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Soft X-Ray Pulsations in Solar Flares

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ISSI Meeting 27 Feb 2017

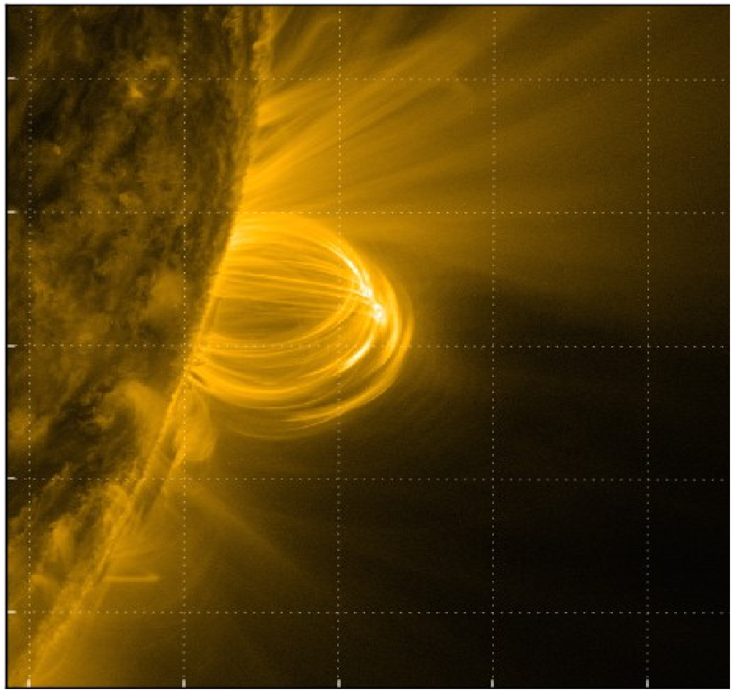
Soft X-ray Emission
Outline

Soft X-ray Emission from Solar Flares

Quasi Periodic Pulsations:

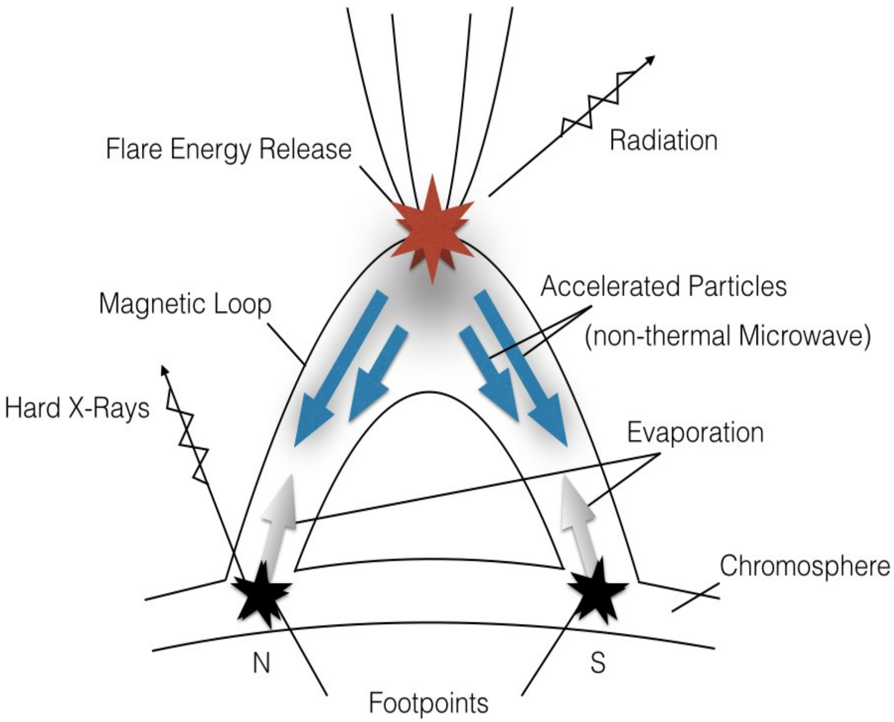
- SXR short time scale variability
- Multiwavelength analysis
  - Impulsive Phase Event (X1.0 Flare)
  - Long Duration Event (M7.7 Flare)
- Statistical Study

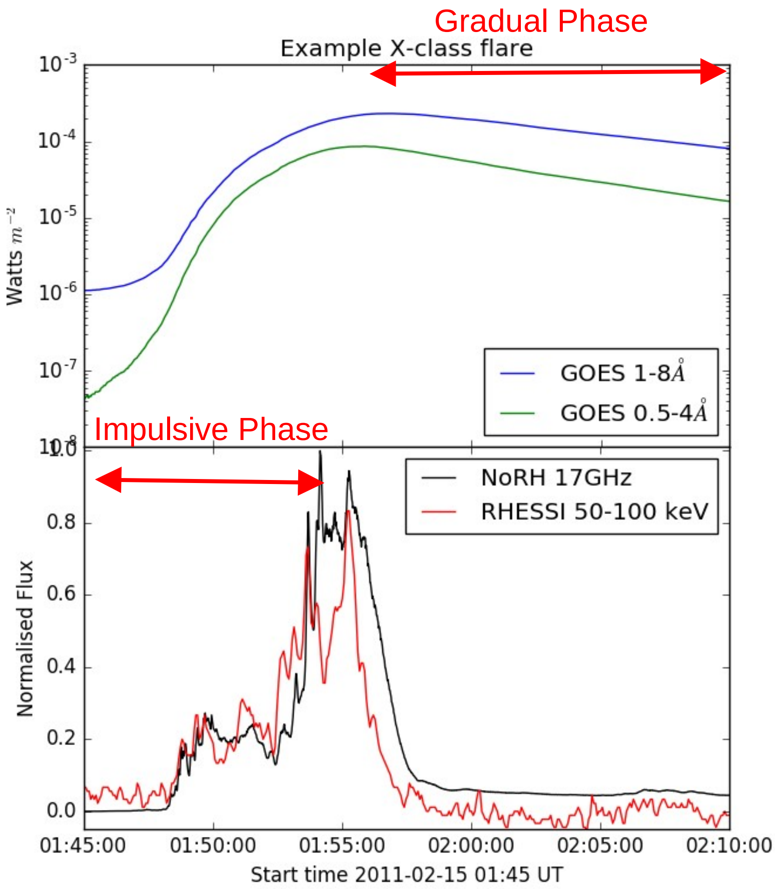
Long Period Soft X-ray pulsations & Geoeffectivness Ionosphere (if time)



Soft X-ray Emission in Solar Flares

Where does it come from? What can it tell us?





Soft X-ray Pulsations

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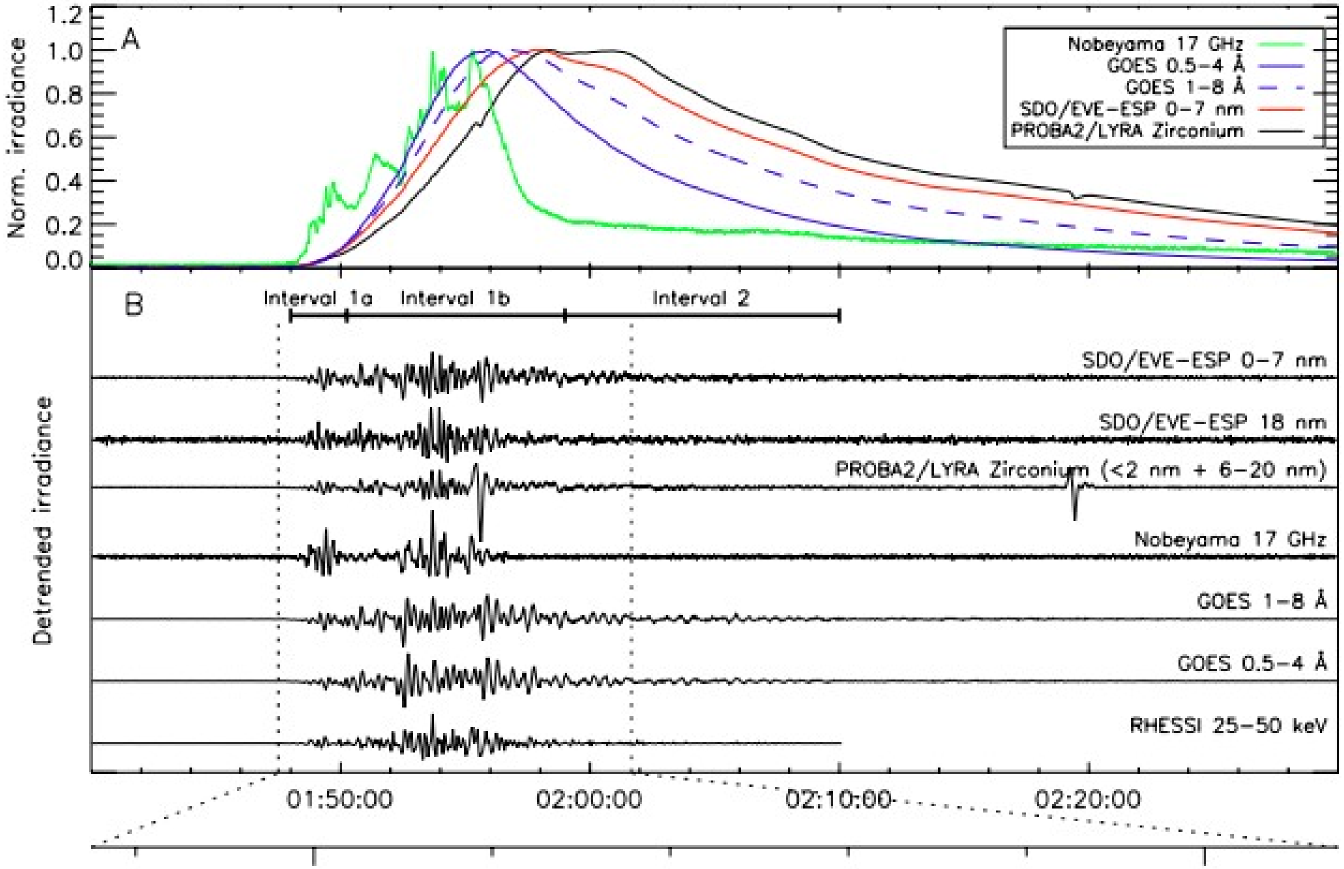

Dolla et al. 2012

Soft X-ray Pulsations

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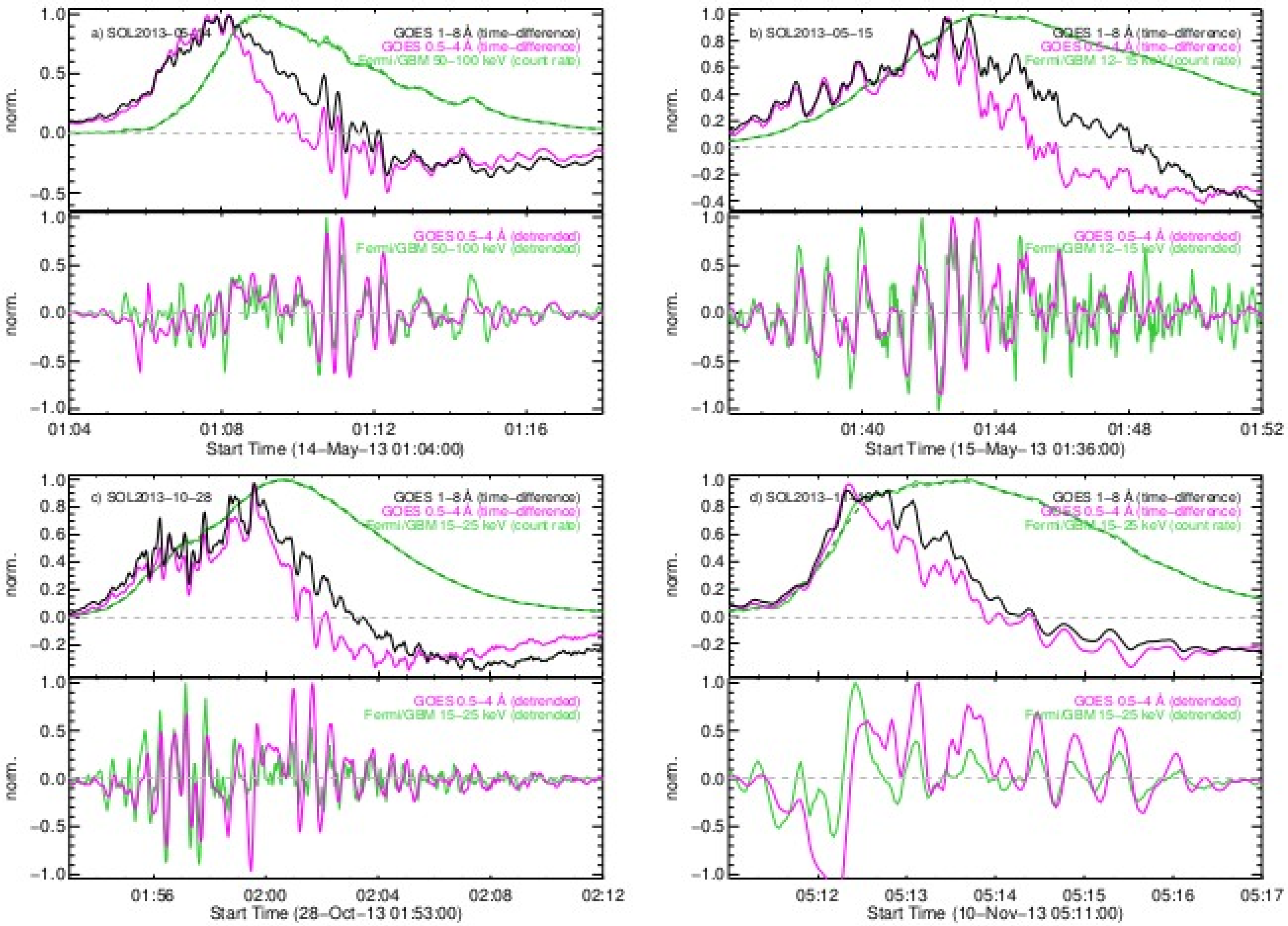
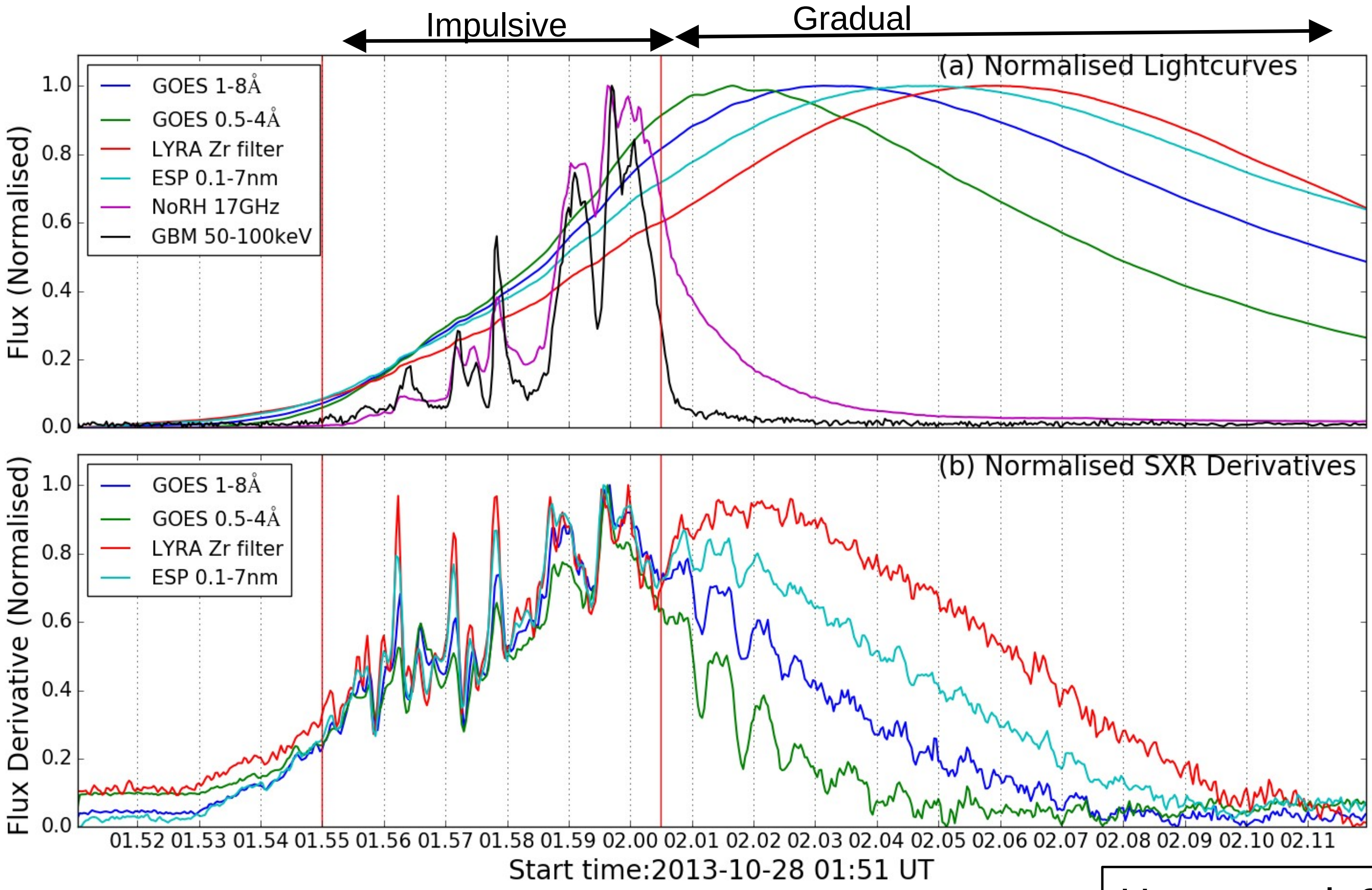


Simoes et al. 2015

Multi-wavelength Analysis

Relating SXR pulsations to other mechanisms in flare



Hayes et al. 2016

Multi-wavelength Analysis

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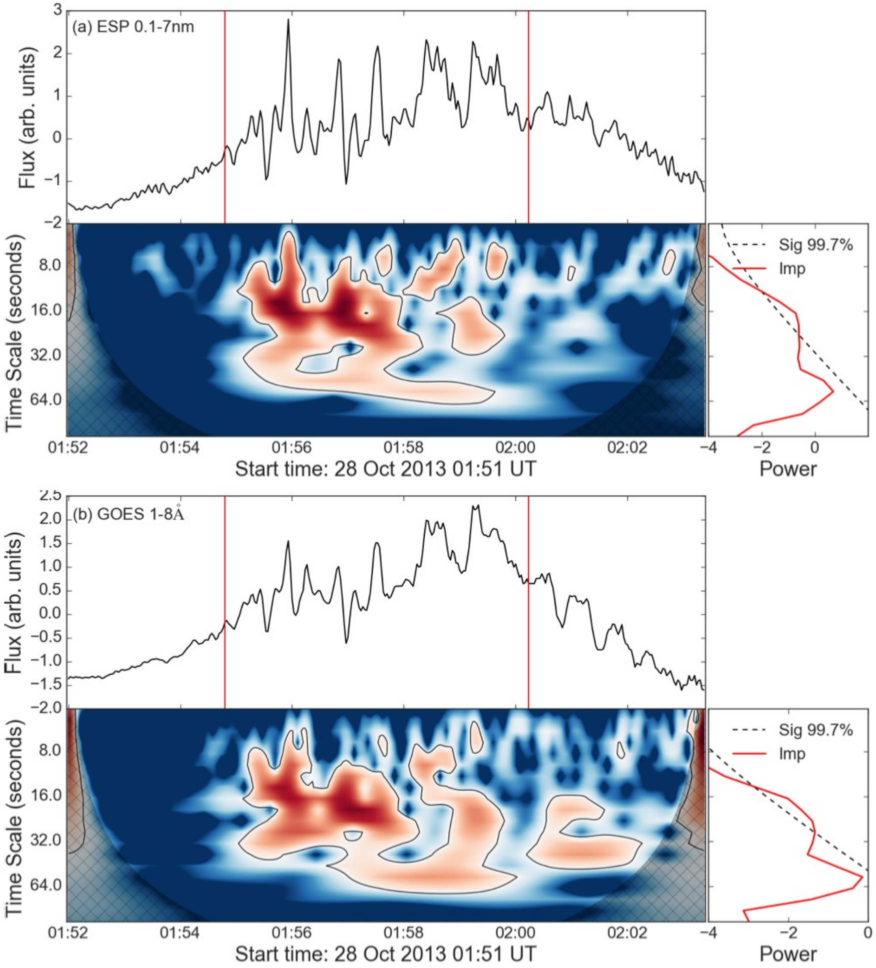


Impulsive Phase

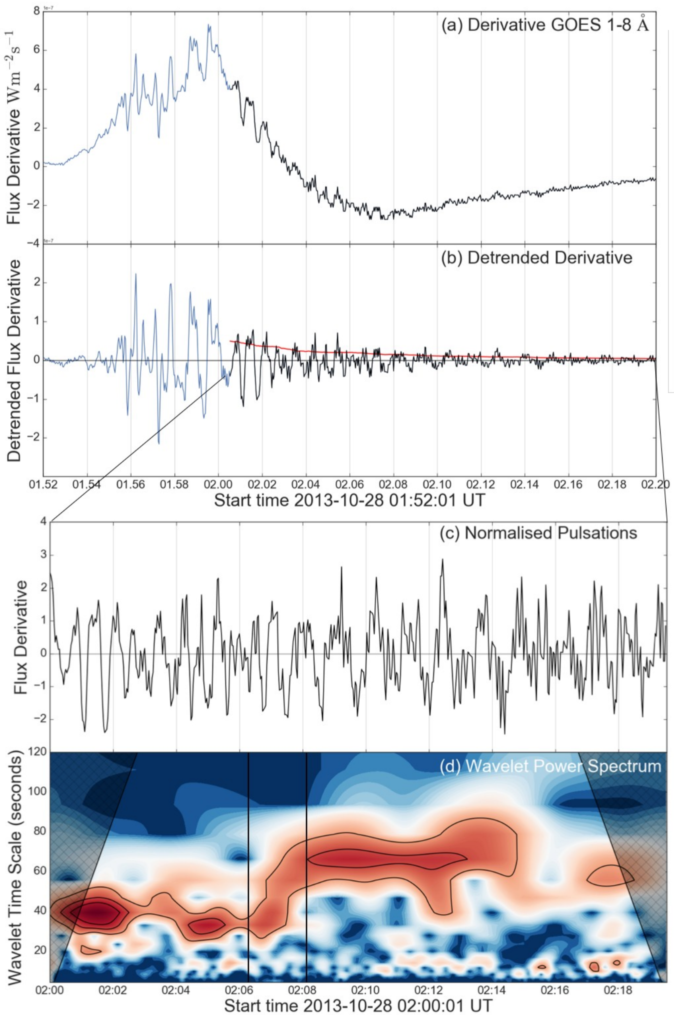
-Wavelet analysis taking into consideration power-law distribution

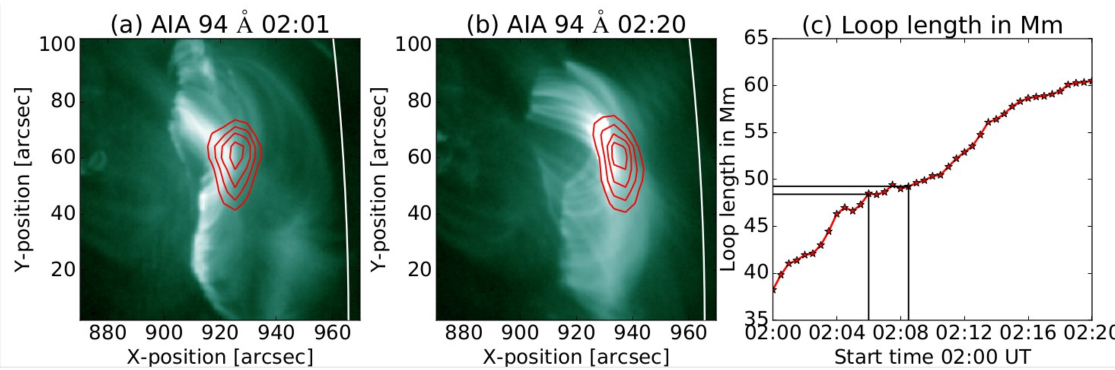
-Characteristic timescales ~20s across all channels

-In non-thermal emission, find second characteristic timescale of ~55s

Multi-wavelength Analysis

Relating SXR pulsations to other mechanisms in flare





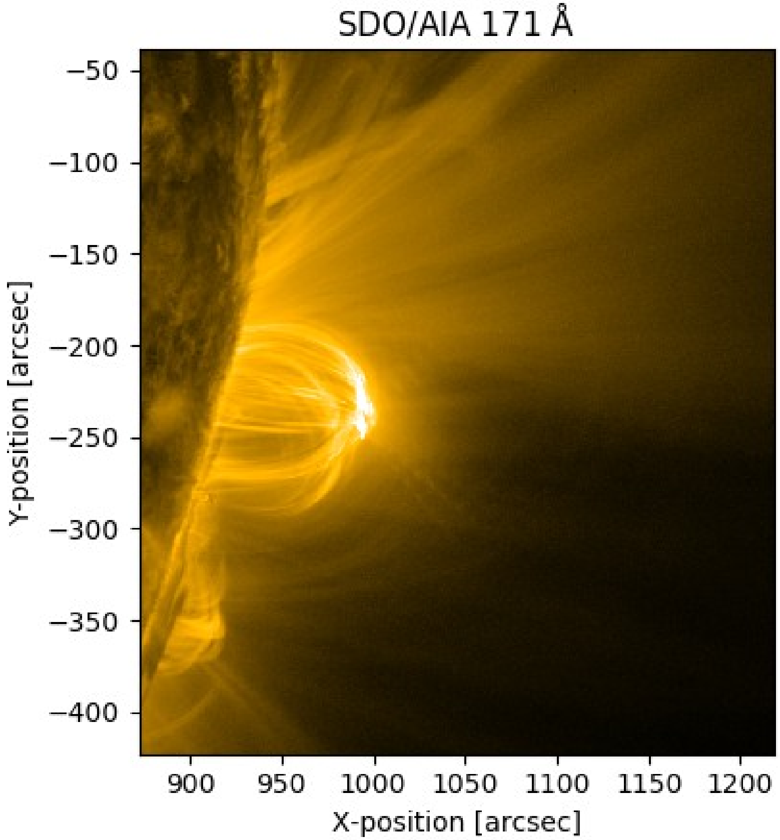
Thermal Pulsations occur for 20 mins after non-thermal emission cease

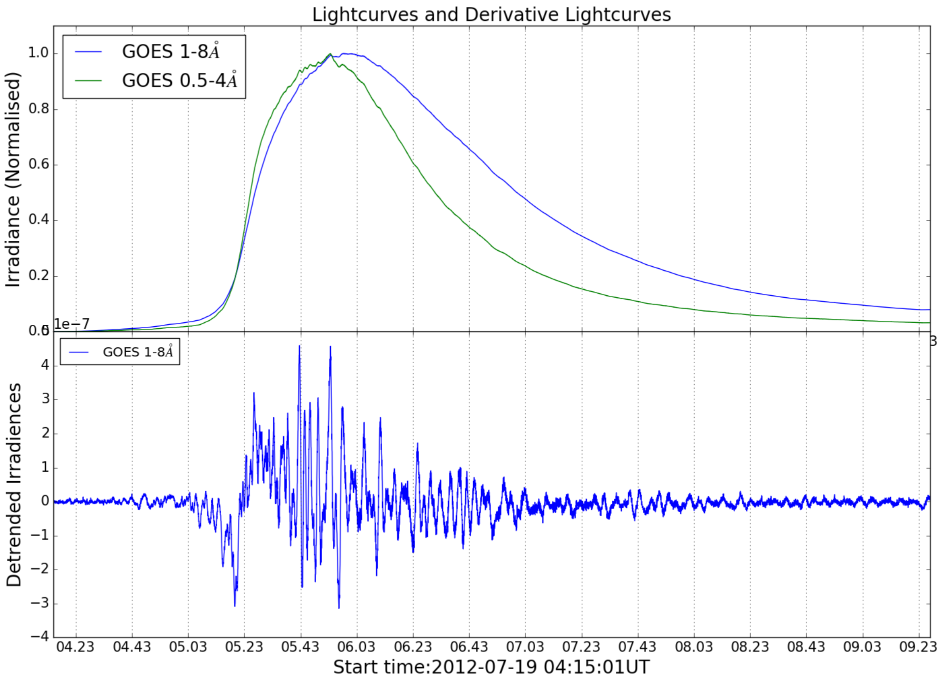
Increase in timescale from ~40 – 70s

Impulsive Phase:
-10 different wavebands with ~ 20s timescale
-Intermittent reconnetion?
Gradual Phase:
-Distinct pulsations in the high temperature plasma persist – timescale increase ~40-70s
-MHD in post flare loops? Sausage or V. Kink?

Long Duration QPP in Decay Phase

M7.7 Limb Flare

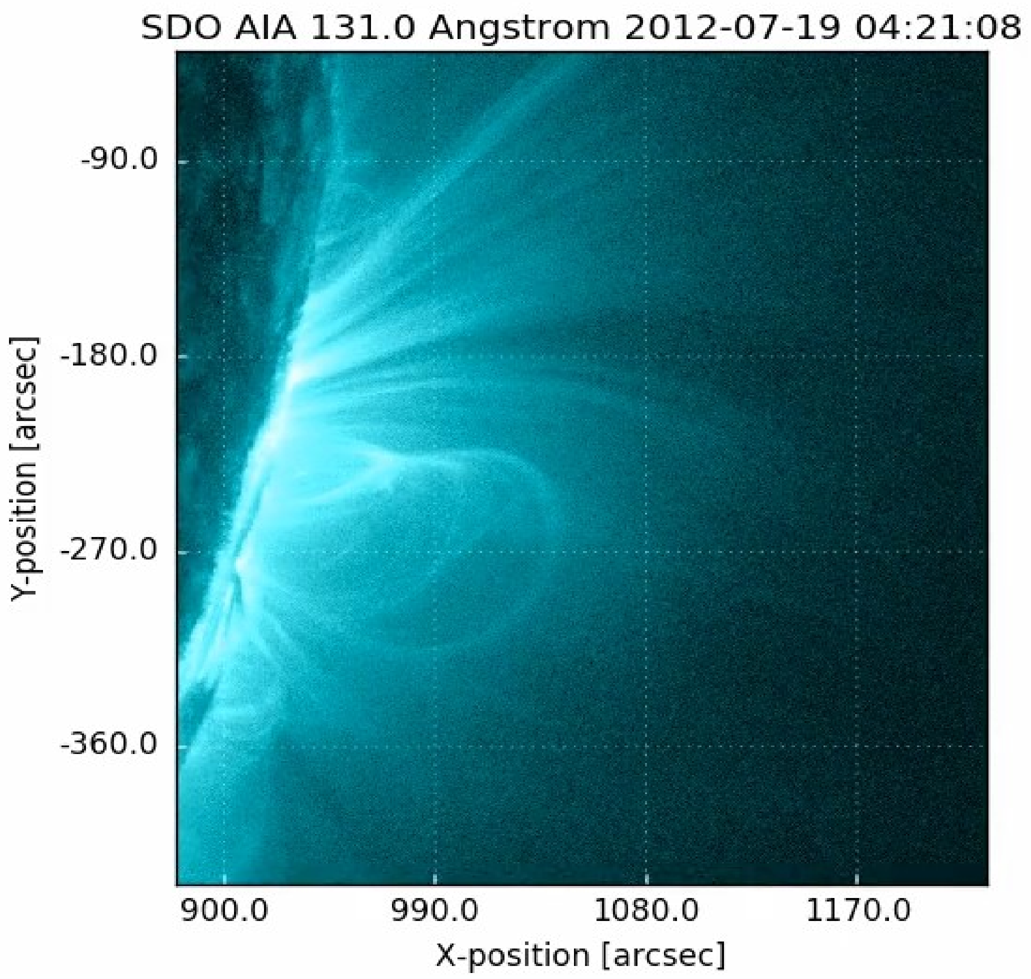




Event studied by many previous authors Lui et al. 2013, Krucker & Battaglia 2014

QPP reported in impulsive phase in HXR, MW and MHz Huang et al. 2016

M7.7 Limb Flare



Long Duration QPP in Decay Phase

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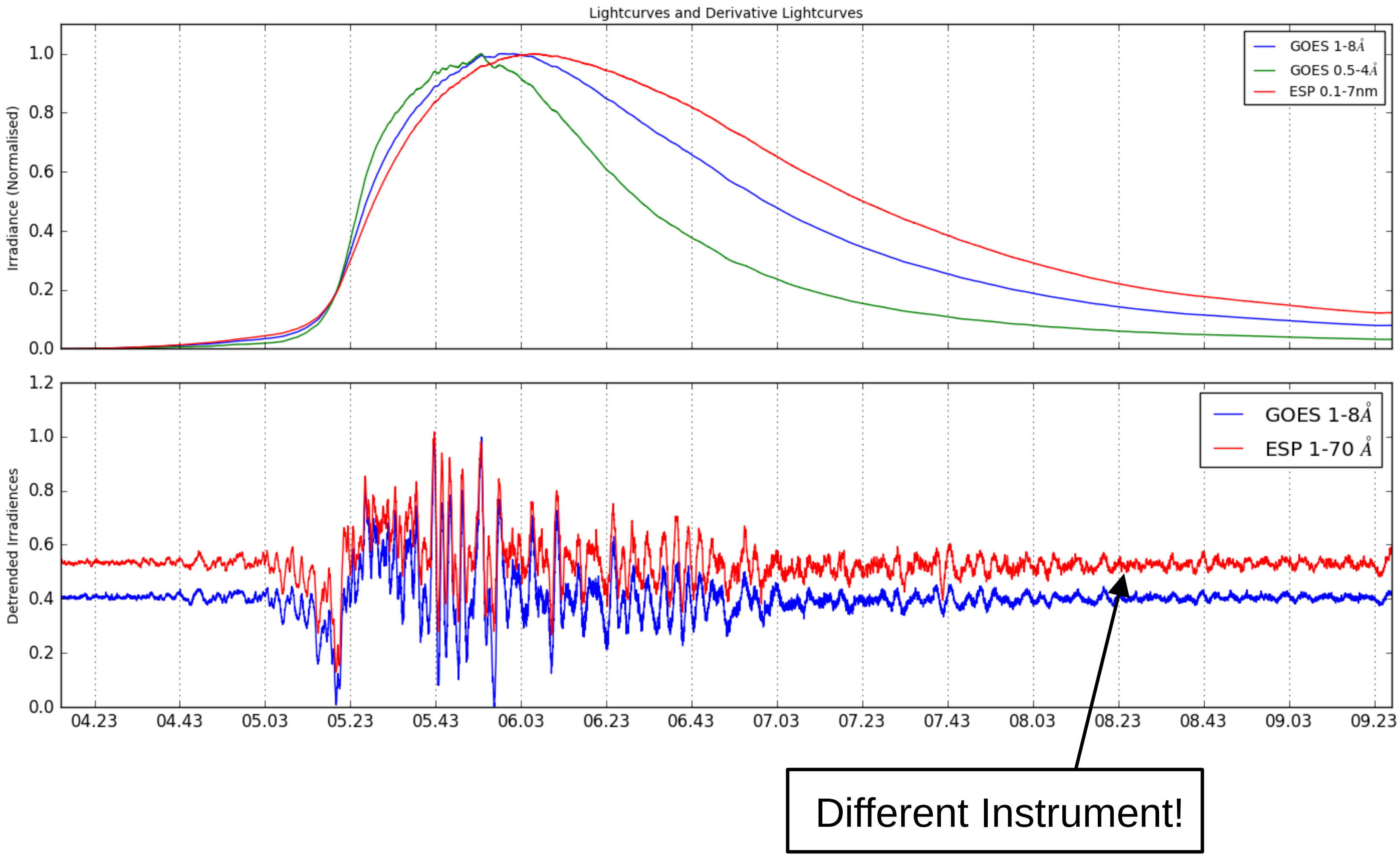

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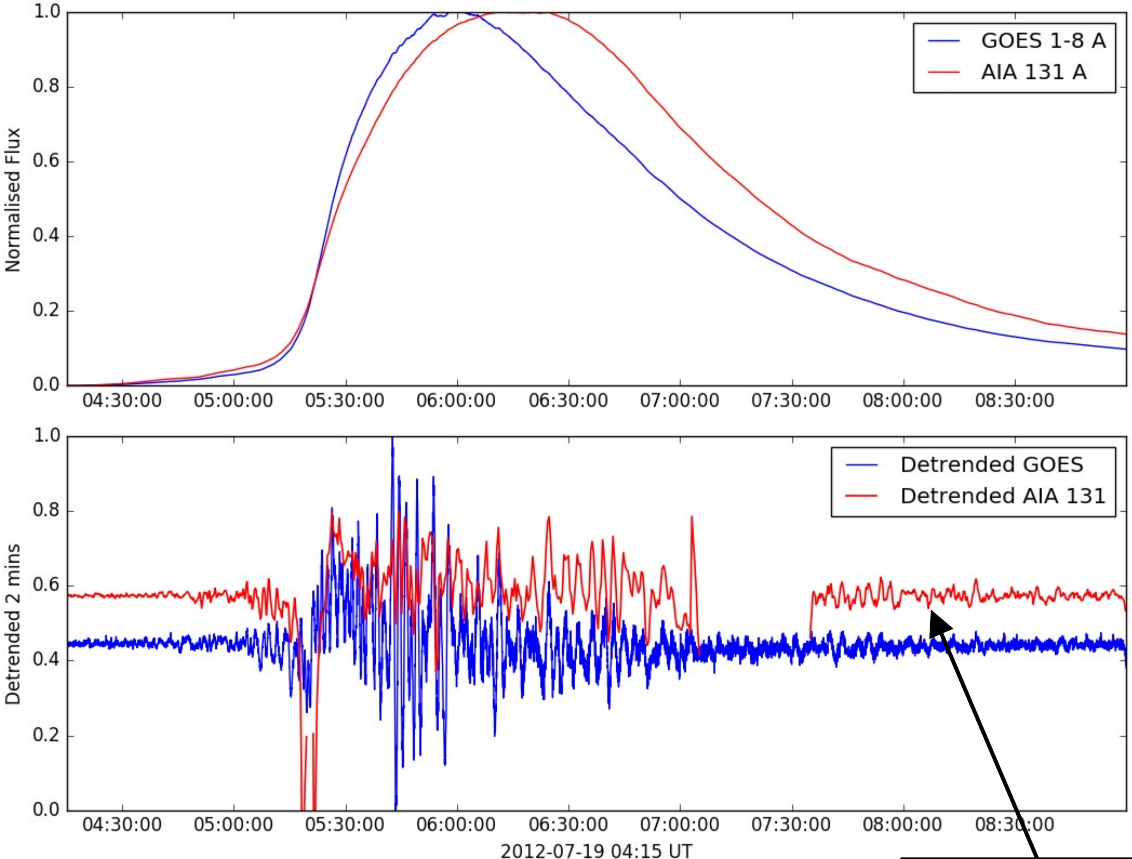
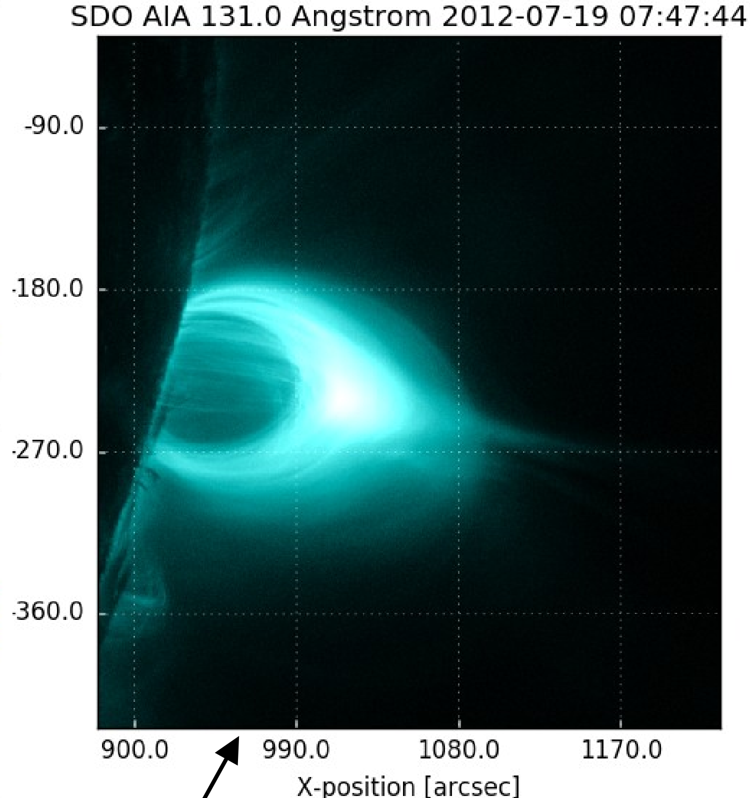
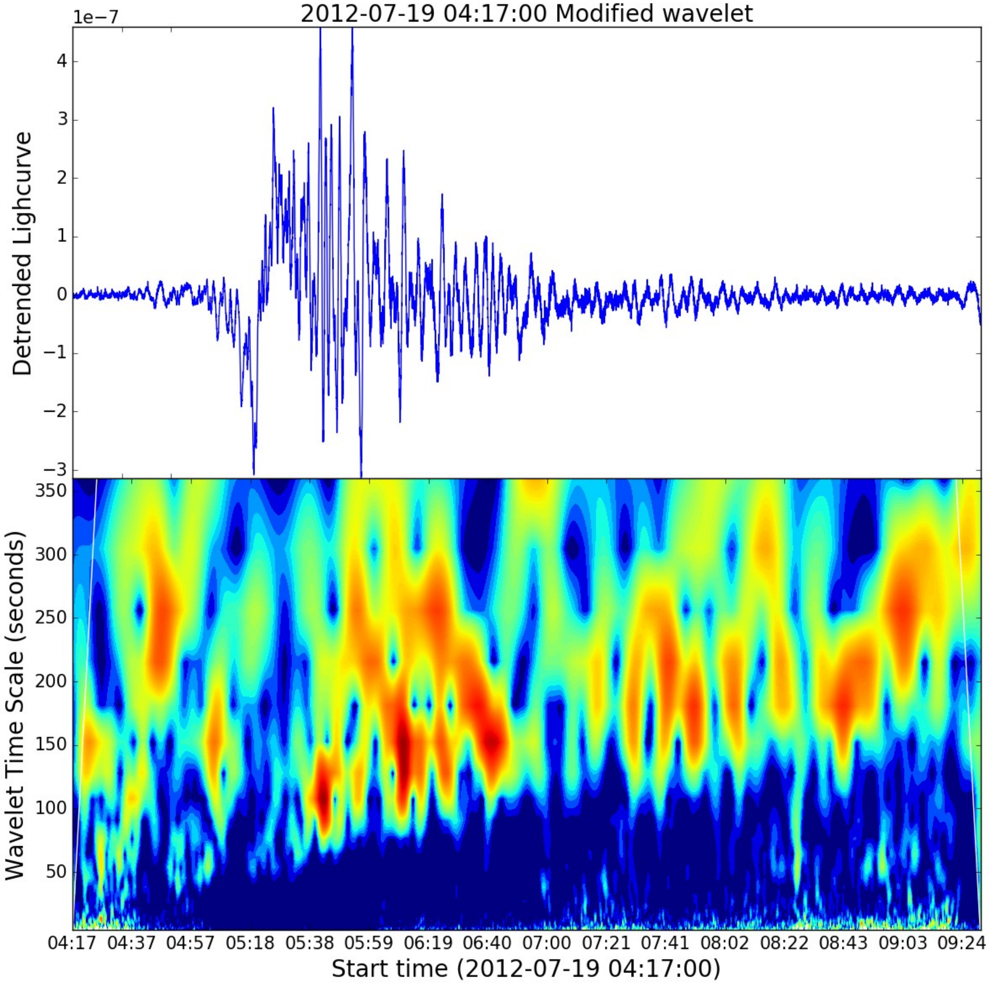




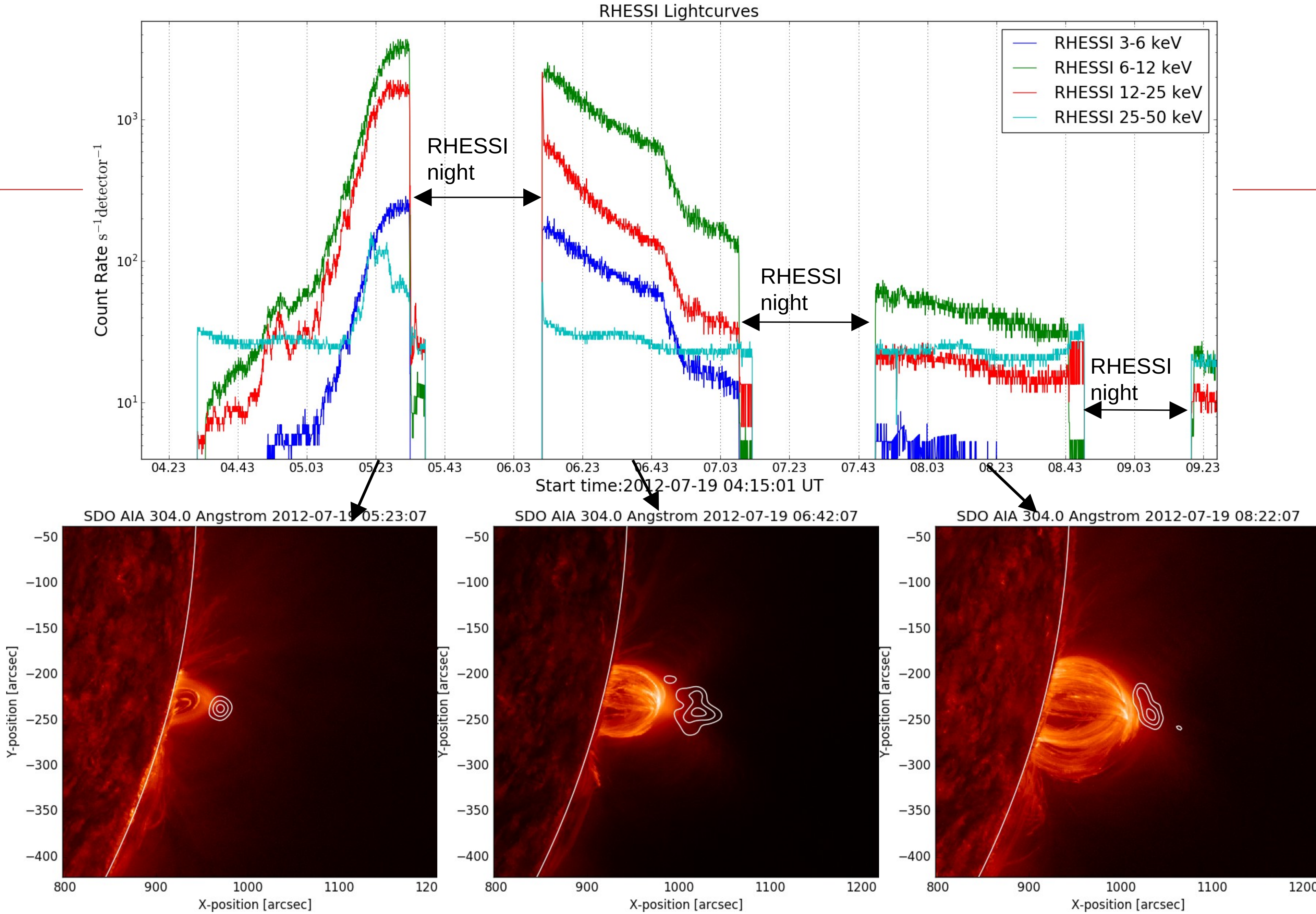
Spatially integrated AIA 131 A shows pulsations are coming from these flaring loops

Long Duration QPP in Decay Phase

M7.7 Limb Flare

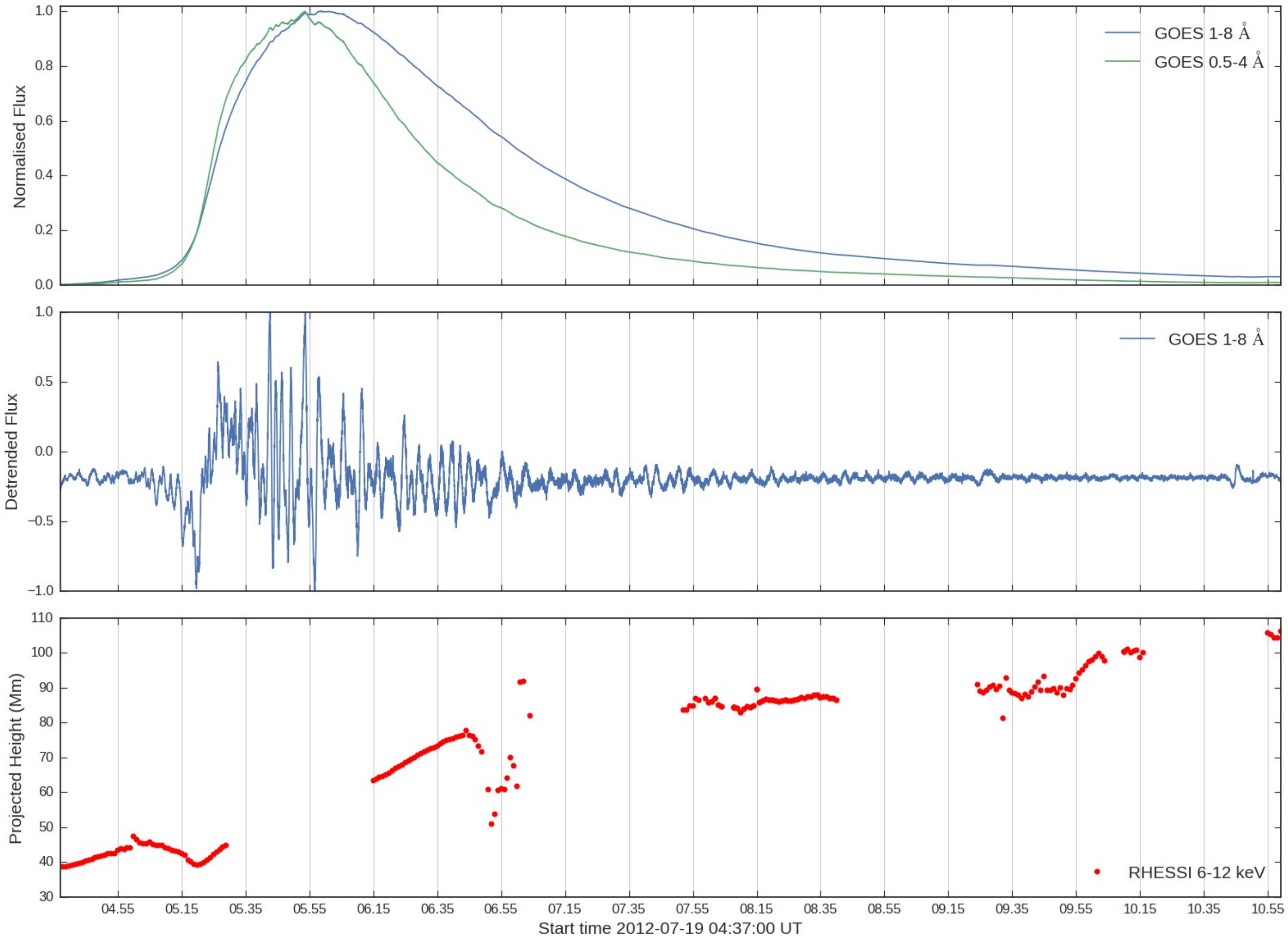


- Wavelet analysis shows increase in timescale of pulsations throughout flare
- Timescale increases up to ~ 4minutes
- Similar results found via peak to peak analysis by eye.
- Related to source height of energy release or length of loops?



RHESSI Lightcurves
RHESSI 3-6 keV
RHESSI 6-12 keV
RHESSI 12-25 keV
RHESSI 25-50 keV
RHESSI night
RHESSI night
RHESSI night
Count Rate s^{-1}detector^{-1}
Start time:2012-07-19 04:15:01 UT
SDO AIA 304.0 Angstrom 2012-07-19 05:23:07
SDO AIA 304.0 Angstrom 2012-07-19 06:42:07
SDO AIA 304.0 Angstrom 2012-07-19 08:22:07
Y-position [arcsec]
X-position [arcsec]

Long Duration QPP in Decay Phase
M7.7 Limb Flare



-RHESSI 6-12 keV centroid height from limb - ~ location of SXR emission

-Systematic increase - **increase in loop length?**

-Correlated with increase in period

Similar period and source increase as Dennis et al. 2017

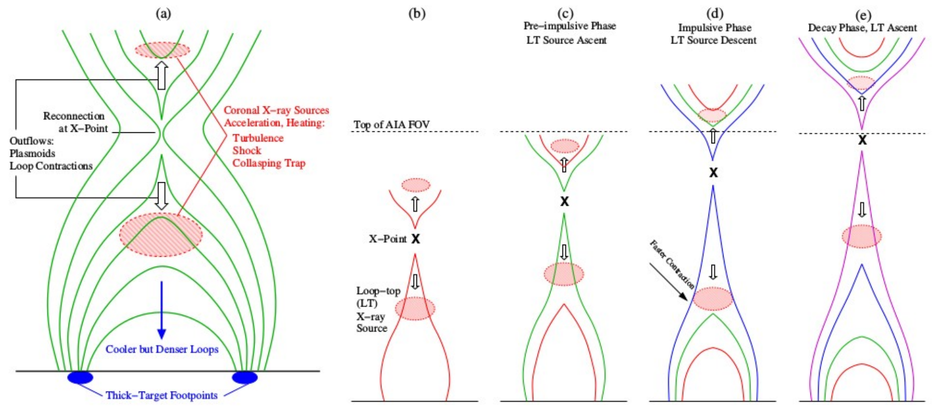
Long Duration QPP in Decay Phase

M7.7 Limb Flare

- What causes prolonged pulsations in soft X-ray? Signature of continued heating and reconnection at higher altitudes?

- Source height increase - longer loop lengths, possibly kink modes triggered in loops of longer length?

- Liu, W et al. 2013 find plasmoid ejections and downward contractions of reconnected loops late into this event - possibly resulting in these observed pulsations



Vertical kink mode trigger by new loops?
Can estimate B field (Dennis et al. 2016)

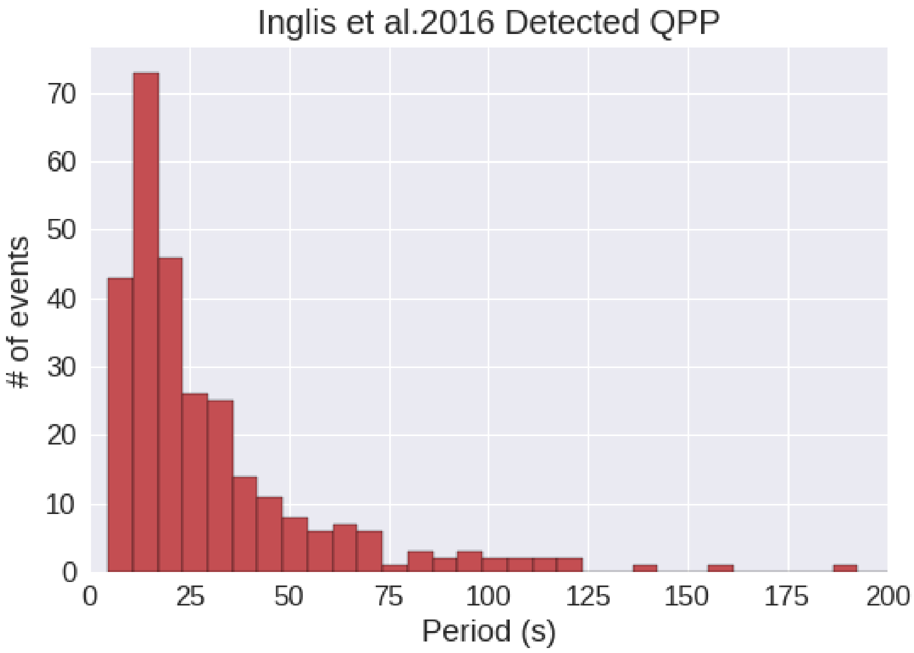
$$B = \sqrt{2}\,\pi\,h\,\rho^{1/2}/(D\,\tau).$$

More to do....

Large Scale Statistical Study
Inglis et al. 2016

Automated Flare Inference of Oscillations (AFINO)

More later with Andy's talk!



M & X Class Flare (Feb 2011 - Dec 2015 ~ 674 events)

Model Comparison to search for statistical enhancement in Fourier spectrum taking into consideration power law distribution.

30 % GOES 1-8 Å showed signatures of QPP characteristics

Preferred Period of ~5-30 seconds (MHD timescales?)

Inglis et al. 2016

Large Scale Statistical Study

Inglis et al. 2016

Automated Flare Inference of Oscillations (AFINO) results table

Last updated: 2017-01-30T06:00:08.806337

AFINO was designed to search for signatures consistent with quasi-periodic pulsations (QPP) in solar flares. It uses a model comparison technique to analyse the Fourier Power Spectral Density (PSD) of solar flares in GOES 1-8A X-ray data. Events showing a strong preference for a localized frequency enhancement in the PSD are flagged as flares of interest (see bold entries)

These results are freely available for reference by anyone interested. If you do make use of this list, please cite the following papers where the AFINO techniques and results were published: Inglis et al. ApJ, 798, 108, (2015) , Inglis et al., ApJ, 833, 284, (2016)

Key

Model S0: A single power-law plus constant model of the PSD
Model S1: A single power-law plus constant, plus a localized enhancement consistent with a QPP signature
Model S2: A broken-power law plus a constant
BIC: The Bayesian Information Criterion. BIC = -2 Ln(L) + k Ln(n), where L is the likelihood function
ΔBIC S_0 vs S_1: The difference in BIC between models S0 and S1. A positive value >10 indicates a strong preference for S1 over S0
ΔBIC S_0 vs S_2: The difference in BIC between models S0 and S2. A positive value >10 indicates a strong preference for S2 over S0
ΔBIC S_2 vs S_1: The difference in BIC between models S2 and S1. A positive value >10 indicates a strong preference for S1 over S2
Detection: If model S1 is preferred over all others by ΔBIC > 10, the criteria are met for a QPP detection
χ^2_{Sn} p_{Sn}: Goodness of fit estimate, and associated p-value for each model n=0,1,2
P(s): Best-fit period, in seconds, of the localized enhancement, where appropriate
width: Best-fit width, in log-f space, of the localized enhancement, where appropriate
Flags: S = short data series (< 200 data points), B0 = bad fit to model S0 (p_{S0} < 0.01), B1 = bad fit to model S1 (p_{S1} < 0.01), B2 = bad fit to model S2 (p_{S2} < 0.01)

Date	GOES class	Start time	End time	Instrument	Wavelength	ΔBIC S_0 vs S_1	ΔBIC S_0 vs S_2	ΔBIC S_2 vs S_1	Detection	χ^2_{S0}	p_{S0}	χ^2_{S1}	p_{S1}	χ^2_{S2}	p_{S2}	P (s)	width	Flags	Summary Plot	Helioviewer
20161129	M1.2	232900	233958	GOES	1-8A	2.2	5.4	-3.2	No	1.07	0.35	0.96	0.55	0.95	0.56	8.1	0.25	[]	PDF	show
20161129	M1.0	171900	172558	GOES	1-8A	-4.5	-1.6	-2.9	No	0.69	0.87	0.64	0.91	0.64	0.91			[]	PDF	show
20160807	M1.3	143700	144758	GOES	1-8A	5.1	27.9	-22.8	No	1.14	0.25	0.96	0.54	0.85	0.74	298.9	0.12	[]	PDF	show
20160723	M5.5	052700	053259	GOES	1-8A	5.2	4.1	1.1	No	0.89	0.61	0.74	0.8	0.68	0.86	6.1	0.06	['S']	PDF	show
20160723	**M7.6**	**050000**	**052358**	**GOES**	**1-8A**	**33.7**	**12.8**	**20.9**	**Yes**	**1.17**	**0.13**	**0.98**	**0.54**	**1.09**	**0.26**	**19.8**	**0.25**	**[]**	**PDF**	**show**

Large Scale Statistical Study

Inglis et al. 2016

Automated

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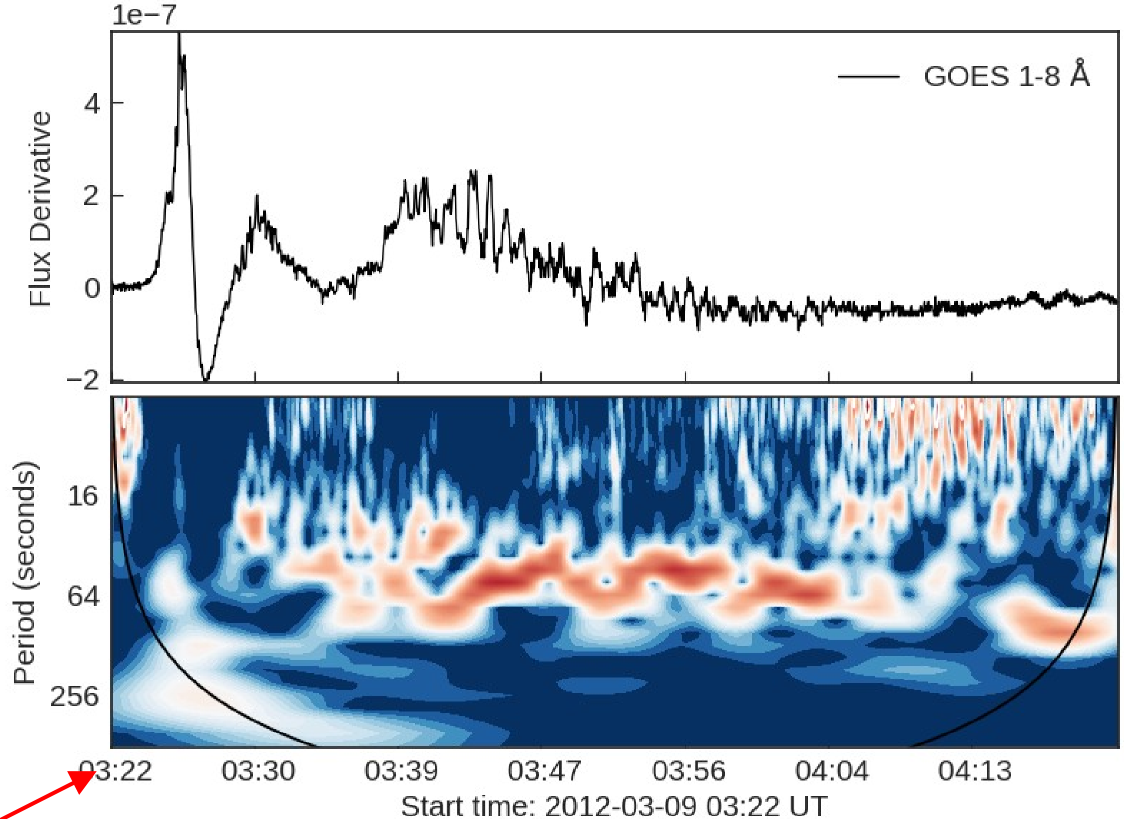

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20120310	M8.4	171500	182959	GOES	1-8A	128.3	125.2	3.2	Yes	3.07	0.0	2.8	0.0	2.71	0.0	55.9	0.25	['B0', 'B1', 'B2']	PDF	show
20120309	**M6.3**	**032201**	**041758**	**GOES**	**1-8A**	**74.9**	**17.4**	**57.6**	**Yes**	**1.31**	**0.0**	**1.15**	**0.07**	**1.27**	**0.0**	**65.8**	**0.14**	**['B0', 'B2']**	**PDF**	**show**
20120307	**X1.3**	**010501**	**012258**	**GOES**	**1-8A**	**15.8**	**-0.4**	**16.2**	**Yes**	**1.14**	**0.21**	**1.01**	**0.46**	**1.13**	**0.23**	**46.5**	**0.16**	**[]**	**PDF**	**show**

Soft X-ray Pulsations

Where we are at now....

What we know so far

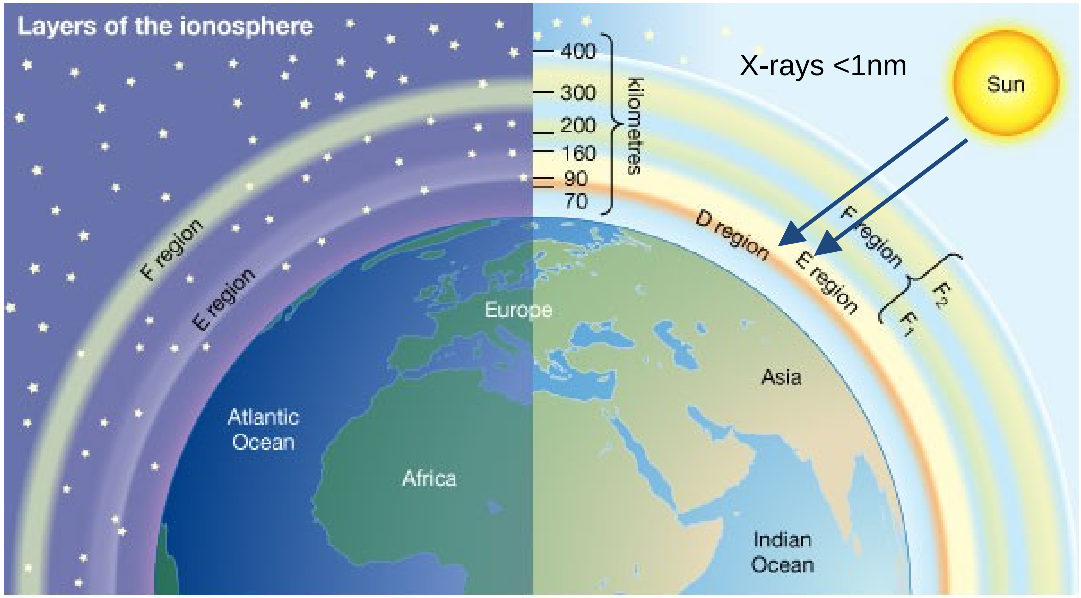
- Soft X-ray pulsations are a common, if not **intrinsic feature of solar flares**
- **Different characteristics in impulsive and decay phase**, probably related to different mechanisms
- Can last late into decay phase of some solar flares

What needs to be done?

- **Large scale multi-wavelength analysis of QPP** with particular attention of soft X-ray thermal emissions throughout impulsive and decay phases of flares
- Relate characteristic time scales to some physical parameters:
  - Higher altitude of energy release site or related to length of loops?
  - Length scales of reconnection?
  - Distinguish between impulsive and gradual processes

Pulsations in the Ionosphere

Synchronised Pulsations in SXR and the lower ionosphere



- X-rays (ƛ < 1nm) penetrate to D region (~50-90 km)
- Induce significant photoionisation manifesting as increase in electron density
- Impacts sub-ionospheric communications & GNSS

Pulsations in the Ionosphere

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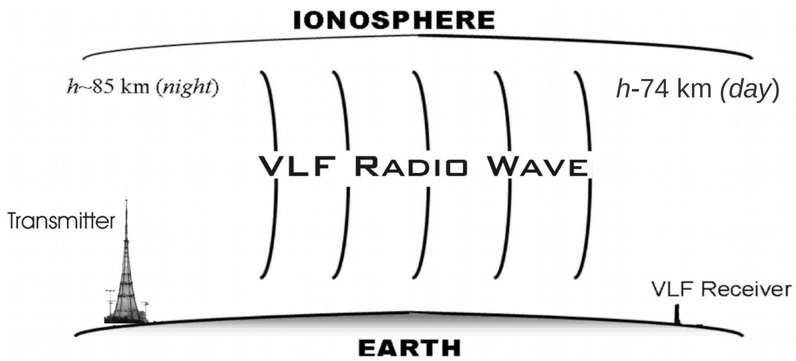
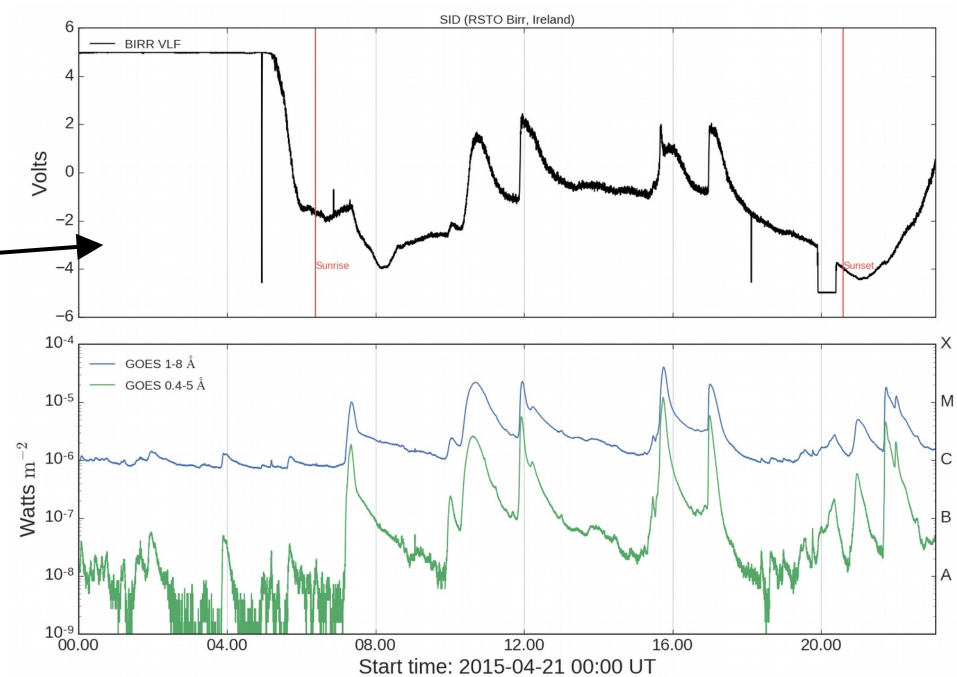


Very Low Frequency (VLF 3-30kHz) reflect at D region boundary

Amp and phase received contain information about behavior of D region

Signals received in Birr Ireland, transmitted from Maine US

Characteristically respond to GOES X-ray emissions as observed in VLF amplitude perturbations



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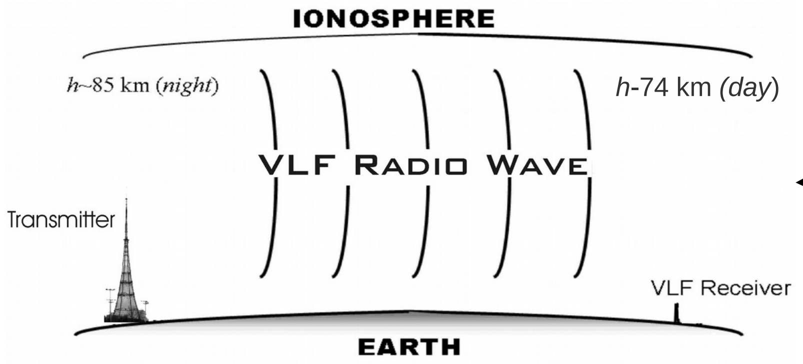

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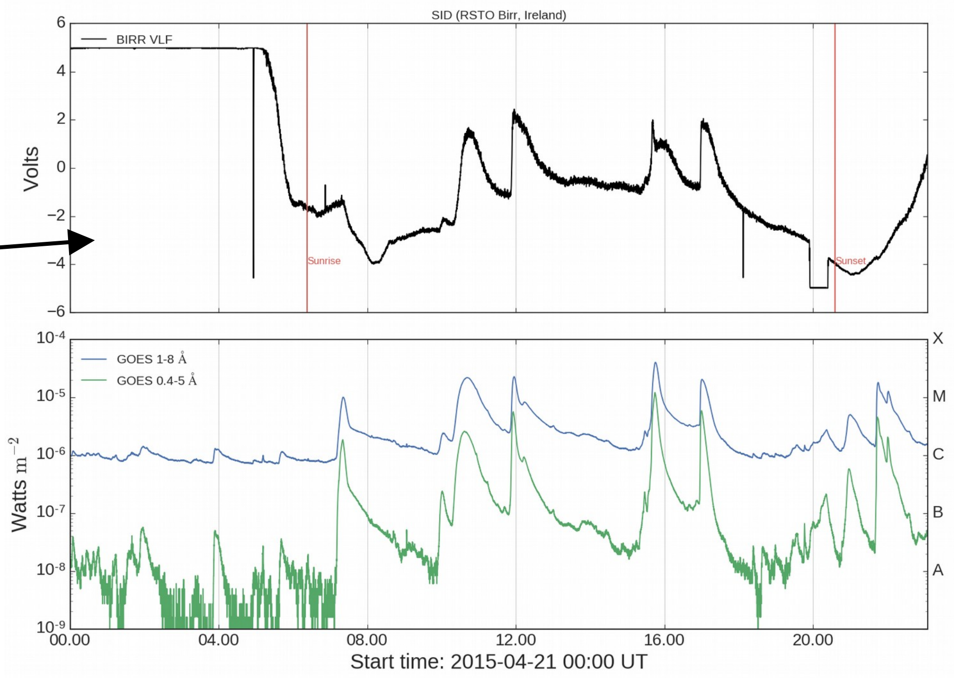
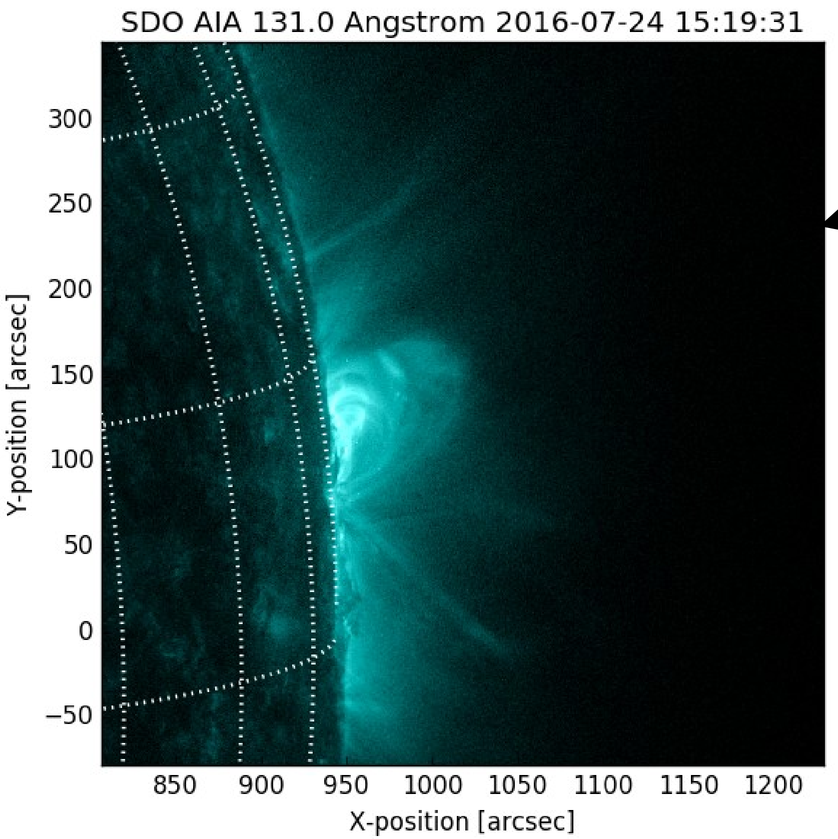


Can oscillatory signatures of solar X-ray emission appear in terrestrial observables?

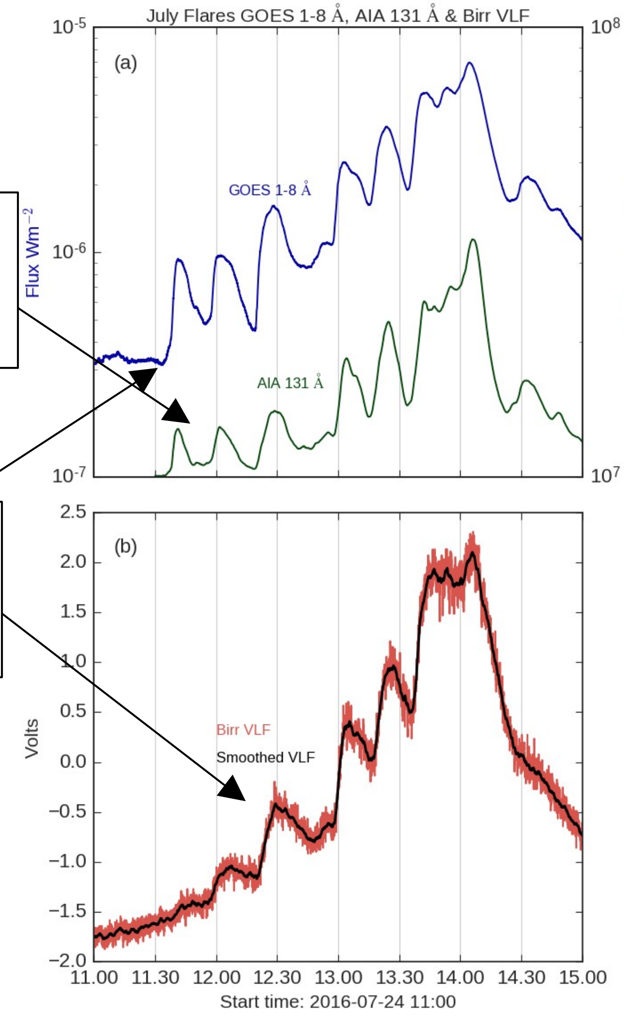
Pulsations in the Ionosphere

Synchronised Pulsations in SXR and the lower ionosphere



Limb Flaring AR and integrated lightcurve AIA 131

GOES 1-8 A soft X-ray flux and VLF response



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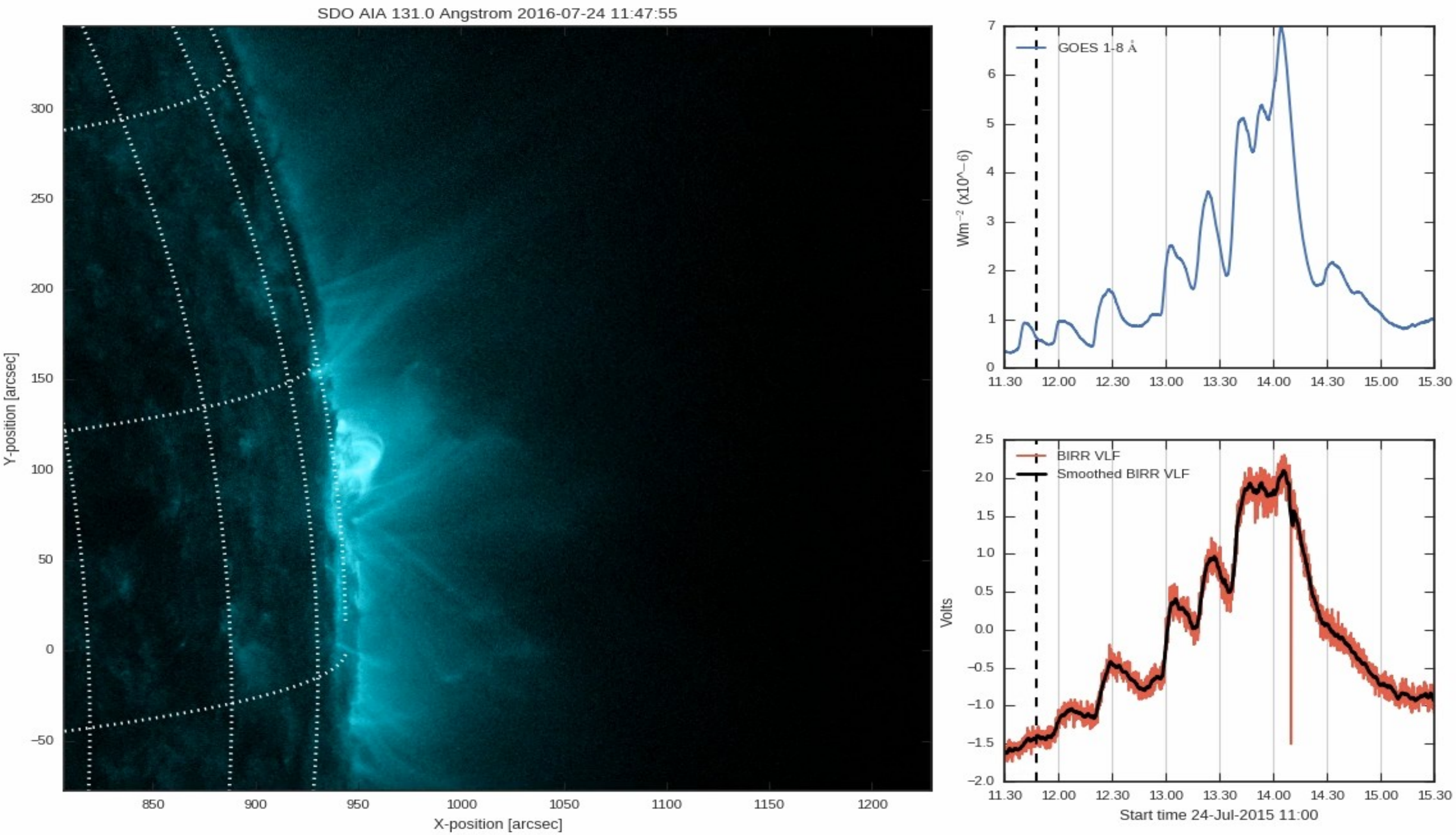

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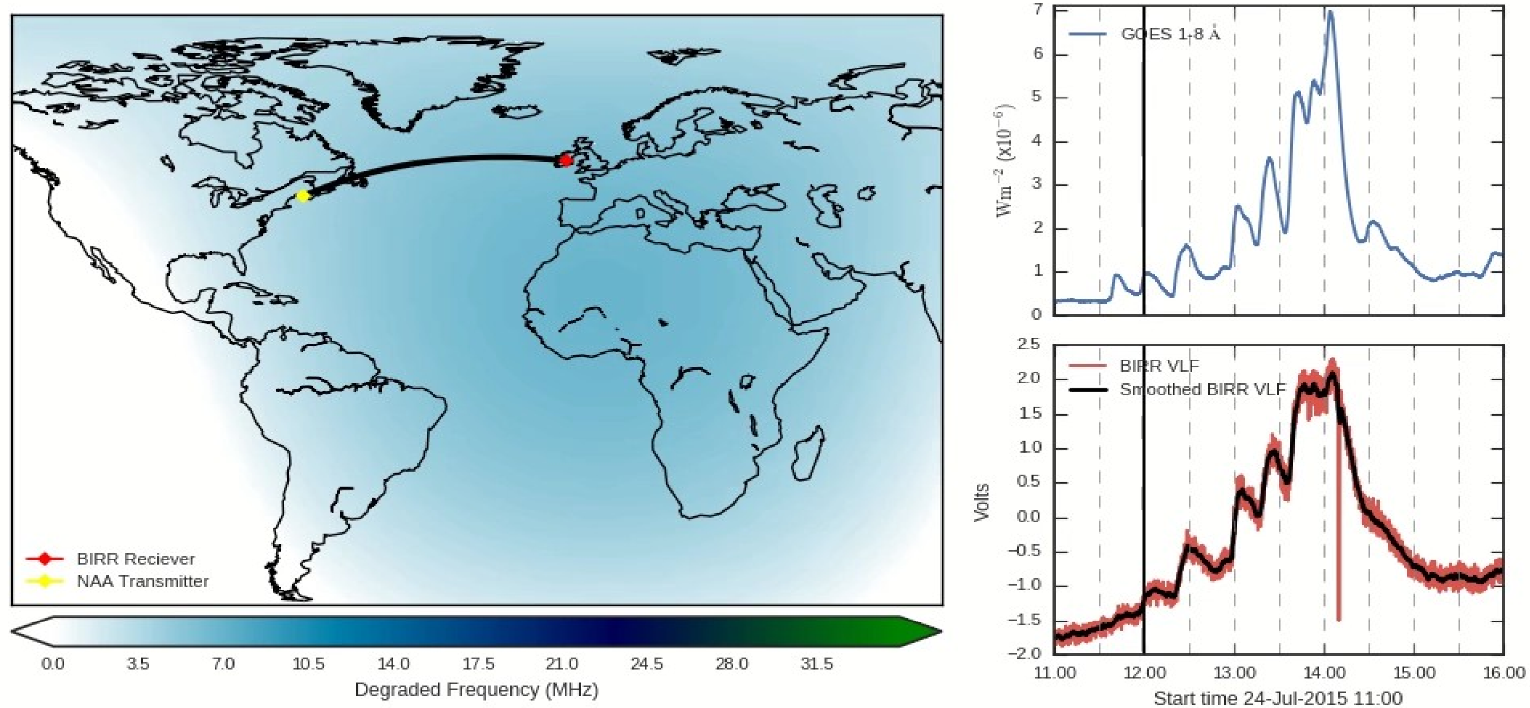

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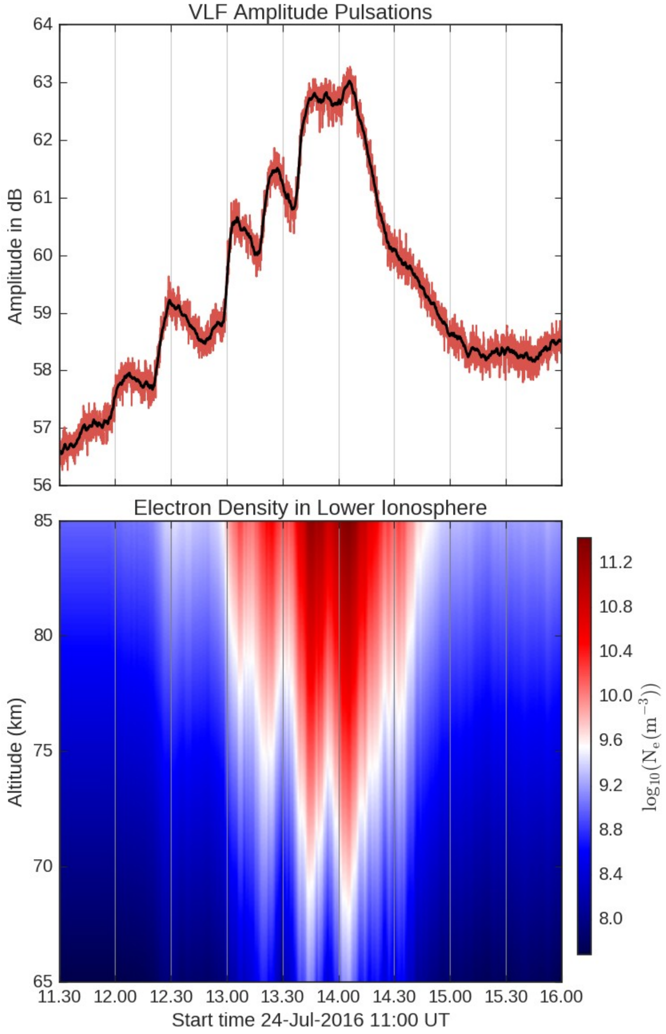

Model D Region Electron Density:

Wait parameters *h'* and ? - reference height and 'sharpness'

$$N_e(h, H', \beta) = 1.43\times10^{13}e^{-0.15H'}e^{(\beta-0.15)(z-H')}$$

Simulate VLF propagation using LWPC to determine *h'* and ? throughout flare. Provides electron density height profile.

Electron density increases by two orders of magnitude.

Pulsations significant effect on-D region

Hayes et al. (in prep)

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