IRIS9 WORKSHOP (E-POSTER)

Statistical Investigation of Low Atmospheric Response During Flares Using the Multi-Wavelengths Observations by Hinode, IRIS, and SDO

Kyoung-Sun Lee (NAOJ), Kyoko Watanabe (NDA),
Shinsuke Imada (Nagoya Univ.),
David H. Brooks (George Mason Univ.), Hirohisa Hara (NAOJ)

Poster

4. Eruptions in the solar atmosphere

Statistical investigation of low atmospheric response during flares using the multi-wavelengths observations by IRIS, Hinode, and SDO

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When a flare occurs, we can observe solar plasma response in multi-wavelengths from optical to HXR. Especially, some strong flares produce white light emissions, white light (WL) flares, and flare ribbons are observed in the low atmosphere. To understand how the energy transports to the low atmosphere and how the low atmosphere responses to the solar flares, we investigated the UV and EUV spectral lines and WL continuum images statistically. We have investigated the Mg II triplet, Si IV emission and WL continuum in 60 M and X class flares, which detected by the IRIS, SDO/HMI and Hinode/SOT from 2014 to 2016. From the analysis, we have found that the Mg II triplet mostly becomes emission during flares along the flare ribbons and footpoints of the flaring loop region, which indicates that the low atmospheric heating. At the same time, we also examined the Doppler velocity of the Si IV emission, and mostly they show the red-shifted emission ($\sim$40 km s^{-1}) correlated in time and location of the Mg II triplet emission. WL continuum also enhanced during several flares (17 flares), but not in all the flares. By comparison between the Mg II triplet and WL continuum, we also discuss the energy transport process, such as thermal conduction, electron beam, or Alfvn wave, in the flares with/without WL flares.

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FLARE - OBSERVATIONS & MODEL

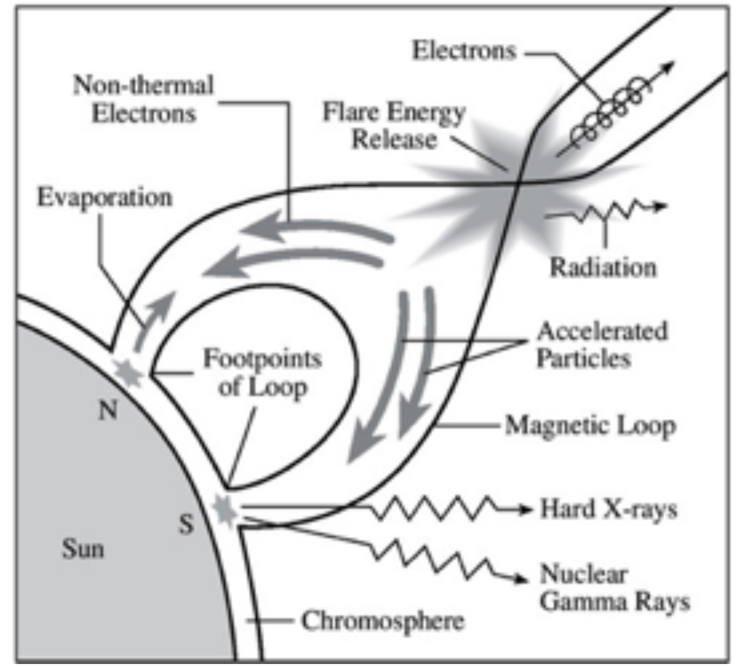
- Magnetic reconnection at the higher corona
- Energetic particles are accelerated at the reconnection site

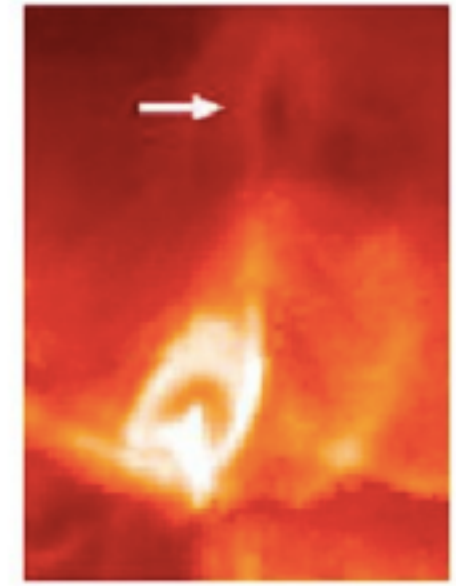
  - Particles precipitates along the magnetic loop (radio emission) and hit the chromosphere footpoints (Hard X-ray emission, Hα emission and flare ribbon)

  - Heated chromospheric plasma evaporates into the corona (soft X-ray emission, post flare loop arcade)
- Evaporation flows

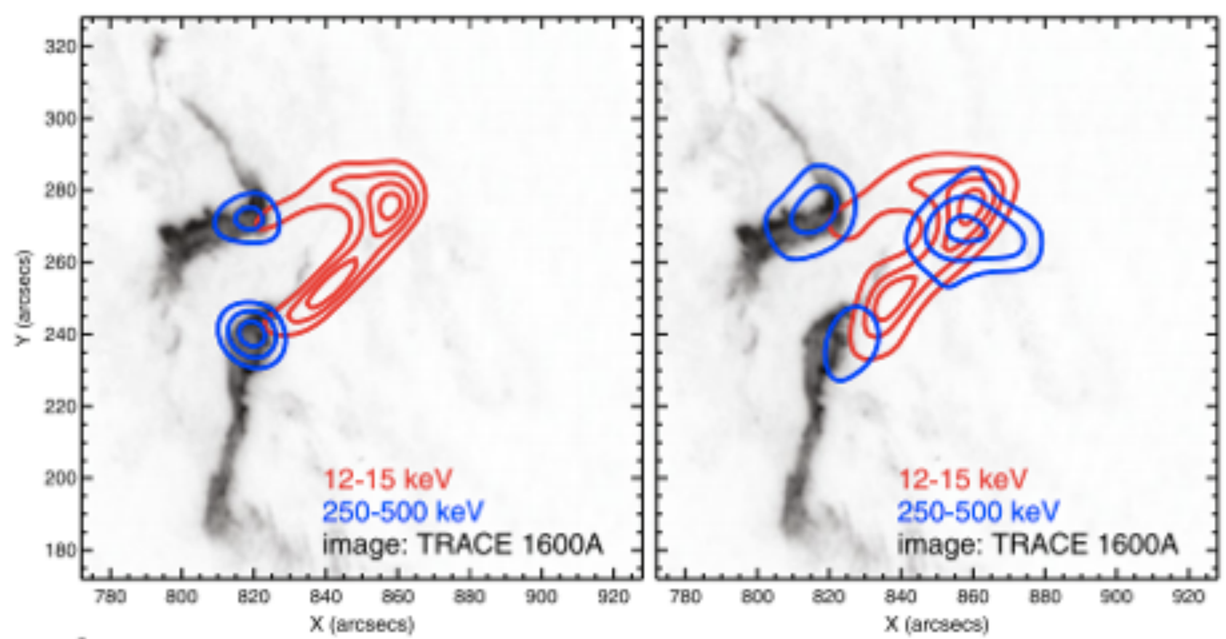
  - From the spectroscopic observation, evaporation flows are observed by Doppler velocity measurements

- Sometimes, strong flares produce white light continuum enhancement, white light flare (WLF).
- White light flares and HXR emissions are well correlated in spatially and temporally (Neidig 1989; Hudson et al. 1992; Krucker et al. 2015).





Plasmoid ejection associated with LDE flare (Yohkoh/SXT)



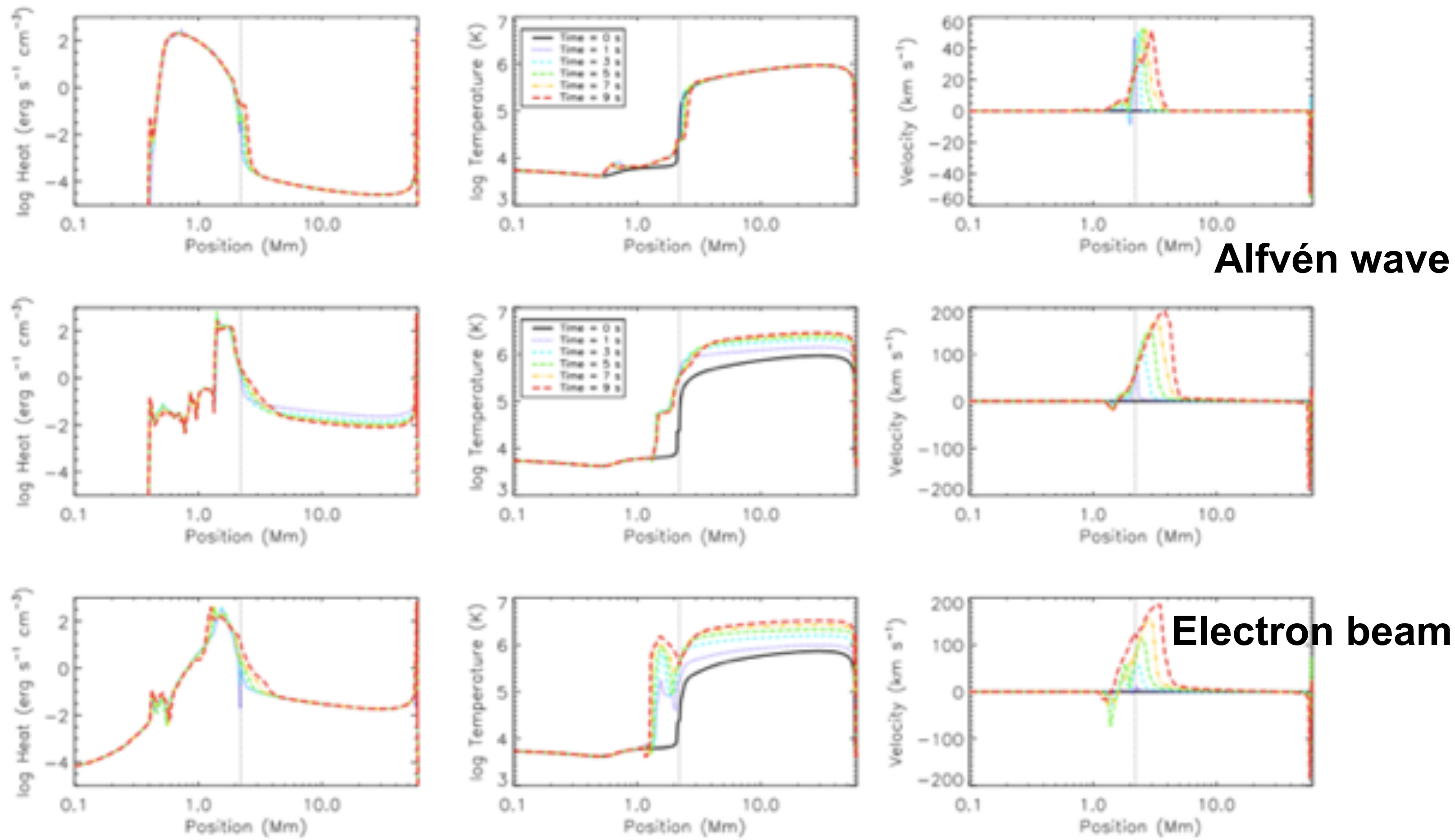
Krucker et al. (2008)

INTRODUCTION: ENERGY TRANSPORT PROCESS

DIFFERENT ENERGY TRANSPORT PROCESS

- THERMAL CONDUCTION
- ELECTRON BEAM
- ALFVÉN WAVE

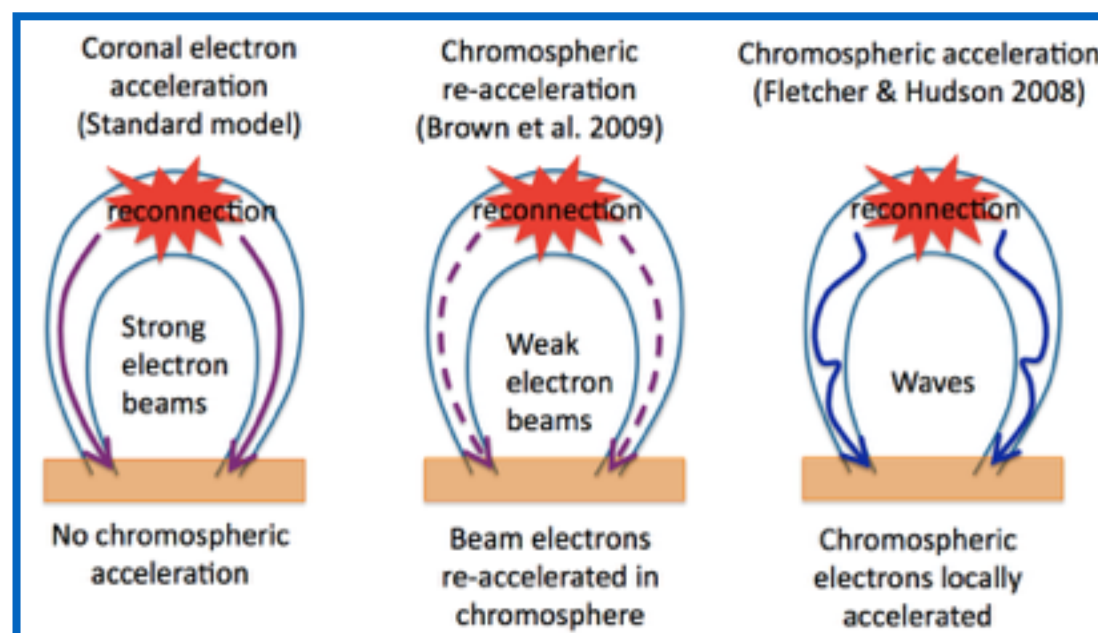
- **Electron beam heating VS. Alfvén wave heating (Reep et al. 2016)**
- **The simulations for different energy transport processes show similar observational velocity trend.**



Q1. How the energy transported to the low atmosphere?

- different energy transport models
- Which is most consistent with observations?

Q2. How much energy flux transported to the low atmosphere? (quantitative estimation)



INTRODUCTION: PREVIOUS STUDY

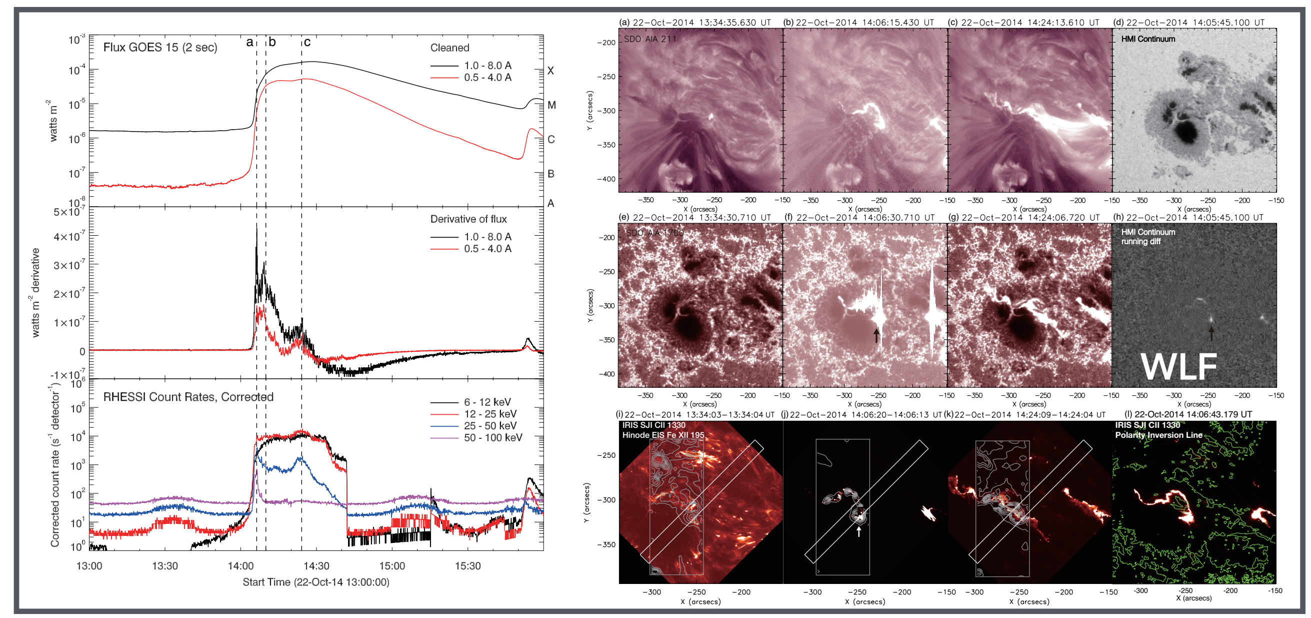
A CASE STUDY OF WLF WITH CHROMOSPHERIC EVAPORATION

- SPECTROSCOPIC INVESTIGATION OF A WLF

Lee et al. (2017)

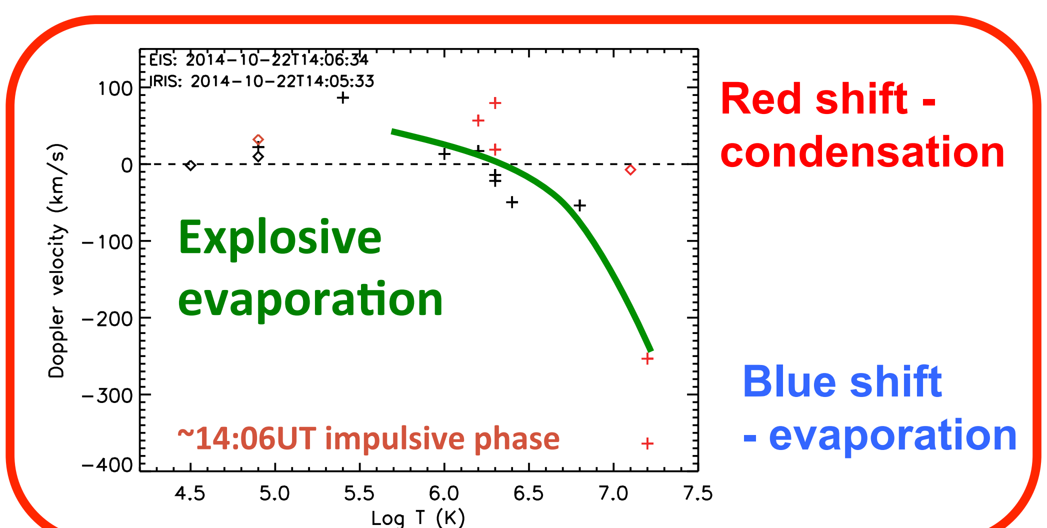
Q1. How the energy transported to the low atmosphere?

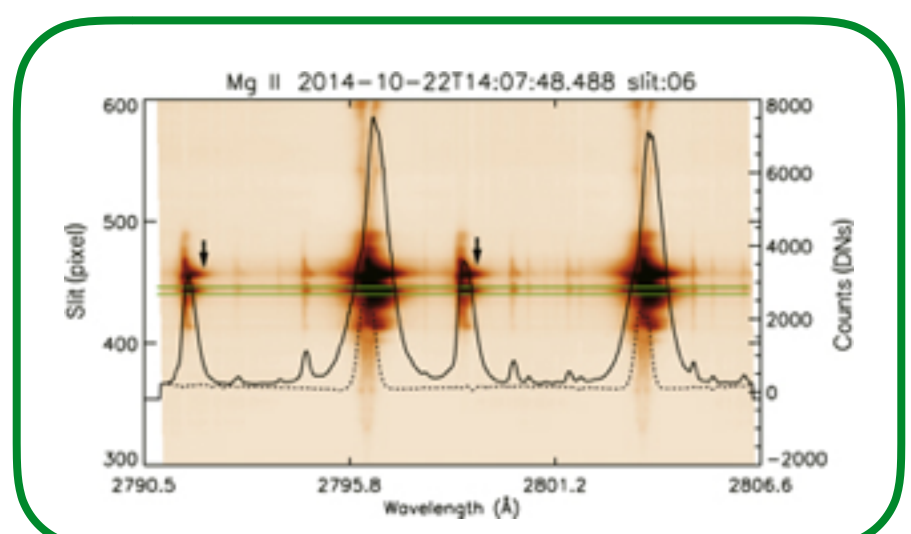
- Different energy transport models
- Which is most consistent with observations?
  - Doppler velocity measurement
  - Temporal correlation of the HXR, EUV, UV, WL continuum observations
  - Electron beam heating model

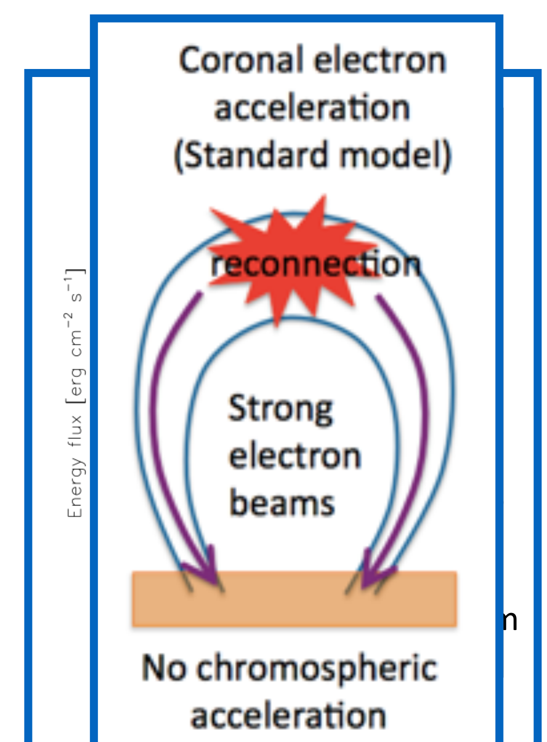


Q2. How much energy flux transported to the low atmosphere? (quantitative estimation)

- First time to applied temperature diagnosis for low atmosphere using Mg II triplet (core to wing ratio)
- Measuring the energy flux enhancement of low atmosphere
- Compare with chromospheric evaporation flow strength
- Consistent with Electron beam heating model







STATISTICAL INVESTIGATION OF FLARES

STATISTICAL INVESTIGATION WITH SPECTROSCOPIC OBSERVATIONS OF FLARES

- So far, several case studies have been done about flares and chromospheric evaporations.
- We have been investigated flares with spectroscopic observations with continuum images statistically.
- A list of flares with IRIS observation from 2014 to 2016
  - M & X class flares
  - IRIS observations with active region and flare observational mode
  - Including the Si IV, Fe XXI, and Mg II wavelength windows
  - 47 flares are selected for the analysis
- We investigated the spatial and temporal correlation between
  - WL flares vs. Mg II triplet emission (low atmospheric heating)
  - Mg II triplet emission vs. Doppler velocity variation (evaporation)

FLARE LIST

TABLE 1

LIST OF FLARE (> M CLASS) OBSERVED BY IRIS WITH WLFS DURING 2014-2016

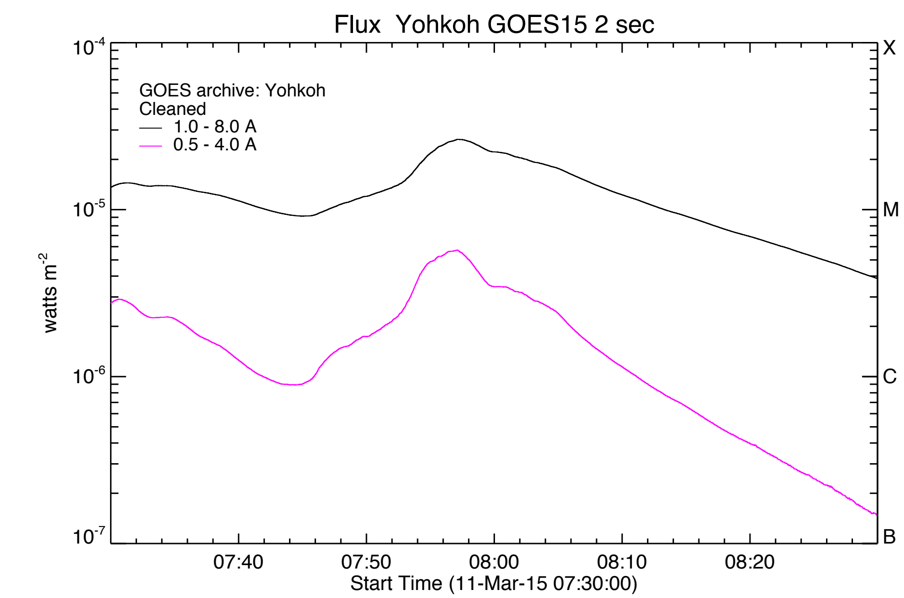
	GOES Flare Informaition					IRIS obs.								RHESSI obs.	
Number	Flare class	date	start (UT)	peak (UT)	end (UT)	obs mode	x1	y1	x2	y2	x3	y3	WLF	Obs. E range (keV)	HXR peak
1	M3.6	28-Jan-2014	07:25	07:31	07:34	scan	0	668					o	...	
2	M1.3	02-Feb-2014	21:24	22:04	22:14	scan	48	868						25-50	0.08
3	M1.5	04-Feb-2014	15:25	16:02	16:49	scan	15	330	5	205	41	162		25-50	0.5
4	M1.8	13-Feb-2014	01:32	01:40	01:50	scan	1	591	6	580	5	604		41997	0.04
5	X1.0	29-Mar-2014	17:35	17:48	17:54	scan	7	510	1	485	7	492	o	100-300	19.11
6	M7.3	18-Apr-2014	12:31	13:03	13:20	sns	0	648	0	650	0	629		50-100	0.56
7	M3.9	11-Jun-2014	20:53	21:03	21:10	scan	3	103	2	103	4	88		25-50	0.18
8	M1.0	12-Jun-2014	21:01	21:13	21:19	scan	2	51	5	102				41997	0.12
9	M1.5	01-Aug-2014	17:55	18:13	18:43	scan	40	453	20	381	11	238		...	
10	M1.1	06-Sep-2014	16:50	17:09	17:22	sns	0	258	0	314				50-100	0.86
11	X1.6	10-Sep-2014	17:21	17:45	18:20	sns	0	400	0	305	0	298		...	
12	M1.0	28-Sep-2014	16:34	17:33	18:00	scan	0	82	1	84	1	54		41997	0.05
13	M8.7	22-Oct-2014	01:16	01:59	02:28	sns	0	417	0	590			o	100-300	7.76
14	X1.6	22-Oct-2014	14:02	14:28	14:50	scan	6	443					o	100-300	16.39
15	X3.1	24-Oct-2014	21:07	21:41	22:13	sns	0	222	0	146	0	136	o[1]	100-300	9.31
16	X1.0	25-Oct-2014	16:55	17:08	18:11	sns	0	72	0	15				25-50	2.73
17	X2.0	26-Oct-2014	10:04	10:56	11:18	sns	0	181	0	253			o	...	
18	M1.0	26-Oct-2014	17:08	17:17	17:30	sns	0	102	0	218				...	
19	M2.4	26-Oct-2014	19:59	20:21	20:45	sns	0	67	0	133				...	
20	M7.1	27-Oct-2014	00:06	00:34	00:44	sns	0	90	0	159				25-50	0.46
21	M1.0	27-Oct-2014	01:44	02:02	02:11	sns	0	80	0	154				41997	0.06
22	M1.3	27-Oct-2014	03:35	03:41	03:48	sns	0	96	0	154				25-50	0.12
23	X2.0	27-Oct-2014	14:12	14:47	15:09	scan	0	63	1	342	6	127	o	50-100	2.98
24	M1.4	27-Oct-2014	17:33	17:40	17:47	scan	1	94	3	88				50-100	0.78
25	M3.4	28-Oct-2014	02:15	02:42	03:08	sns	0	118	0	282	0	192		...	
26	M6.6	28-Oct-2014	03:23	03:32	03:41	sns	0	284	0	305	0	326		25-50	0.59
27	M1.6	28-Oct-2014	13:54	14:06	14:23	scan	56	489	26	287	55	742		25-50	0.24
28	M1.0	29-Oct-2014	16:06	16:20	16:33	sns	0	147	0	160				...	
29	M1.0	07-Nov-2014	10:13	10:22	10:30	scan	7	230	7	272	10	228		25-50	0.08
30	X1.6	07-Nov-2014	16:53	17:26	17:34	scan	3	664	0	558			o[2]	...	
31	M2.3	09-Nov-2014	15:24	15:32	15:38	scan	2	326					o[2]	50-100	0.74
32	M5.6	13-Jan-2015	04:13	04:24	04:38	scan	4	22					o	...	
33	M5.8	09-Mar-2015	23:29	23:53	00:12	scan	4	346	4	326	4	336		...	
34	M2.9	10-Mar-2015	23:46	00:02	00:06	scan	3	240					o	100-300	11.12
35	M1.8	11-Mar-2015	07:10	07:18	07:43	scan	1	567	6	695	7	717		...	
36	M2.6	11-Mar-2015	07:51	07:57	08:03	scan	1	553	1	550	1	548		...	
37	X2.1	11-Mar-2015	16:11	16:22	16:29	scan	2	255	0	297	1	269	o	50-100	1.64
38	M1.6	12-Mar-2015	11:38	11:50	11:50	sns	0	287	0	243	0	188		...	
39	M1.4	12-Mar-2015	12:09	12:14	12:18	sns	0	200	0	290	0	240		...	
40	M1.8	13-Mar-2015	05:49	06:07	06:12	sns	0	282	0	241				50-100	0.18
41	M1.6	16-Mar-2015	10:39	10:58	11:17	scan	2	204	1	108	1	42		...	
42	M1.0	17-Mar-2015	22:49	23:34	23:48	scan	2	216						50-100	0.43
43	M6.5	22-Jun-2015	17:39	18:23	18:51	scan	6	216	14	80	2	79	o	50-100	1.76
44	M2.9	27-Aug-2015	04:48	05:44	06:03	scan	7	145	0	122				25-50	
45	M2.1	20-Sep-2015	17:32	18:03	18:29	sns	0	102	0	68				...	
46	M3.7	04-Nov-2015	13:31	13:52	14:13	scan	14	257	15	189	3	309		50-100	
47	M1.9	23-Jul-2016	01:46	02:11	02:23	scan	235	290	303	186				25-50	

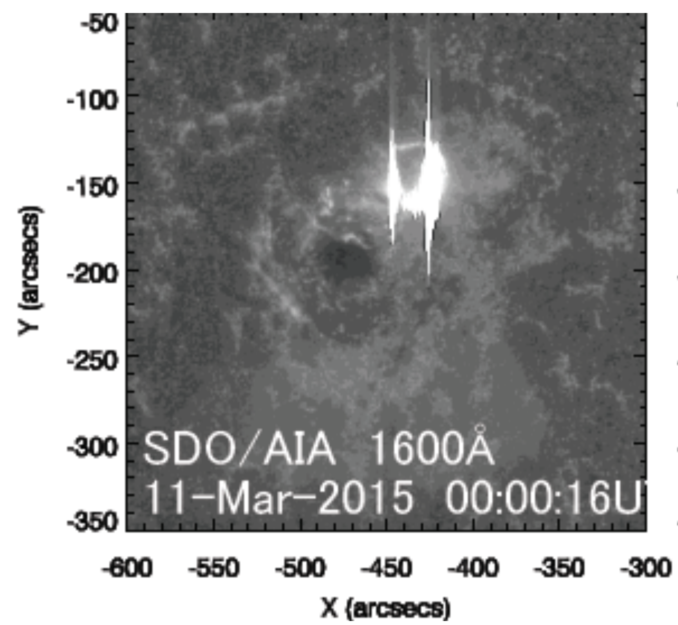
ANALYSIS: FLARE CONTEXT - WLF

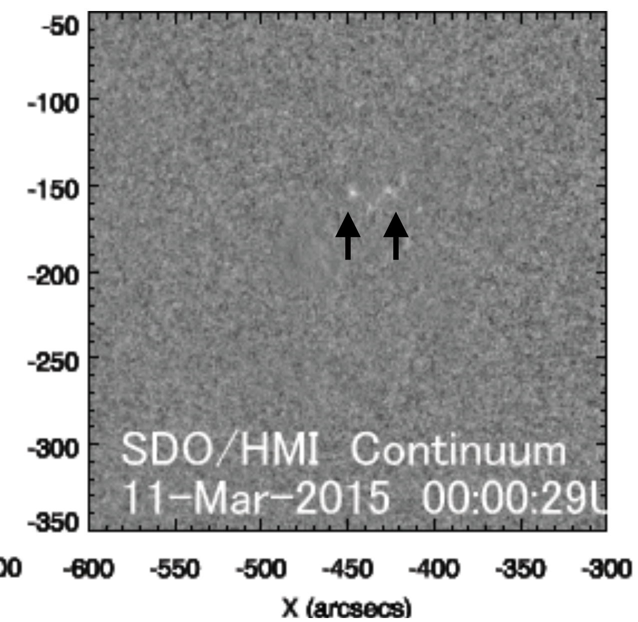
WHITE LIGHT FLARES IN SDO/AIA 1600Å & SDO/HMI CONTINUUM

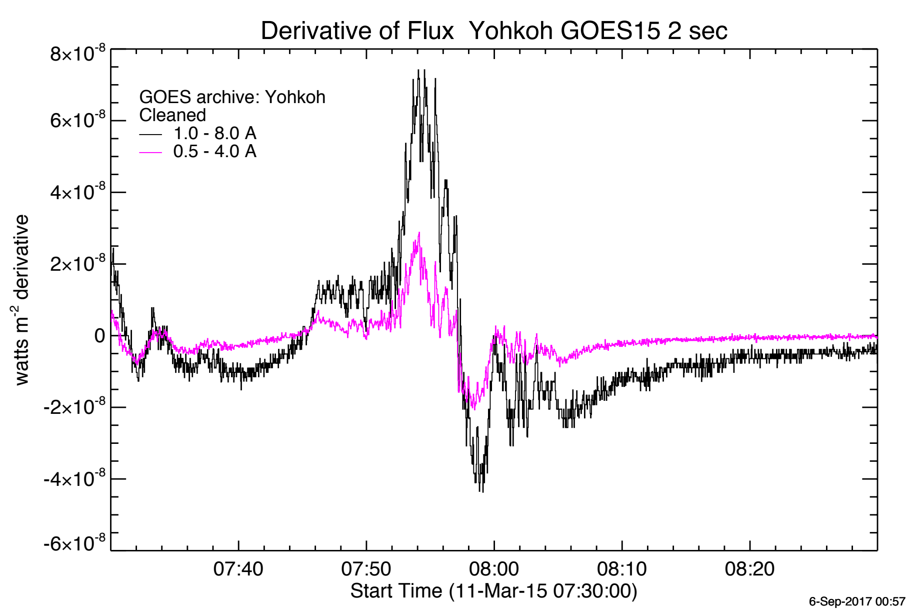
- Flare ribbons in SDO/AIA 1600Å intensity images and running difference images of SDO/HMI and Hinode/SOT were used for checking the WL enhancement during flare.
- 13 flares (among 47 flares, 28%) show the WL enhancement at the flare start timing.

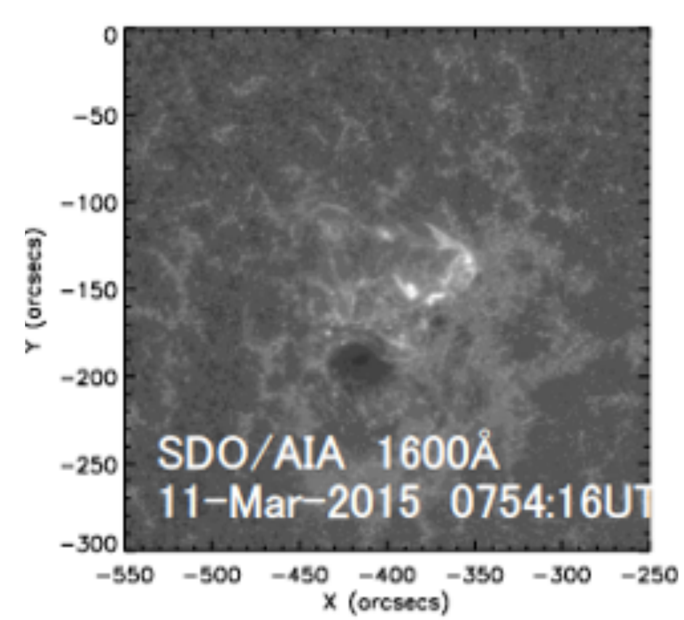
  - **A sample events: M 2.9 flare on 2015 March 10 (WLF) / M2.6 flare on 2015 March 11**











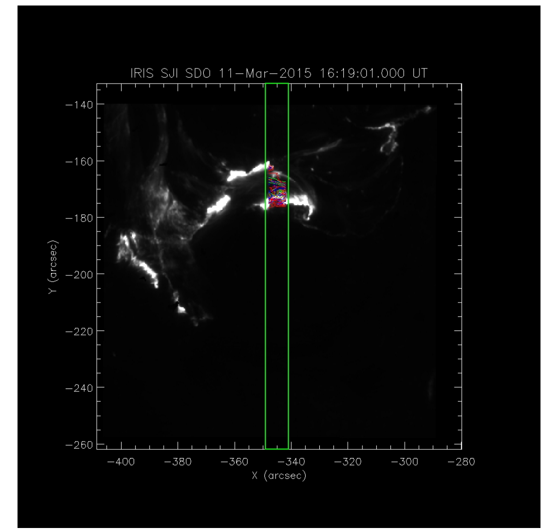
no continuum enhancement

ANALYSIS: MG II TRIPLET - LOW ATMOSPHERIC HEATING

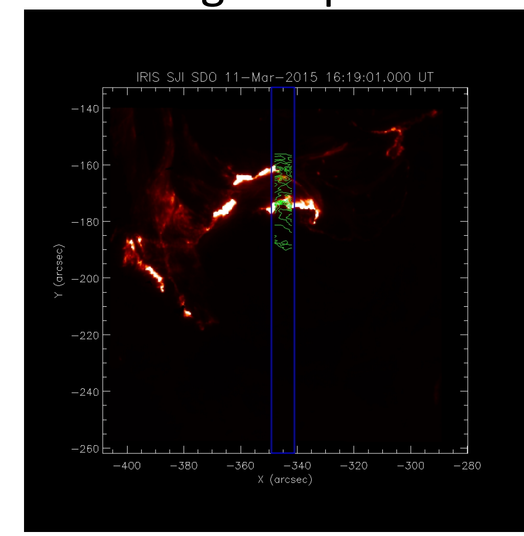
MG II TRIPLET EMISSION

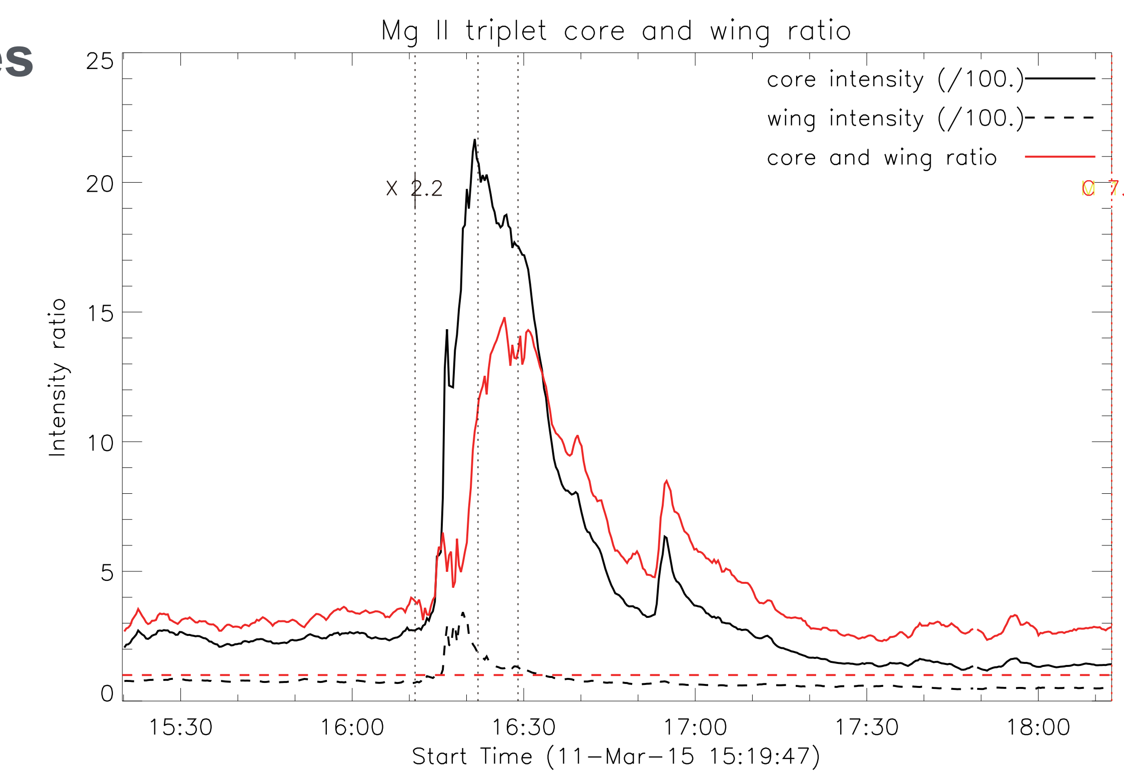
- Mg II triplet: 2798.66-2798.82Å(core, including 2798.75, 2798.82Å), 2799.32Å (wing)
- Usually the Mg II triplet are observed as absorption profile in quiet sun regions.
- When the low atmosphere is heated (e.g. Ellerman bombs, flares), the absorption profile become emission.
- It is possible to diagnose the temperature changes quantitatively at the low atmosphere, near temperature minimum region (Pereira et al. 2015)
- If the slit located the flare ribbon regions, all flares show the Mg II triplet emission during flares.

Fe XXI

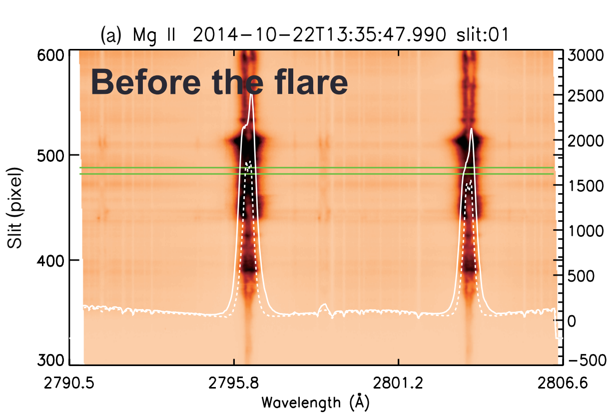


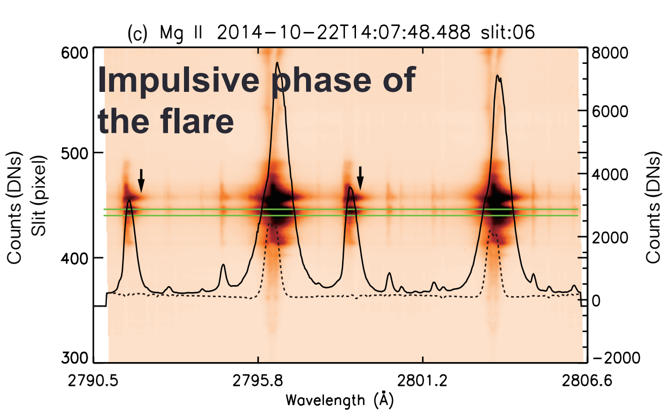
Mg II triplet





Mg II observation from IRIS





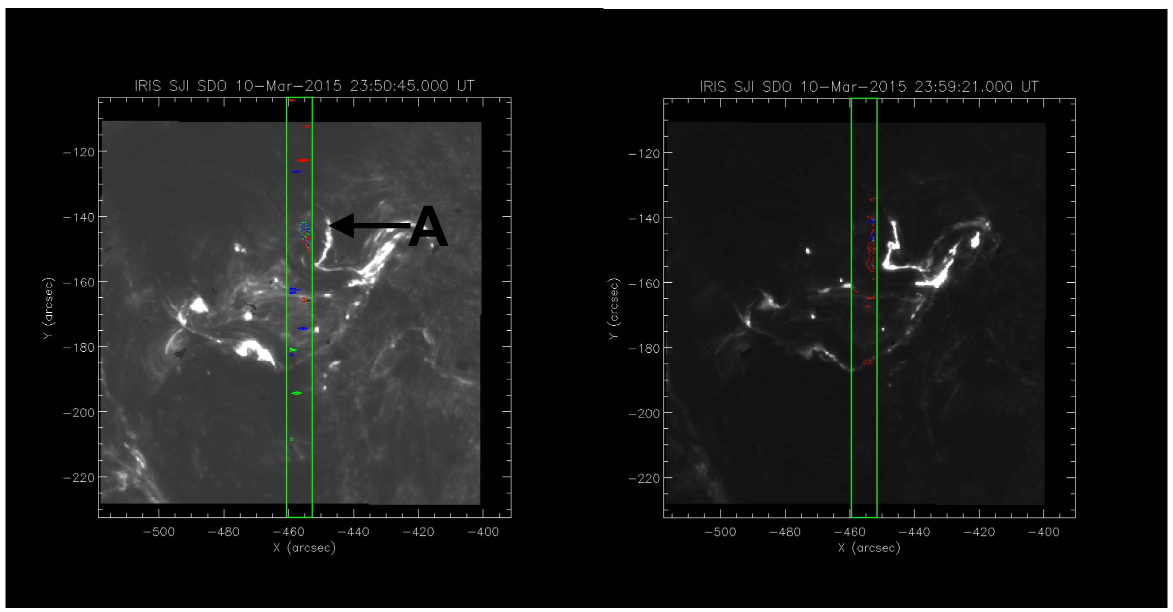
Mg II triplet become emission

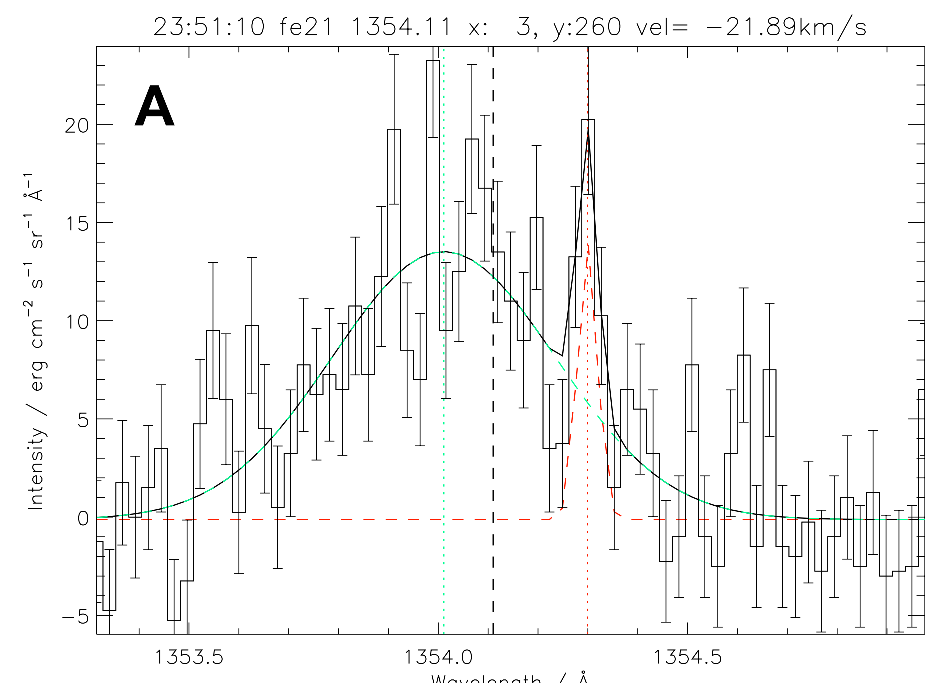
ANLAYSIS: EUV SPECTROSCOPY - EVAPORATION

DOPPLER VELOCITY MEASUREMENT FROM SI IV & FE XXI

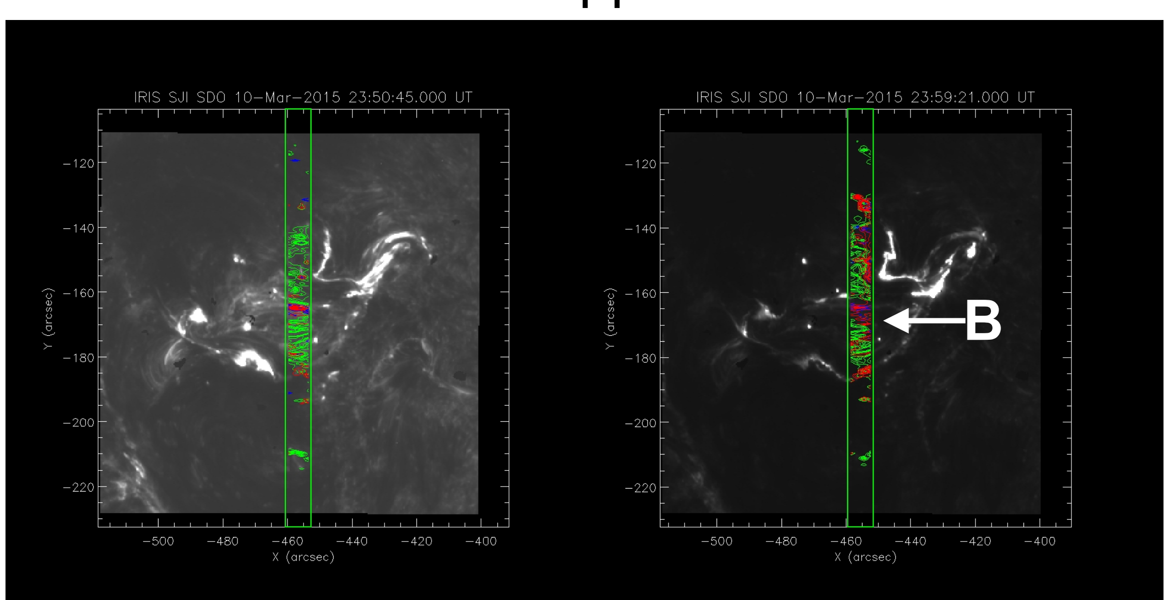
- **Intensity images from the blue and red wing of the IRIS spectra**
  - **Fe XXI: 1354.1Å, (blue ~40-60 km/s), (red ~40-60 km/s)**
  - **Si IV: 1402.8Å, (blue ~40-60 km/s), (red ~40-60km/s)**

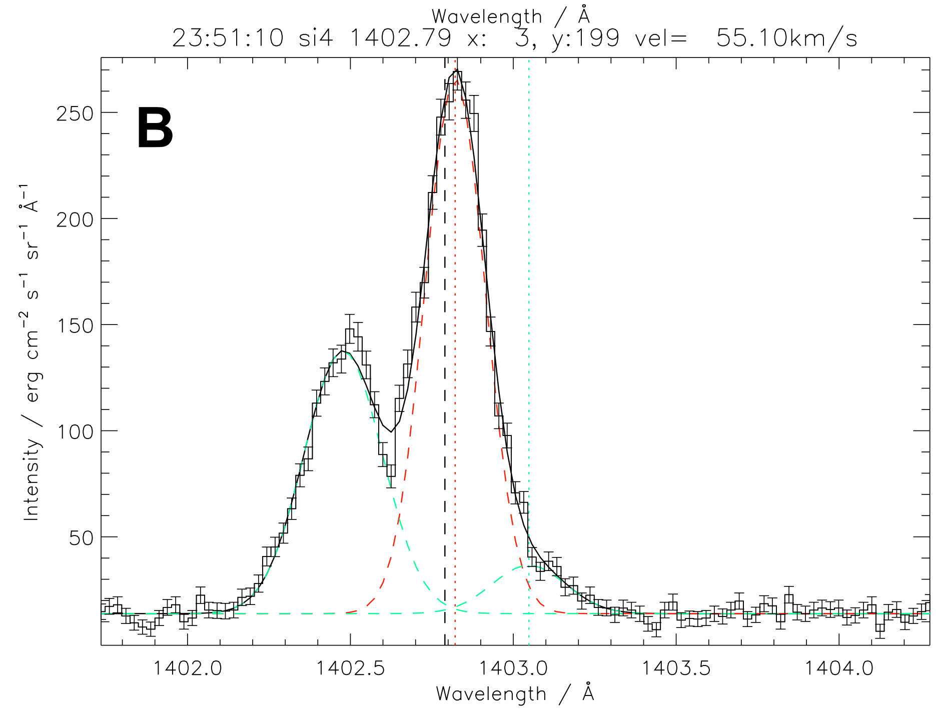
M 2.9 Fe XXI Doppler





Si IV Doppler

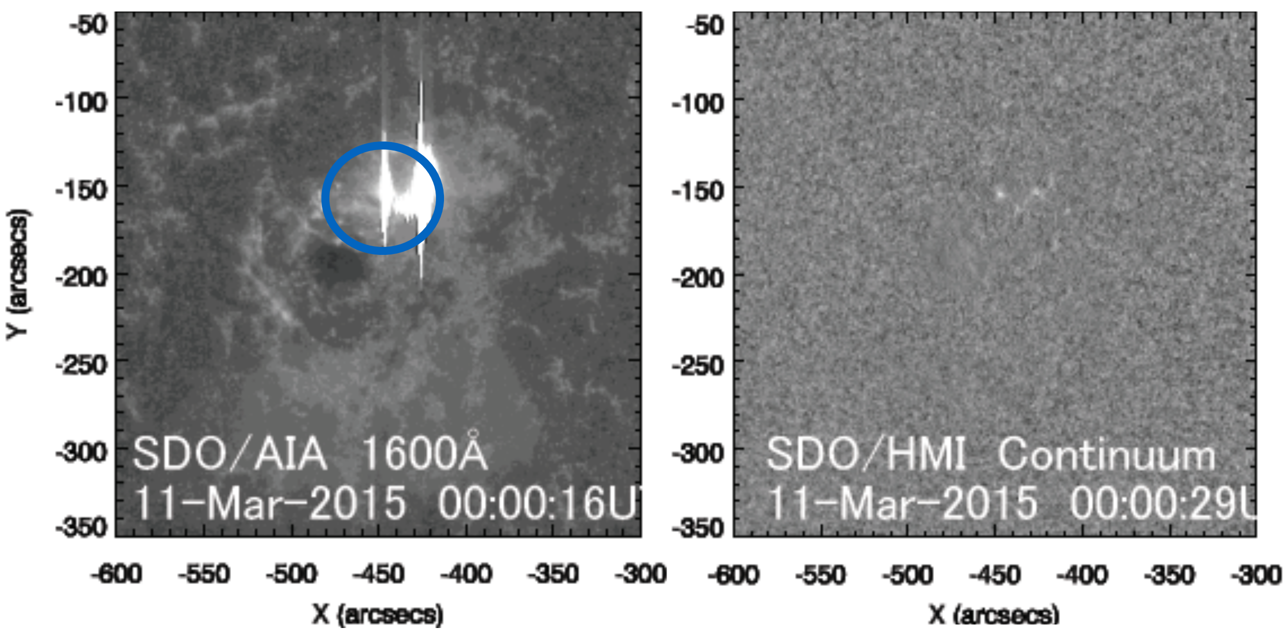




RESULTS: LOW ATMOSPHERIC HEATING & EVAPORATIONS

SPATIAL CORRELATIONS

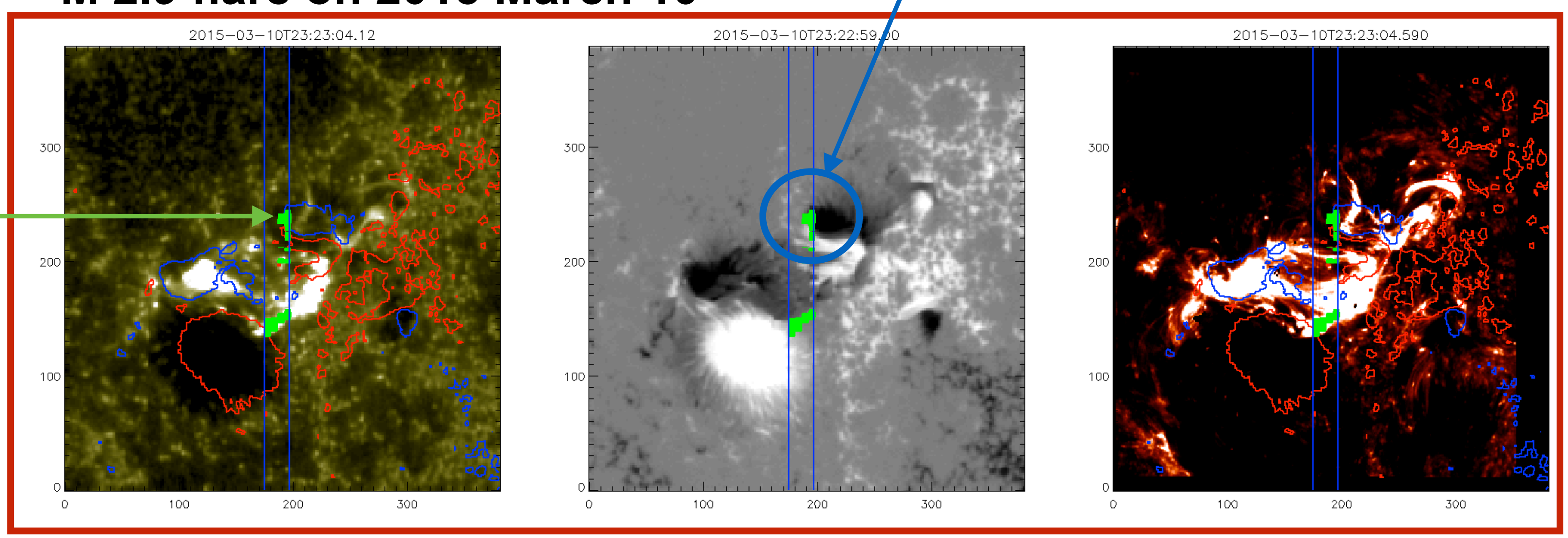
- The locations of the Mg II triplet emission and outflowing region of the Fe XXI intensity are correlated
  - Mg II triplet emission appears along flare ribbons
  - Significant outflow (Doppler velocity) in Fe XXI observed at near the footpoints of flaring loop, not all the flare ribbon.
  - WL flare kernel locations: combination of Mg II emitting region & Fe XXI outflowing region



- M 2.9 flare on 2015 March 10

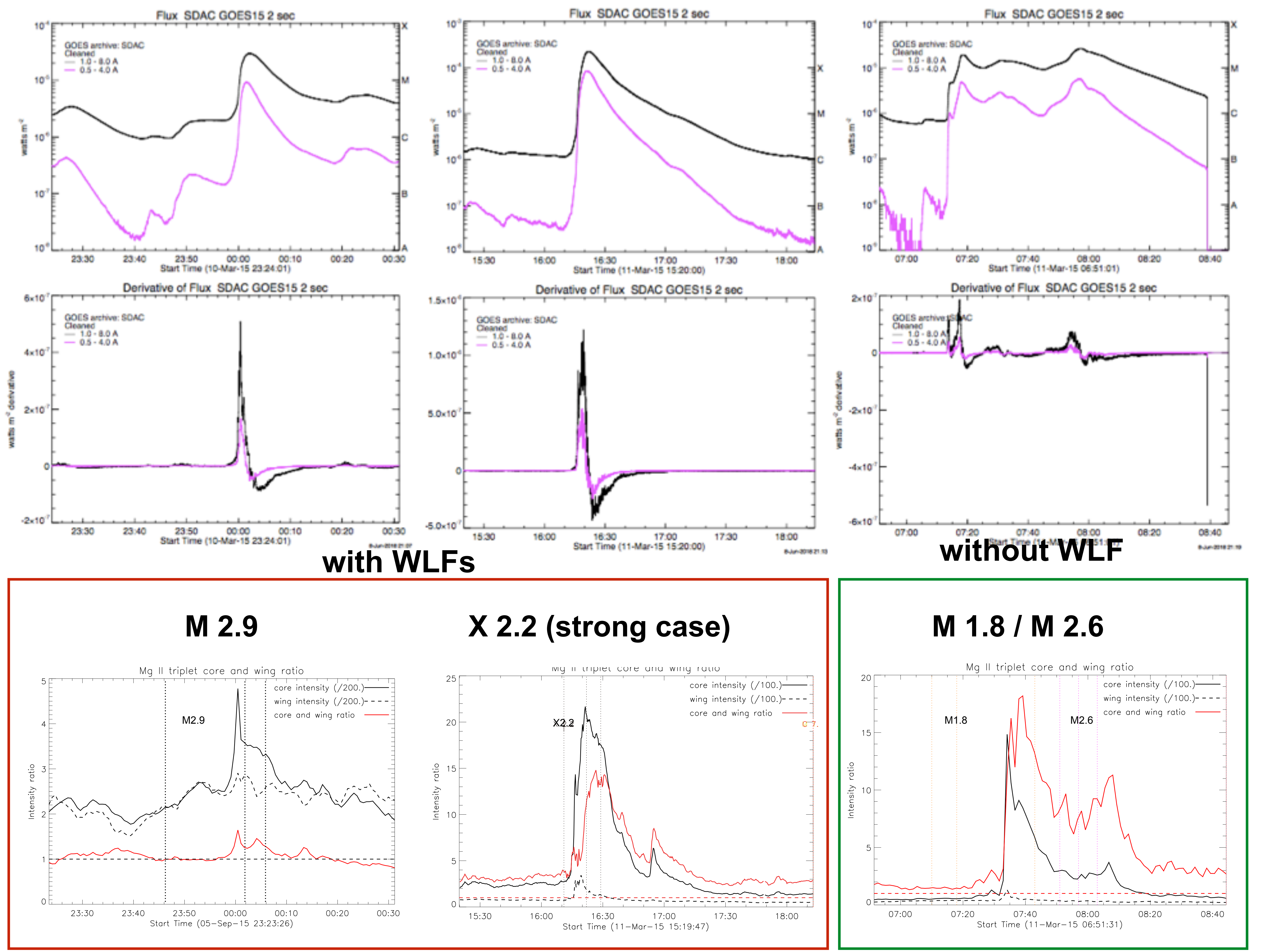
strong flow in IRIS spectra Fe XXI

Mg II triplet emission observed by IRIS



A sample of aligned observation of IRIS & SDO for a flare

SDO/AIA 1600Å SDO/HMI LOS magnetogram IRIS/SJI 1330Å



Flux SDAC GOES15 2 sec
GOES archive: SDAC
Cleaned
1.0 - 8.0 A
0.5 - 4.0 A
Start Time (10-Mar-15 23:24:01)
Start Time (11-Mar-15 15:20:00)
Start Time (11-Mar-15 06:51:01)
Derivative of Flux SDAC GOES15 2 sec
with WLFs
without WLF
M 2.9
X 2.2 (strong case)
M 1.8 / M 2.6
Mg II triplet core and wing ratio
core intensity (/200.)
wing intensity (/200.)
core and wing ratio
M2.9
Intensity ratio
Start Time (05-Sep-15 23:23:26)
core intensity (/100.)
wing intensity (/100.)
X2.2
Start Time (11-Mar-15 15:19:47)
M1.8
M2.6
Start Time (11-Mar-15 06:51:31)

DISCUSSION: LOW ATMOSPHERIC HEATING & LINE FORMATION

FORMATION HEIGHT OF THE WL FLARES AND MG II TRIPLET

- 28% of events with strong flares with impulsive events have WL flares, while most of events have Mg II triplet wing & core ratio strongly enhanced (become emission).
  - White light flare formation height - photosphere
  - Mg II triplet line formation height - photosphere or chromosphere
  - Recent simulation shows that the Mg II triplet emission formation heigh would be chromosphere similar to the Mg II k and h
- The Mg II triplet emission region and Fe XXI outflowing region spatially correlated at the flare ribbon footpoints
  - If WL flares are exist, the locations are also spatially correlated

DISCUSSION: LOW ATMOSPHERIC HEATING & ENERGY TRANSPORT PROCESS

WITH/WITHOUT WL FLARES

- **Impulsive flares with strong HXR intensity cases have WL enhancement**, which consistent with the Watanabe et al. (2017).
  - The impulsiveness of the flare would be related to the WL flare productivity.
  - The strong HXR intensity and the WL flare existence shows that the low atmosphere heated directly by electron beam.

- **Without WL flare case**:
  - it shows that the electron beam could not penetrated to the low atmosphere and dissipated at the **chromosphere - only Mg II triplet emission observed**
  - or the **energy transport process could be different with electron beam case**, which shows the different temporal evolution of Mg II triplet core and wing ratio.

- To check the different energy transport process, we need to check the strength of the evaporations and magnetic field strength

SUMMARY & FUTURE WORK

- **GOES + IRIS**: When the flare ribbons detected to the IRIS slit observations, the **flare ribbons (not all the ribbon region) show the Fe XXI emission enhancement** and Doppler velocities.

- **IRIS Fe XXI intensity** (shifted wavelength intensity) + **Mg II triplet core and wing intensity ratio**: From the comparison between the Fe XXI and Mg II triplet emission, they are mostly correlated in the location and time.

- **White light continuum enhancement:**
  - with (13 flares) /without (34 flares) WLFs, the temporal profiles of the Mg II triplet emission is different
  - The energy transport processes seem to be different with those cases.

- Future work
  - WLF intensity variation & Mg II triplet emission intensity variation
  - Magnetic field configurations & field strength
  - Evaporation strength by measuring the velocity variation