Variability of Lyman-Alpha Emission During Solar Flares and Implications for Planetary Atmospheres

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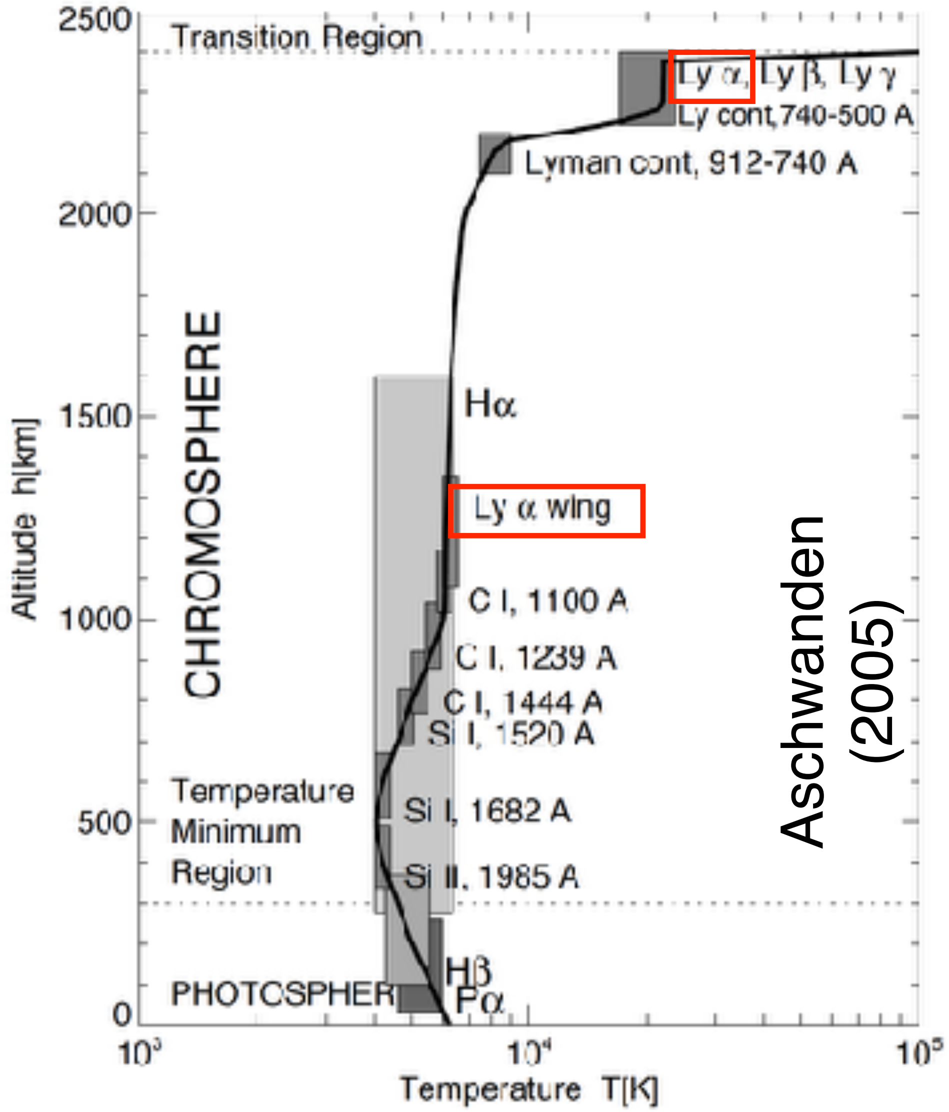
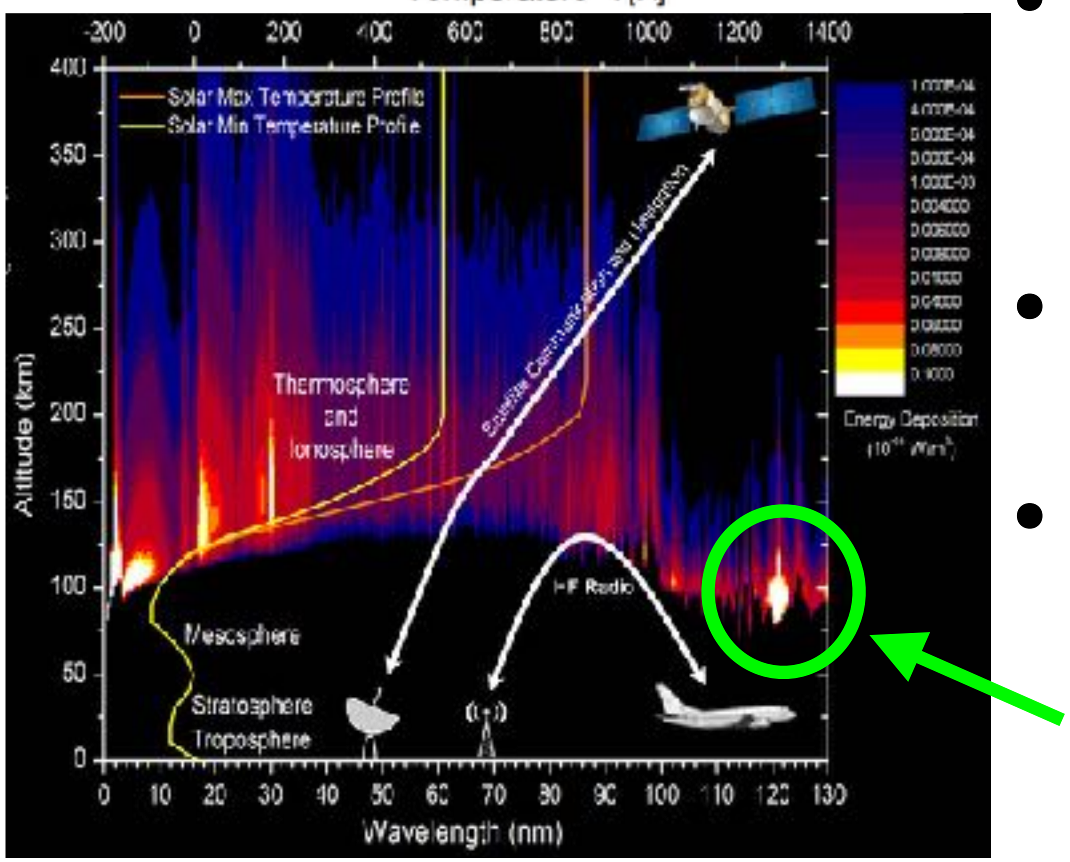
Lyman-alpha

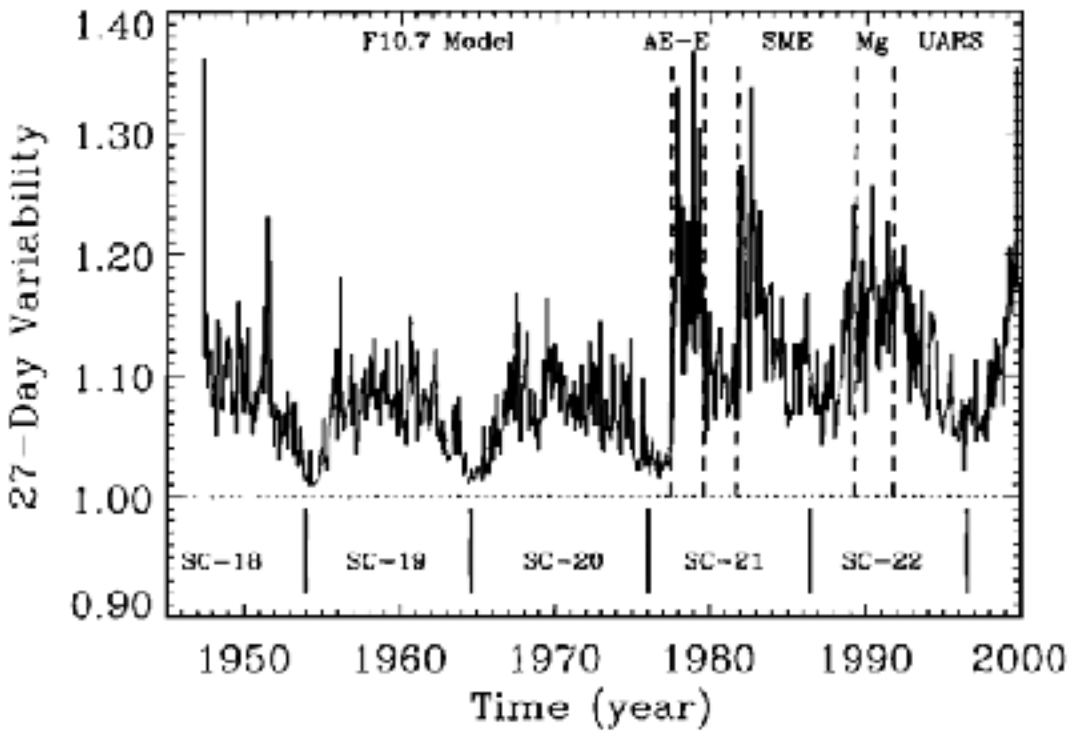


Aschwanden (2005)



- Lyman-alpha (Lyα; 1216Å) line of H I is the strongest emission line in the solar spectrum
- Line core is formed in the lower TR; wings are formed mid-chromosphere (quiet Sun)
- During solar flares, Lyα comes predominantly from the ribbons/footpoints
- Lyα is optically thick
- Lyα photons cause photodissociation of water in the mesosphere (ozone) and ionizes nitric oxide generating the D-layer of the ionosphere (80-110km; Lean+ 1985)

Lyα Variability

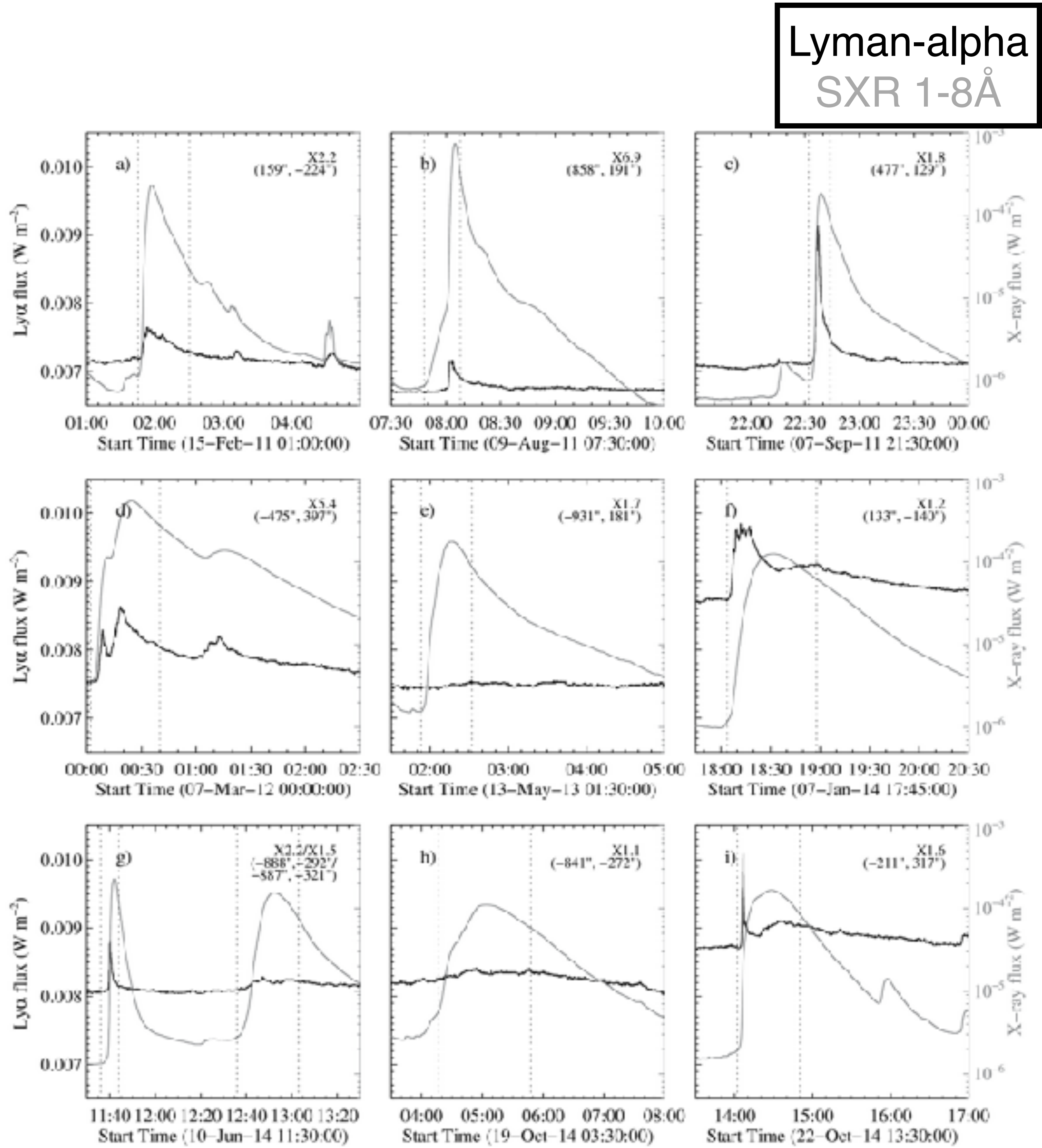


Woods+ (2000)

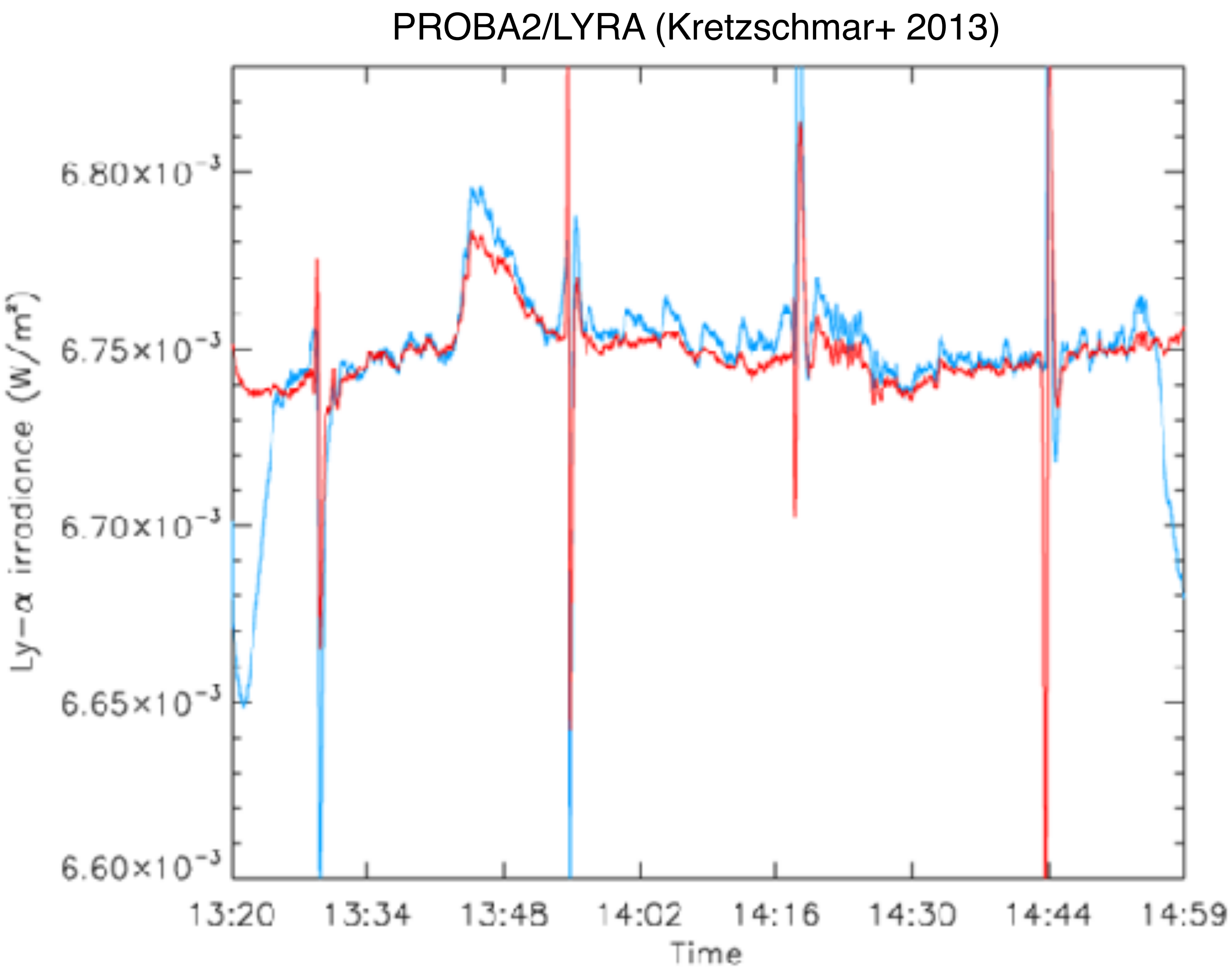
- Medium (AR) and long-term (SC) variability in Lyα irradiance have been well studied, however flare observations have been notoriously absent
- Many instruments have not had the sensitivity, cadence, or duty cycle to capture flare increases above the intense solar background
- Of the few flares observations obtained, most are “Sun-as-a-star” with no spatial or spectral information, and measurements have been known to contradict one another

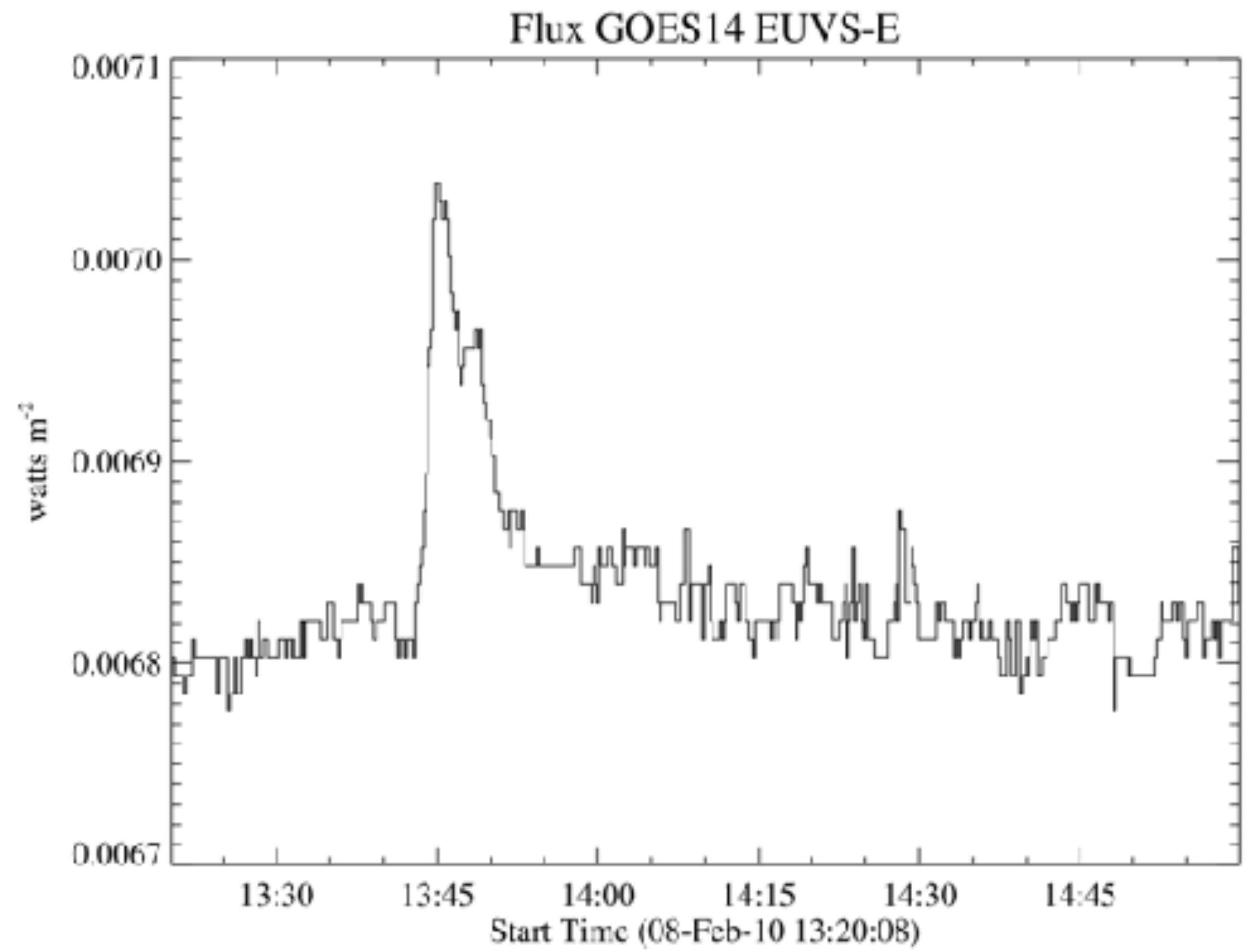
Lyα Flare (Irradiance) Observations

- Milligan+ (2020) published a statistical study of ~500 M+X class flares using GOES-15/EUVS-E data. Follow up included B+C class flares (Milligan 2021).
- These data are spatially and spectrally integrated, and based on a Quiet-Sun line profile
- What are the spatial and spectral variations of Lyα emission during flares? GOES-class dependence?



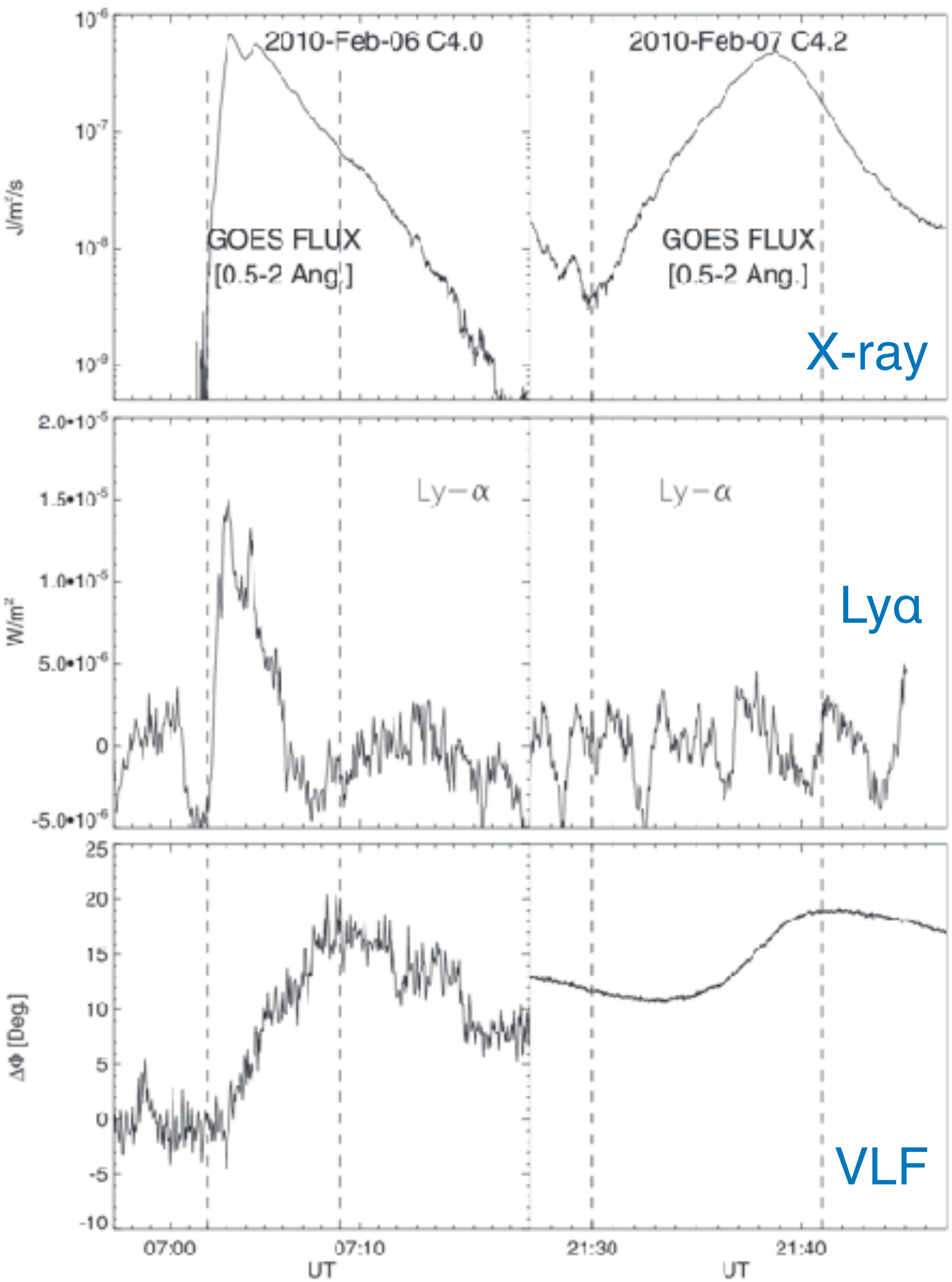
Contradicting Measurements





- For an M2 flare (8-Feb-2010) PROBA2/LYRA showed a *gradually-varying* profile, with a 0.3% enhancement above background (Kretzschmar+ 2013; similar to SDO/EVE. See also Milligan & Chamberlin 2016)
- For the same flare, GOES-14/EUVS-E showed an *impulsive* profile, with an ~3% contrast (similar to SORCE/SOLSTICE)

Raulin et al. (2013)

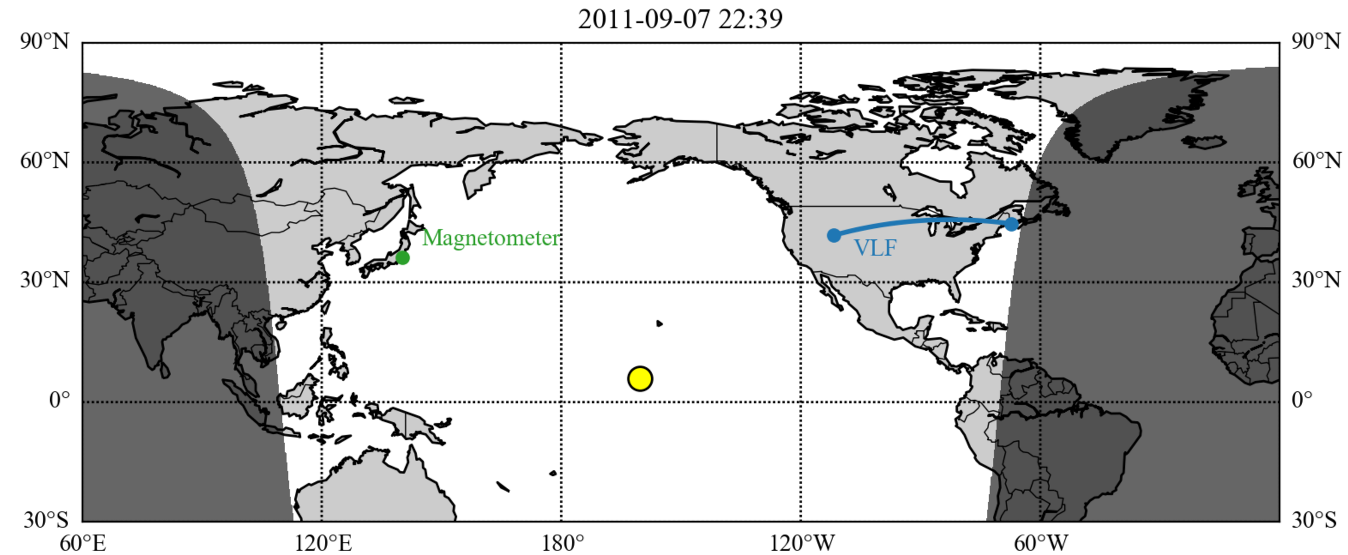


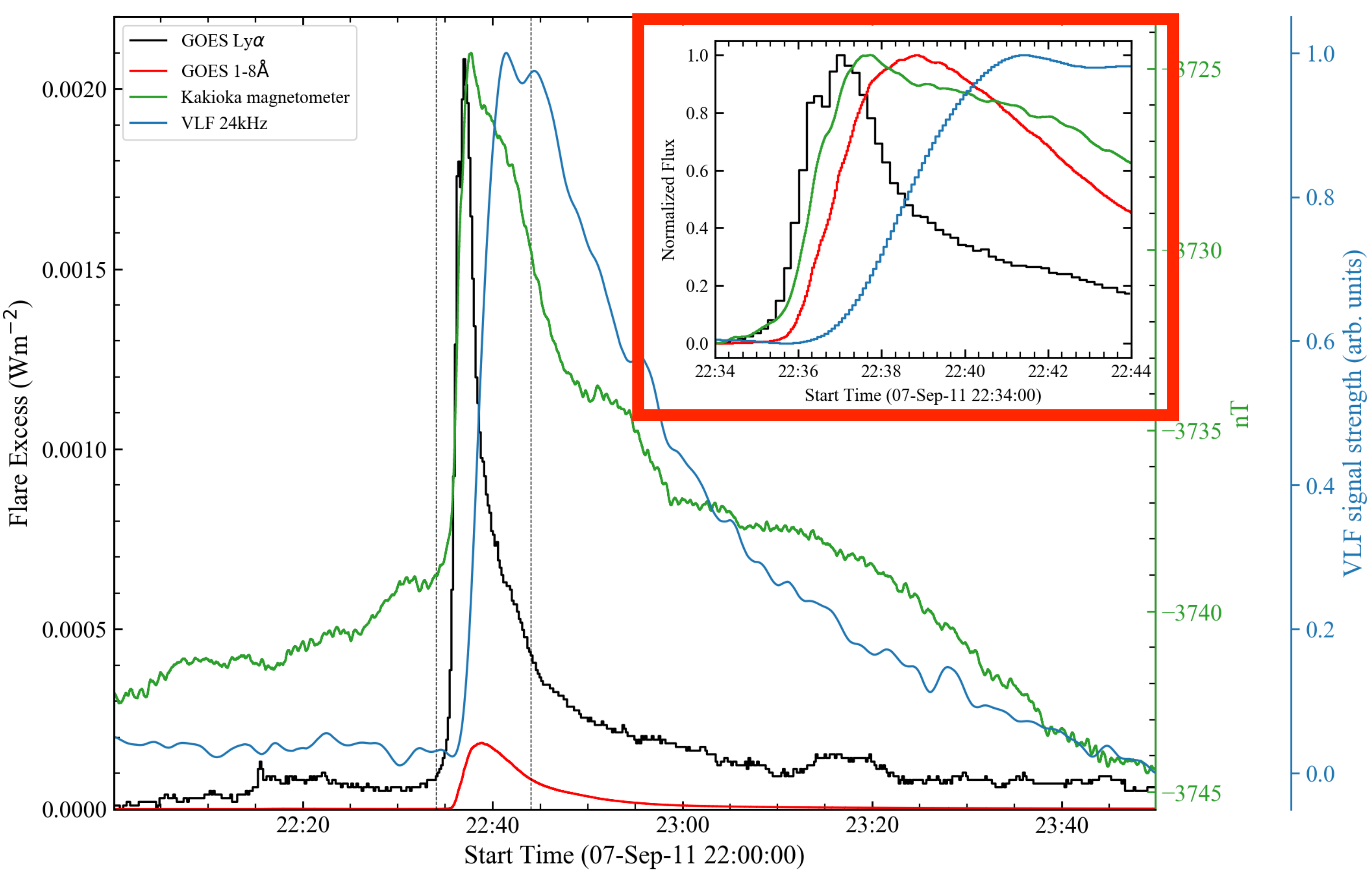
Raulin+ (2013)

- Looked for correlation between Lyα (from PROBA2) and D-layer response (from VLF) for seven C and low-M flares
- Lyα contrasts were found to be <1%
- "…we have shown that the impact of transient solar Lyman-a excesses on the electrical conductivity of the D region is negligible"

- PROBA2/LYRA significantly underestimates Lyα enhancements compared to GOES/EUVS (Geocoronal absorption? See also Wauters+ 2022)
- C-class flares are less likely to produce Lyα enhancements above the background, especially in the case of limb flares
- In Milligan+ 2020, we show that Lyα increases correlate with E-layer response

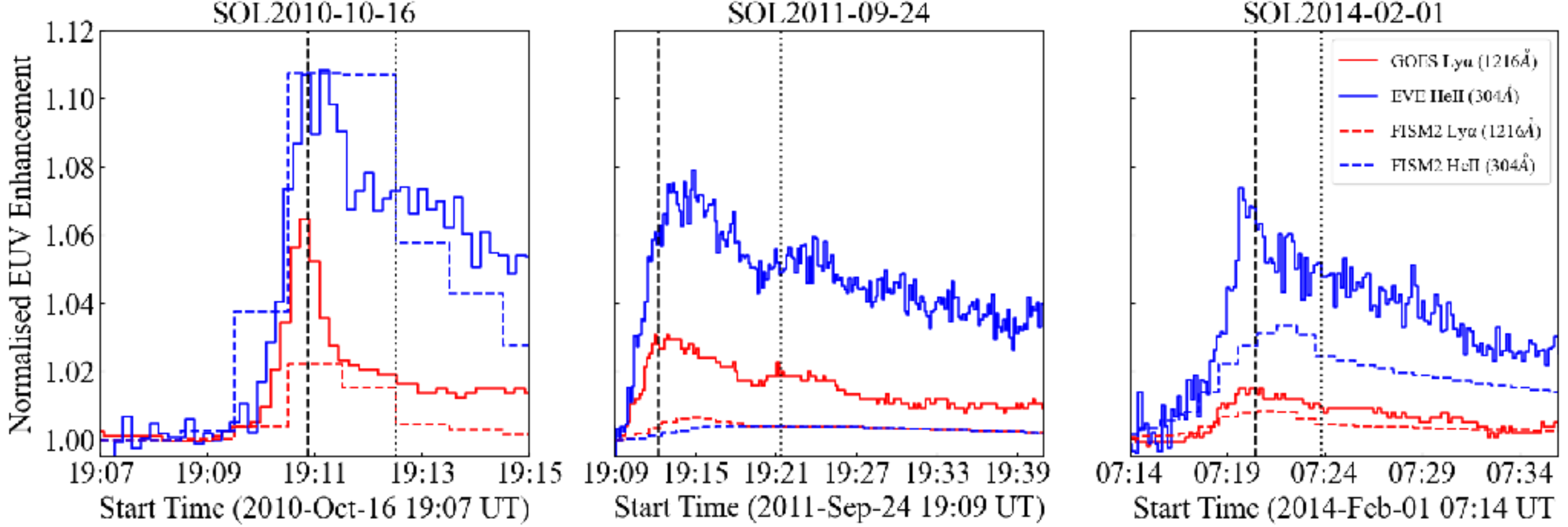
Ionospheric Effects of Lyα





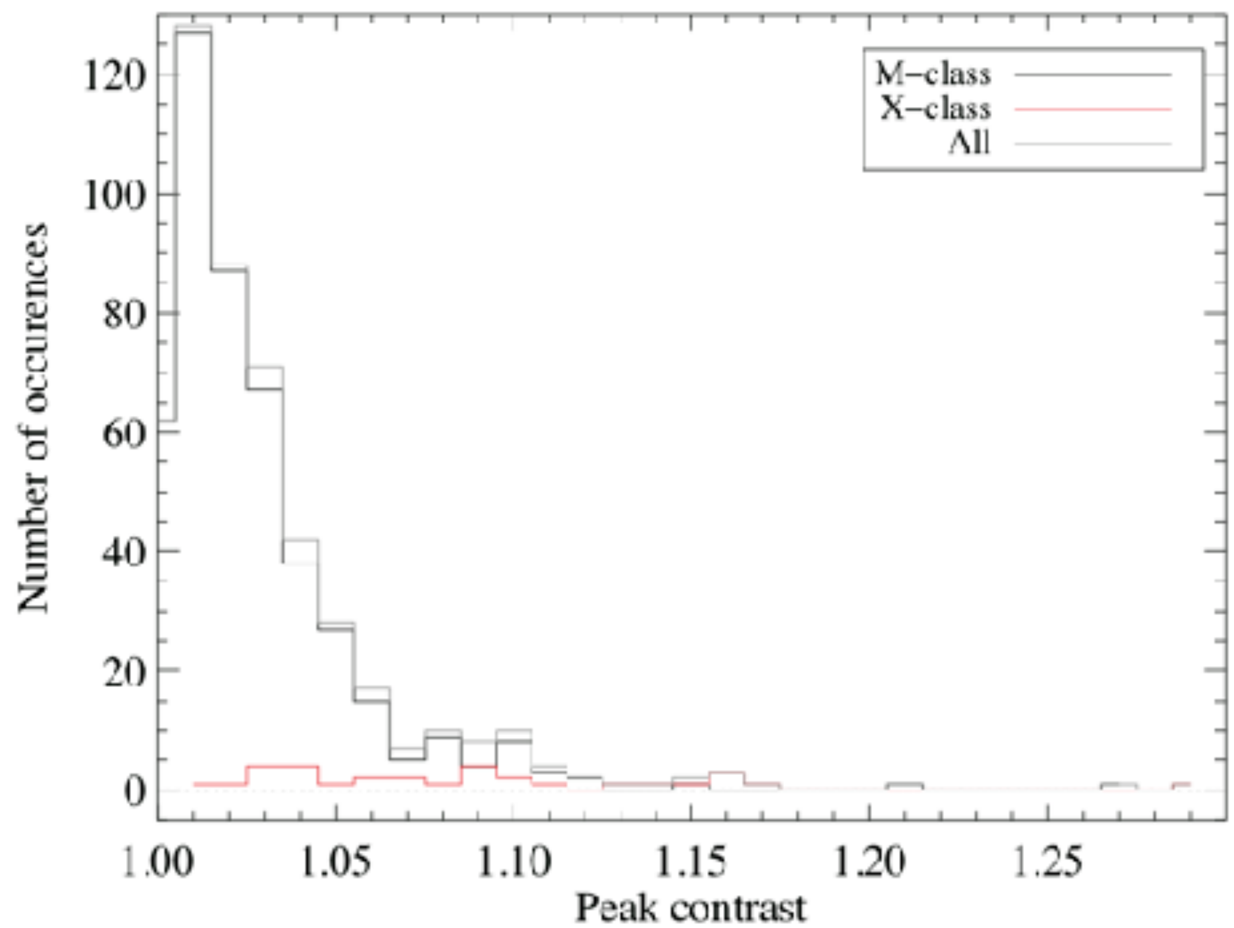
- During the 7-Sep-2011 X-class flare, enhanced E-layer conductivity closely followed the increased **Lyα emission**
- Due to increased ionisation of nitric oxide (“Solar Flare Effect/ Magnetic Crochet”)
- Corresponding X-rays lagged the E-layer response, implying that they could not have been the driver (Raulin+ 2013)
- The X-ray profile resembled the D-layer response from VLF observations with the known ~3-minute delay (“sluggishness”)
- How common is this correlation? Was NO abundance abnormally high during this event?

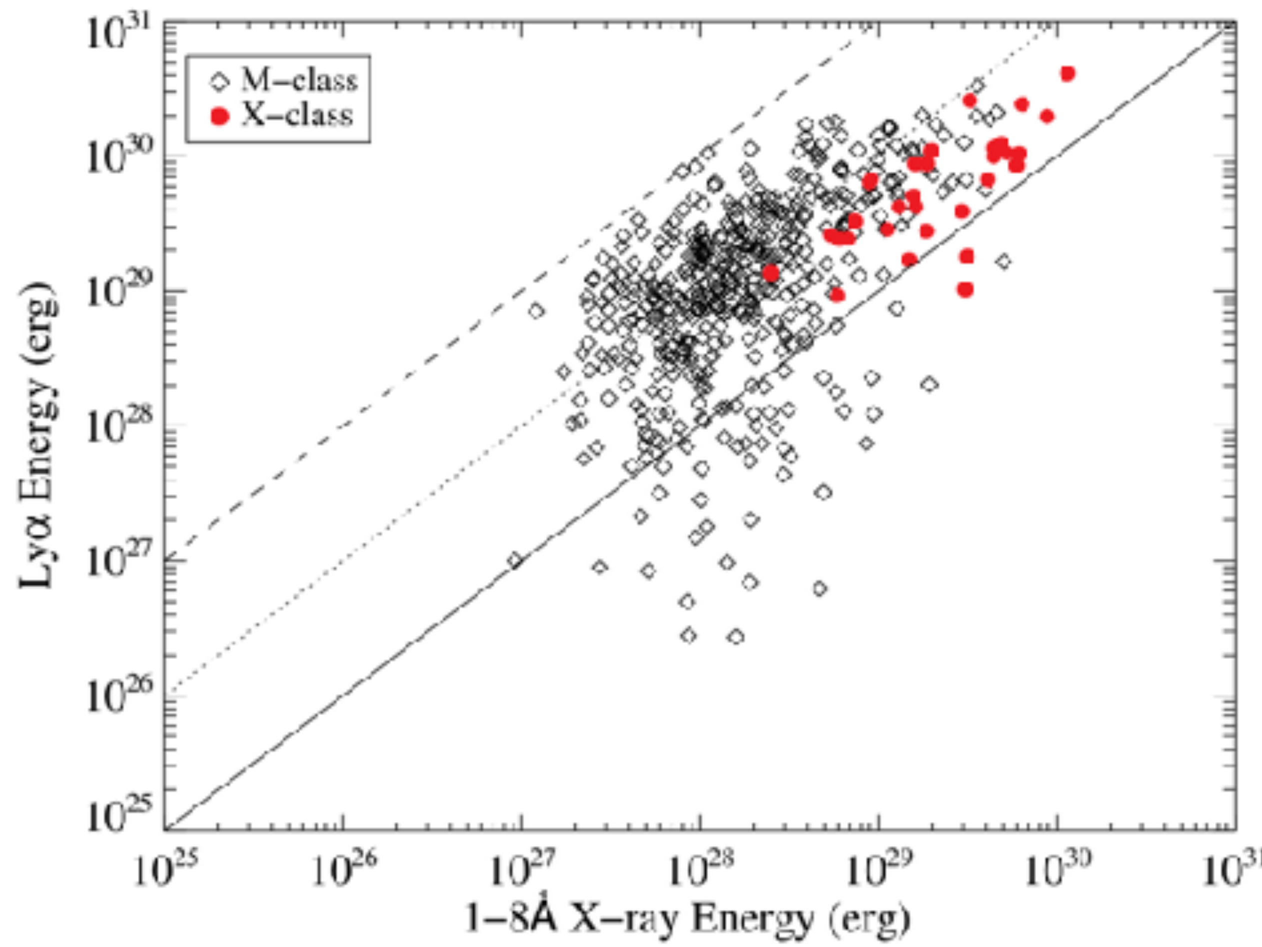
Milligan+ (2020)



- Why do flares of comparable X-ray magnitude (and similar locations) have different Lyα responses?
- Greatorex+ (2023) studied three M3 flares with different Lyα (and He II) responses
- FISM2 significantly underestimates the increases in Lyα for each event
- HXR spectroscopy revealed that `harder' nonthermal electron distributions tend to produce greater Lyα enhancements
- Lyα was found to radiated 2-8% of the non thermal energy in agreement with Milligan+ (2014)
- What are the corresponding ionospheric responses for these events?

Lyα Contrast and Energetics

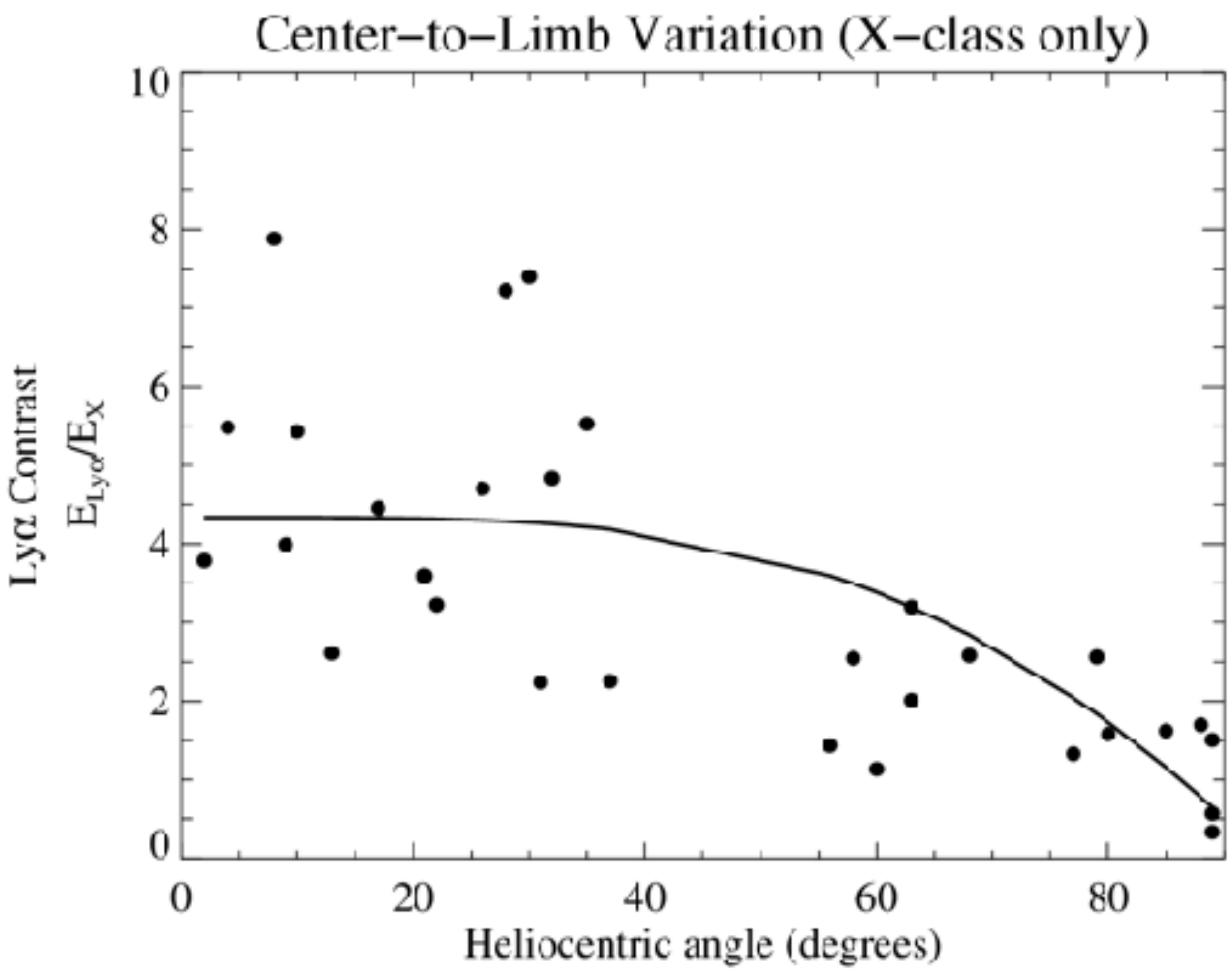


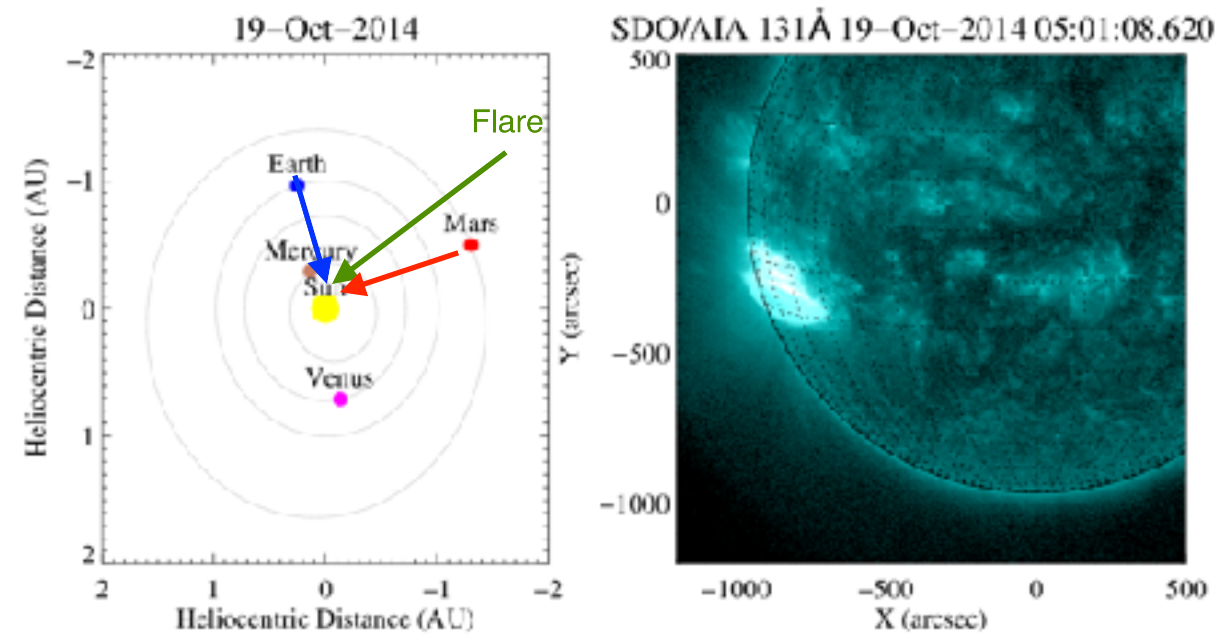


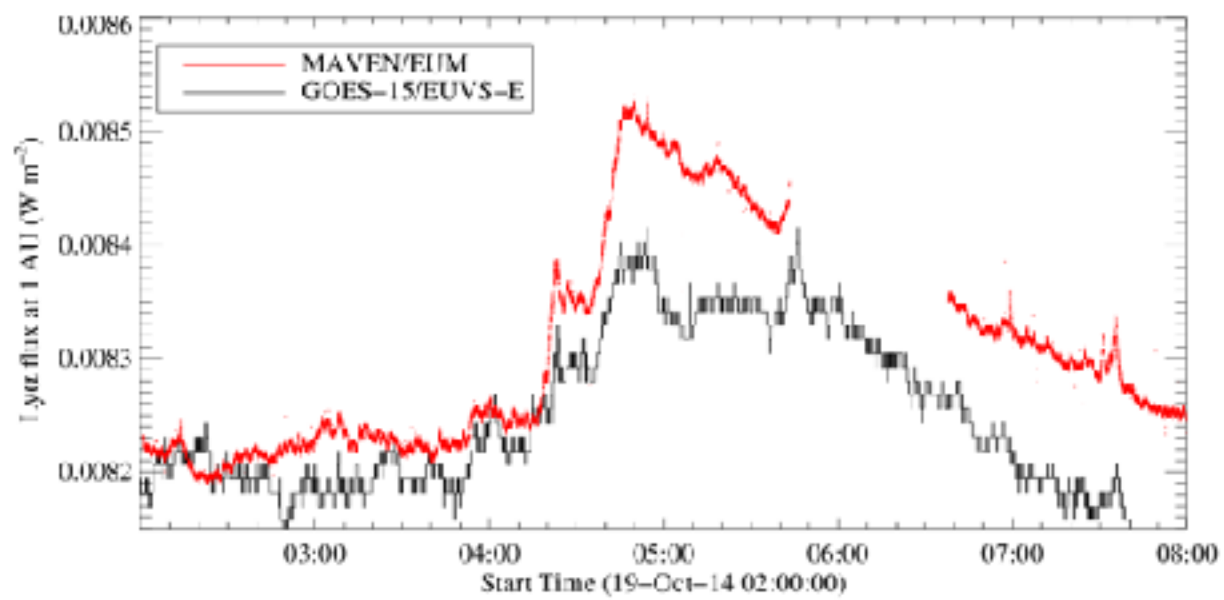
- Enhancements of Lyα emission above background do not exceed 30% for the ~500 flares studied, typically <5%
- Comparable to variability due to AR rotation, albeit on much shorter timescales (Woods+ 2000)
- Total radiated energy in Lyα was up to 100 times more than in the associated X-rays
- Flares that occurred closer to the solar limb showed less of a Lyα enhancement

Milligan+ (2020)

Center-to-Limb Variation



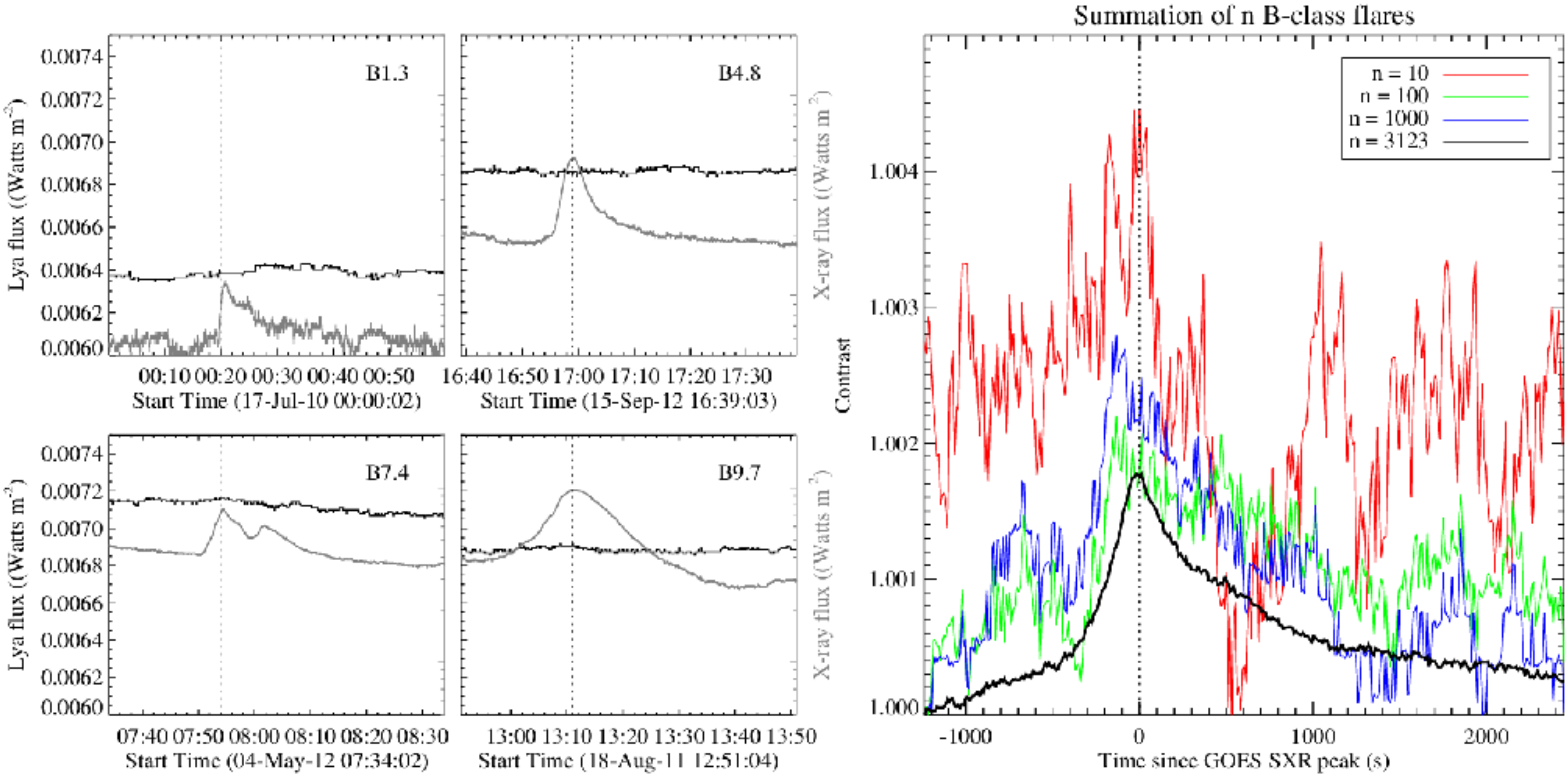




- CLV has been found for flares of all classifications using a superposed epoch analysis.
- Is this purely an opacity effect or a foreshortening of the flare ribbons?

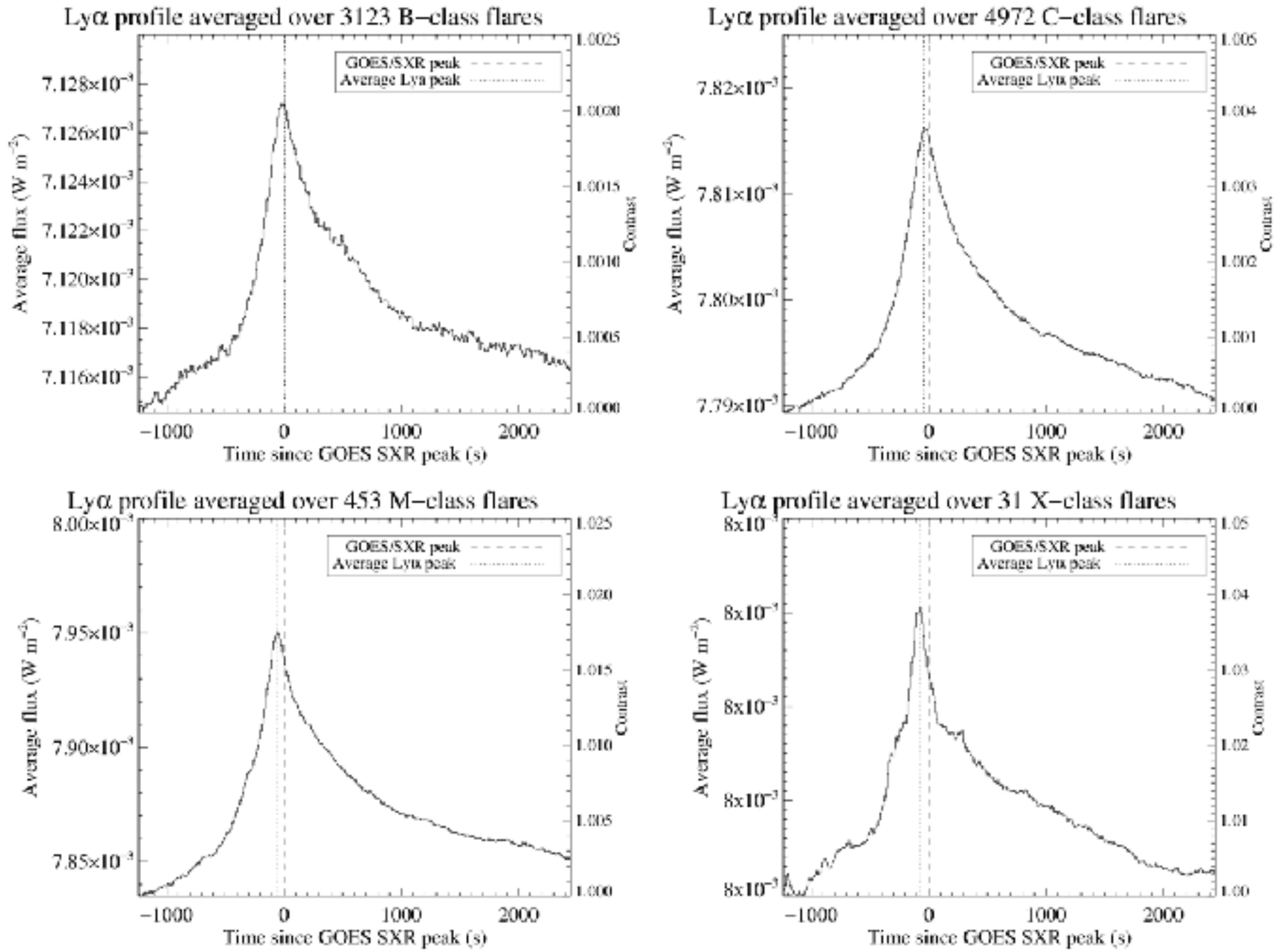
- Confirmed by stereoscopic observations of an X-class flare observed by GOES (on the limb) and MAVEN (at disk centre)

Left: Milligan (2021); Right: Milligan+ (2020)



- Weaker GOES events are not readily visible in disk-integrated emission.
- A superposed-epoch analysis was carried out in order to increase the S/N.
- Timerange was taken as SXR peak -20 minutes/+40 minutes

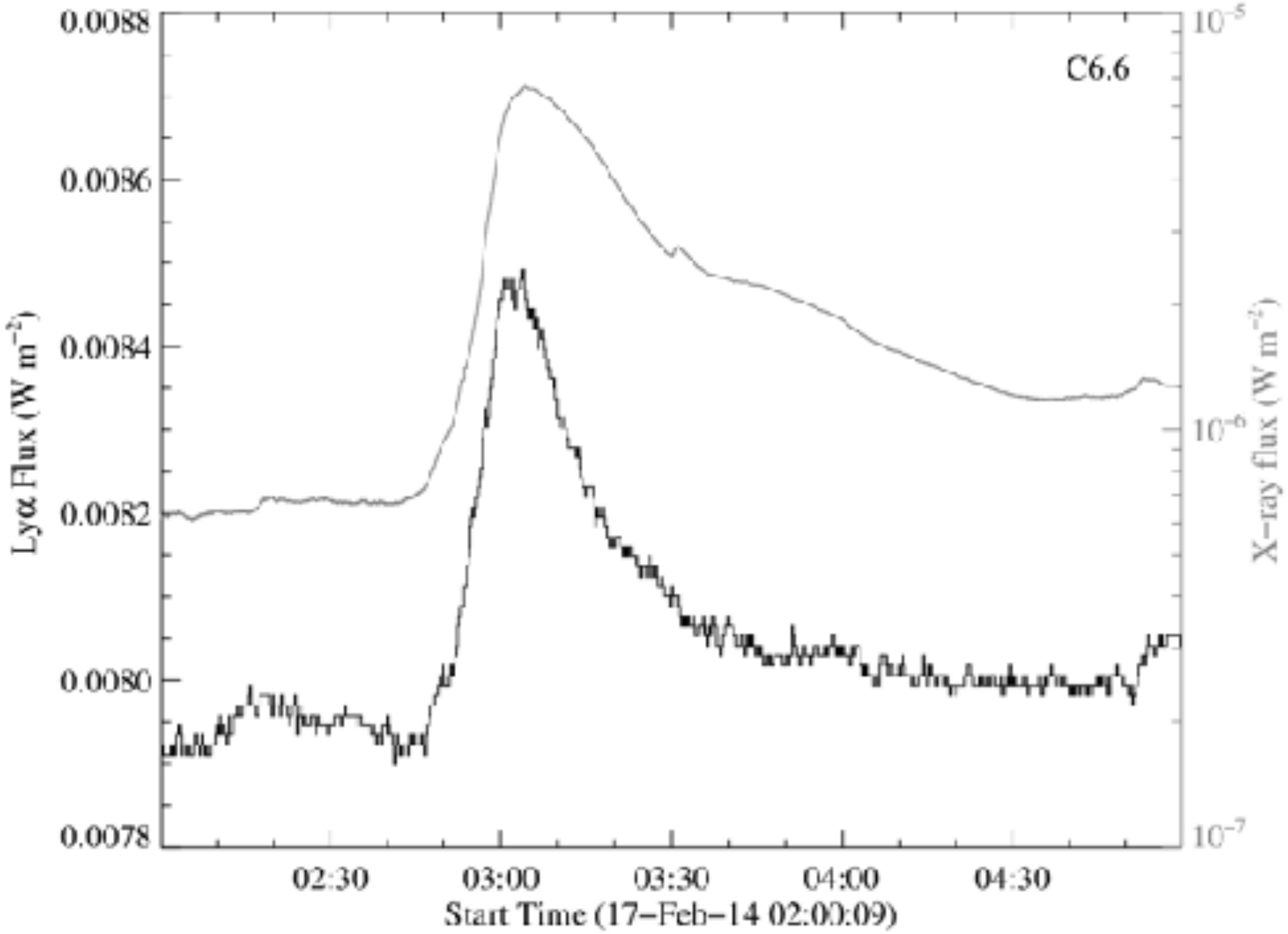
Milligan (2021)

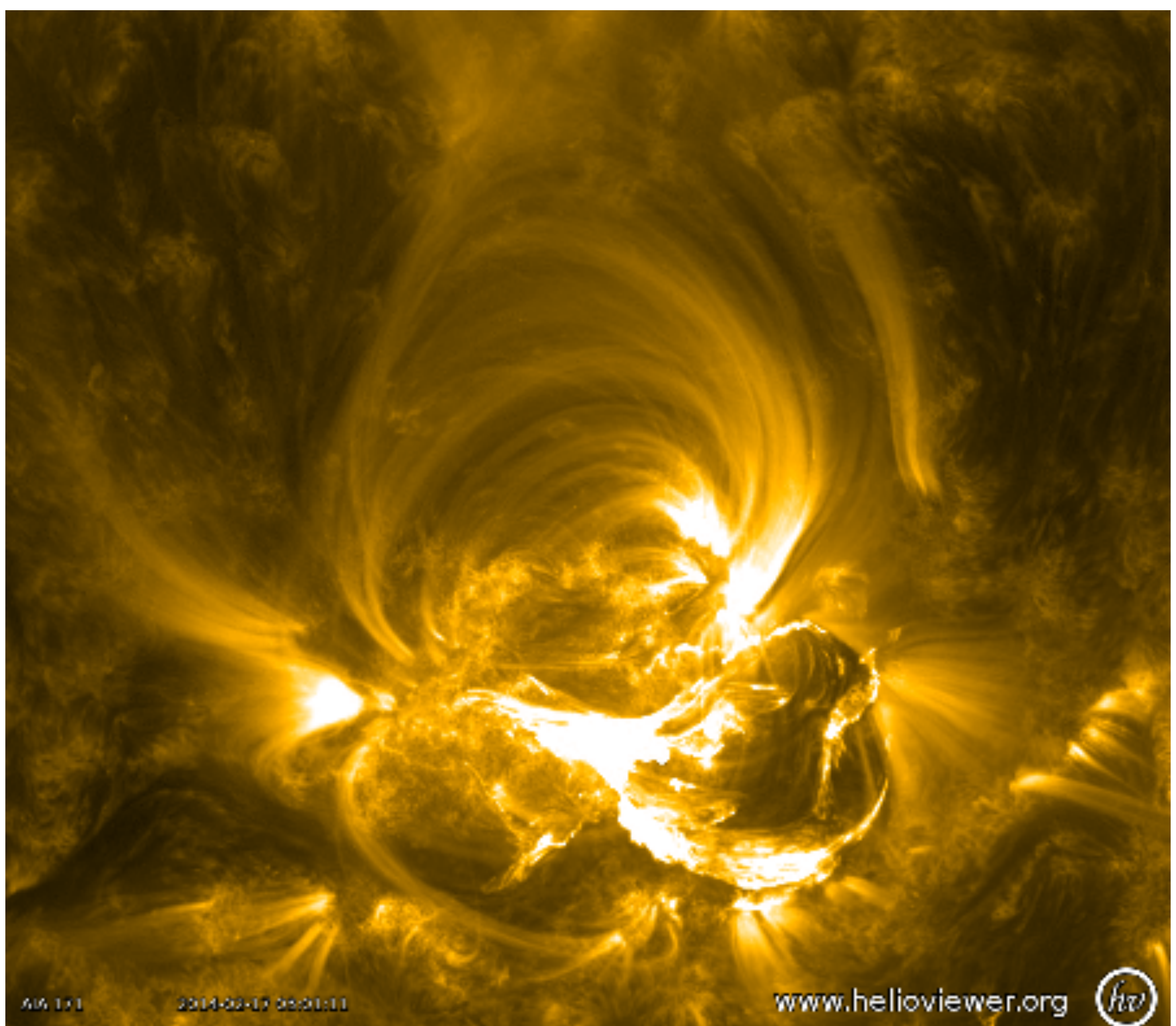


	No. of events	Average Peak Contrast	Peak time relative to
B-class	3123	0.18%	0s
C-class	4972	0.35%	-40.96s
M-class	453	1.5%	-51.20s
X-class	31	3.8%	-71.68s

Milligan (2021)

An Unusual C-class Flare





- One event in the study - a C6.6 flare - produced a remarkable 7% increase in Lyα!
- This equates to 10^{30} ergs of energy
- Such enhancements were believed to be associated with X-class flares
- Appears to be due to a failed filament eruption
- Evidence for Lyα emission from the corona? Would this be optically thin? (see also Rubio da Costa+ 2009, Wauters+ 2022)

Milligan (2021)

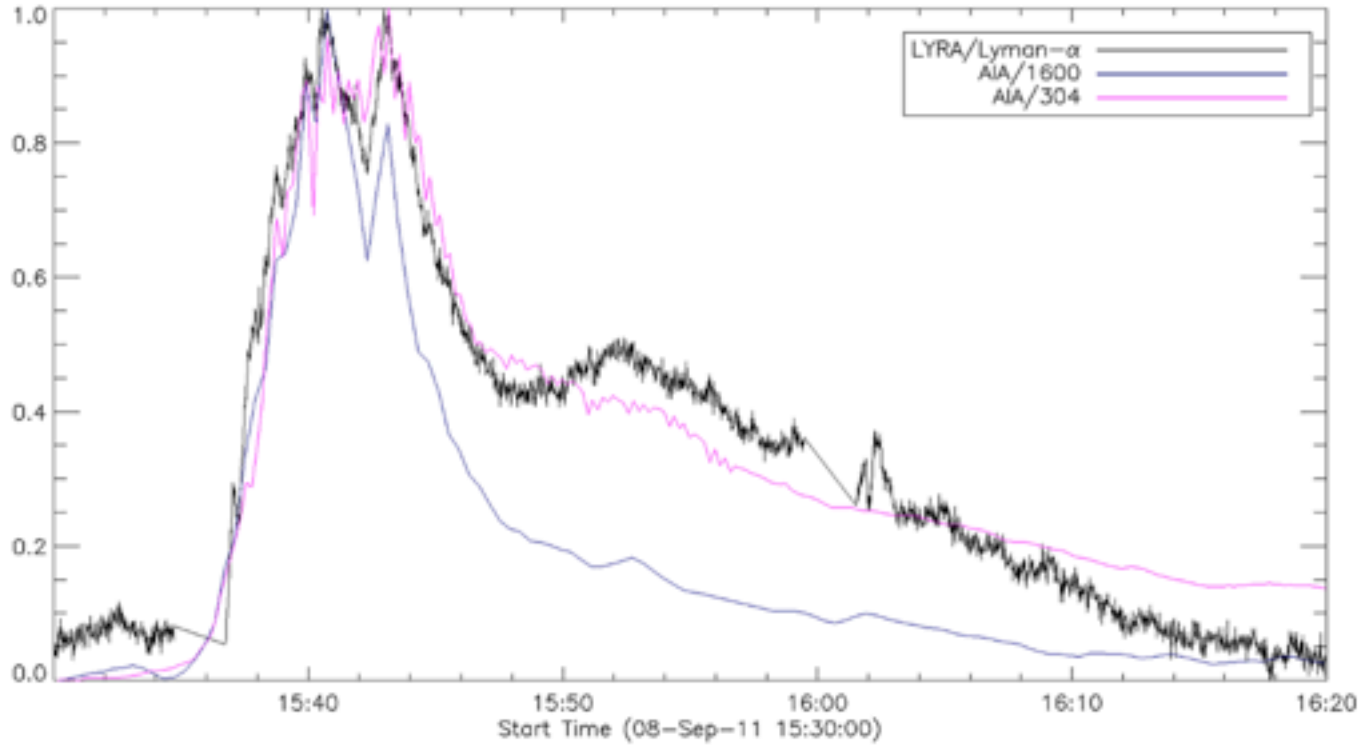


Figure 5 Comparison of the normalized irradiance variation in LYRA/Lyman-α (*black*), AIA 160 nm (*blue*), and AIA 30.4 nm (*pink*).

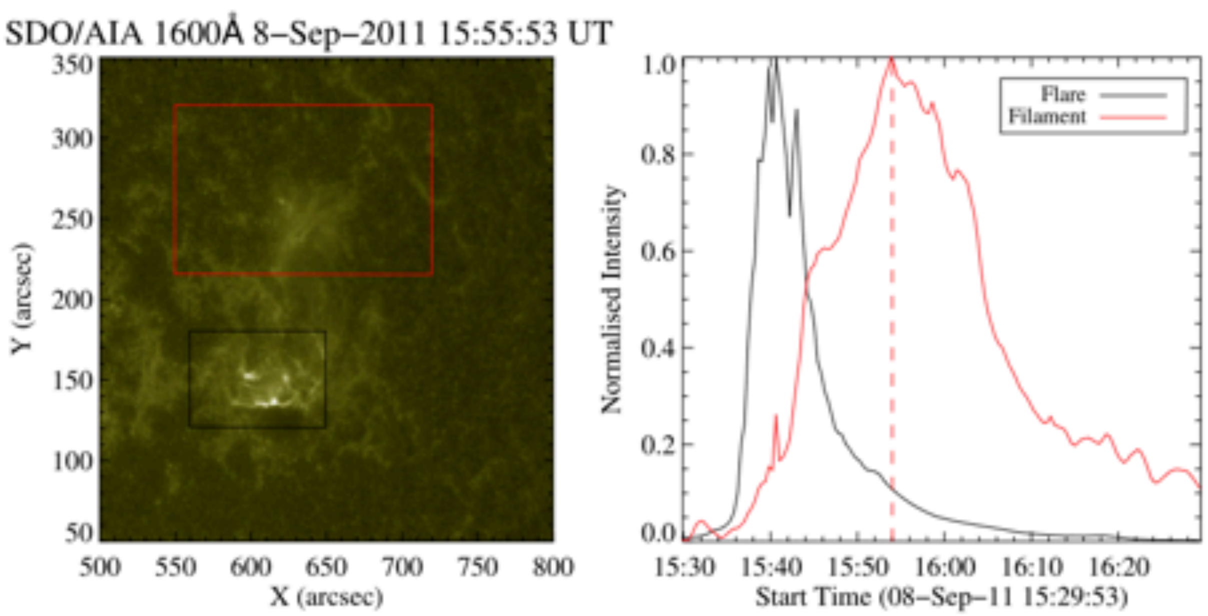
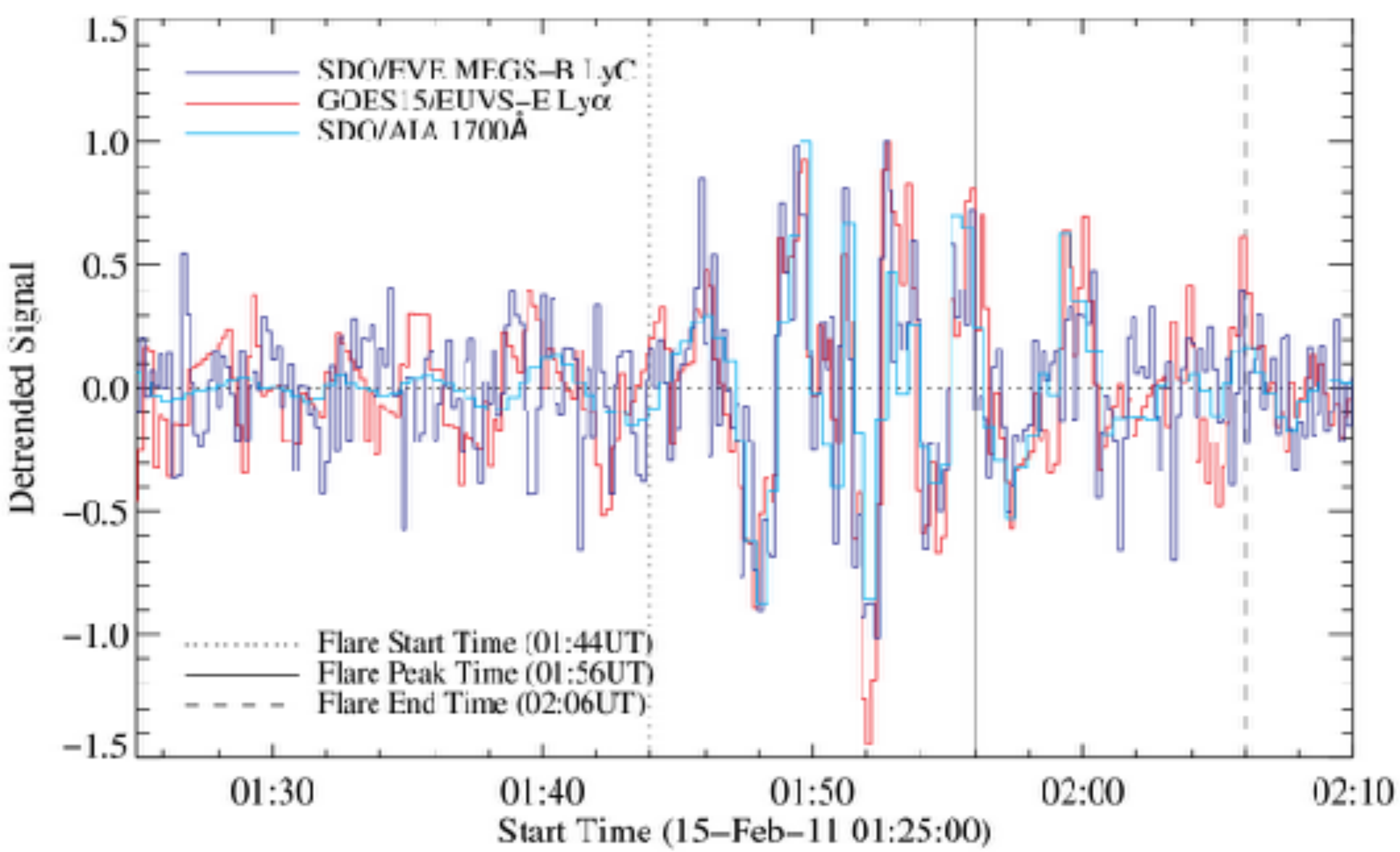


Figure 6 The *left panel* shows the regions corresponding to the flare (*white-square*) and to the filament (*red-square*) as observed at 15:55 by AIA 160.0 nm. The *right panel* shows the time series corresponding, respectively, to the flare (*white*) and filament (*red*) integrated intensities.

- Wauters+ (2022) studied an M6 flare that displayed an increase in Lyα irradiance during the decay phase (both GOES and PROBA2)
- This enhancement did not correspond to any increase in SXR or HXR
- Using SDO/AIA 1600Å images we generated separate lightcurves for the flare and an erupting filament
- Late-phase Lyα increases were therefore attributed to the filament eruption in the corona
- Additional evidence for coronal Lyα emission…?

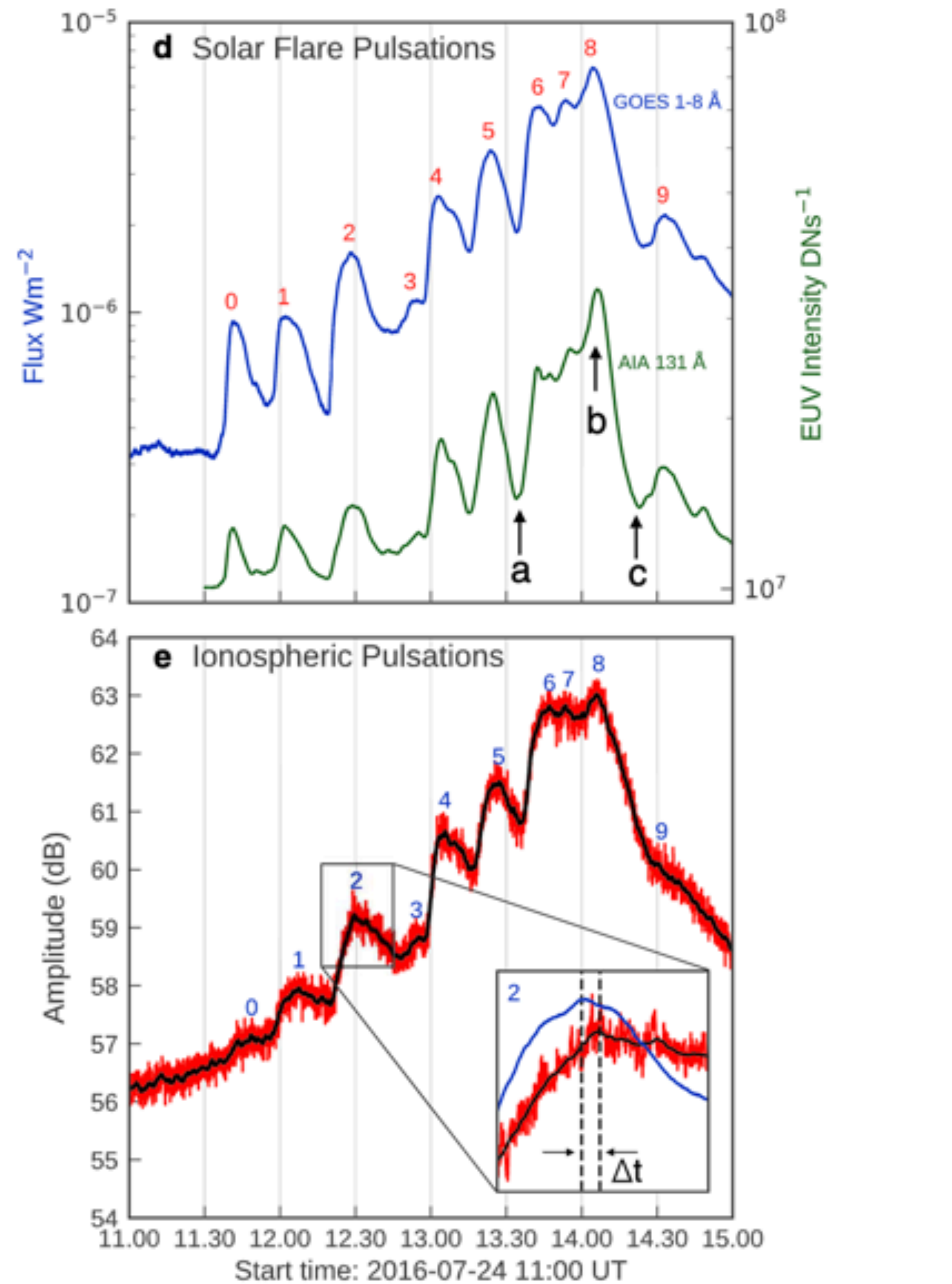
Acoustic Oscillations

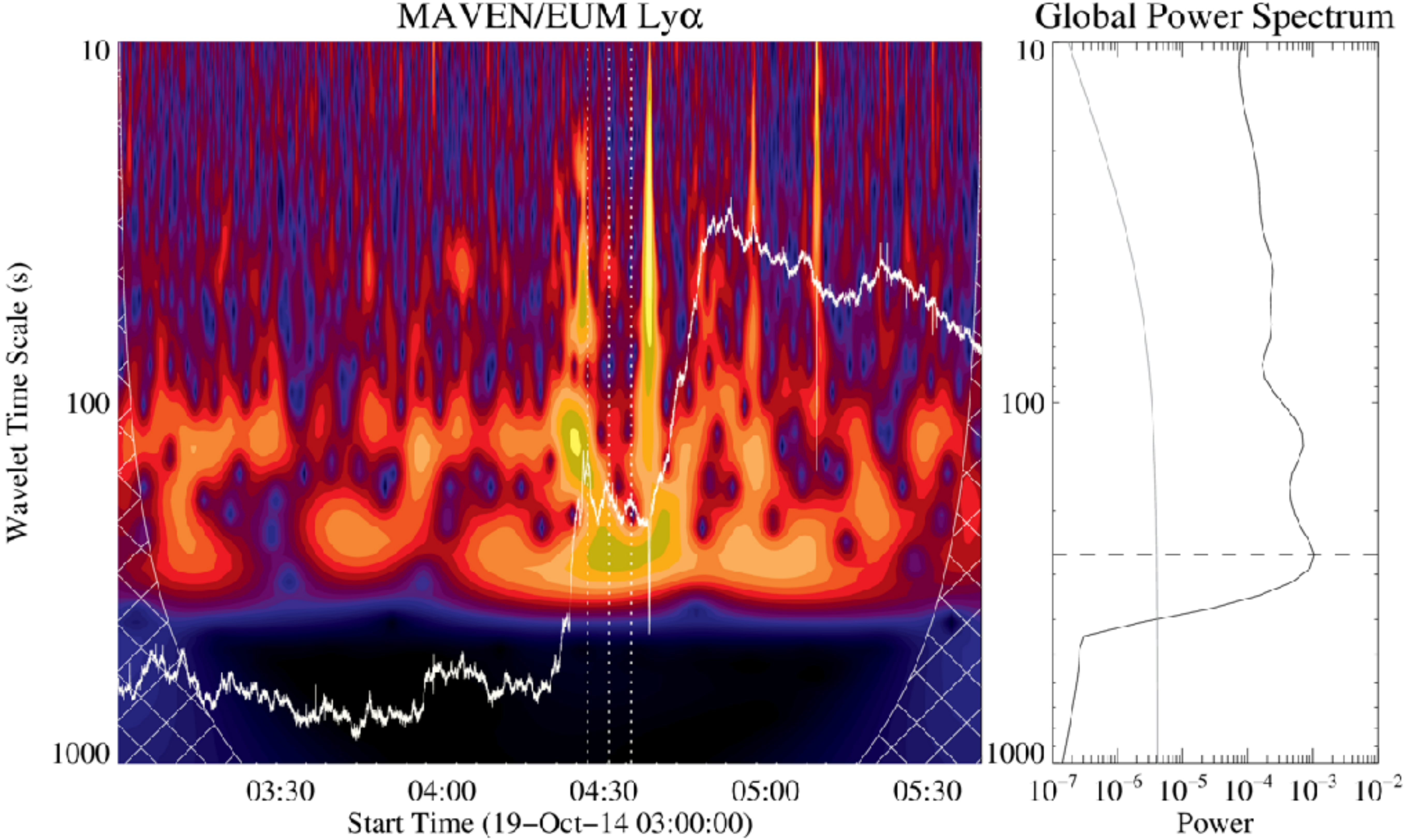
- 3-minute oscillations have been detected in Lyα during a solar flare
- Believed to be a dynamic response at the acoustic cutoff frequency of the chromosphere to an impulsive injection of energy



Milligan+ (2017)

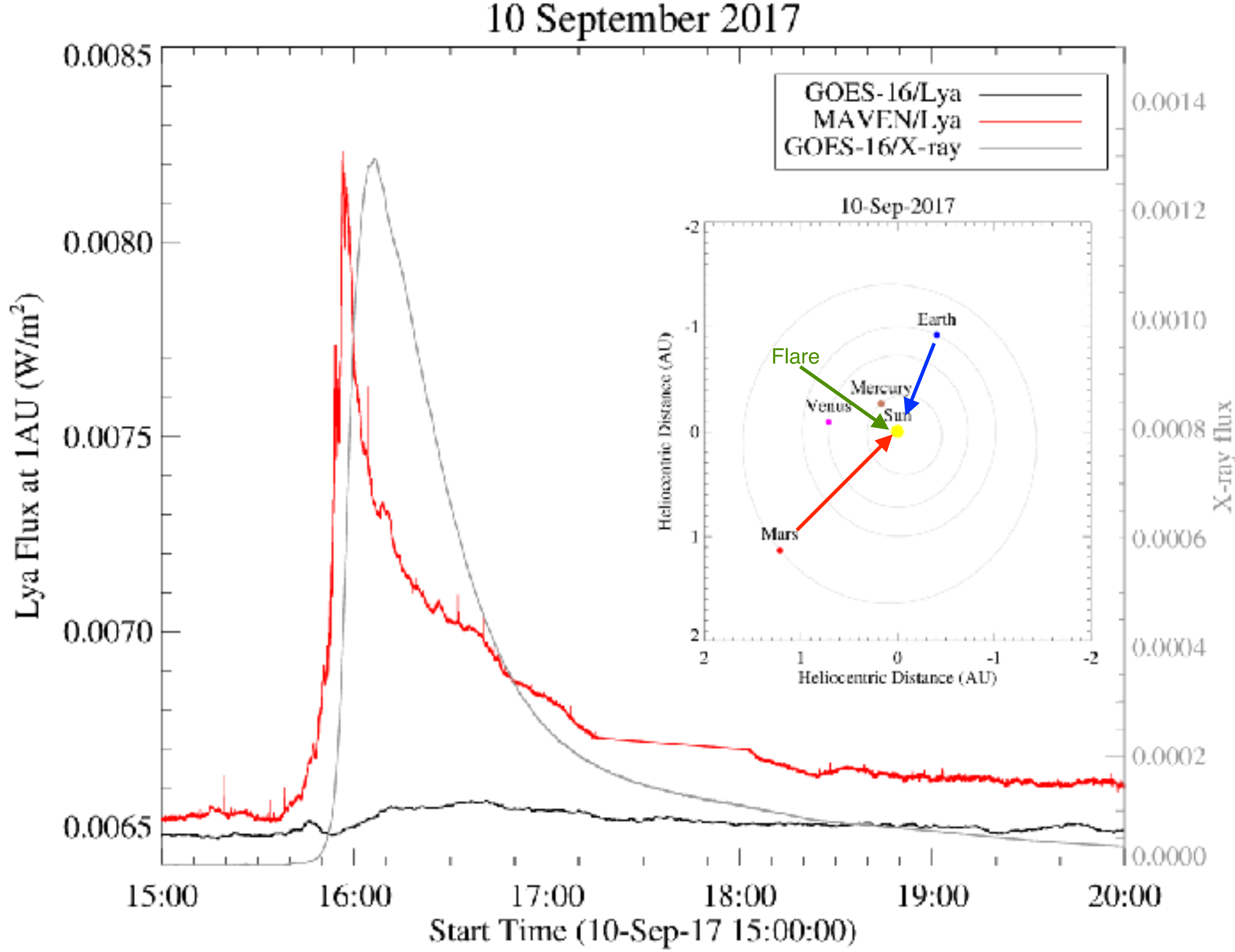
- Could this induce a quasi-periodic response in the ionosphere, similar to that found for X-rays by Hayes+ (2017)?

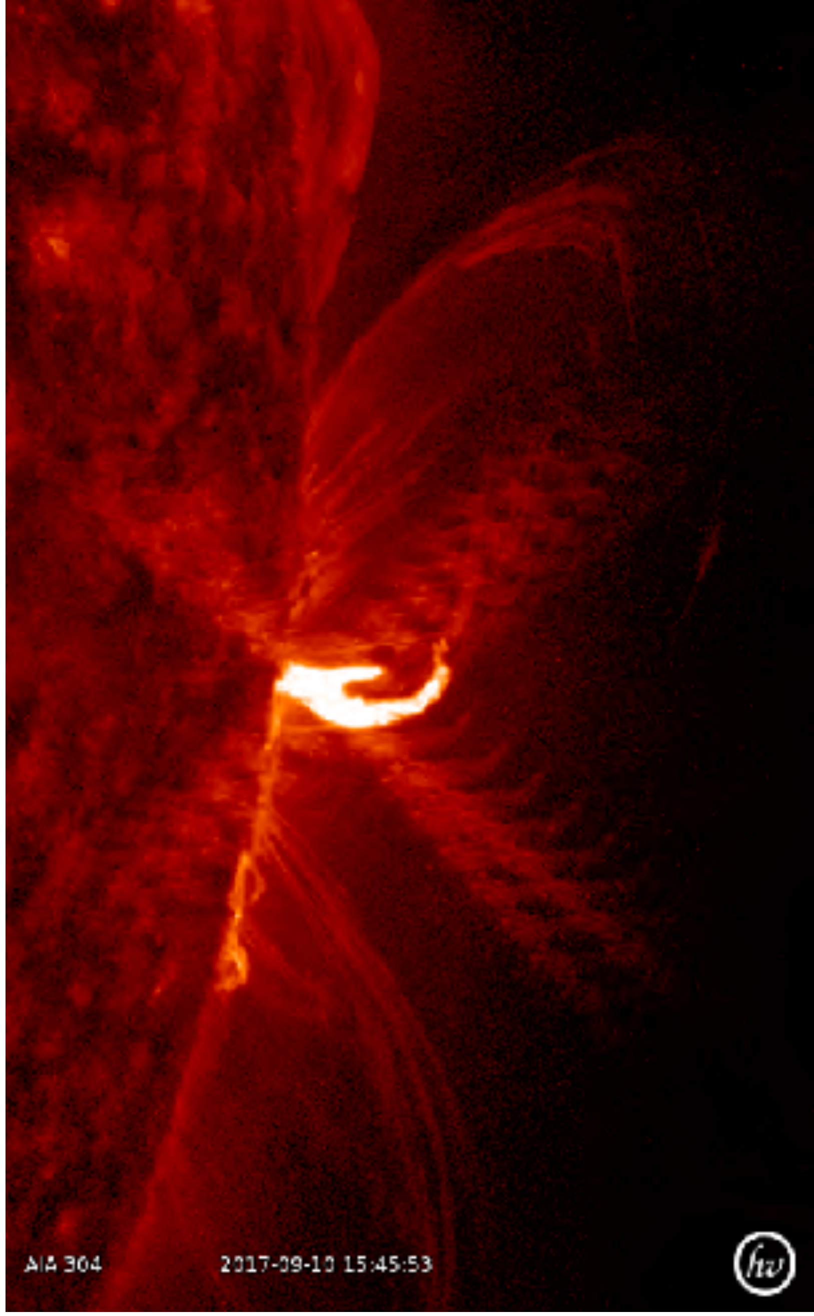




Lyα profiles from MAVEN/EUM (1s cadence) also appear to show evidence for "acoustic oscillations" (4.4 minutes)

Milligan+ (2020)

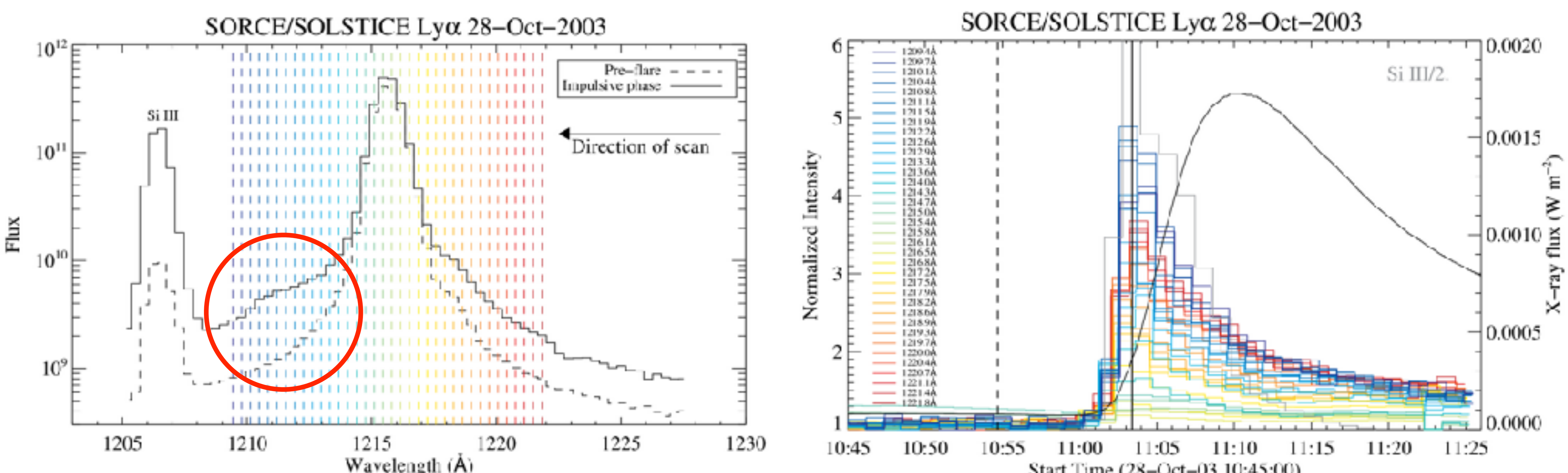




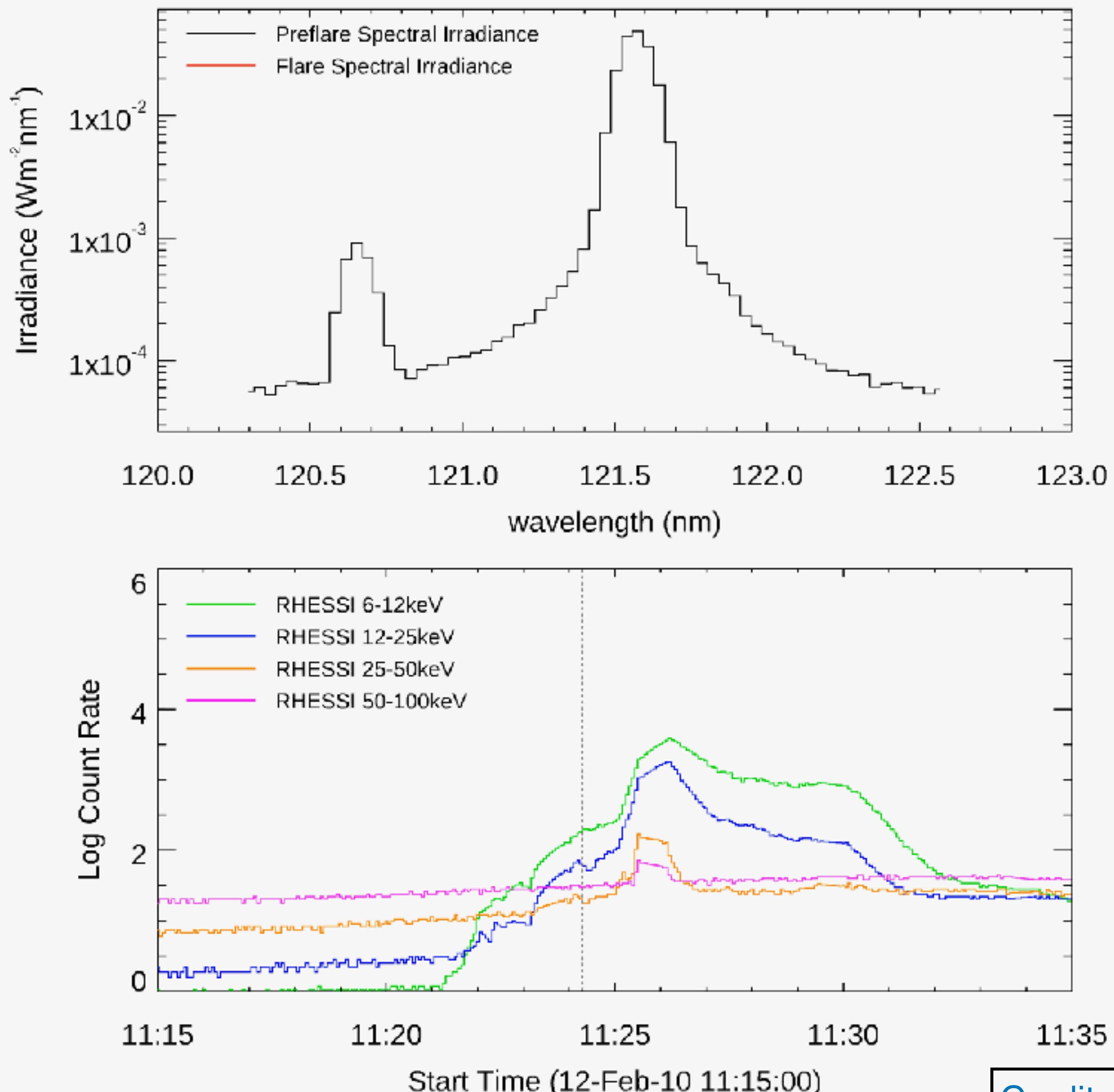
MAVEN/EUM data showed a ~26% increase in Lyα during the 10-Sept-2017 flare. Largest increase measured by GOES-15 for Solar Cycle 24 was 29%. Is there some fundamental upper limit to how much flares can increase the Lyα irradiance by?

Lyα Flare Spectra

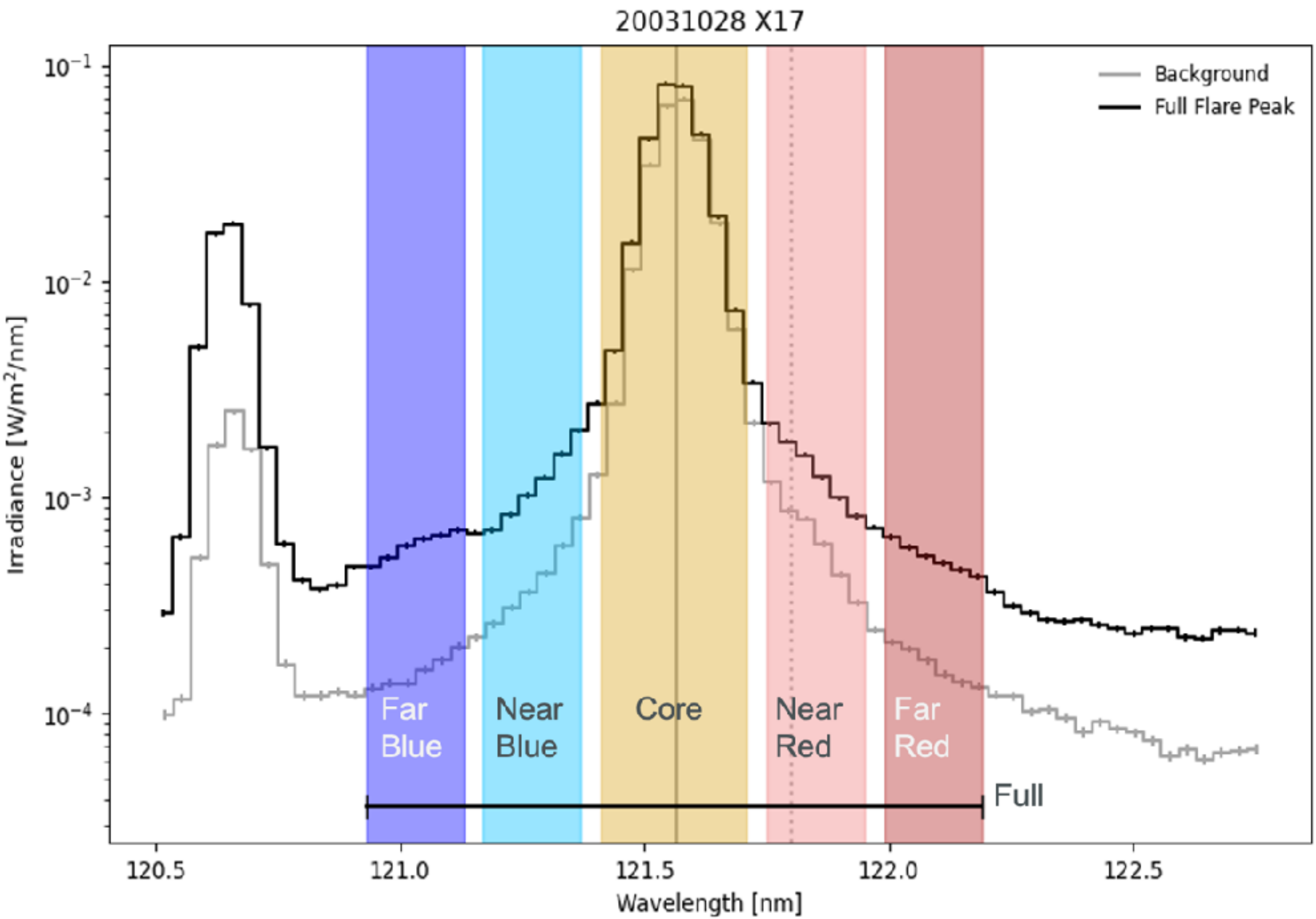
- SORCE/SOLSTICE scans across the Lyα line at 60s cadence once per orbit. Only one published result from 28 October 2003 X17 flare.
- Spectrally-resolved Lyα increased by 20% in the line core, x2 in the wings (Woods+ 2004). Blue wing responded more than the red wing (filament eruption ~1500 km/s..?). Is this behavior commonplace? What does this tell us about formation height/energy deposition?
- All line scans are now (as of December 2020) publicly available (https://lasp.colorado.edu/home/sorce/data/ssi-data/)



Milligan & Chamberlin (2016)

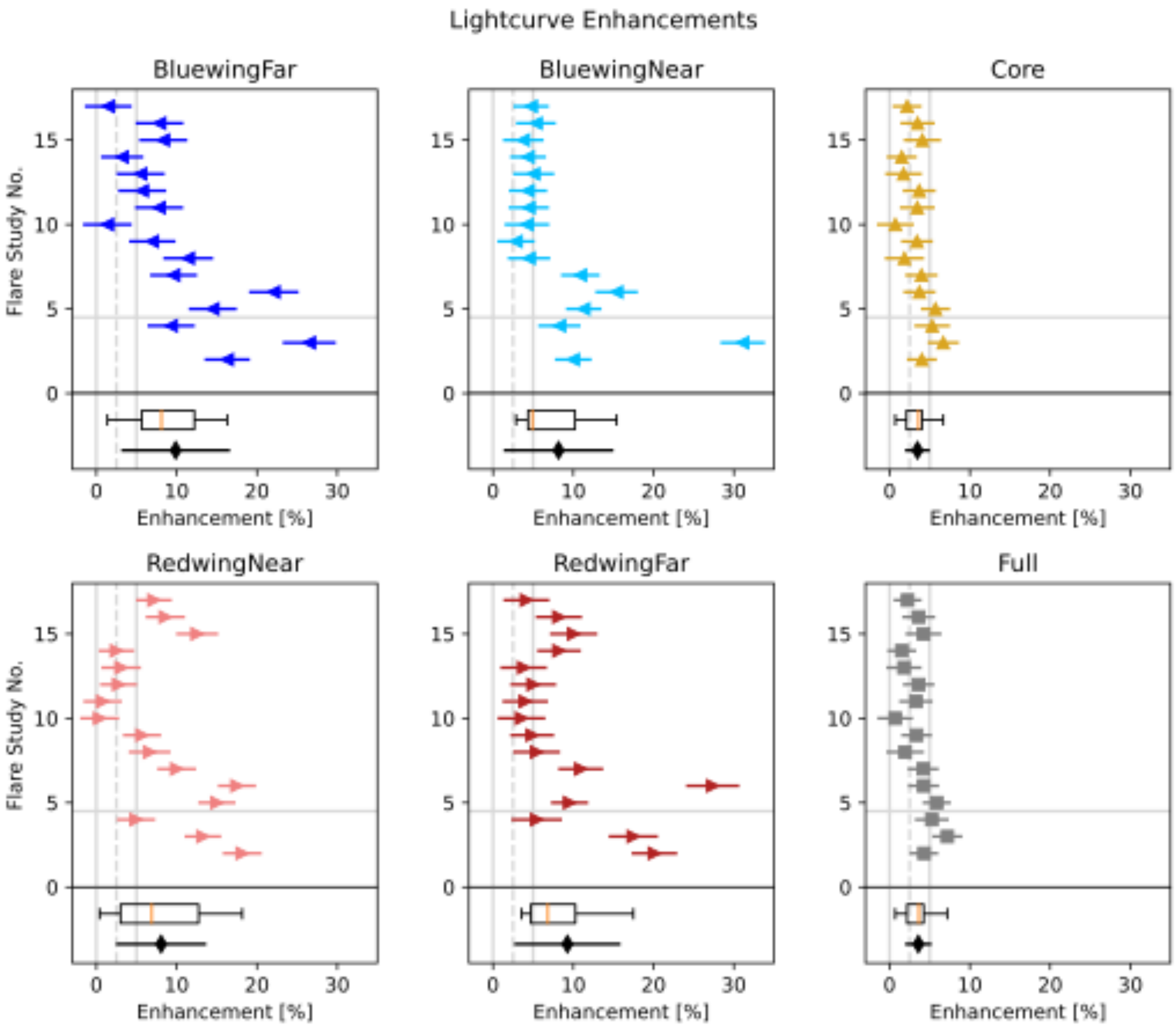


Credit: Luke Majury



Butler+ (2023; In Prep.)

Core vs. wing enhancements



- Examined 18 M+X flares that SOLSTICE captured the impulsive phase of
- Wings generally enhanced more than the core, but also respond earlier (wings are formed deeper; background effect?)
- Core emission dominates broadband irradiance

Butler+ (2023; In Prep.)

Main Conclusions

- Lyα emission during flares - and its ionospheric effects - has been overlooked in recent decades. New instrumentation is now making detailed, statistical studies possible.
- Increases of <30% are observed in Lyα during flares (typically <5%). Comparable to that of active region evolution but on much shorter timescales.
- Impulsive Lyα emission induces currents in the E-layer of the ionosphere (previously attributed to X-rays, which affect the D-layer) during one major event.
- Energy radiated in Lyα can be up to 100 times that of X-rays.
- Center-to-limb variation is significant for flares of all magnitudes due to either opacity effects or foreshortening of the flare ribbons (confirmed by coordinated observations between GOES/EUVS and MAVEN/EUM)
- We eagerly anticipate more Lyα flare data from GOES-15 (September 2017 flares), GOES-R (pseudo line profiles), SORCE/SOLSTICE (spectra), Solar Orbiter/EUI (images), ASO-S/LST (imager+coronagraph), Solar-C/EUVST (spectra) +SoSpIM (photometry), and SNIFS rocket (spatial, spectral, and temporal)

Outstanding Questions

- What property of Lyα emission determines its geoeffectiveness? Wavelength? Total radiated energy? Contrast?

- What dictates Lyα irradiance variability during flares? Flux of nonthermal electrons? Spatial extent of flare ribbons? Coronal contributions? Greatorex+ (2023)

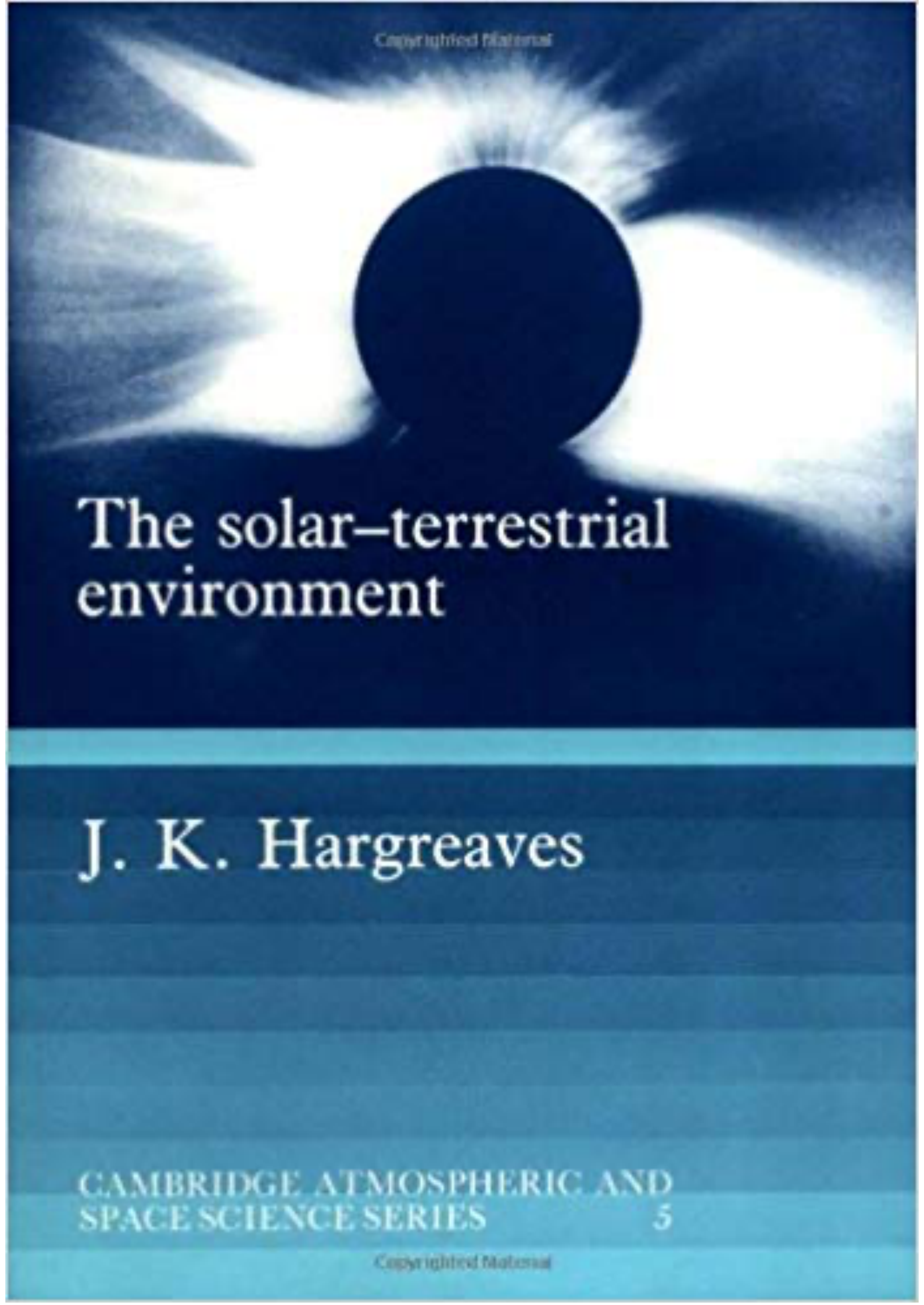
- Does Lyα consistently drive an E-layer response? Was the NO abundance abnormally high during the event presented in Milligan+ (2020)?

- Why do different instruments, with similar response functions, derive different Lyα contrast values for the same events? Geocoronal absorption? Assumed underlying spectrum? Calibration?

- FISM2 (Chamberlin+ 2020) is commonly used to drive ionosphere/thermosphere models, but drastically underestimates Lyα flux during flares. By how much does this affect the modelled terrestrial response? Greatorex+ (2023)

Other ideas..?

- Lyα/Hα ratio is temperature sensitive (Canfield+ 1981)
- Lyα/LyC (Lyβ, Lyγ, Lyδ,…) can tell us about ionisation fractions (Brown+ 2018)
- Redwing asymmetry in Lyα line has been theorised as evidence for accelerated protons through charge exchange (the Orral-Zirker effect; Orral+Zirker 1976, Hudson+ 2012)
- Investigate CLV and coronal contributions through coordinated stereoscopic observations with MAVEN (Chamberlin+ 2018)
- Search for further acoustic oscillations in Lyα (and other chromospheric lines; Millar+ 2021)
- Measure ionospheric responses (D-, E-, and F-layers) for disk/limb flares (on both Earth and Mars). How does this response ultimately depend on nonthermal electron distribution?
- How do irradiance measurements depend on the assumed underlying (QS) line profile?
- More detailed radiative hydrodynamic modelling (RADYN currently truncates the line) —> contribution functions for different heating rates (compare with other models, e.g. HYDRAD)



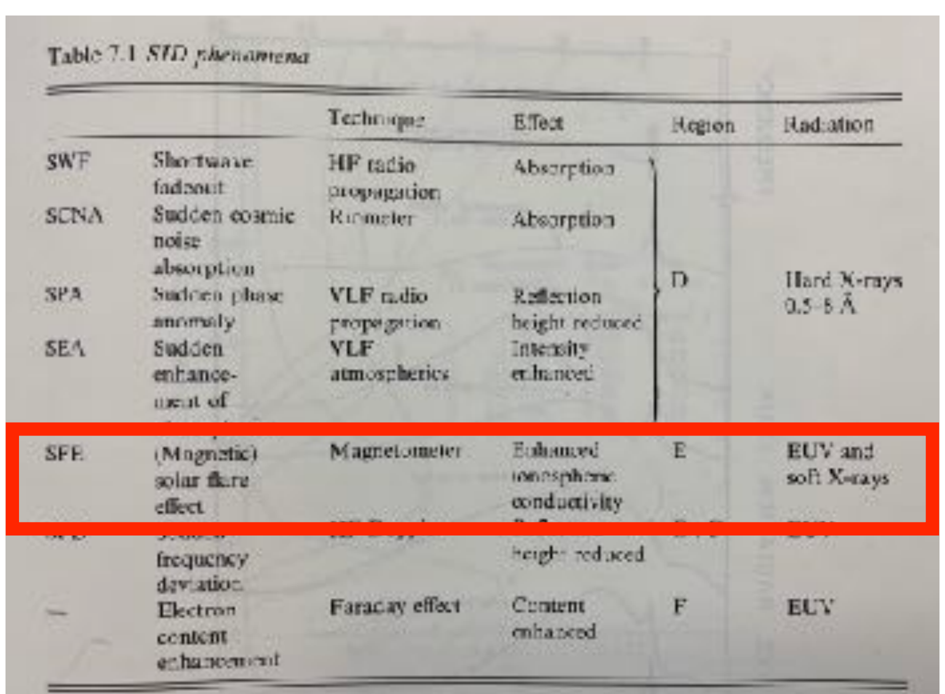
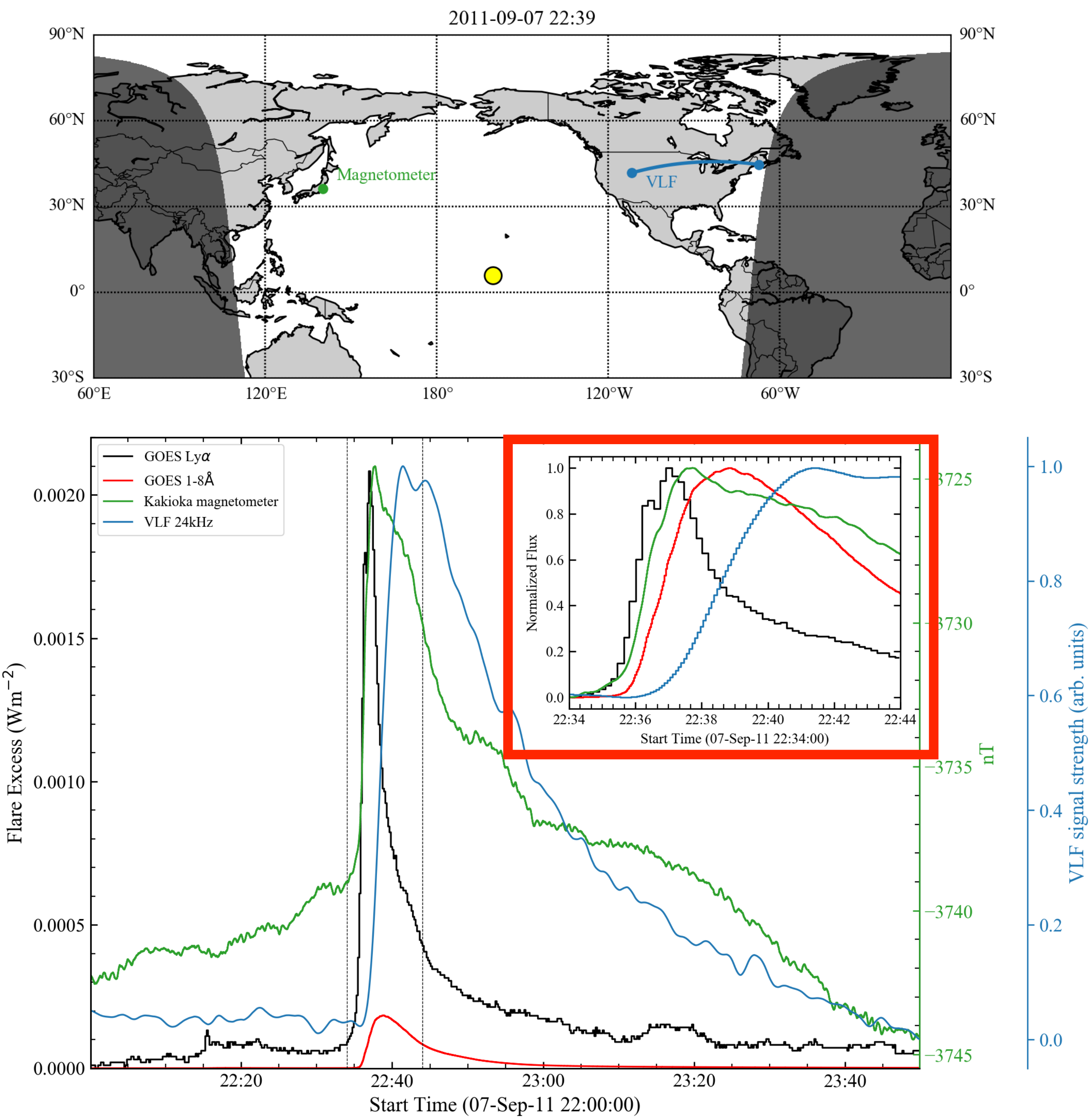


Table 7.1 *SID phenomena*

		Technique	Effect	Region	Radiation
SWF	Shortwave fadeout	HF radio propagation	Absorption	D	Hard X-rays 0.5–8 Å
SCNA	Sudden cosmic noise absorption	Riometer	Absorption	D	Hard X-rays 0.5–8 Å
SPA	Sudden phase anomaly	VLF radio propagation	Reflection height reduced	D	Hard X-rays 0.5–8 Å
SEA	Sudden enhancement of	VLF atmospherics	Intensity enhanced	D	Hard X-rays 0.5–8 Å
SFE	(Magnetic) solar flare effect	Magnetometer	Enhanced ionospheric conductivity	E	EUV and soft X-rays
[illegible]	[illegible] frequency deviation	[illegible]	[illegible] height reduced	[illegible]	[illegible]
—	Electron content enhancement	Faraday effect	Content enhanced	F	EUV

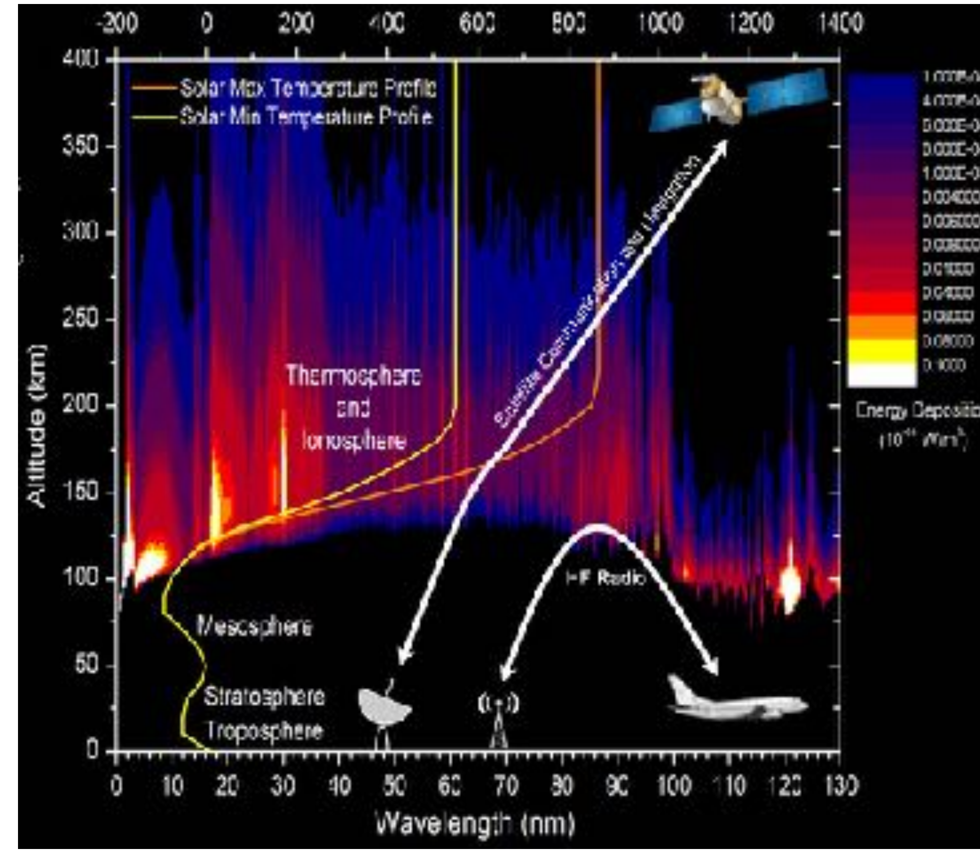
- "Lyα… penetrates below 95km and ionises the minor species NO whose ionisation limit is 1340Å"
- "… the electron density in the D-region has increased. Thus the enhancement is most likely to be in the Lyman-α line or in the X-ray flux."
- "Lyman-α is enhanced by a few percent during a flare…But… X-rays… intensified by several powers of ten. Thus the SWF is now attributed to X-rays."
- "One good reason for studying the effects of solar flares is that nuclear explosions also create dramatic effects in the ionosphere and it is important not to confuse the two!"

Ionospheric Effects of Lyα



- The Kakioka magnetometer in Japan measures changes in ionospheric conductivity due to increased ionisation
- During the 7-Sep-2011 X-class flare, enhanced E-layer conductivity closely followed the increased Lyα emission
- Excess Lyα flux was an order of magnitude greater than X-rays
- The corresponding X-rays lagged the ionospheric response, implying that they could not have been the driver
- The X-ray profile resembled the D-layer response from VLF observations with the known ~3-minute delay ("sluggishness")

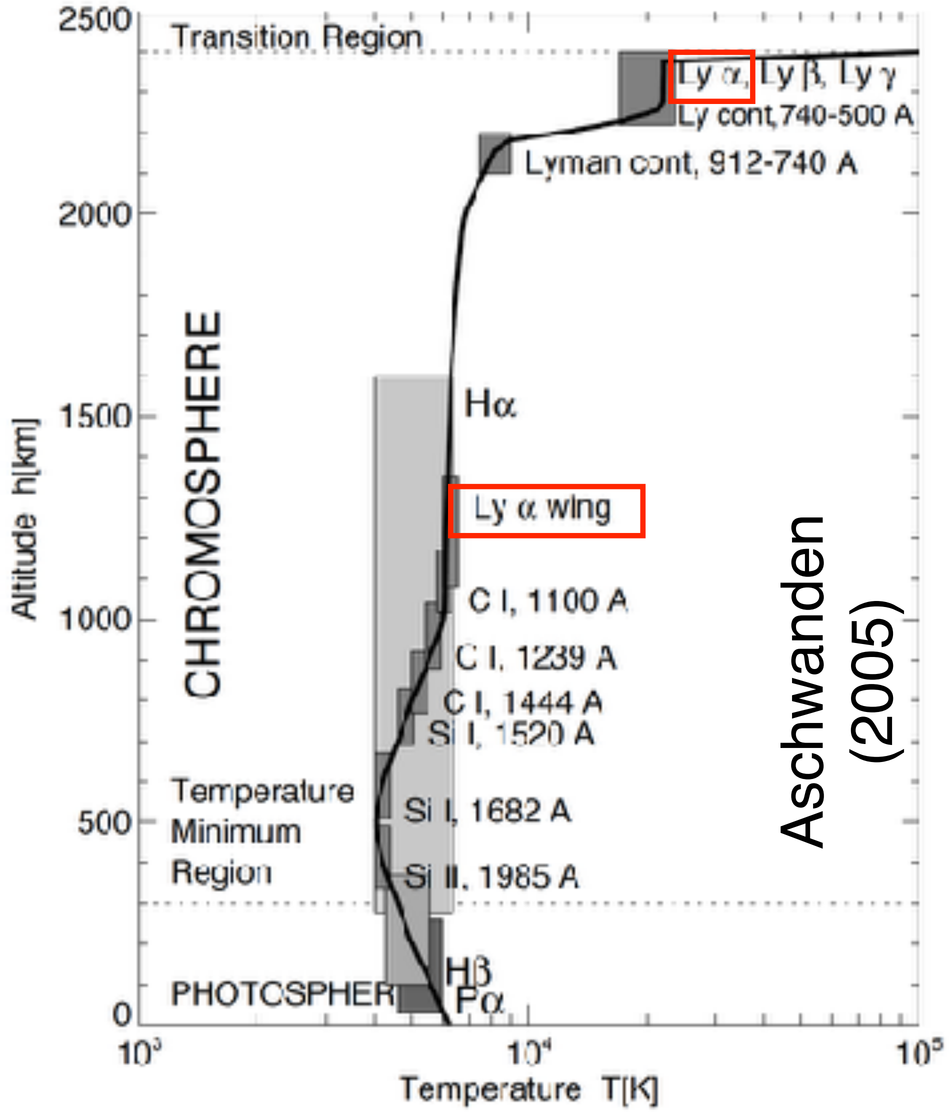
Why study solar flares in Lyα?

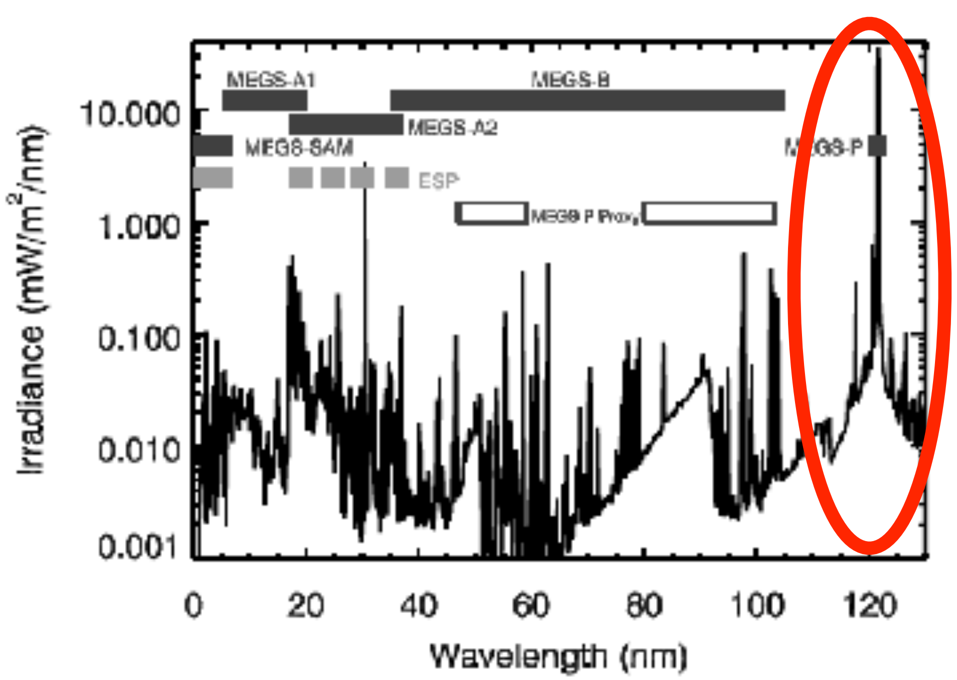


- Lyα photons cause photodissociation of water in the mesosphere (ozone), and ionises NO (nitric oxide) generating the D-layer of the ionosphere (80-110km; Lean+ 1985)
  - *Important for satellite drag, GPS accuracy, RF propagation*

- Lyα is believed to be a signifiant radiator of energy deposited in the chromosphere by nonthermal electrons (Milligan+ 2014)

- In the search for habitable exoplanets, knowledge of a star's Lyα radiation field - and how it varies - is crucial (Linsky+ 2013)





Lyman-alpha

- Lyman-alpha (Lyα; 1216Å) is the strongest emission line in the solar spectrum (H I: 2p→1s, T=8-40x10^3K)
- Line core is formed in the lower TR; wings are formed mid-chromosphere (quiet Sun)
- During solar flares, Lyα comes predominantly from the ribbons/footpoints
- Lyα is optically thick
- Lyα photons cause photodissociation of water in the mesosphere (ozone), and ionises NO (nitric oxide) generating the D-layer of the ionosphere (80-110km; Lean+ 1985)

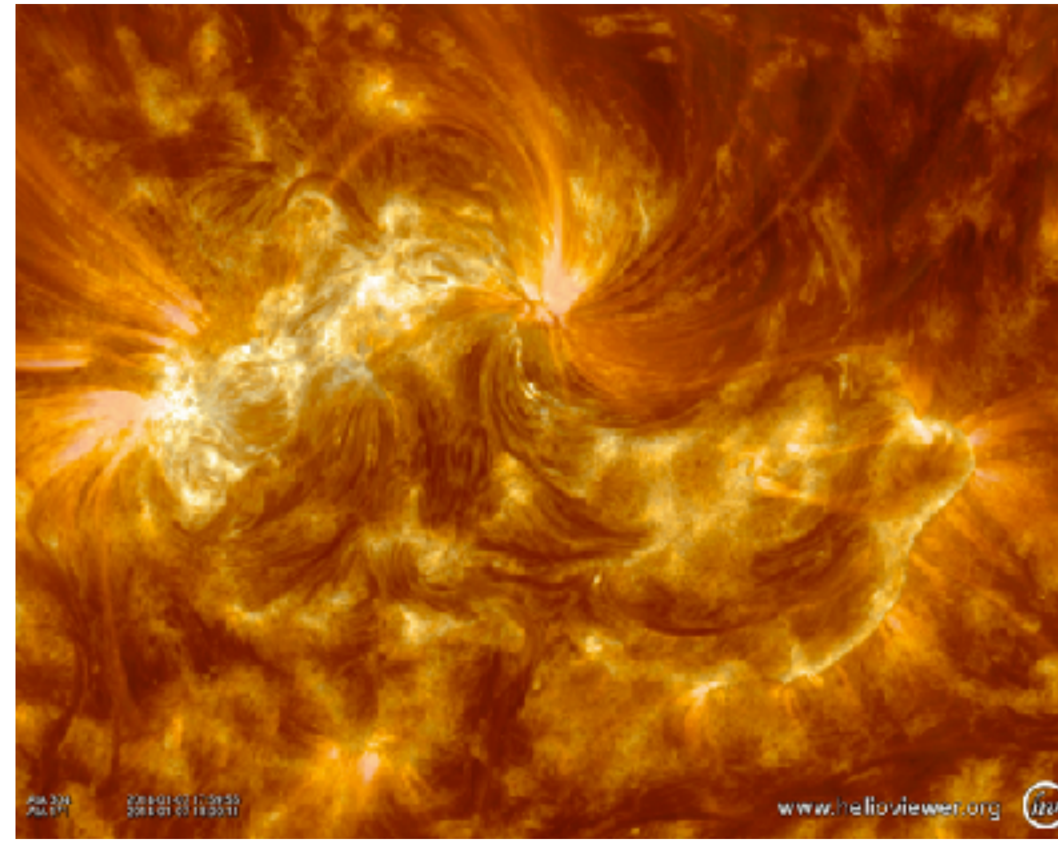
Solar Flares: Fundamental Challenges

- Magnetic reconnection facilitates the rapid liberation of stored energy to accelerate particles, heat plasma and drive bulk motions

- How does the Sun accelerate particles so efficiently? And how do these particles drive increases in radiation?

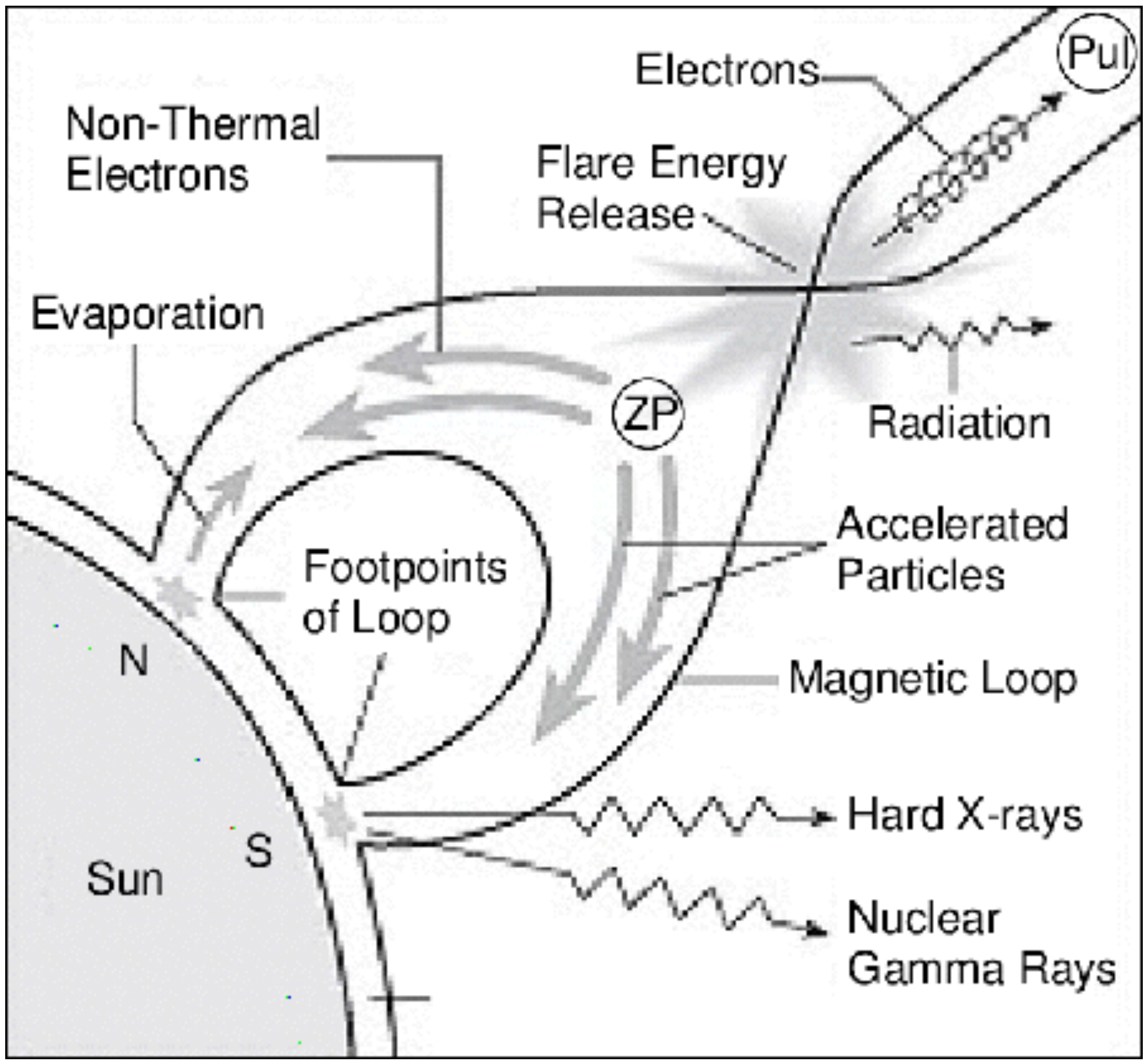
- How does this release of energy get distributed throughout the solar atmosphere?

- What are the implications for planetary atmospheres?



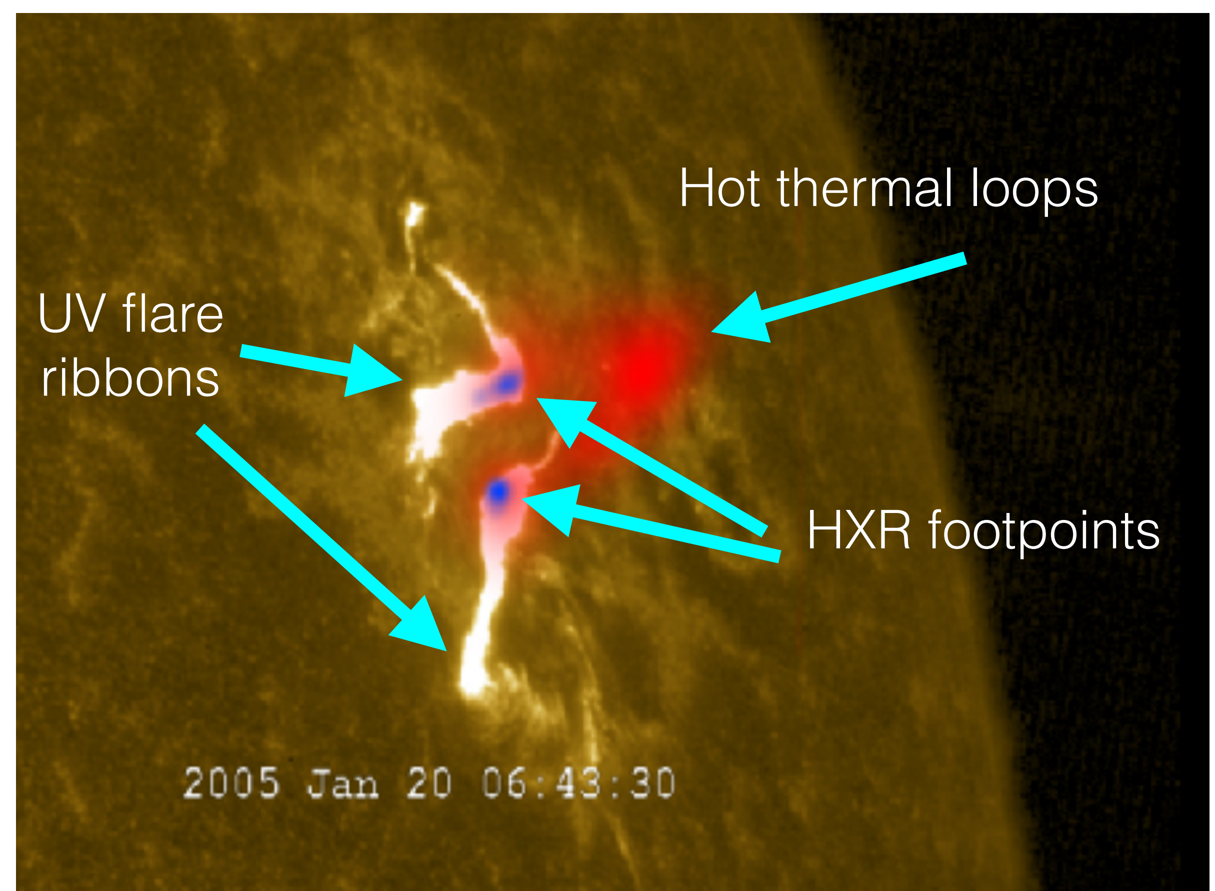
My research focuses on understanding heating and energy transport processes in the solar atmosphere through a combination of state-of-the-art multi-wavelength observations and advanced theoretical models.

Flaring Chromosphere: Cause and Effect

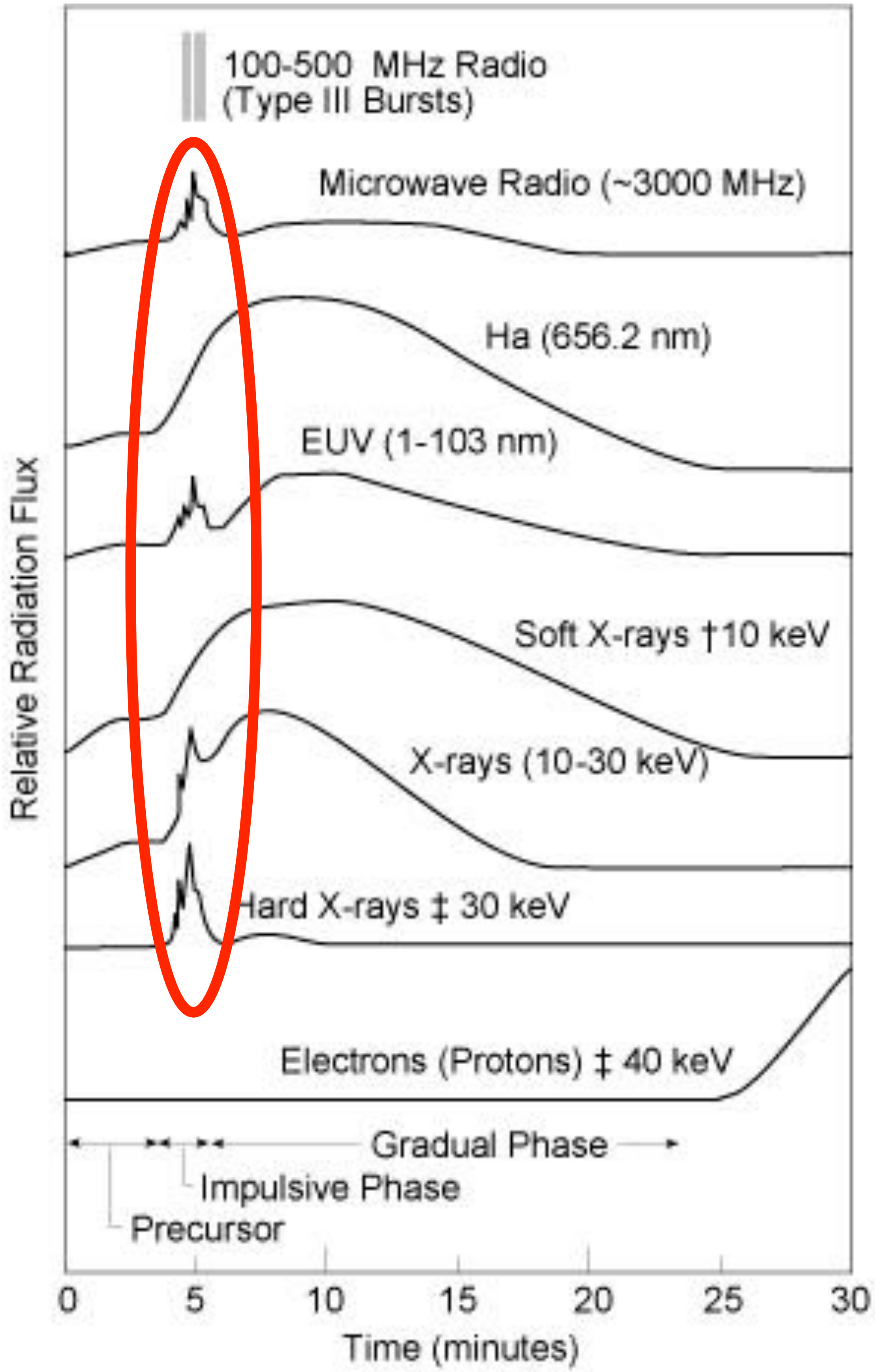


- Cause: incident electron spectrum is derived from hard X-ray (HXR) observations generated by thick-target bremsstrahlung
- Effect: resulting heating is diagnosed from optical, UV, EUV, and soft X-ray (SXR) observations of the chromosphere

Radiative hydrodynamic modelling can establish the physical processes that drive these emissions in response to an injection of energy

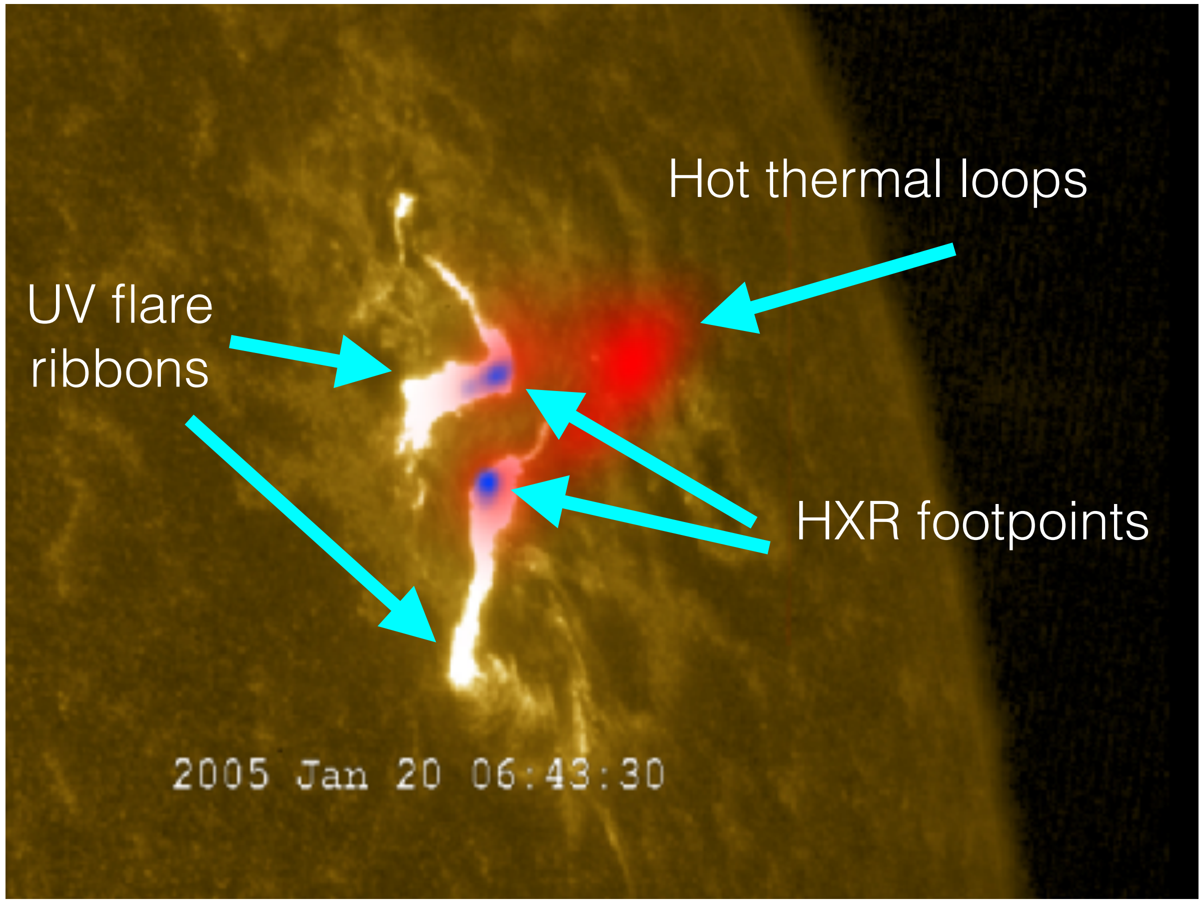


Flaring Chromosphere: Cause and Effect

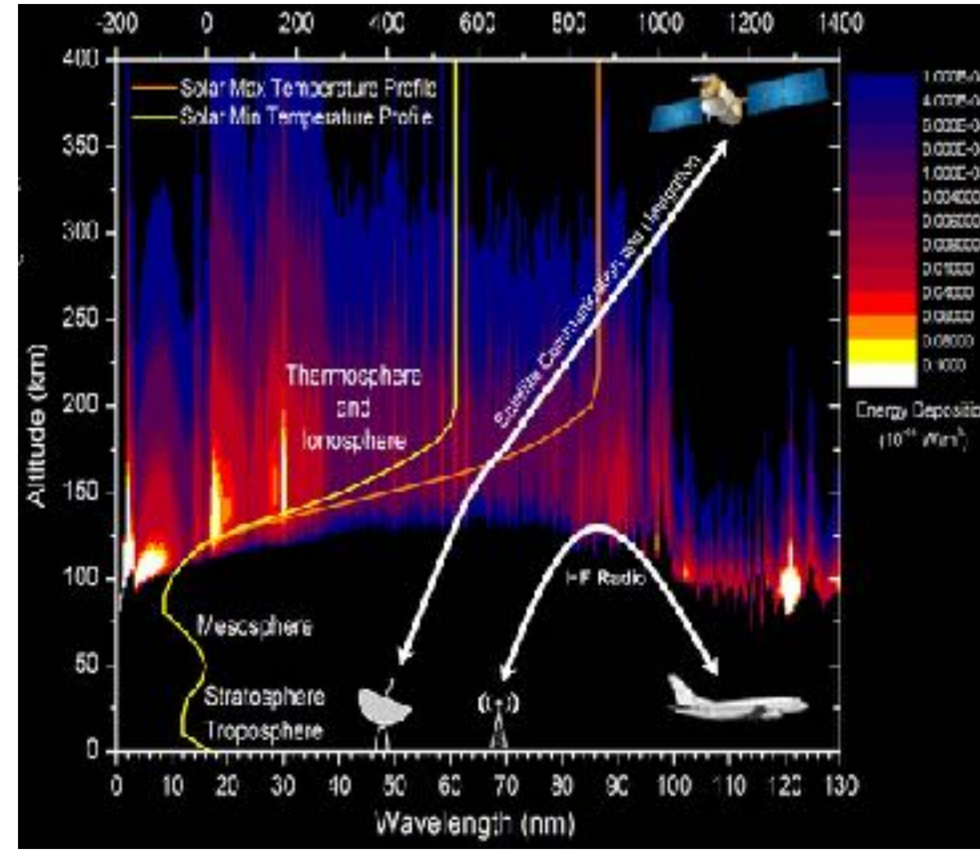


- Cause: incident electron spectrum is derived from hard X-ray observations generated by thick-target bremsstrahlung
- Effect: resulting heating is diagnosed from optical, UV, EUV, and soft X-ray observations of the chromosphere during the impulsive phase

Radiative hydrodynamic modelling can establish the physical processes that drive these emissions in response to an injection of energy



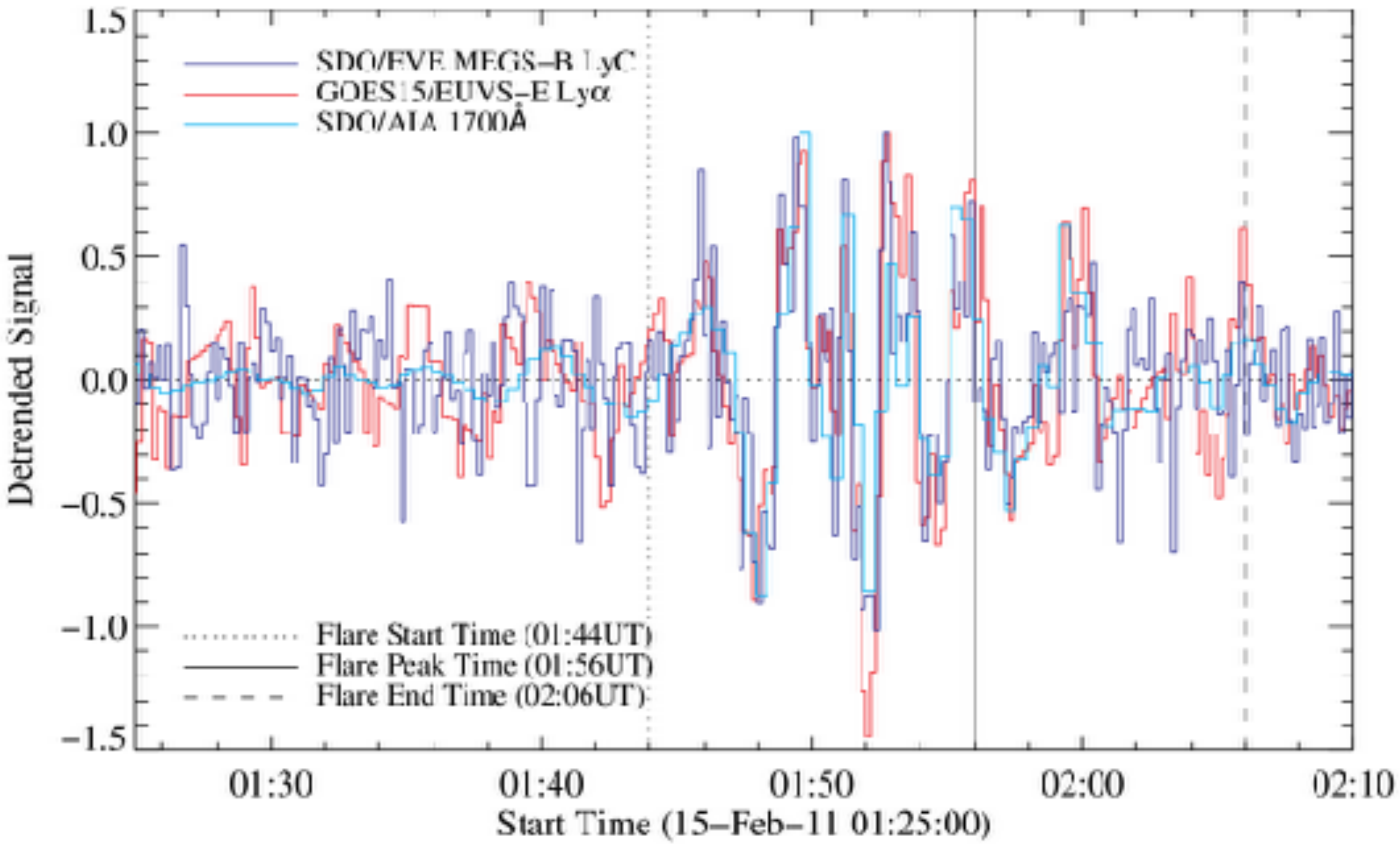
Why study solar flares in Lyα?

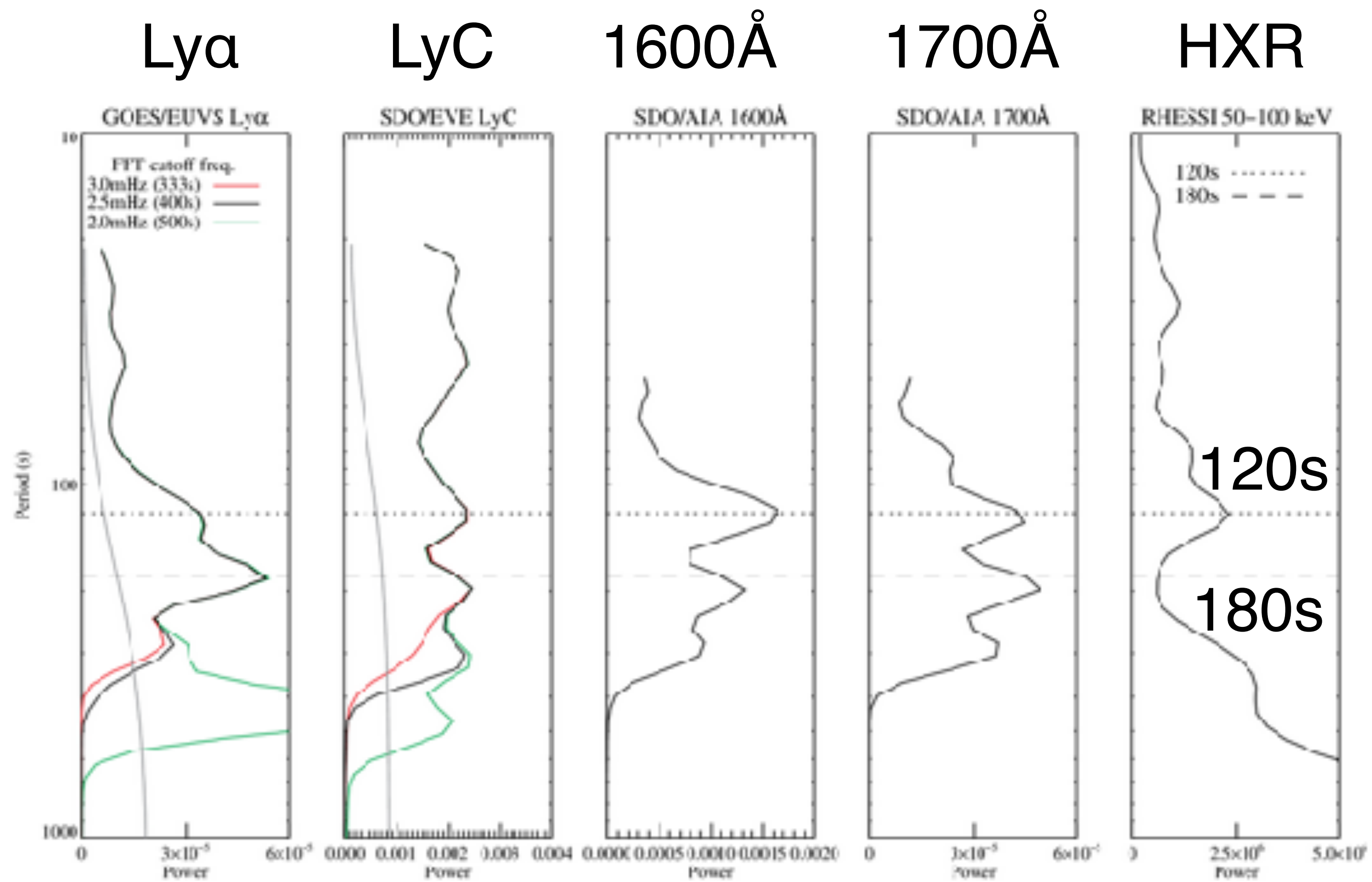


- Lyα photons cause photodissociation of water in the mesosphere (ozone), and ionises NO (nitric oxide) generating the D-layer of the ionosphere (80-110km; Lean+ 1985)
  - *Important for satellite drag, GPS accuracy, RF propagation*
- Lyα is believed to be a signifiant radiator of energy deposited in the chromosphere by nonthermal electrons (Milligan+ 2014)
- In the search for habitable exoplanets, knowledge of a star's Lyα radiation field - and how it varies - is crucial (Linsky+ 2013)

Acoustic Oscillations

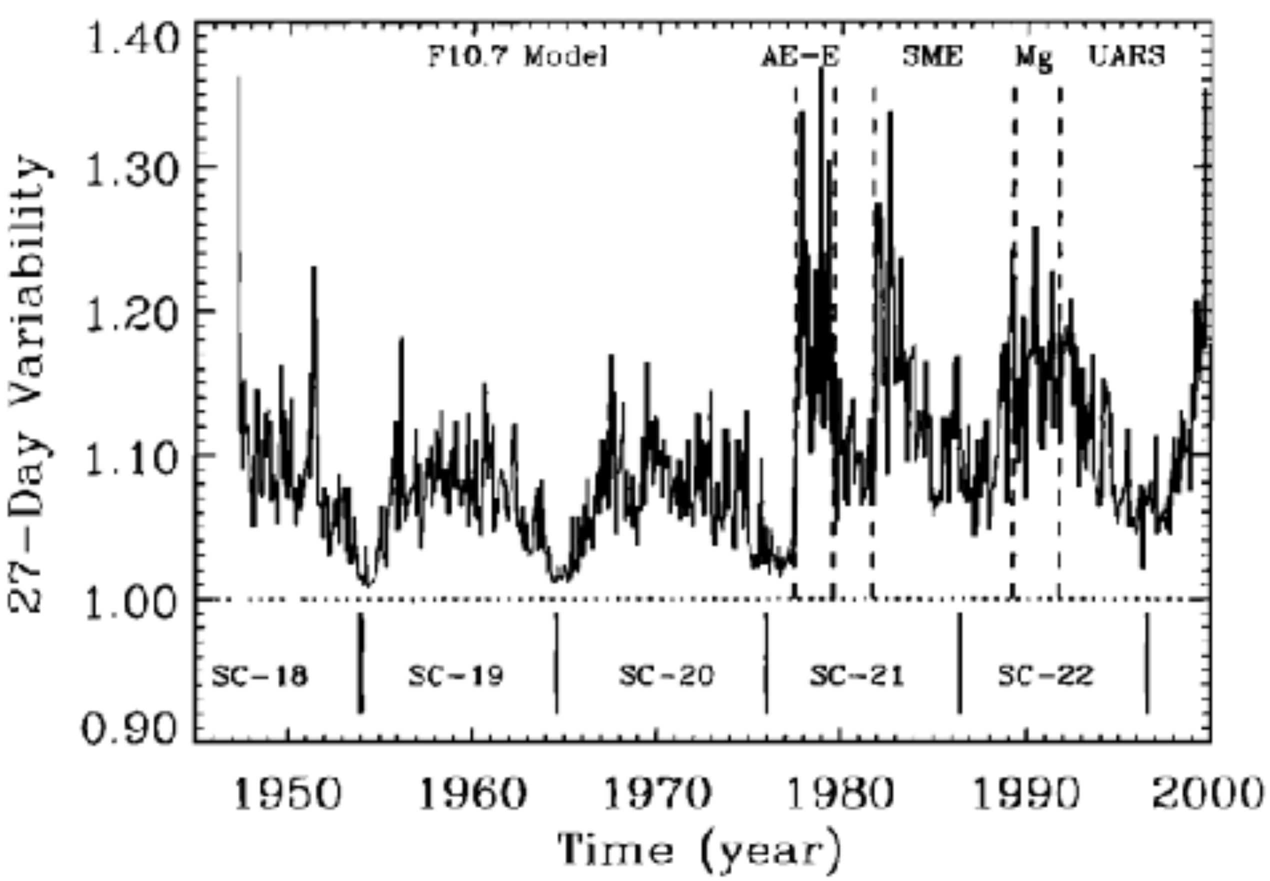
- 3-minute oscillations were detected in Lyα, LyC and 1600Å and 1700Å during a solar flare **from Sun-as-a-star observations!**
- Believed to be a dynamic response at the acoustic cutoff frequency to an injection of energy
- Similar periods were **not** found in HXRs implying the oscillations were independent of the energy injection rate
- Can the wave energy dissipate the nonthermal energy? Does the measured wave frequency depend on deposition height? Or B-field inclination angle (Jess+ 2013)?





Milligan+ (2017)

Solar Cycle/Active Region Variability



Lyα variability from various sources over 5 solar cycles. Woods+ (2000)

- Woods+ (2000) measured the long-term variability of Lyα using AE-E and UARS
- Mean 27-day AR variability = 9% (5% at solar min; 11% at solar max)
- Mean 11-year SC variability = 1.5
- Max 11-year SC variability = 2.1

Solar Lyα Instruments

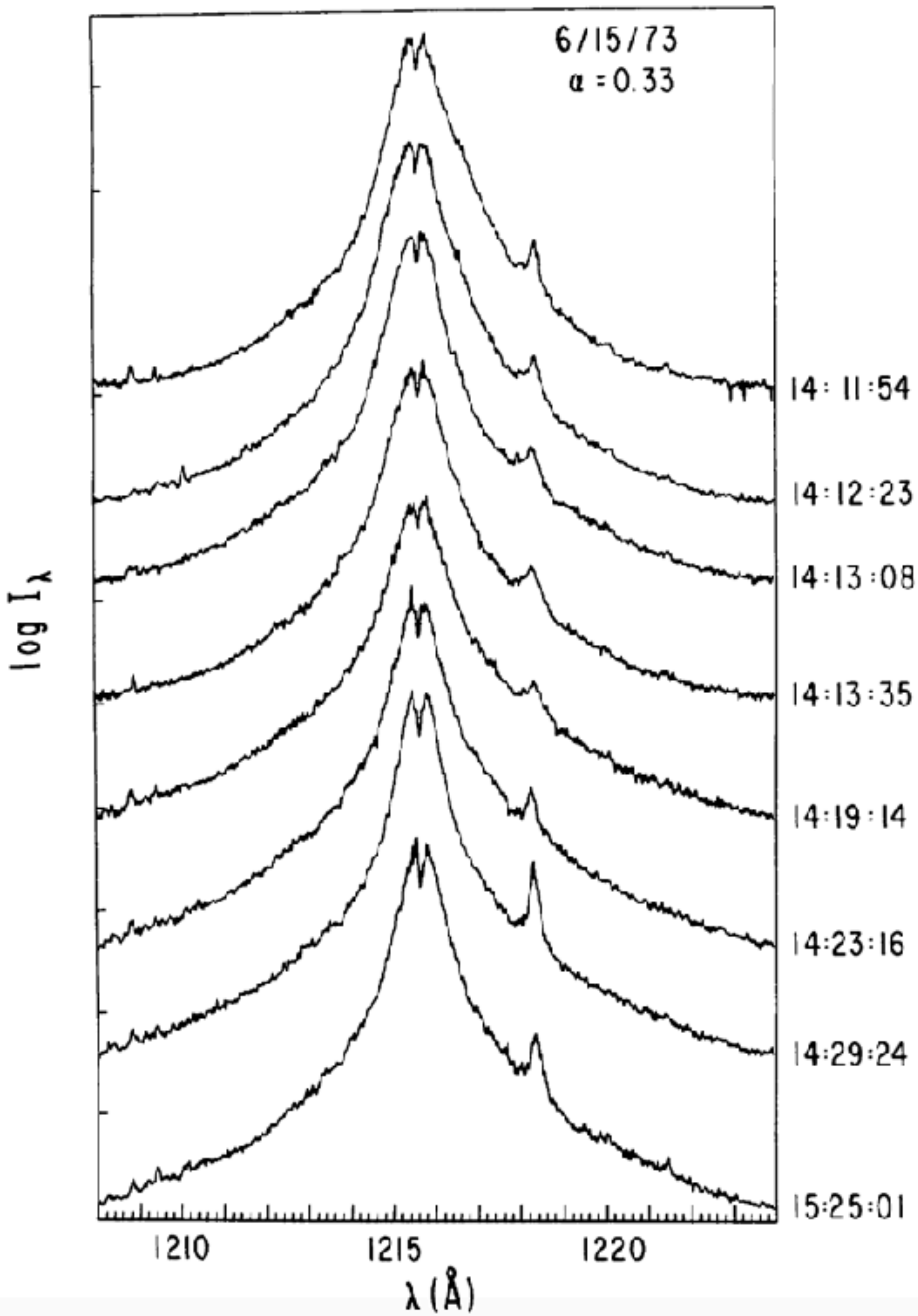
- Past:
  - Solrad-8
  - OSO-3, -4, -5, -6, -8
  - AE-E
  - SME
  - Skylab/ATM (HCO)
  - TRACE
  - CORONOS-F/VUSS
  - SOHO/SUMER+UVCS
  - CLASP, VAULT (+ >60 other sounding rockets)

- Current:
  - PROBA2/LYRA
  - SDO/EVE (MEGS-P)
  - GOES-13, -14, -15 (EUVS)
  - SORCE/SOLSTICE
  - UARS/SOLSTICE
  - MAVEN/EUM (Mars)

- Future:
  - Solar Orbiter/EUI
  - Solar-C/EUVST+SoSpIM
  - ASO-S/LST
  - GOES-16(R), -17(S), -18(T), -19(U) (EXIS)

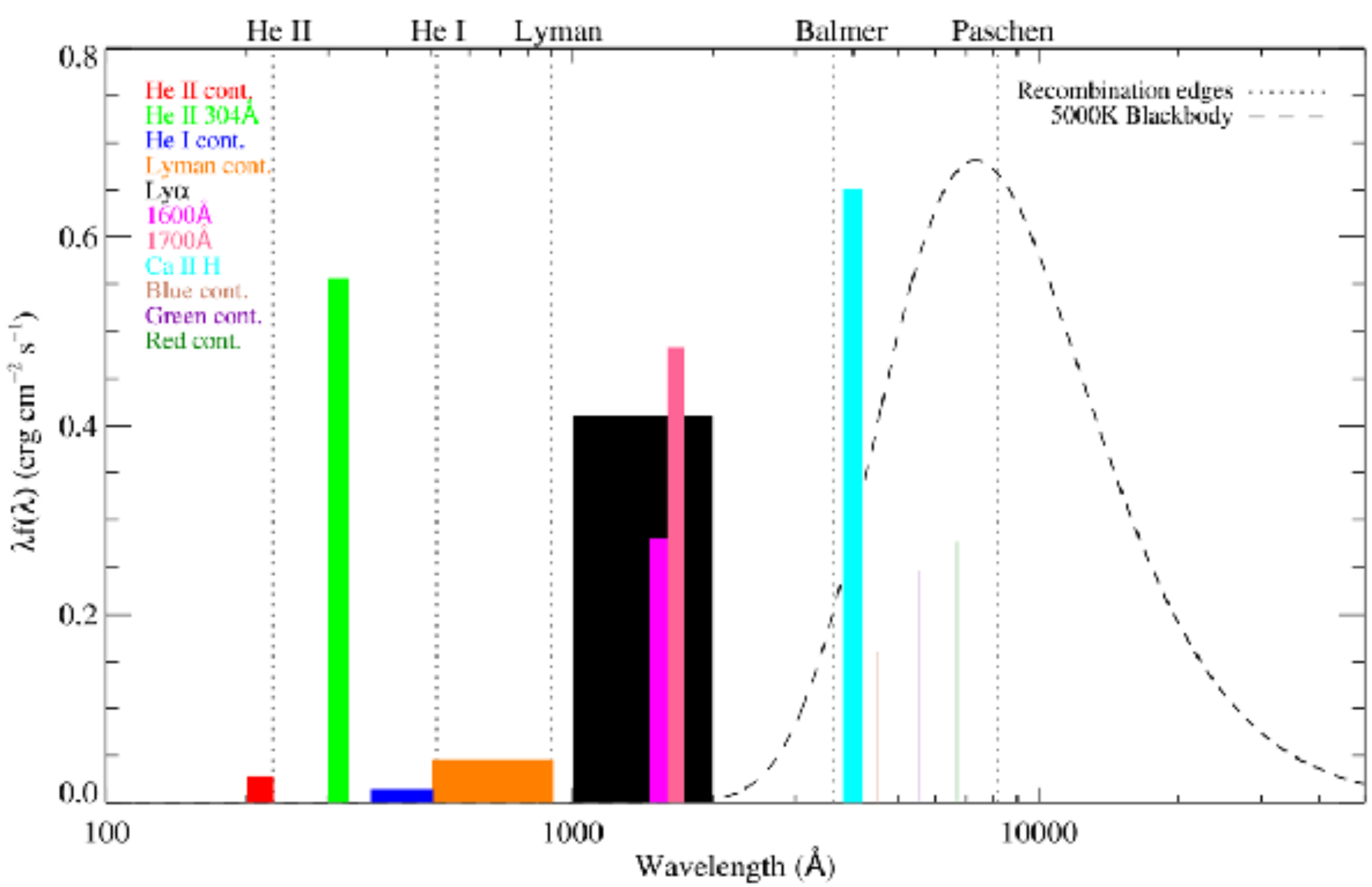
Literature on Lyα Flares

	Instrument	Observation	Result
Canfield+ (1980)	Skylab/ATM	Spectra	Temporal variations
Lemaire+ (1984)	OSO-8	Spectra	Redshift in Lyα
Brekke+ (1996)	UARS/SOLSTICE	Spectra	6% increase
Woods+ (2004)	SORCE/SOLSTICE	Spectra	20% increase in core, wings x2
Nusinov+ (2006)	CORONOS/VUSS	Photometry	~8-10% increase
Rubio de Costa+ (2009)	TRACE	Imager	<10% of nonthermal energy
Vourlidas+ (2010)	VAULT	Imager	Impulsive microflare
Johnson+ (2011)	SOHO/UVS	Photometry	$L \sim 10^{25-27}$ erg s^{-1}, 4 events off-limb
Chubb+ (2012)	Rocket	Photometry	No change detected
Milligan+ (2012)	SDO/EVE	Photometry	$L \sim 10^{30}$ erg during X-class
Raulin+ (2013)	PROBA2/LYRA	Photometry	No ionospheric response
Kretzschmar+ (2013)	PROBA2/LYRA	Photometry	0.6% increase/gradual variations
Milligan+ (2014)	SDO/EVE	Photometry	6-8% of nonthermal energy
Kretzschmar (2015)	GOES15/EUVS	Photometry	Scaling power of α=2.3-2.9
Milligan+ (2016)	SDO/EVE	Photometry	Anomalous temporal behaviour
Milligan+ (2017)	GOES15/EUVS	Photometry	Acoustic (~3 min) oscillations
Dominique+ (2018)	PROBA2/LYRA	Photometry	Used to isolate BaC
Chamberlin+ (2018)	MAVEN/EUM	Photometry	Neupert Effect



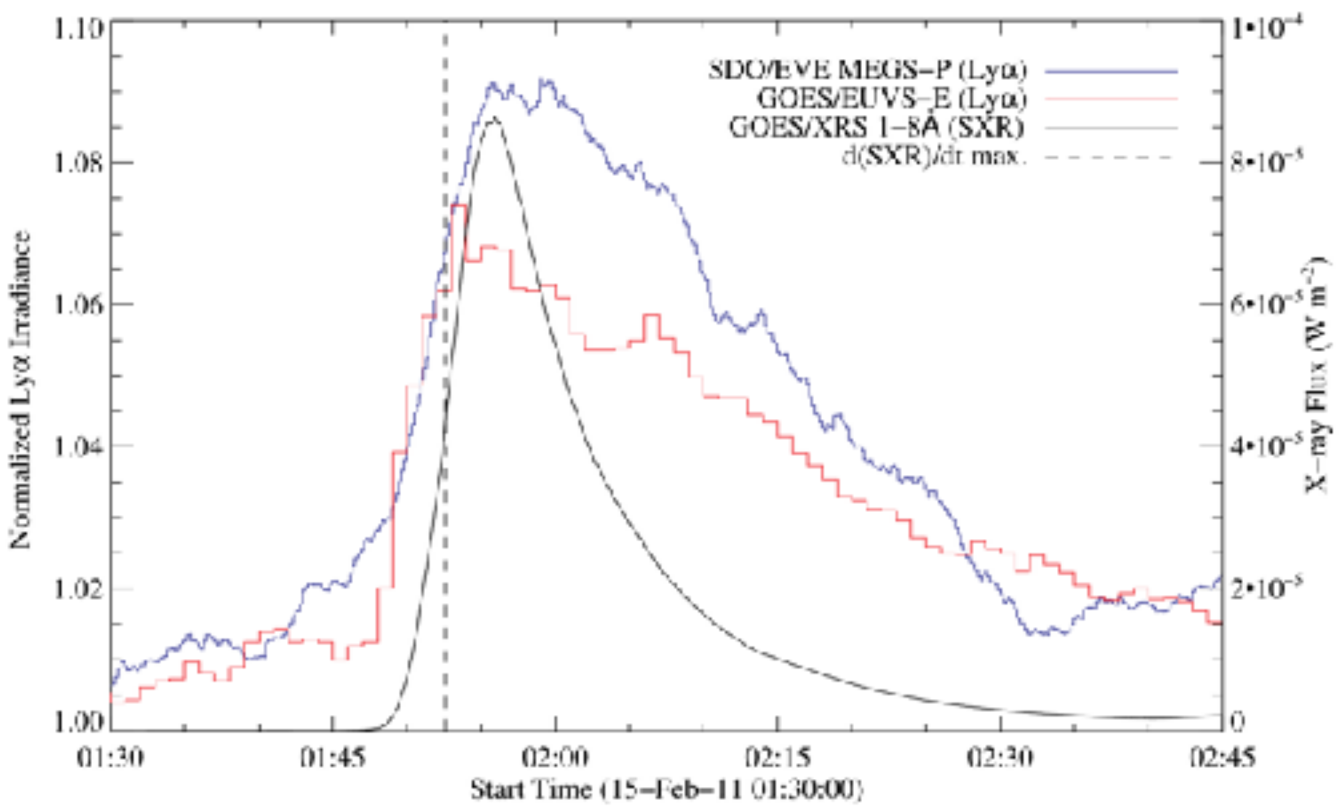
Canfield+ (1980) used Skylab/ATM to investigate the energetics of Lyα during two major flares… in 1973!

- Milligan et al. (2014) used multi-wavelength observations of the 15 February 2011 X-class flare to determine the radiated energy budget of the flaring chromosphere
- RHESSI HXR data were used to determine the amount of energy deposited by nonthermal electrons (>2x10^{31} erg)
- SDO (EVE+AIA) and Hinode (SOT) were used to quantify the radiative losses in the chromosphere (~3x10^{30} erg; ~15% of the nonthermal energy. i.e. 85% is "missing")
- Lyα dominated the radiative losses (~8%; see also Rubio de Costa+ 2009)



Milligan+ (2014)

Anomalous Temporal Behaviour



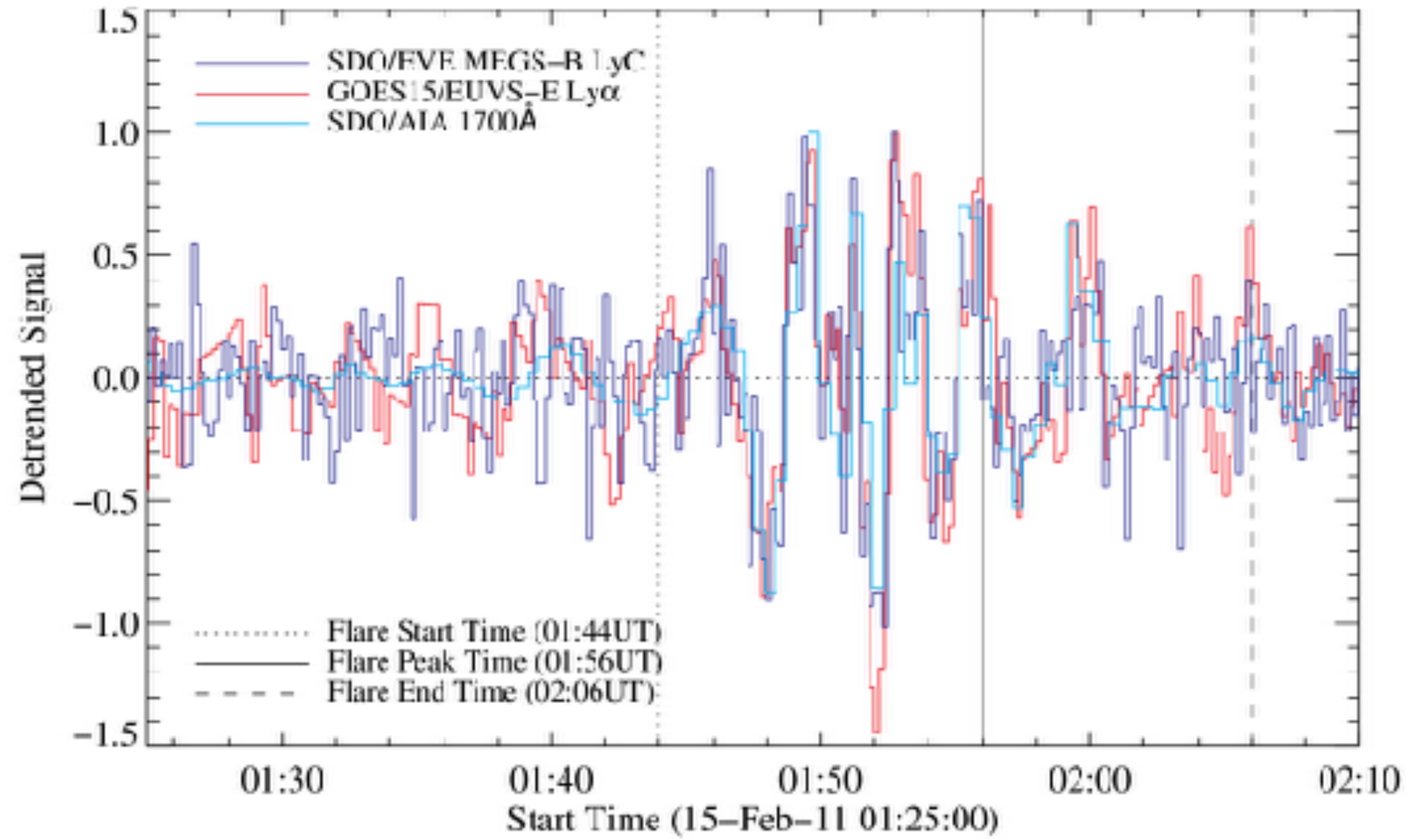
Milligan & Chamberlin (2016)

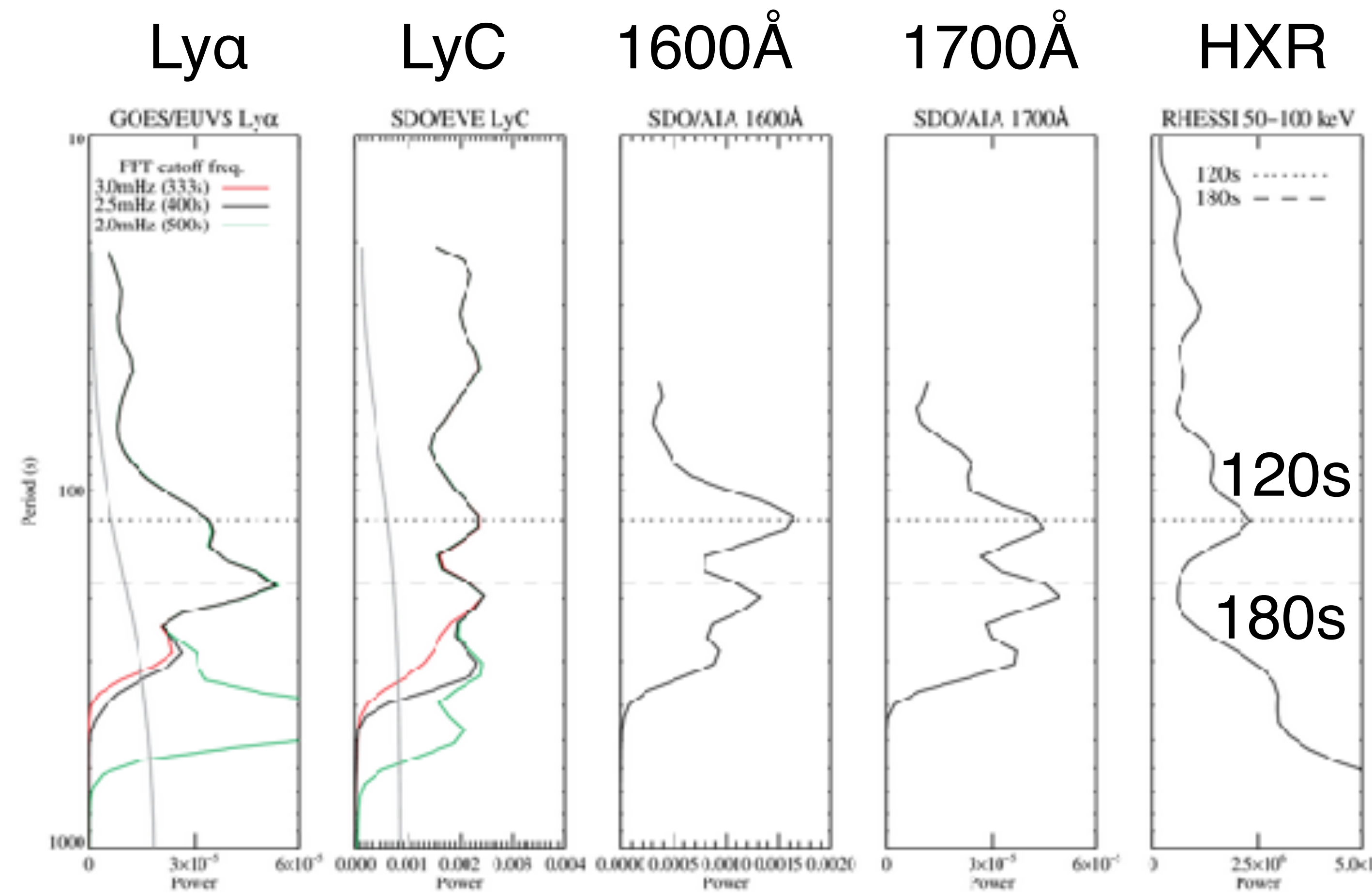
- Milligan & Chamberlin (2016) showed that the Lyα flare time profiles from SDO/EVE and GOES/EUVS differed
- GOES/EUVS peaked during the impulsive phase, SDO/EVE peaked after the X-ray peak
- This was later attributed to a Kalman filter used to smooth the EVE data on the ground

- 3-minute oscillations were detected in Lyα, LyC and 1600Å and 1700Å during a solar flare **from Sun-as-a-star observations!**

- Believed to be a dynamic response at the acoustic cutoff frequency to an injection of energy

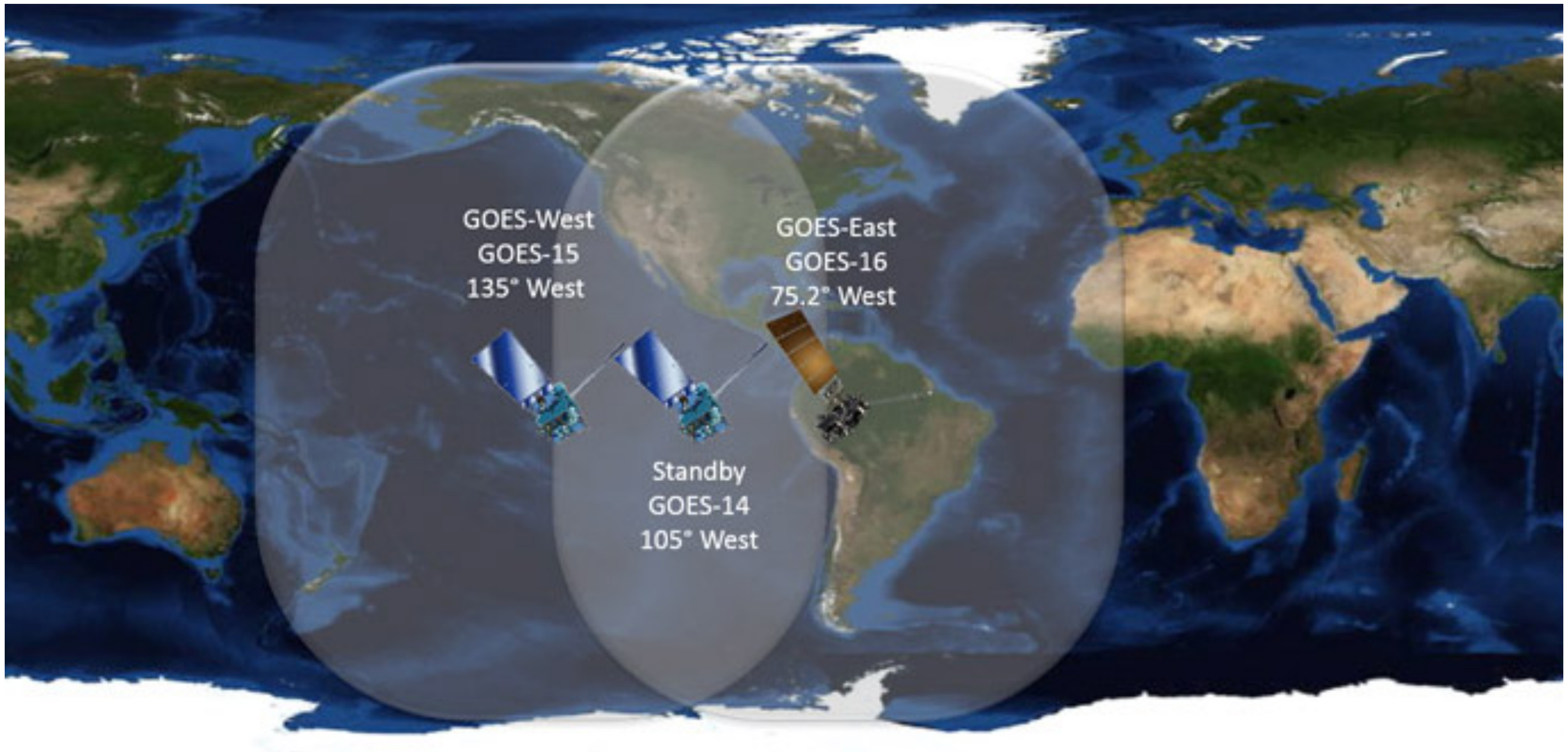
- Similar periods were **not** found in HXRs implying the oscillations is independent of the energy injection rate





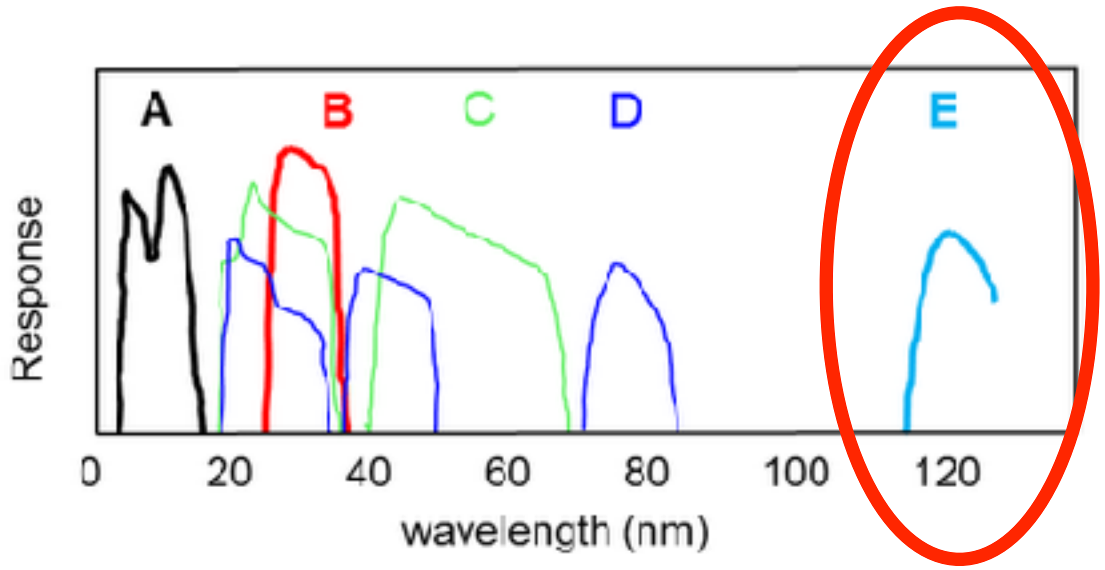
Milligan+ (2017)

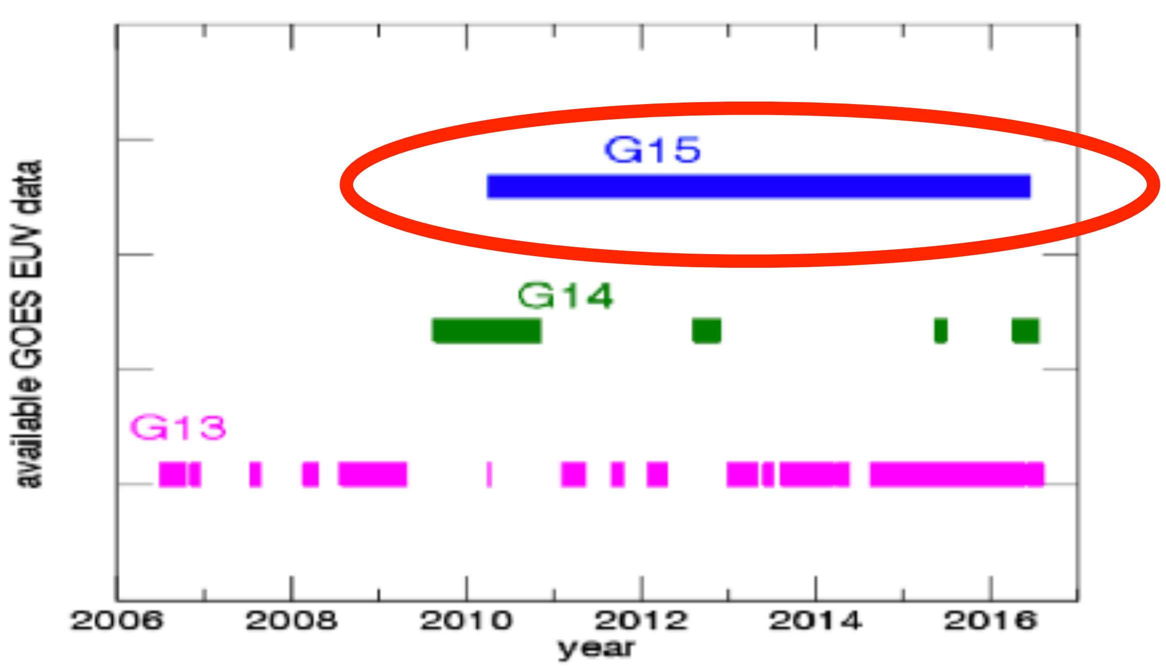
Geostationary Operational Environmental Satellites (GOES)



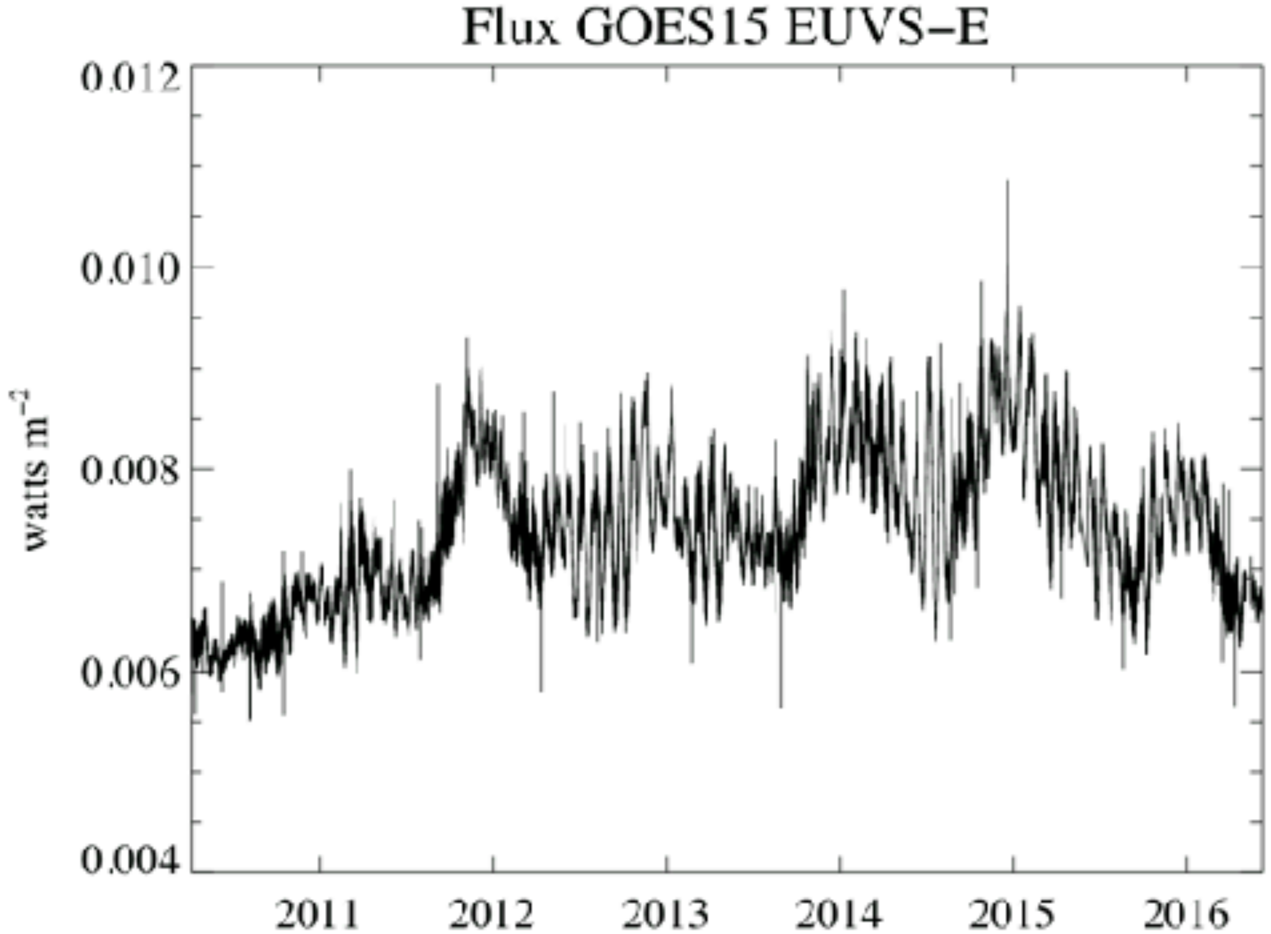
- GOES satellites have been used by NOAA to monitor weather in the US since 1975 (altitude ~35,000 km)
- Beginning with GOES-12 (2001) they have included a Space Environment Monitor (SEM) to measure the effects of the Sun on the near-Earth environment
- GOES X-ray Sensor (XRS) data are the “industry standard” for solar flare classification (A, B, C, M, X)

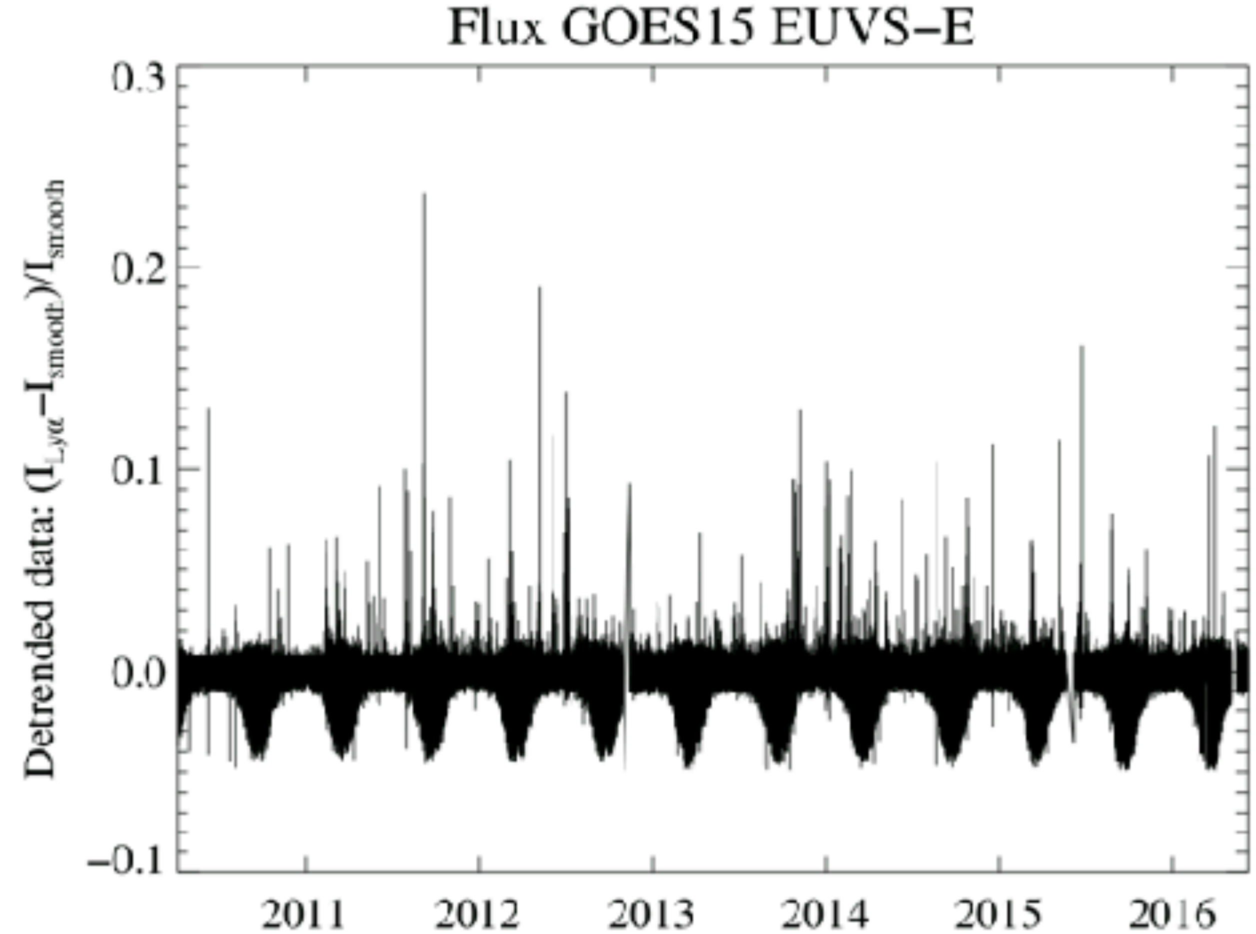
GOES/EUV Sensor (EUVS)





- GOES-13, -14, and -15 have been observing the EUV since 2006 at 10.24s cadence
- The E channel is 100Å wide and centred on the Lyα line (10Å sub-band)
- GOES-15 is the most reliable but only data up until summer 2016 have been released
- The data are scaled to the SORCE/SOLSTICE measurements, but also suffer from ‘geocoronal absorption’ for a few hours each day.



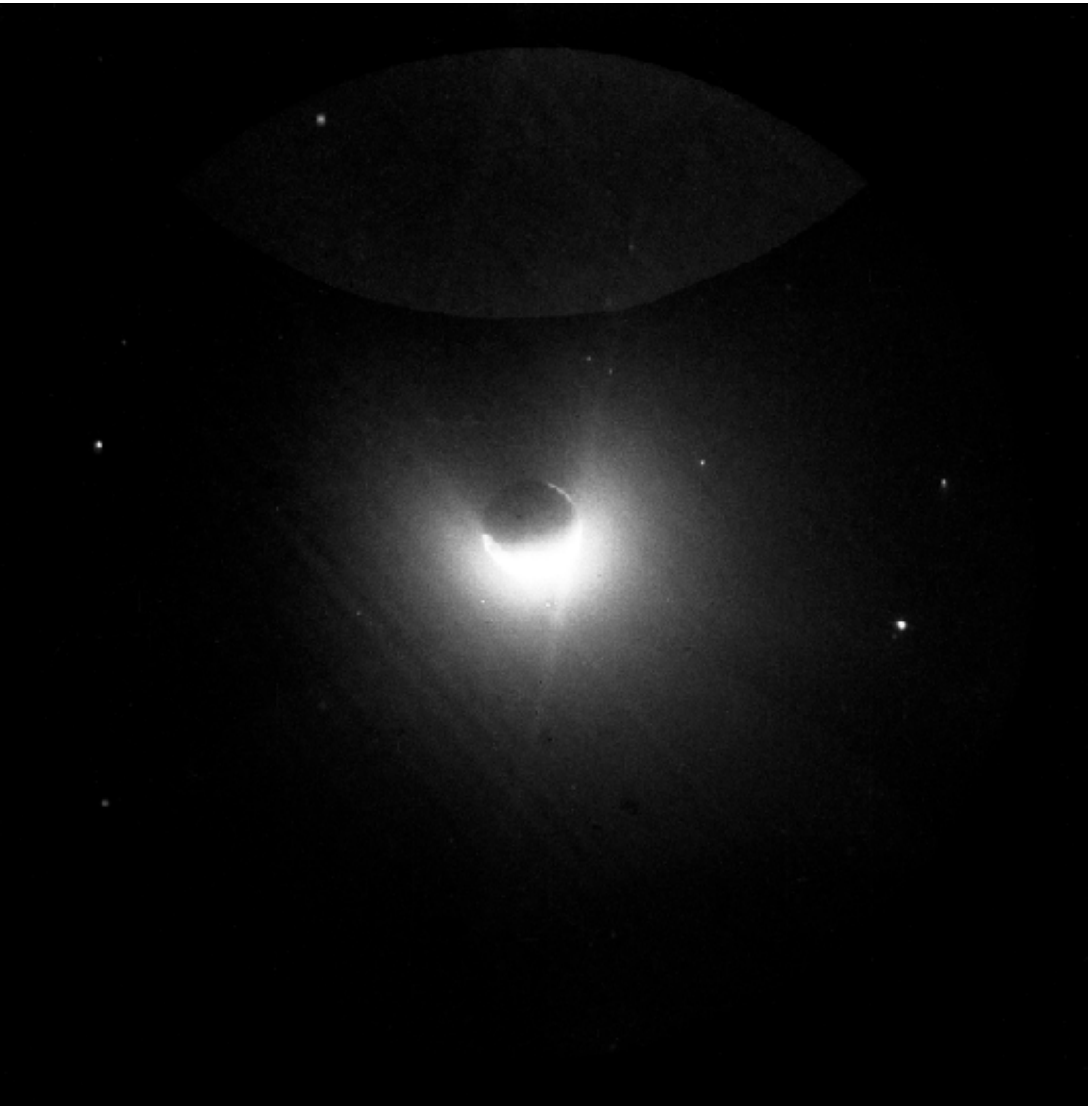


- GOES-15/EUVS-E data are currently available from 7-Apr-2010 to 6-Jun-2016

- During this period there were 677 M-class flares and 45 X-classes

- C-class flares often do not produce an appreciable response in full-disk Lyα

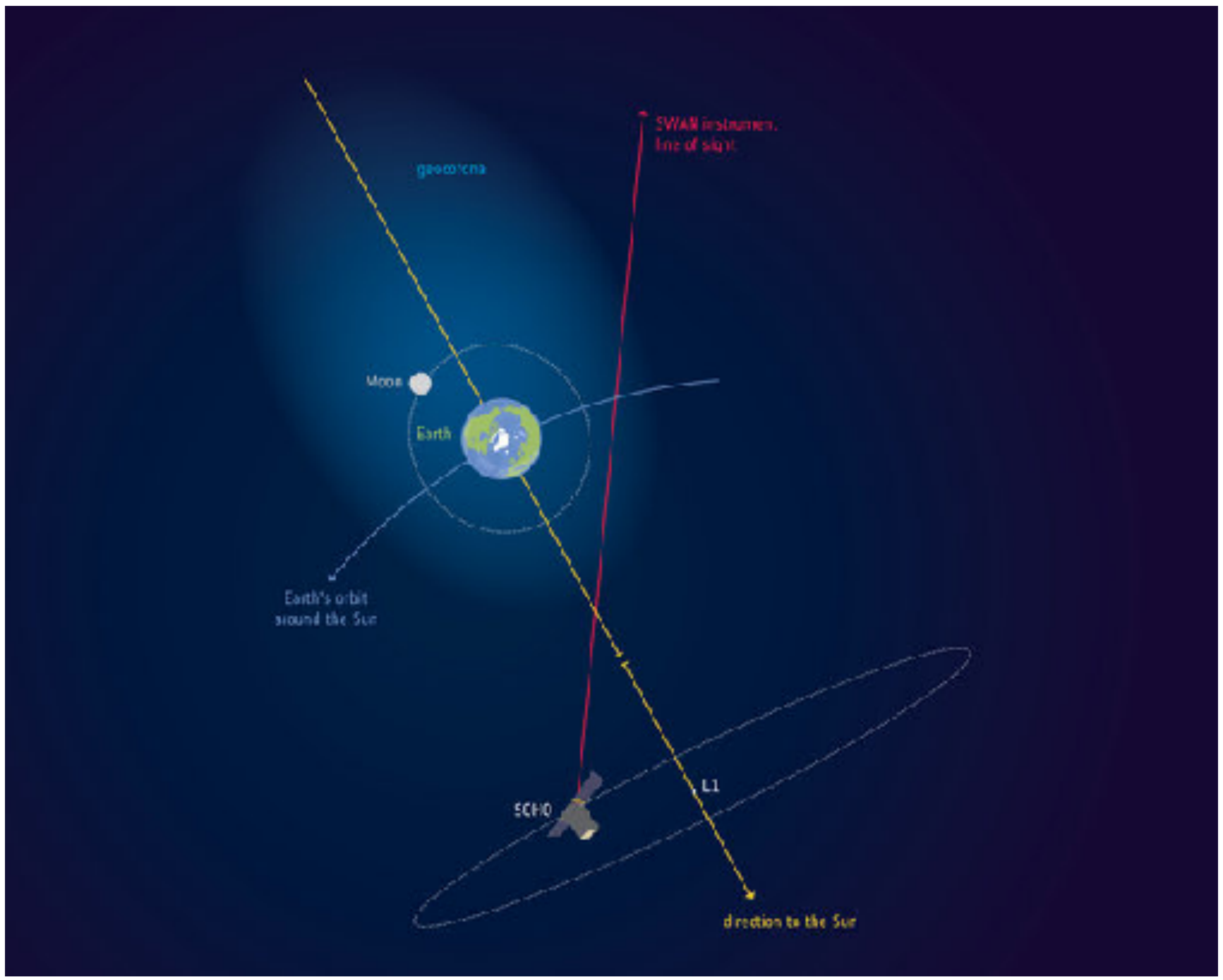
Geocoronal Absorption



Earth's geocorona as seen from
the moon by Apollo 16 astronauts in 1972

- The geocorona is the luminous part of Earth's outer atmosphere
- Primarily seen in solar Lyα due to scattering from neutral H
- Extends out to ~50$R_\oplus$ (beyond the orbit of the moon)

Geocoronal Absorption



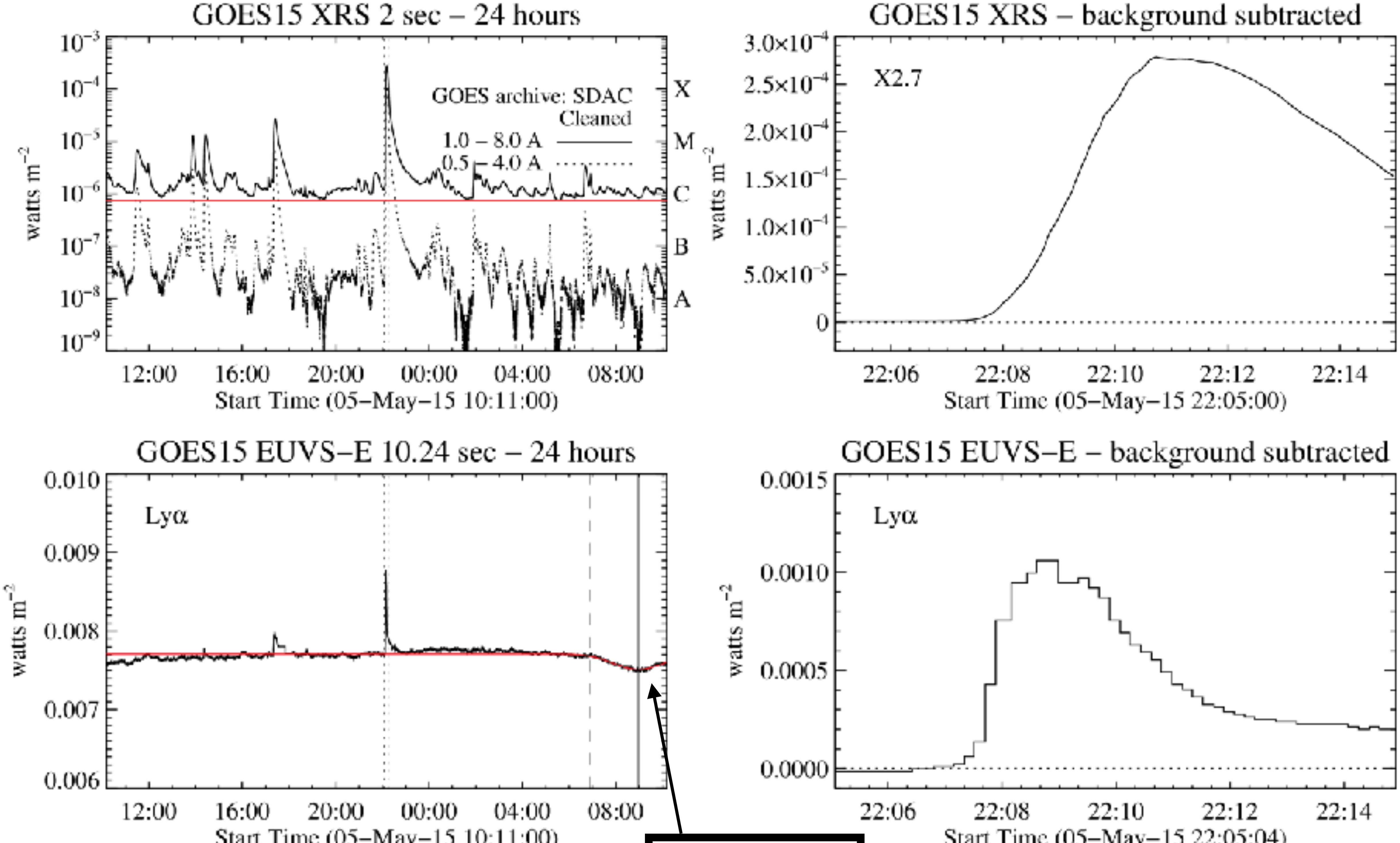
Baliukin+ (2019)

- The geocorona is the luminous part of Earth's outer atmosphere
- Primarily seen in solar Lyα due to scattering from neutral H
- Extends out to ~50$R_\oplus$ (beyond the orbit of the moon)

A “Typical” Lyα Flare

X-rays

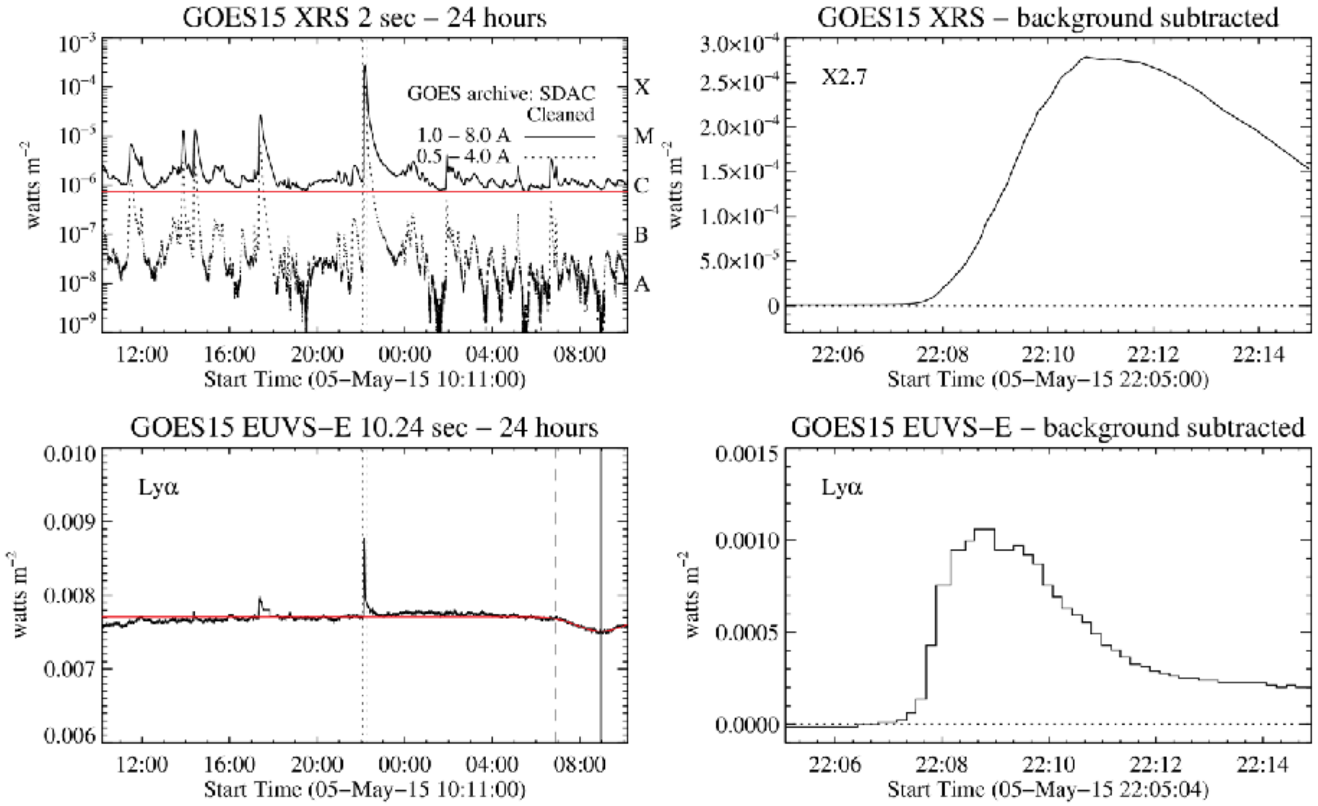
Lyman-alpha



Geocoronal Absorption

24 hours

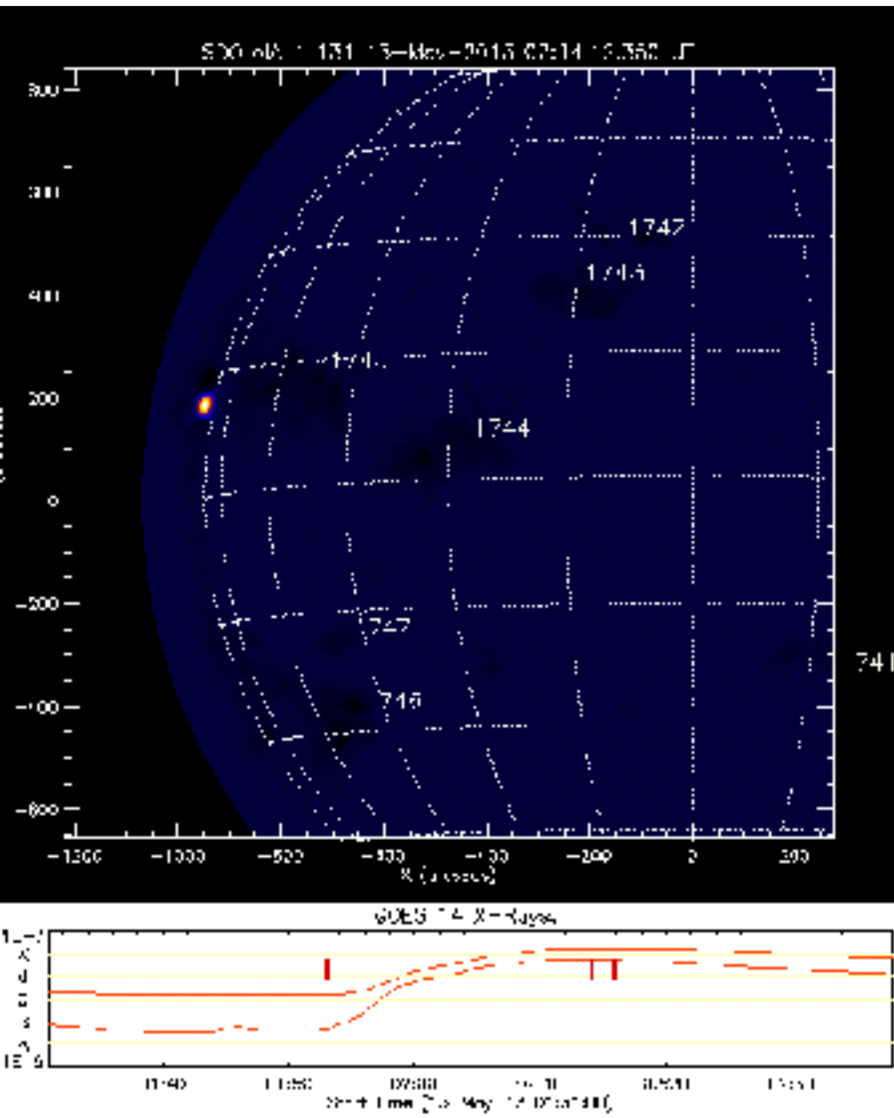
The flare

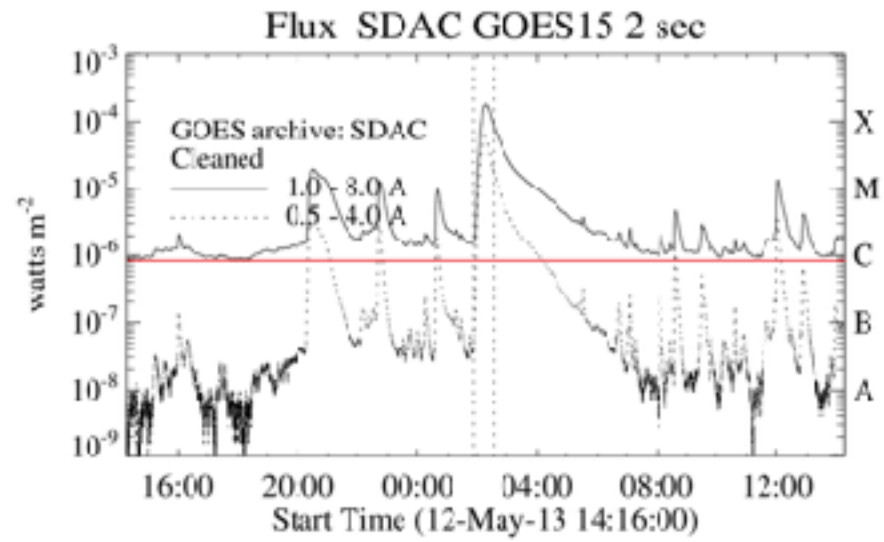


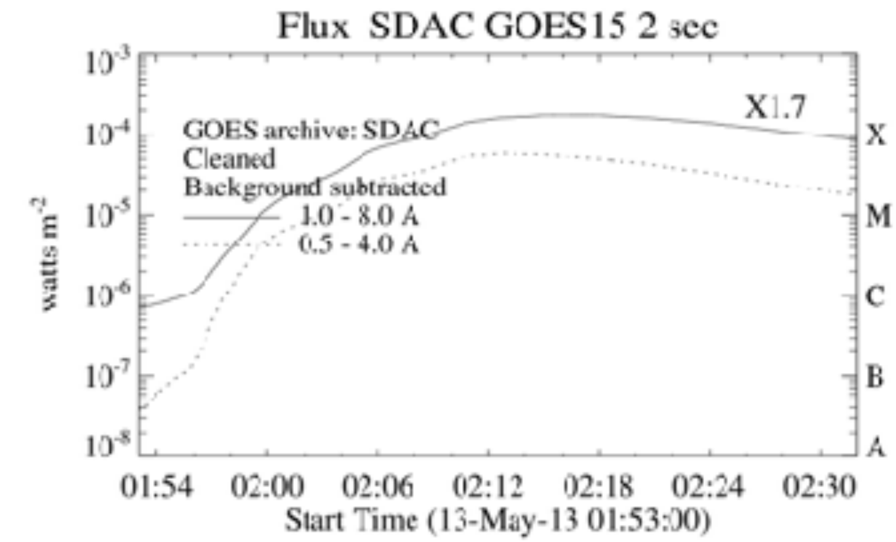
Methodology

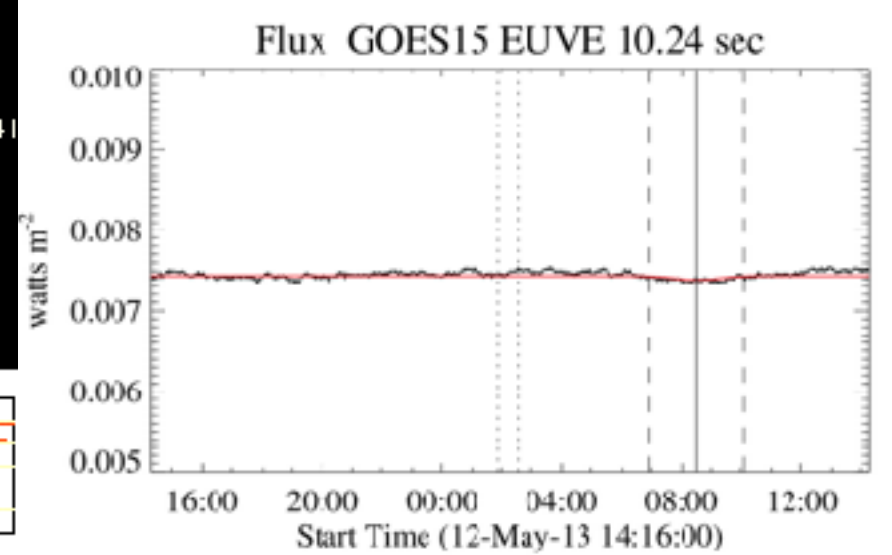
- Start with the HEK/GOES event list (573 M’s, 33 X’s)
- X-ray background: minimum value within ±12h of X-ray peak
- Lyα background: fit lightcurve (±12h of X-ray peak) with constant (modal value) plus Gaussian (for geocoronal absorption)
- Ignore events with GOES start/end time within ±2σ of dip minimum (leaves **446 M’s, 31 X’s**; for comparison, SDO/EVE saw 94 M’s, 8 X’s)
- Integrate between GOES start/end times - both X-rays and Lyα - and convert from flux to power (1 W m^{-2} = 1.406×10^{30} erg s^{-1})

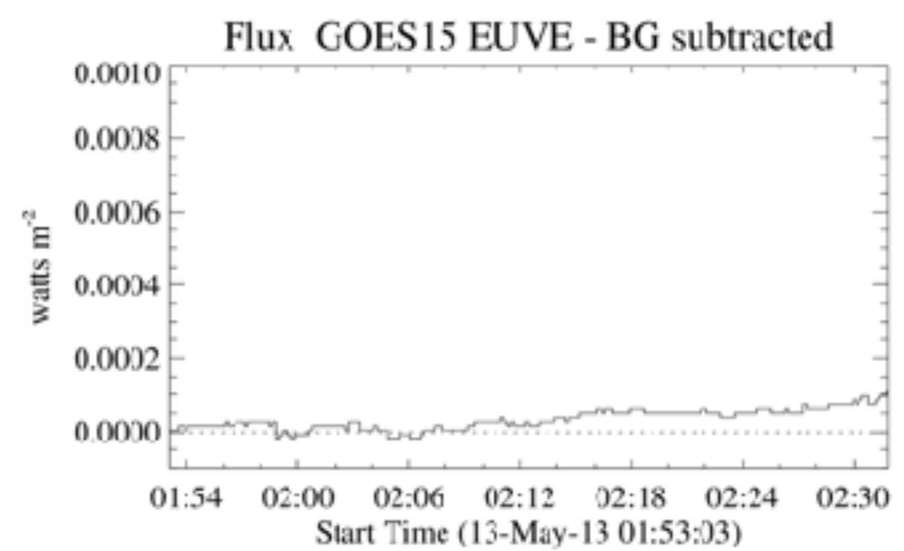
Limb Flares



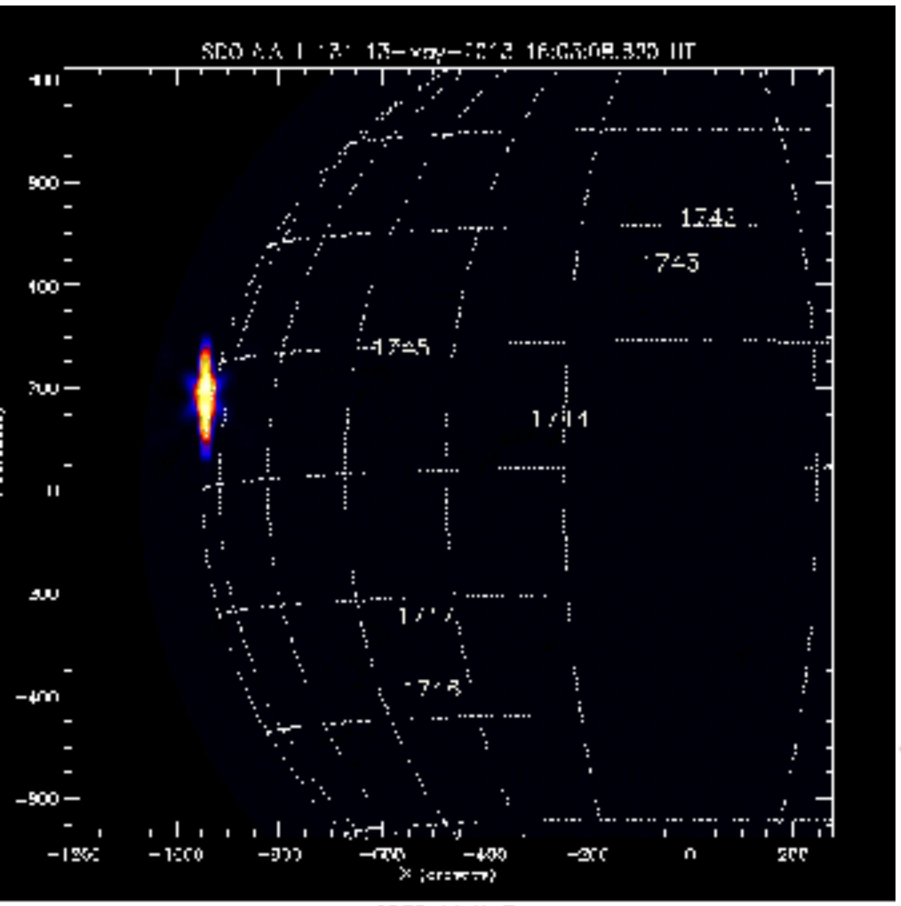

Flux SDAC GOES15 2 sec
GOES archive: SDAC
Cleaned
1.0 - 8.0 A
0.5 - 4.0 A
watts m^-2
X
M
C
B
A
16:00 20:00 00:00 04:00 08:00 12:00
Start Time (12-May-13 14:16:00)

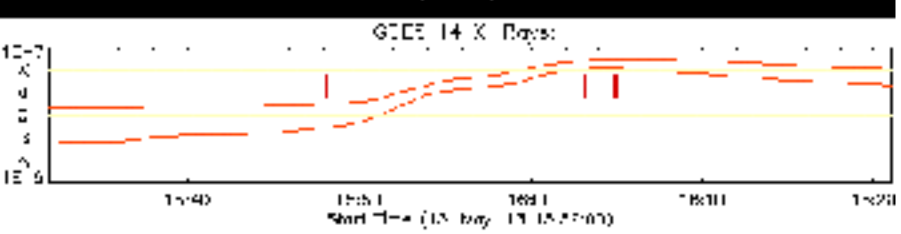

Flux SDAC GOES15 2 sec
X1.7
GOES archive: SDAC
Cleaned
Background subtracted
1.0 - 8.0 A
0.5 - 4.0 A
watts m^-2
X
M
C
B
A
01:54 02:00 02:06 02:12 02:18 02:24 02:30
Start Time (13-May-13 01:53:00)

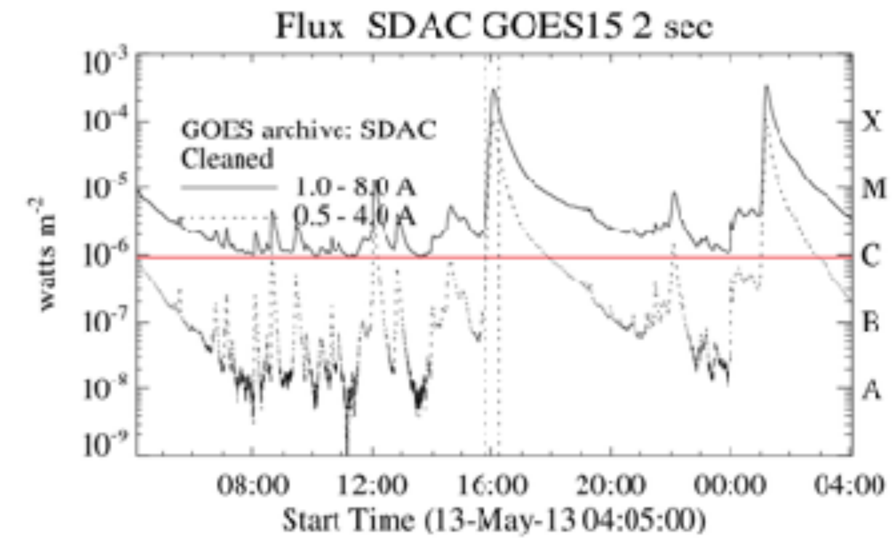

Flux GOES15 EUVE 10.24 sec
watts m^-2
0.010
0.009
0.008
0.007
0.006
0.005
16:00 20:00 00:00 04:00 08:00 12:00
Start Time (12-May-13 14:16:00)

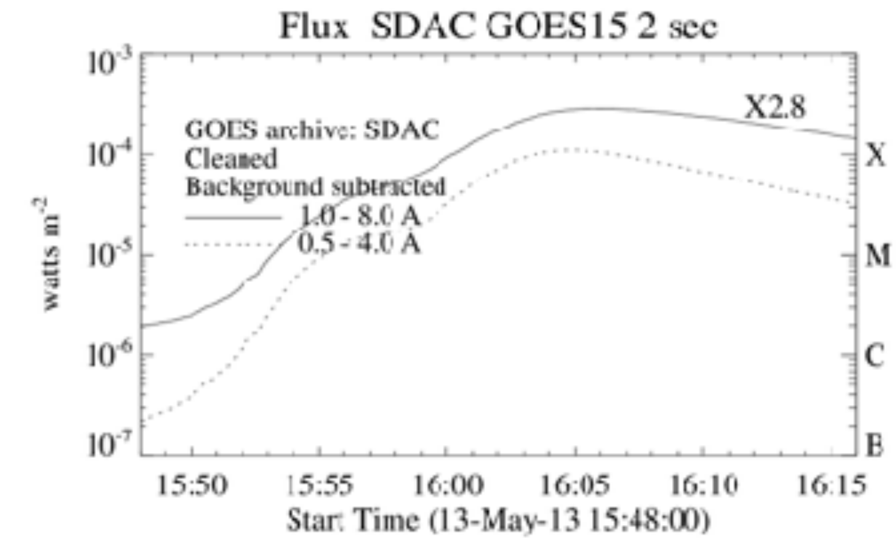

Flux GOES15 EUVE - BG subtracted
watts m^-2
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
01:54 02:00 02:06 02:12 02:18 02:24 02:30
Start Time (13-May-13 01:53:03)

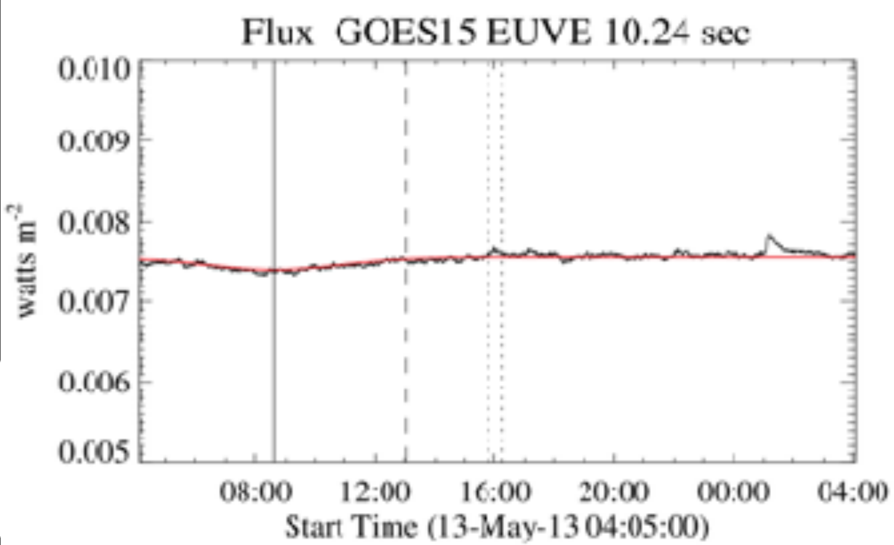
Limb Flares

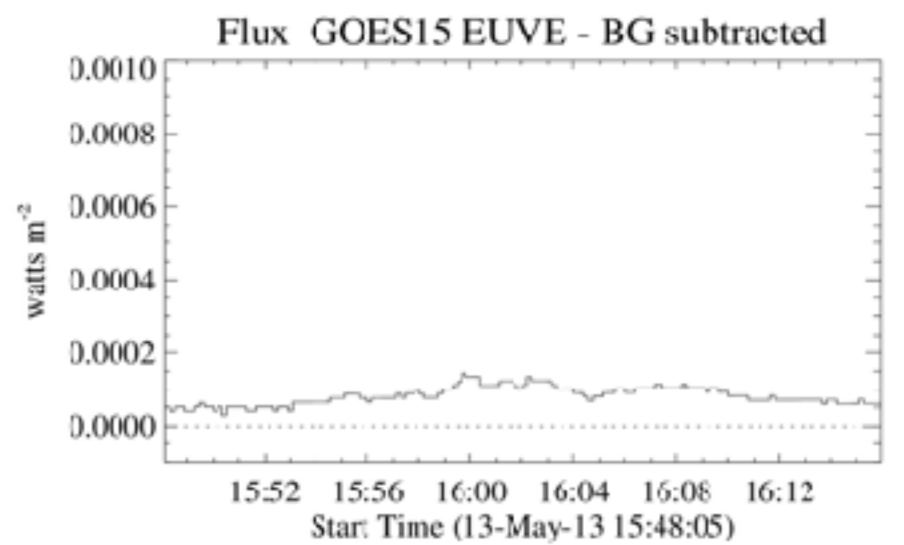




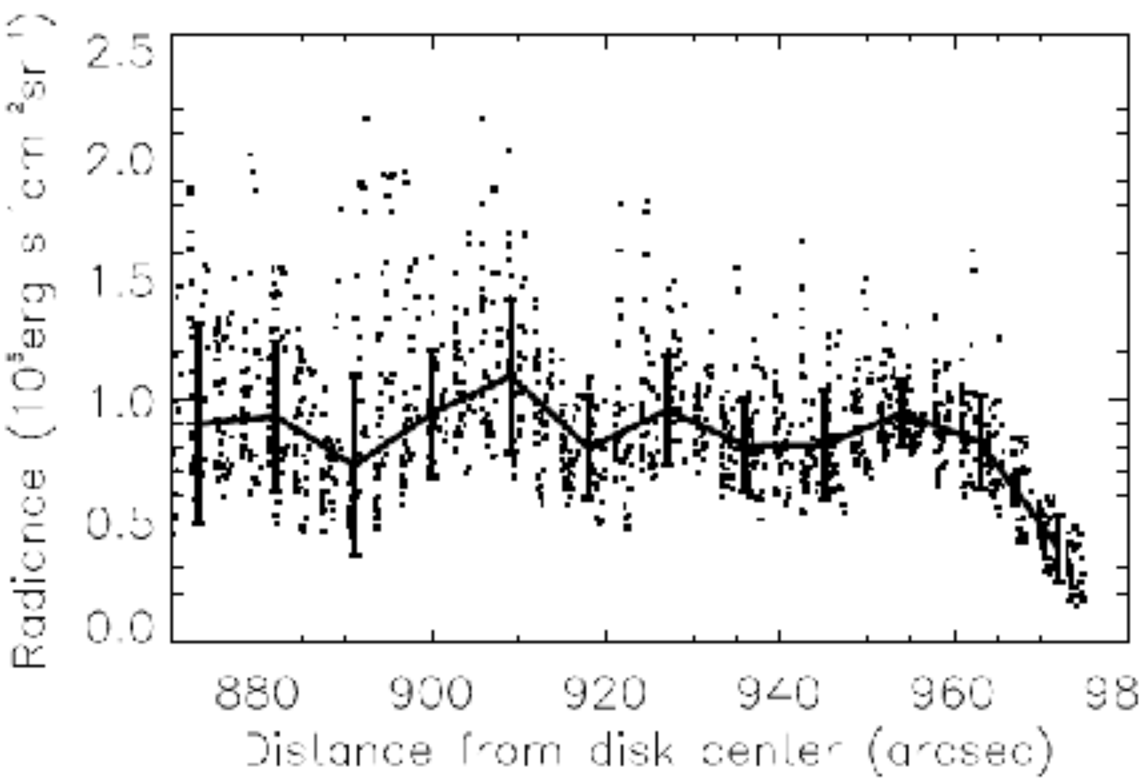

Flux SDAC GOES15 2 sec
GOES archive: SDAC
Cleaned
1.0 - 8.0 A
0.5 - 4.0 A
watts m^{-2}
X
M
C
B
A
08:00
12:00
16:00
20:00
00:00
04:00
Start Time (13-May-13 04:05:00)


Flux SDAC GOES15 2 sec
GOES archive: SDAC
Cleaned
Background subtracted
1.0 - 8.0 A
0.5 - 4.0 A
X2.8
watts m^{-2}
X
M
C
B
15:50
15:55
16:00
16:05
16:10
16:15
Start Time (13-May-13 15:48:00)

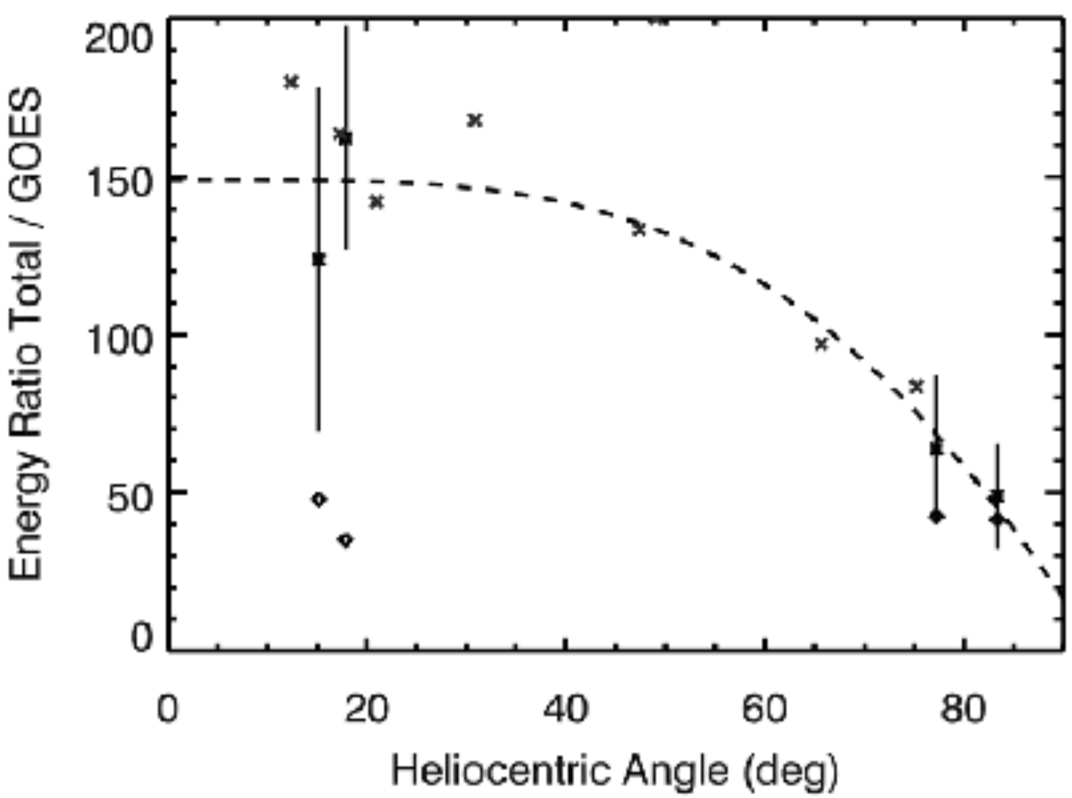

Flux GOES15 EUVE 10.24 sec
watts m^{-2}
08:00
12:00
16:00
20:00
00:00
04:00
Start Time (13-May-13 04:05:00)


Flux GOES15 EUVE - BG subtracted
watts m^{-2}
15:52
15:56
16:00
16:04
16:08
16:12
Start Time (13-May-13 15:48:05)

Center-to-Limb Variation



- Curdt+ (2008) measured the CLV for QS Lyα using SUMER
- They found a slight decrease >960", which suggested a deeper central reversal near the limb

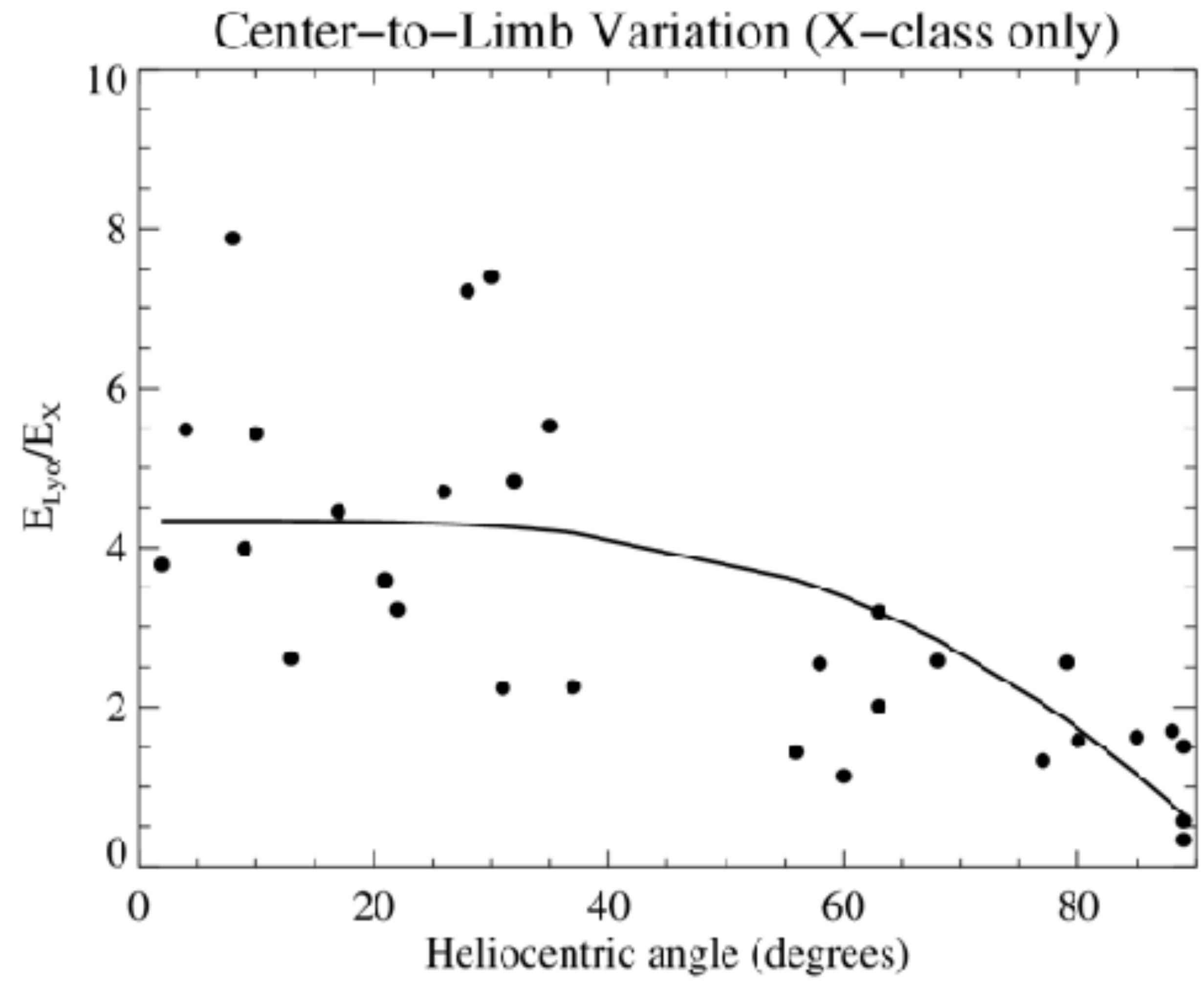


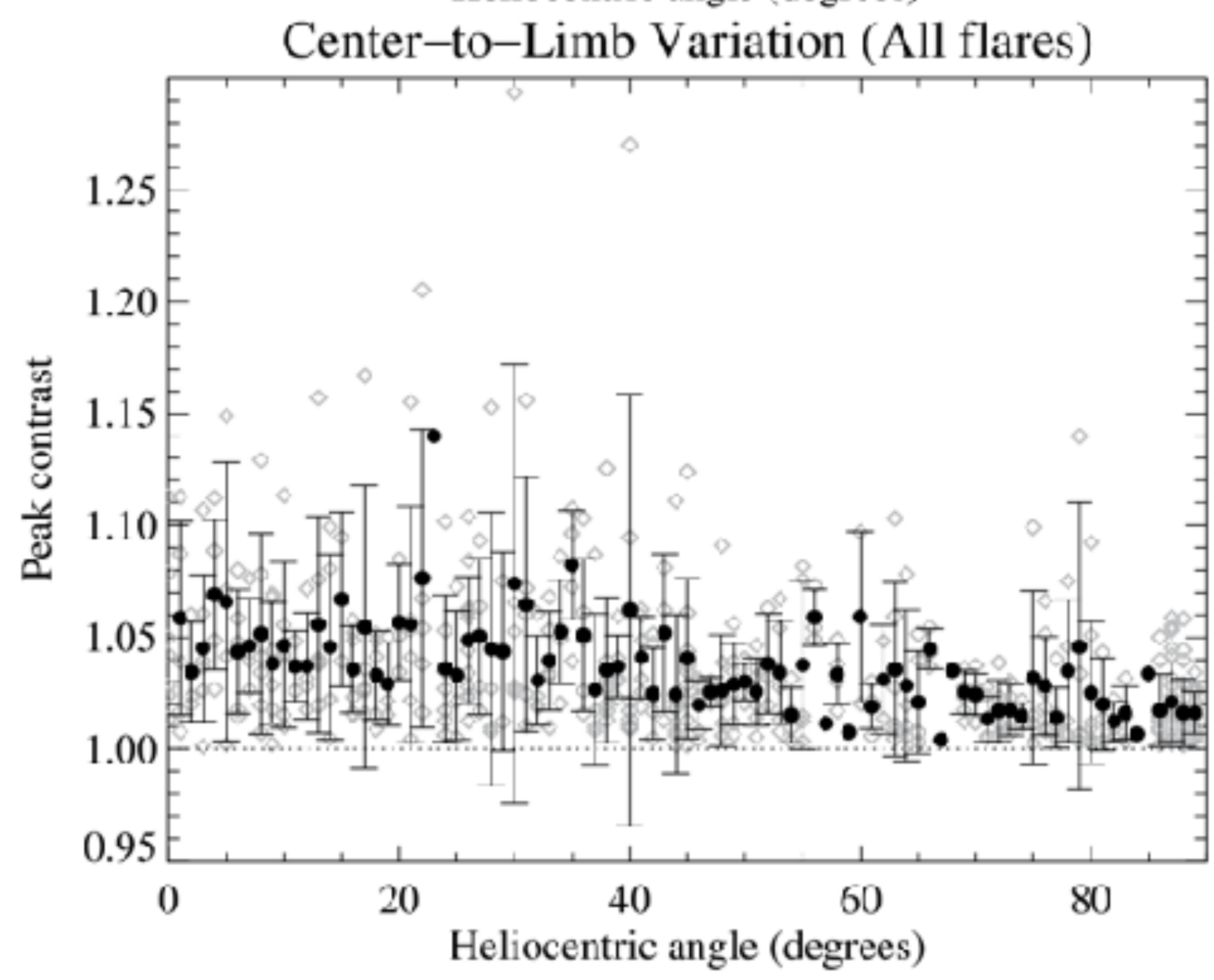
- Woods+ (2006) found a CLV for flares observed in the TSI (4 events)
- The TSI was measured relative to GOES X-rays, which are optically thin

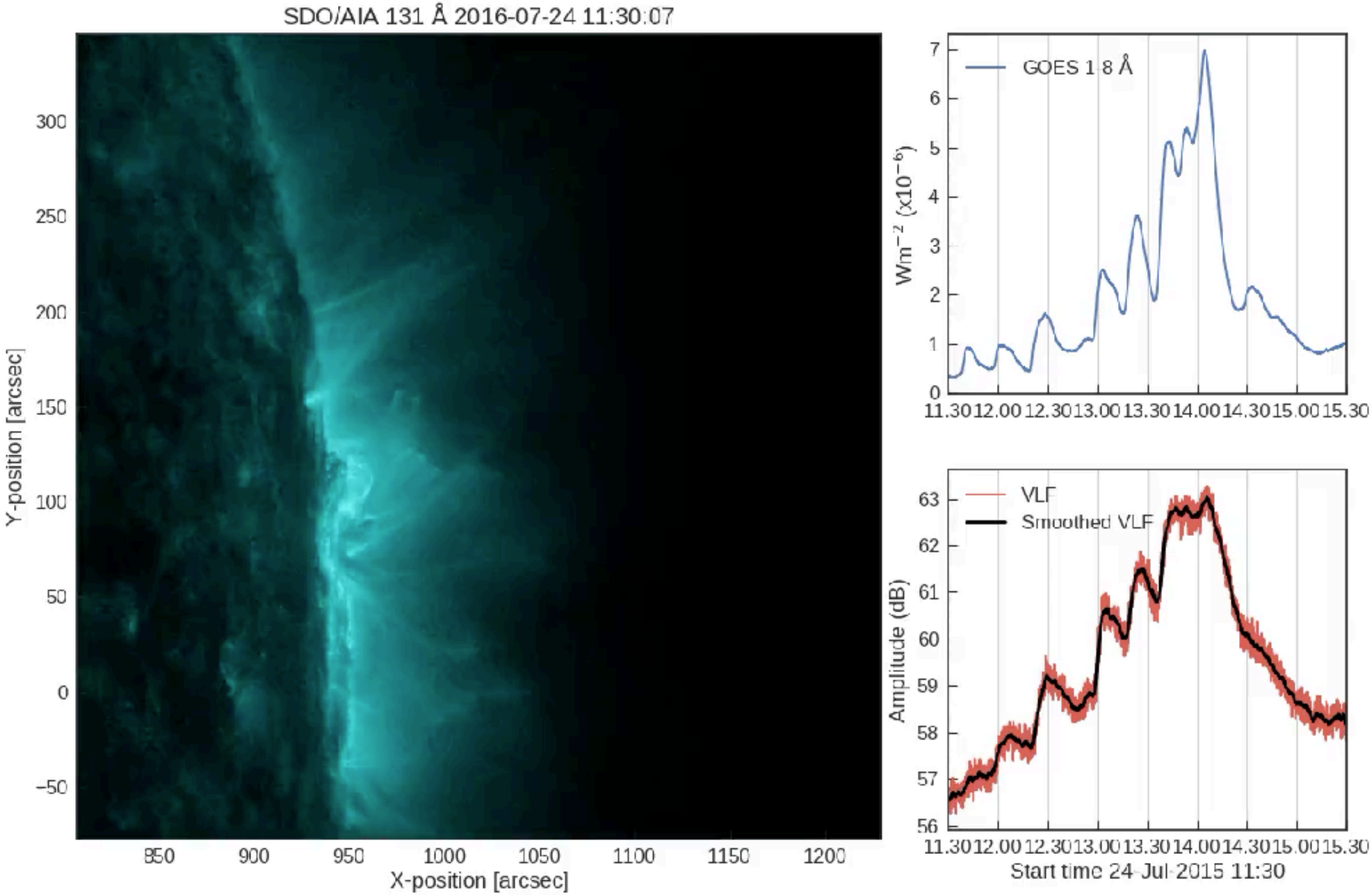
- Following from Woods+ (2006) $E_{Ly\alpha}/E_{X\text{-ray}}$ was plotted against heliocentric angle and fit with:

$$R = R_C\left(k + 2(1-k)\left(\mu - \frac{\mu^2}{2}\right)\right)$$

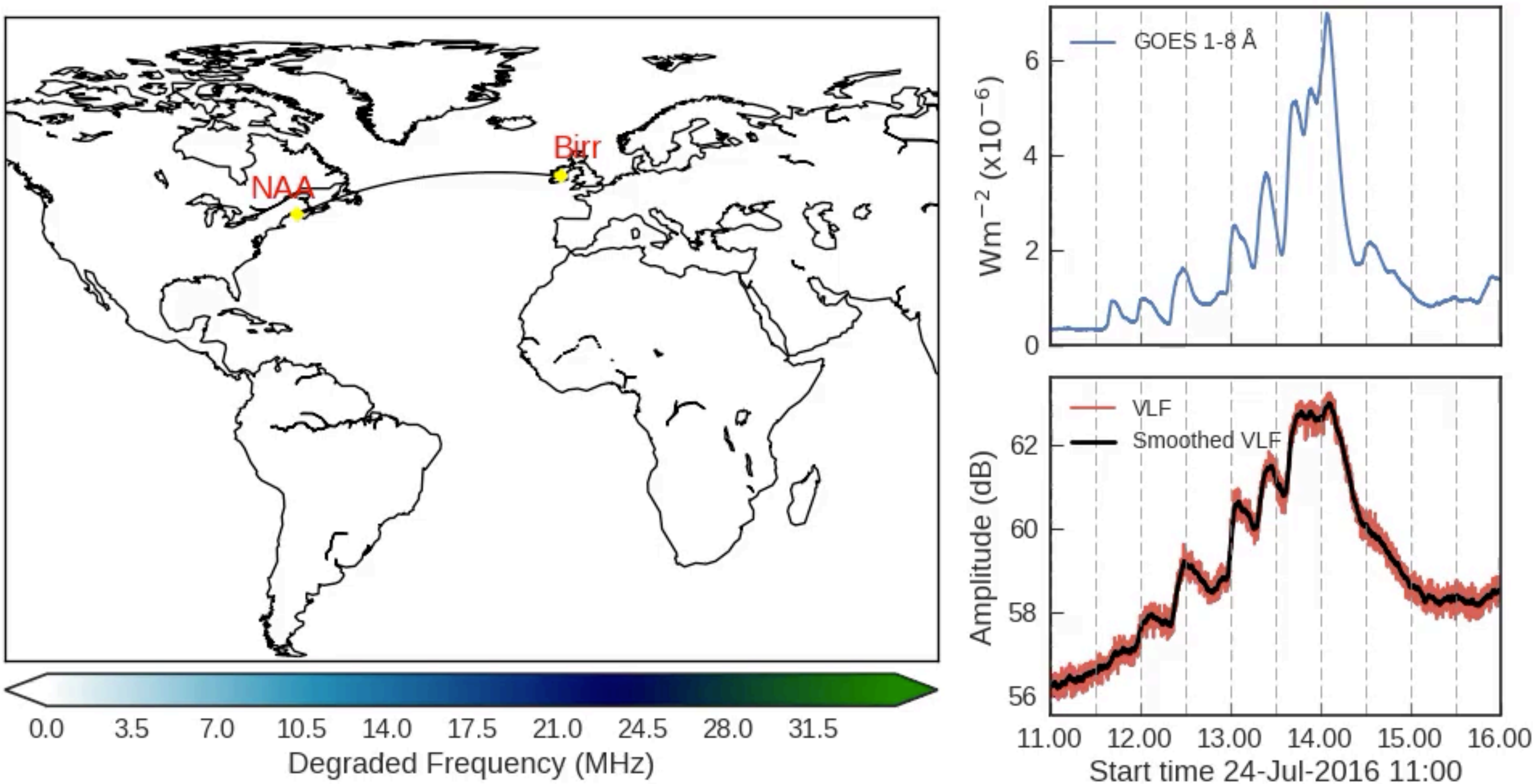
- For X-class flares k=0.11 (Woods+ 2006 also found k=0.11)
- Peak contrast vs. angle also shows some degree of limb darkening
- Possibly due to opacity effects, foreshortening of the ribbons near the limb, or (partially) occulted events





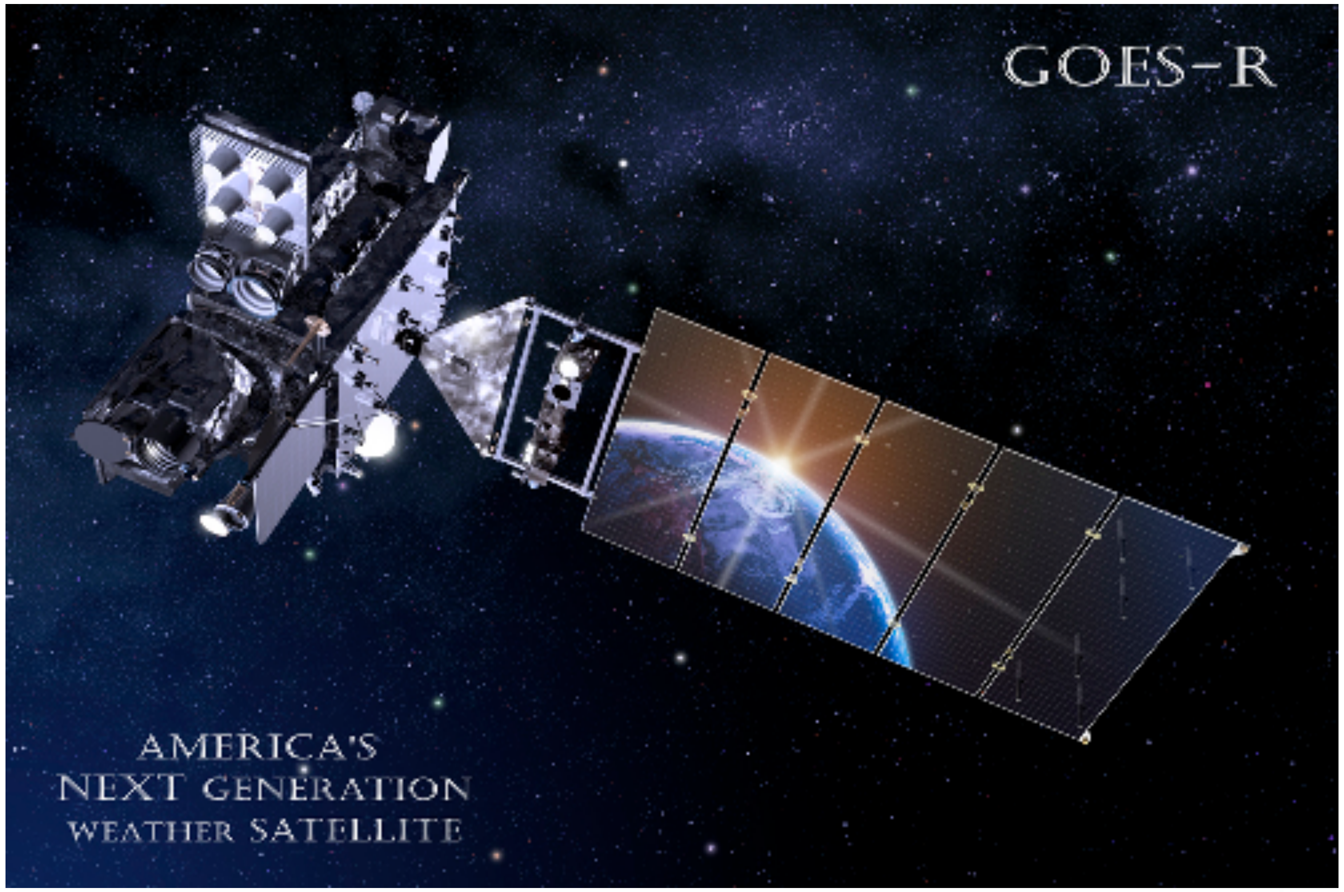

SDO/AIA 131 Å 2016-07-24 11:30:07
Y-position [arcsec]
X-position [arcsec]
300
250
200
150
100
50
0
−50
850
900
950
1000
1050
1100
1150
1200
GOES 1-8 Å
Wm^{-2} (x10^{-6})
7
6
5
4
3
2
1
0
11.30 12.00 12.30 13.00 13.30 14.00 14.30 15.00 15.30
VLF
Smoothed VLF
Amplitude (dB)
63
62
61
60
59
58
57
56
11.30 12.00 12.30 13.00 13.30 14.00 14.30 15.00 15.30
Start time 24-Jul-2015 11:30

Hayes+ (2017)

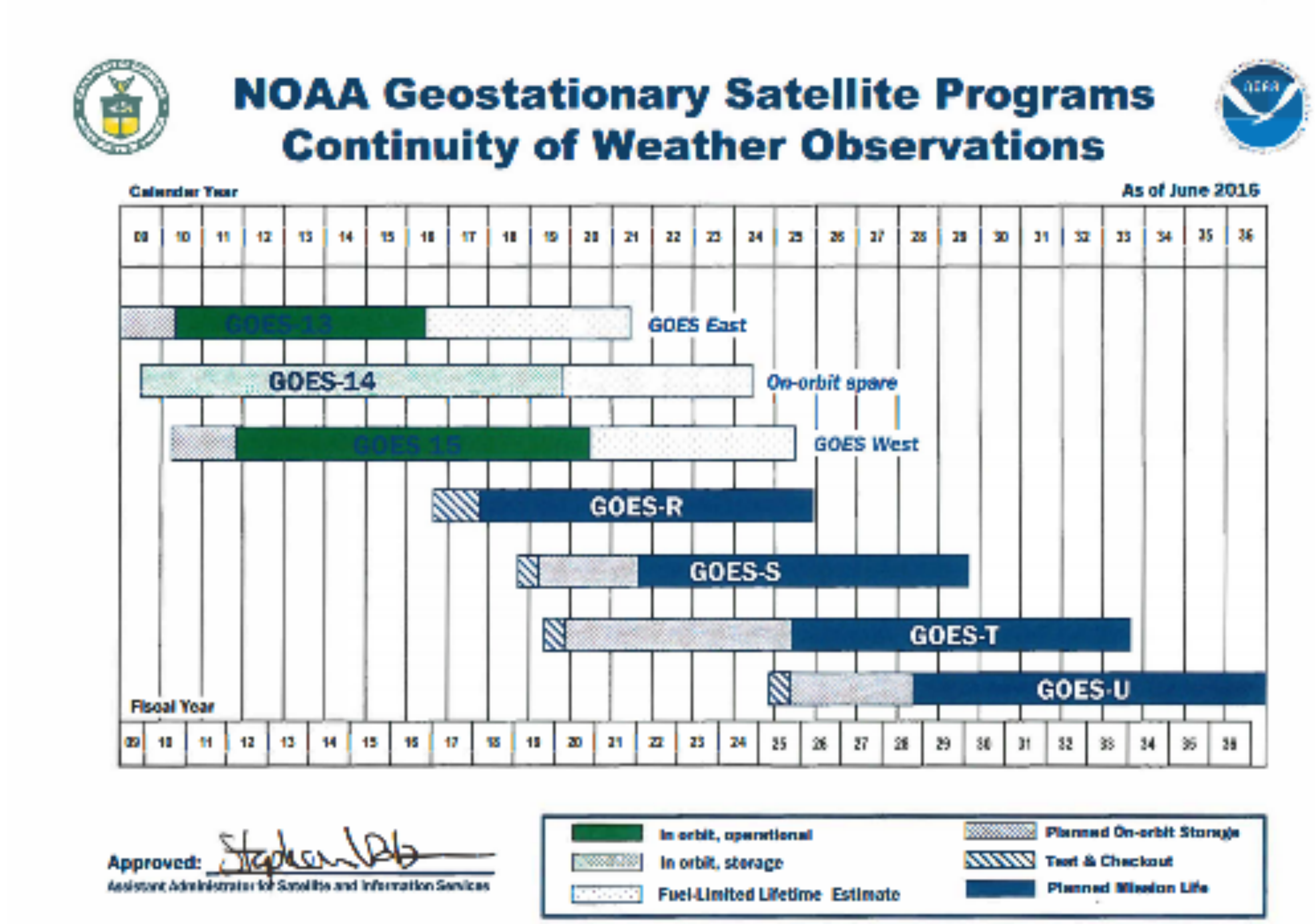


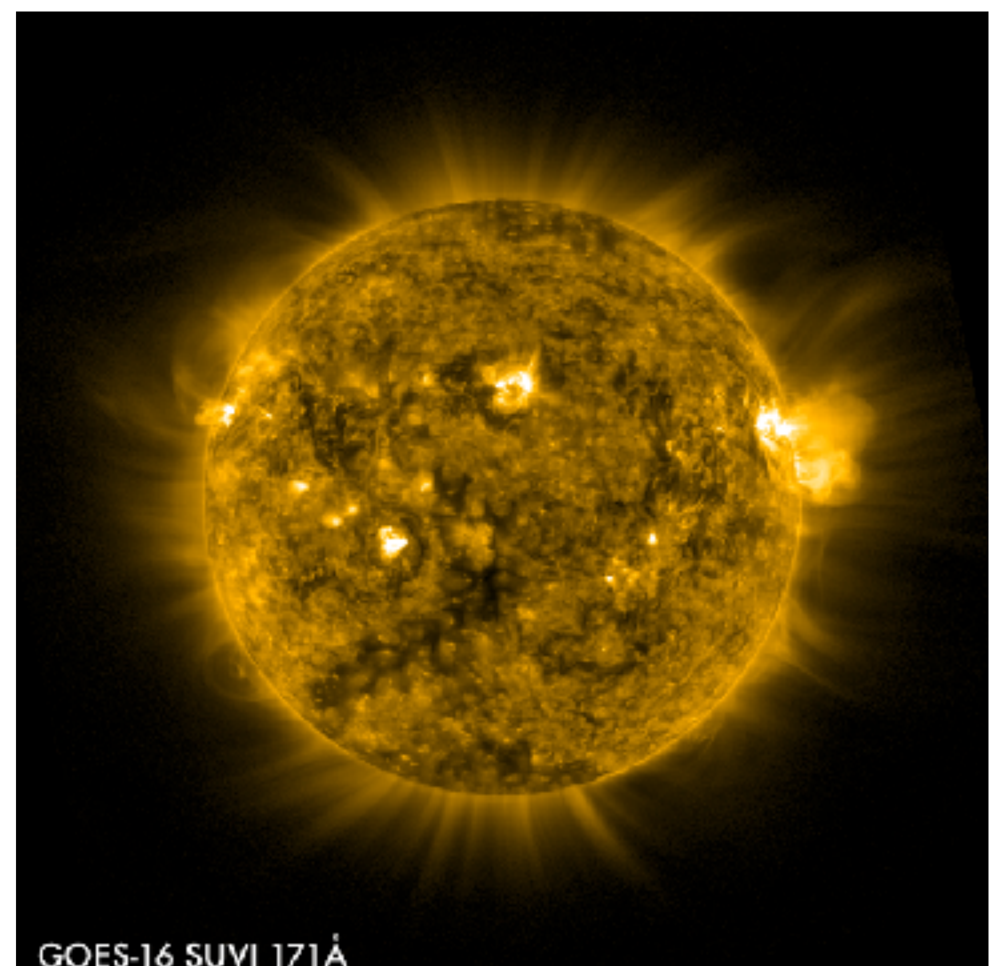
High-frequency radio wave absorption as a result of increased ionisation in the D-layer of the ionosphere

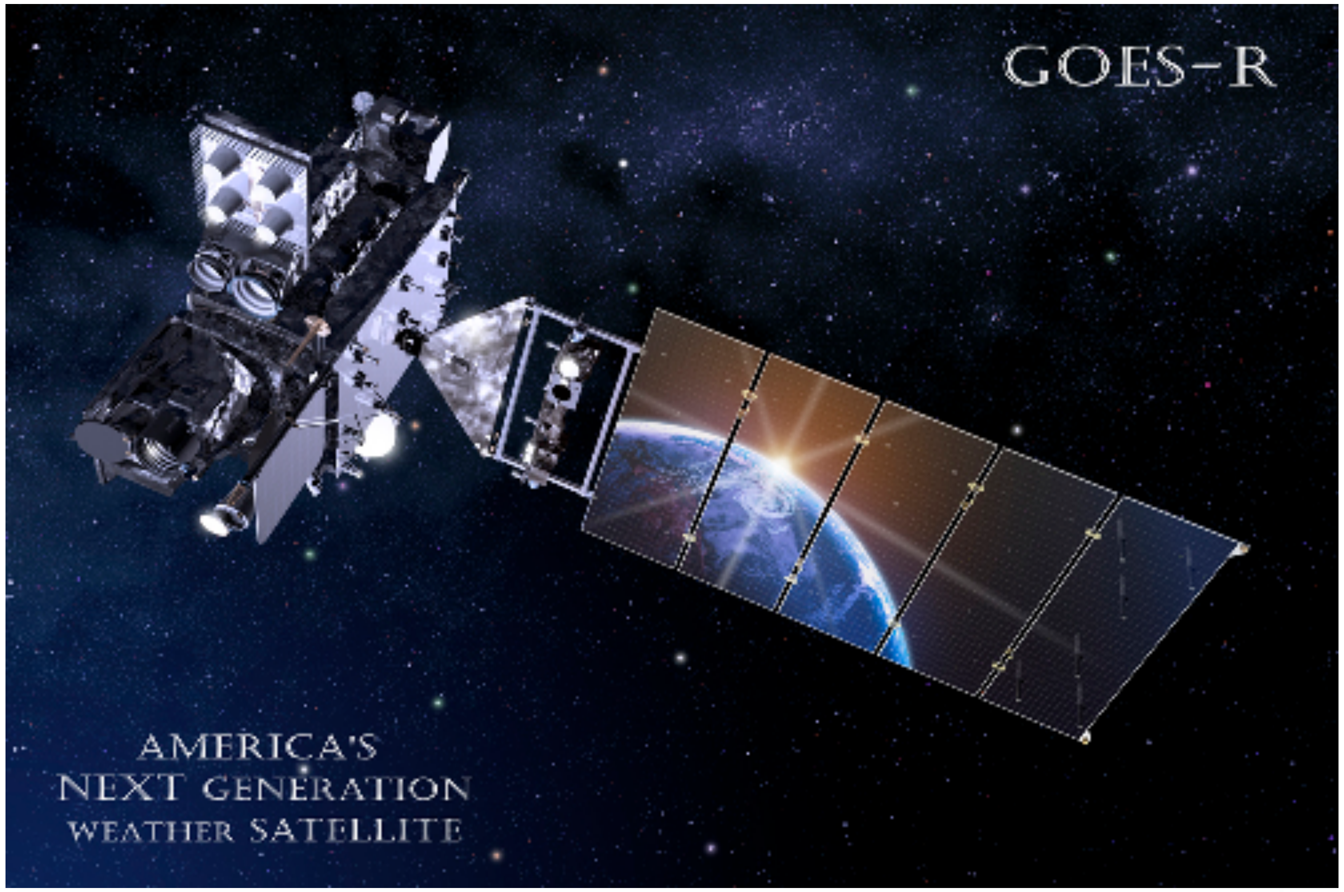
Hayes+ (2017)



- GOES-R series of weather satellites planned for next ~20 years
- Dedicated EUV and X-ray Irradiance Sensors (EXIS) together with the Solar UV Imager (SUVI)
- EXIS will cover Lyα line (1170Å-1270Å at Δλ=1Å) at <10s cadence
- (also 50Å-1150Å at 0.5Å bins)







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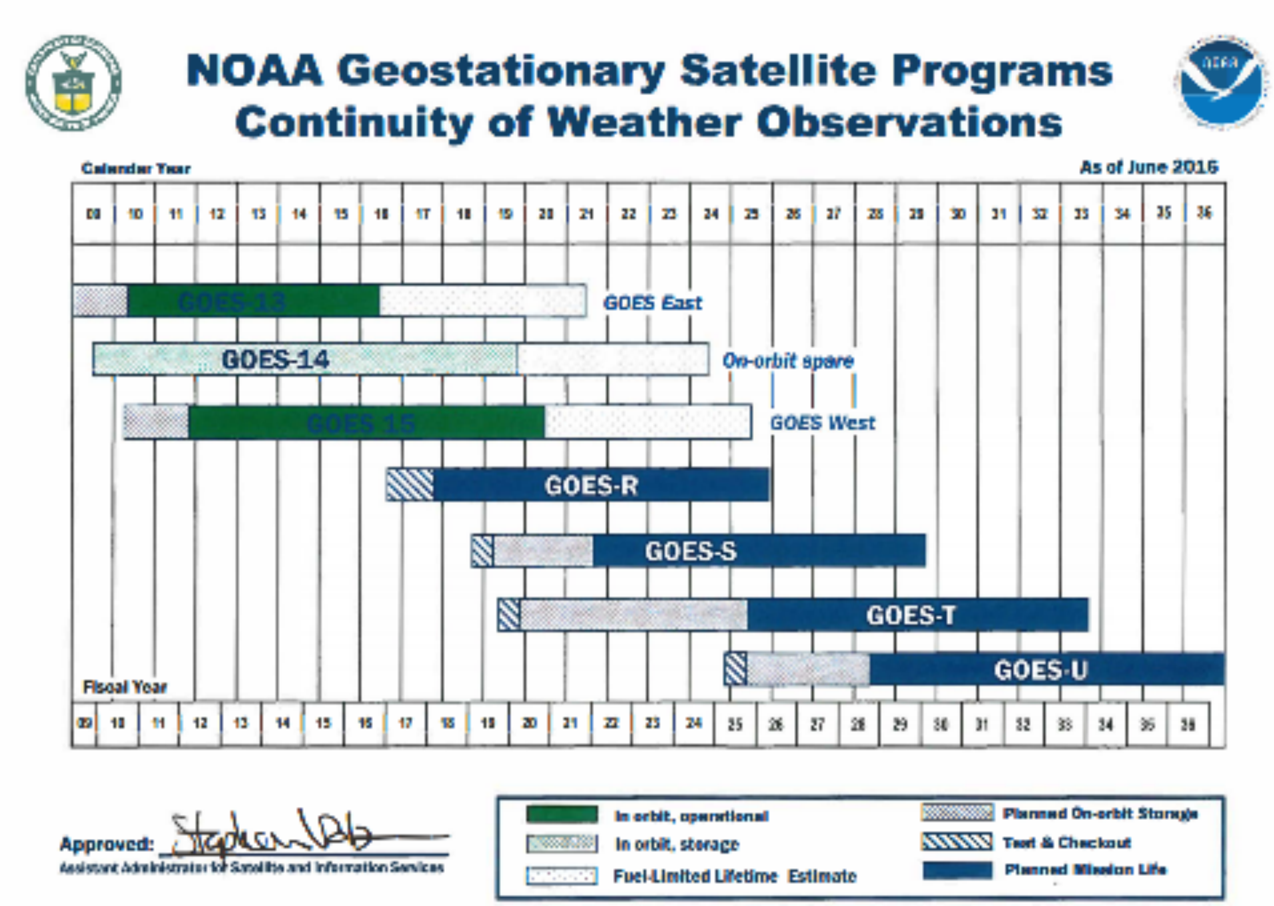
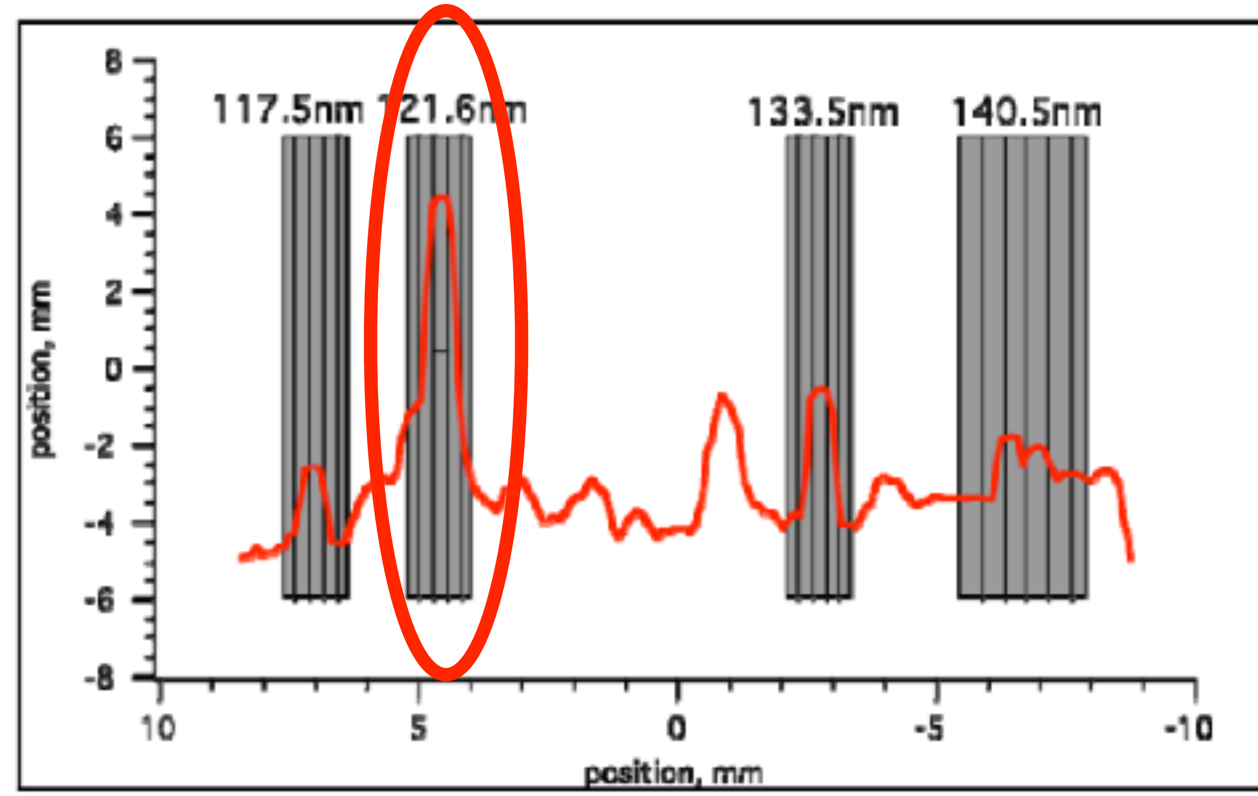
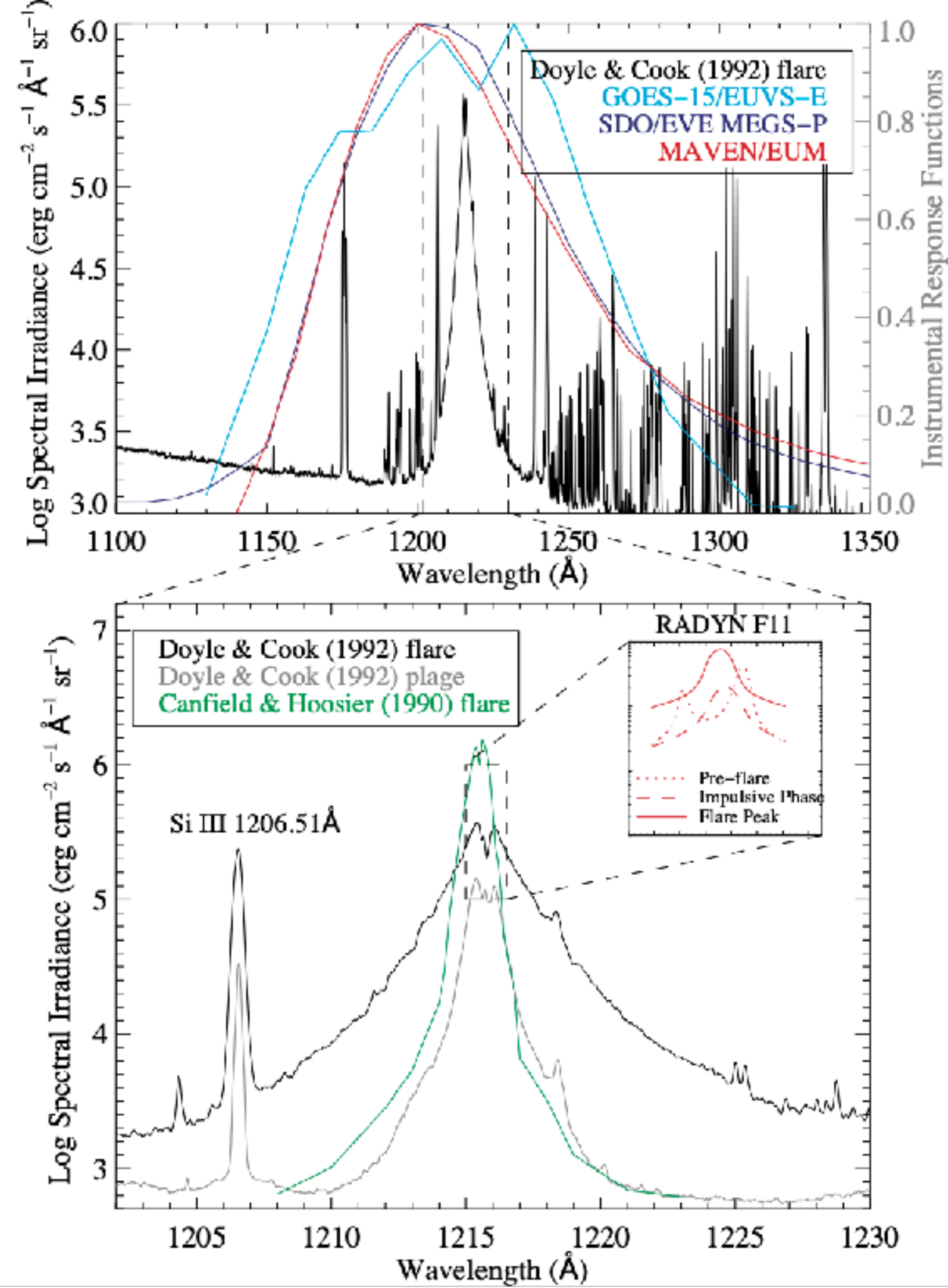
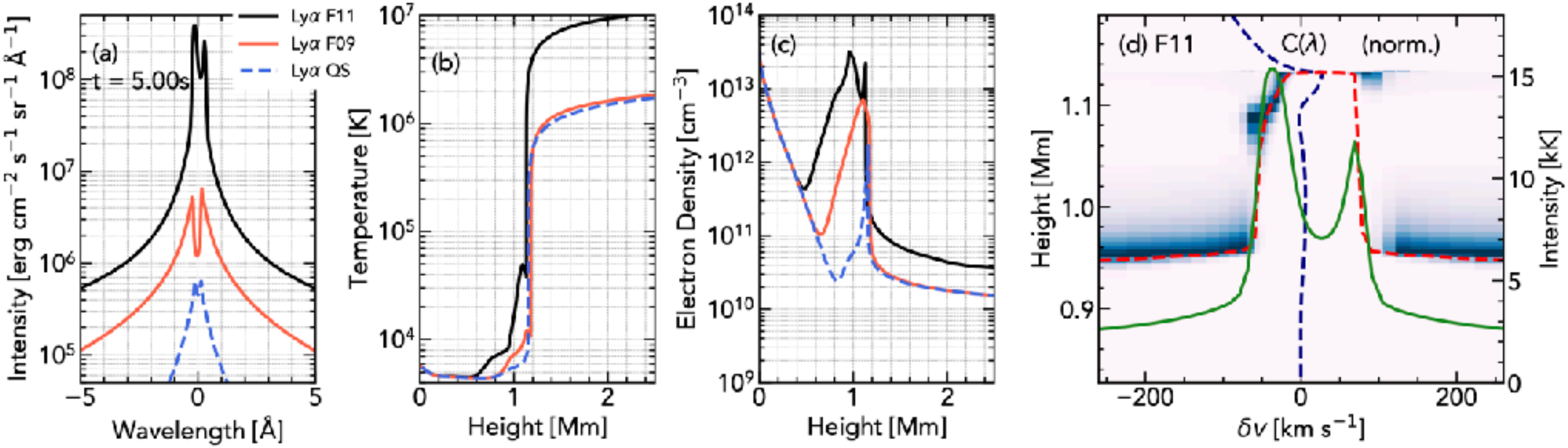




ure 5. The relative positioning and sizes of the pixels on the custom 1-D photodiode array for EUVS-B with a 'esentative solar spectrum from the spectrograph overlaid. The dark pixels on either end of the array are not shown.

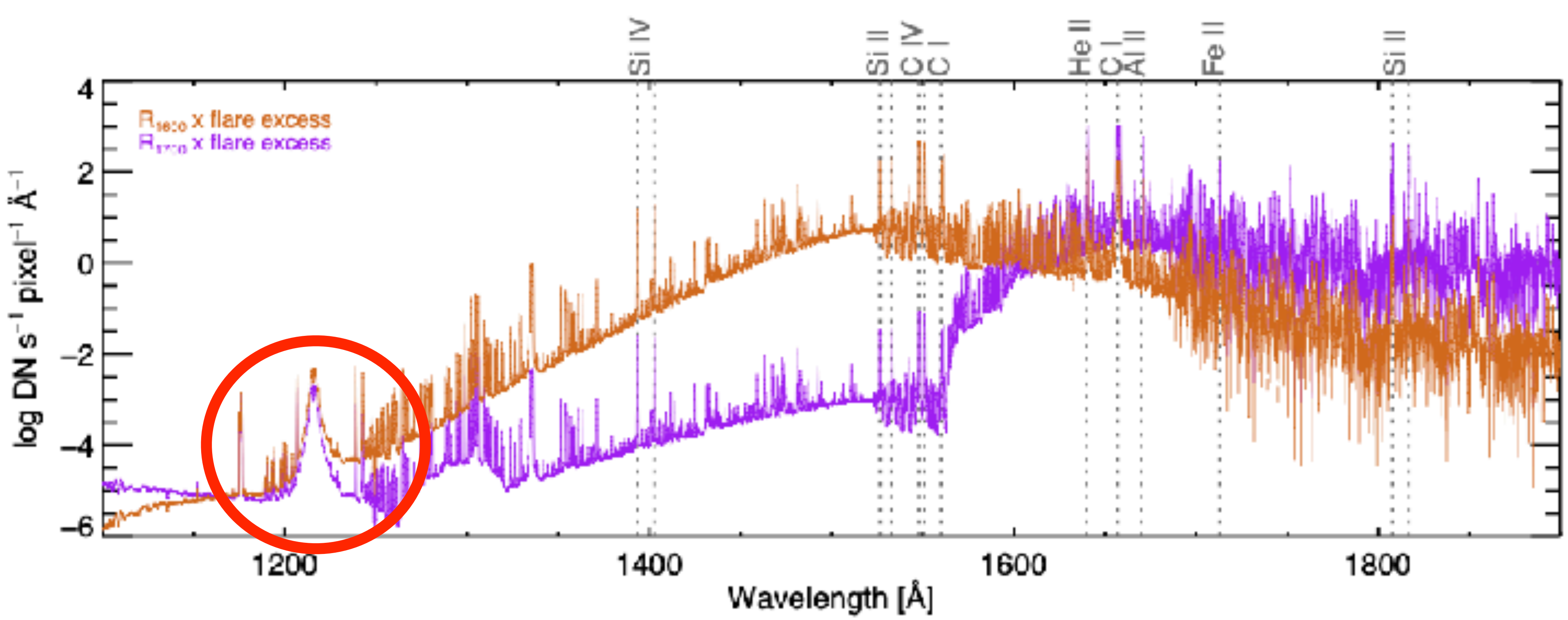


- Instrumental passbands centred on Lyα are often ~100Å FWHM
- Underlying spectra is often based on the quiet-Sun
- Radiative hydrodynamic flare models (e.g. RADYN) are limited to around 2Å at the line peak
- We lack knowledge about how the changes to the line profile affect the broadband response (e.g. core/wing ratio, red/blue asymmetry, central reversal, blends)



- We propose use RADYN(↑) to model the Lyα line profile in response to various heating functions to determine contribution function/formation height

- Resulting profile will be compared with spectra from Skylab(↓) and convolved with instrumental response functions to determine relative contributions to irradiance



Simoes+ (2019)

Future Lyα Data/Missions/Models

- GOES-15 data from intense storm period in Sept. 2017 not yet released
- GOES-16 (Feb ‘17→) and -17 (Jun ‘18→) EXIS data due autumn 2020
- EUVST (Lyα spectrograph) has been selected for Phase A by NASA
- Chinese ASO-S/LST will feature a Lyα imager and Lyα coronagraph
- Solar Obiter (launched in February 2020) includes a Lyα imager
- Solar eruptioN Integral Field Spectrograph (SNIFS) sounding rocket is being proposed by LASP, Colorado (Lyα spectrograph)
- I have submitted a Heliophysics Supporting Research proposal to NASA to carry out detailed modeling of Lyα (and LyC) during flares, as well as an ISSI proposal to bring together solar flare and ionospheric experts

Summary

- A self-consistent, statistical analysis of ~500 solar flares in Lyα is presented (Milligan et al. 2020; Space Weather, In Review..?)

- Increases of <30% are observed in Lyα during flares (typically <10%). Comparable to that of AR evolution but on much shorter timescales

- Energy radiated in Lyα equals 1-100x that of X-rays (0.1-1x that of thermal plasma)

- Center-to-limb variation is significant (confirmed by coordinated GOES/EUVS and MAVEN/EUM observations) - due to either opacity effects, foreshortening of the flare ribbons, or occultation by the solar disk

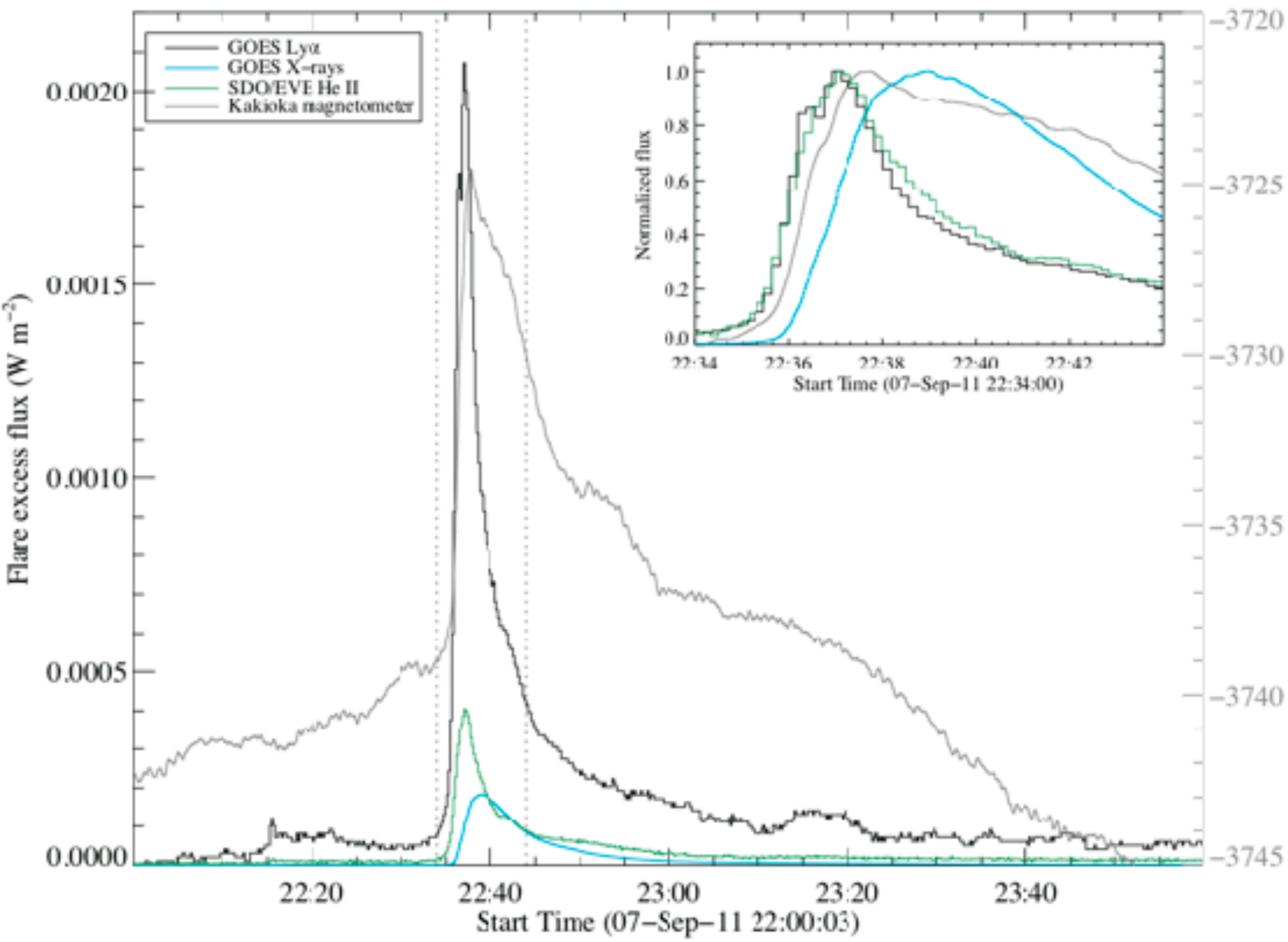
- Impulsive Lyα emission induces currents in the E-layer of the ionosphere (previously attributed to X-rays, which affect the D-layer)

- Eagerly anticipate more Lyα data from GOES-15 (September 2017 flares), GOES-16 and -17 (line profiles), SORCE/SOLSTICE, Solar Orbiter/EUI and ASO-S/LST

Future Work..?

- Lyα/Hα ratio is temperature sensitive
- Lyα/LyC (Lyβ, Lyγ, Lyδ,…) can tell us about ionisation fractions
- Look in more detail at the CLV (establish the cause)
- Search for more jointly observed GOES/MAVEN flares (Sept 2017?)
- Systematic search for acoustic oscillations in Lyα
- Measure ionospheric responses for disk/limb flares (on both Earth and Mars)
- Fraction of nonthermal energy for more events
- More detailed radiative hydrodynamic modelling (RADYN currently truncates the line) —> contribution functions for different heating rates

Ionospheric Effects of Lyα



- The Kakioka magnetometer in Japan measures changes in ionospheric conductivity due to increased ionization
- During the 7-Sep-2011 X-class flare, enhanced conductivity closely followed increased Lyα emission
- Excess Lyα flux was an order of magnitude more intense than X-rays
- The corresponding X-rays lagged the ionospheric response, implying that they could not have been the driver