (+Solar Wind) | **Gas** | **Forces** | **Satellites and Debris**







Solar EUV and FUV Irradiance

Solar Wind

Total Solar Irradiance

Lower Atmosphere

Thermospheric Density

Thermospheric Wind and Composition

Gravity

Drag Force

Solar Radiation Pressure

Tracking Observations

Satellite Trajectory

Many Objects

Catalog Maintenance

Collision Prediction and Avoidance

Owner/Operator Maneuvers

Satellite Mass, Shape, Material, Attitude

The irradiance and the atmosphere are just part of the problem!

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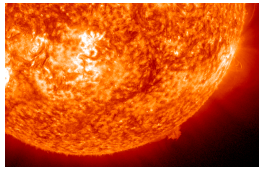

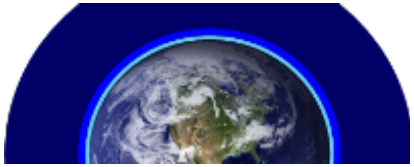

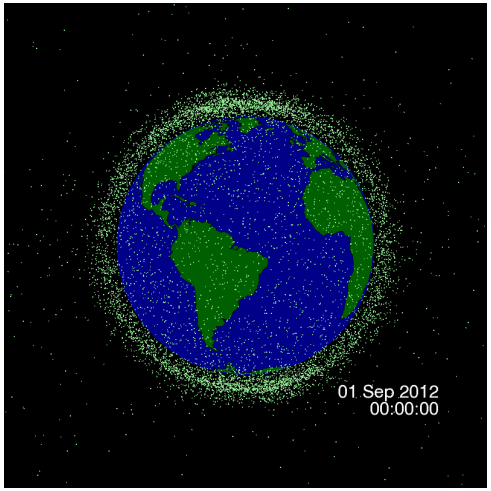

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Outline

- Total Solar Irradiance
  - Measurements
  - Application to climate change
- Solar Spectral Irradiance
  - The Solar Atmosphere
    - Soft X-rays
    - Extreme Ultraviolet
    - Ultraviolet
    - Visible/Infrared
  - Overview of observations
  - Application to satellite drag

- Common proxies for solar activity
- Proxy irradiance models
- A quick note on regression
  - Training/Test/Validation
  - Gaussian Process Regression
- The magnetic flux as a proxy
- Forecasting solar activity
  - Autoregression
  - Magnetic flux transport
- Emission processes
  - Optically thin line emission
- Semi-empirical models
  - Differential emission measure
- My 2 cents on useful tools and skills