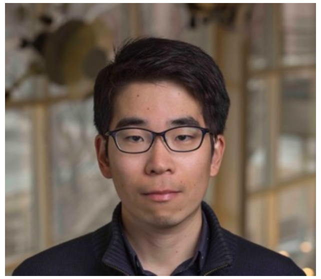
2023 SDO EVE Science Team Meeting
2023 July 27th 9:30-10:00

XUV Spectra of Active Sun-like Stars: Scaling Relations based on the Long-term Sun-as-a-star datasets

Yuta Notsu

University of Colorado Boulder (CU Boulder)
Laboratory for Atmospheric and Space Physics (LASP)
National Solar Observatory (NSO)



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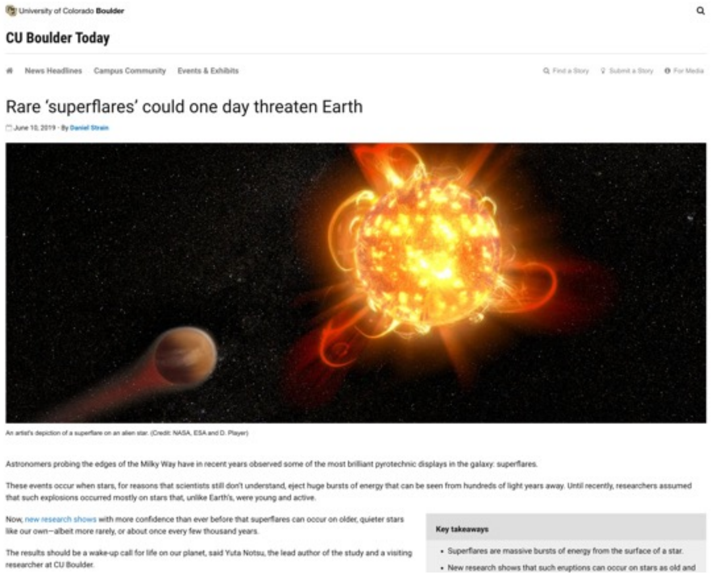
(** MAVEN EUV team)

[My background]

- Stellar flares (and their impacts on planets)
- Observations : Space (optical/X-ray/UV)
  and ground-based telescopes (optical spectroscopy)


Adam Kowalski and Isaiah Tristan
at CU/LASP/NSO



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Rare 'superflares' could one day threaten Earth

June 10, 2019 · By Daniel Strain

An artist's depiction of a superflare on an alien star. (Credit: NASA, ESA and D. Player)

Astronomers probing the edges of the Milky Way have in recent years observed some of the most brilliant pyrotechnic displays in the galaxy: superflares.

These events occur when stars, for reasons that scientists still don't understand, eject huge bursts of energy that can be seen from hundreds of light years away. Until recently, researchers assumed that such explosions occurred mostly on stars that, unlike Earth's, were young and active.

Now, new research shows with more confidence than ever before that superflares can occur on older, quieter stars like our own—albeit more rarely, or about once every few thousand years.

The results should be a wake-up call for life on our planet, said Yuta Notsu, the lead author of the study and a visiting researcher at CU Boulder.

Key takeaways

- Superflares are massive bursts of energy from the surface of a star.
- New research shows that such eruptions can occur on stars as old and

https://www.colorado.edu/today/2019/06/05/superflares

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Menu

A young sun-like star may hold warnings for life on Earth

Share

By Daniel Strain · Dec. 9, 2021

Artist's depiction of the star EK Draconis ejecting a coronal mass ejection as two planets orbit. (Credit: National Astronomical Observatory of Japan)

Astronomers spying on a stellar system located dozens of lightyears from Earth have, for the first time, observed a troubling fireworks show: A star named EK Draconis ejected a massive burst of energy and charged particles in an event that was much more powerful than anything scientists have seen in our own solar system.

The researchers, including astrophysicist Yuta Notsu of the University of Colorado Boulder, published their results Dec. 9 in the journal *Nature Astronomy*.

https://www.colorado.edu/today/2021/12/09/ek-draconis

The Astrophysical Journal, 951:33 (33pp), 2023 July 1 https://doi.org/10.3847/1538-4357/acc94f

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A 7 Day Multiwavelength Flare Campaign on AU Mic. I. High-time-resolution Light Curves and the Thermal Empirical Neupert Effect

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Abstract

We present light curves and flares from a 7 day, multiwavelength observational campaign of AU Mic, a young and active dM1e star with exoplanets and a debris disk. We report on 73 unique flares between the X-ray to optical data. We use high-time-resolution near-UV (NUV) photometry and soft X-ray (SXR) data from the X-ray Multi-Mirror Mission to study the empirical Neupert effect, which correlates the gradual and impulsive phase flaring emissions. We find that 65% (30 of 46) flares do not follow the Neupert effect, which is 3 times more excursions than seen in solar flares, and propose a four-part Neupert effect classification (Neupert, quasi-Neupert, non-Neupert types I and II) to explain the multiwavelength responses. While the SXR emission generally lags behind the NUV as expected from the chromospheric evaporation flare models, the Neupert effect is more prevalent in larger, more impulsive flares. Preliminary flaring rate analysis with X-ray and *U*-band data suggests that previously estimated energy ratios hold for a collection of flares observed over the same time period, but not necessarily for an individual, multiwavelength flare. These results imply that one model cannot explain all stellar flares and care should be taken when extrapolating between wavelength regimes. Future work will expand wavelength coverage using radio data to constrain the nonthermal empirical and theoretical Neupert effects to better refine models and bridge the gap between stellar and solar flare physics.

Unified Astronomy Thesaurus concepts: Red dwarf flare stars (1367); Stellar activity (1580); Stellar flares (1603); Optical flares (1166); Stellar x-ray flares (1637); Planet hosting stars (1242)

Supporting material: machine-readable table

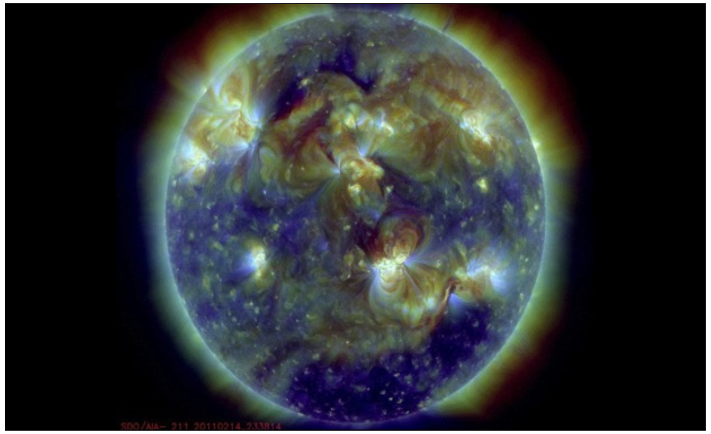
One of our recent paper on "Neupert effect"
of stellar flares (Trsitan et al., ApJ, 951, 33)

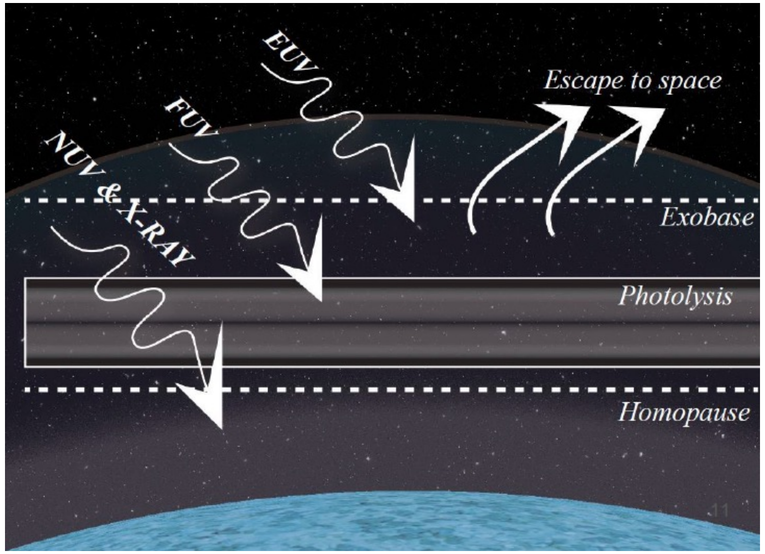
Introduction: Importance of the investigation of Stellar XUV flux/spectra

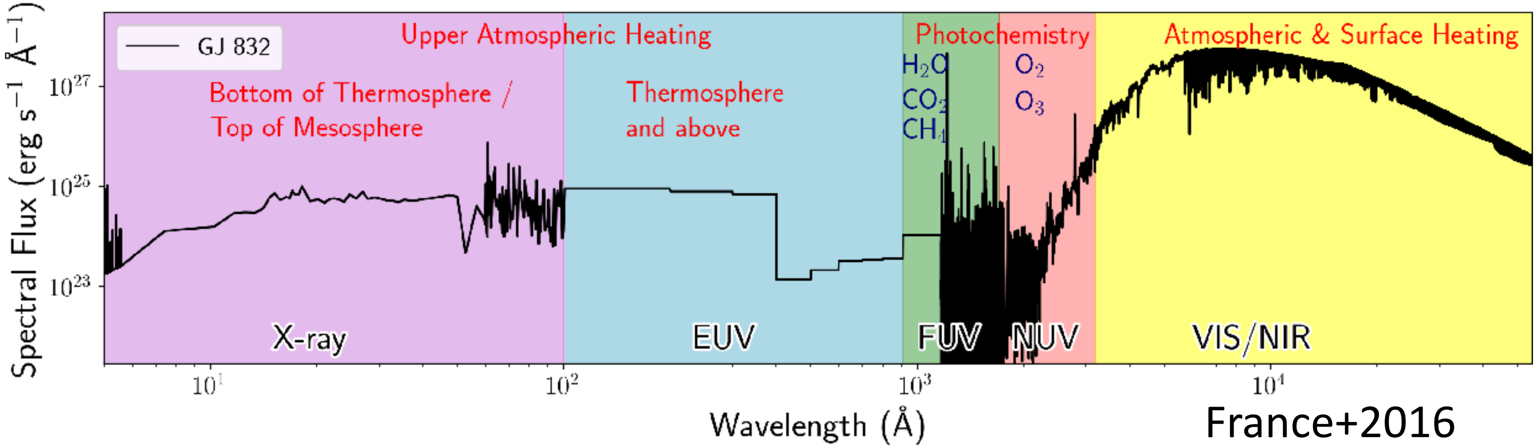
Stellar X-ray & EUV (hereafter, **XUV**) flux, and FUV fluxes are required to

i. Constrain the effects on (exo)planetary evolution and habitable environments of rocky (exo)planets (X-ray & EUV fluxes drive planetary atmospheric escapes)

Stellar XUV radiation
[from upper atmosphere]

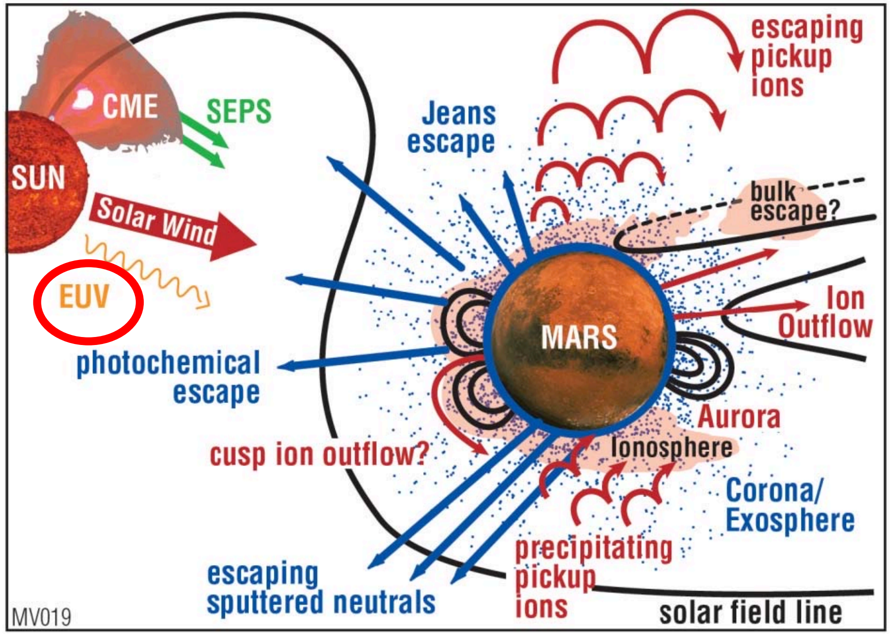






France+2016

Not only exoplanets,
but also solar-system planets !



Credit: The Lunar and Planetary Institute and LASP

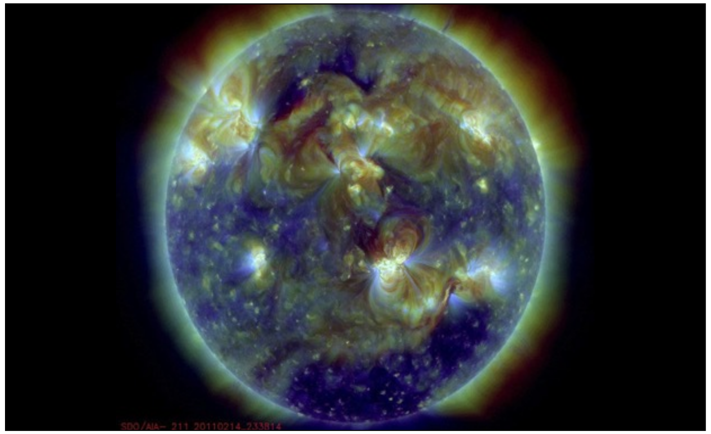
Introduction: Importance of the investigation of Stellar XUV flux/spectra

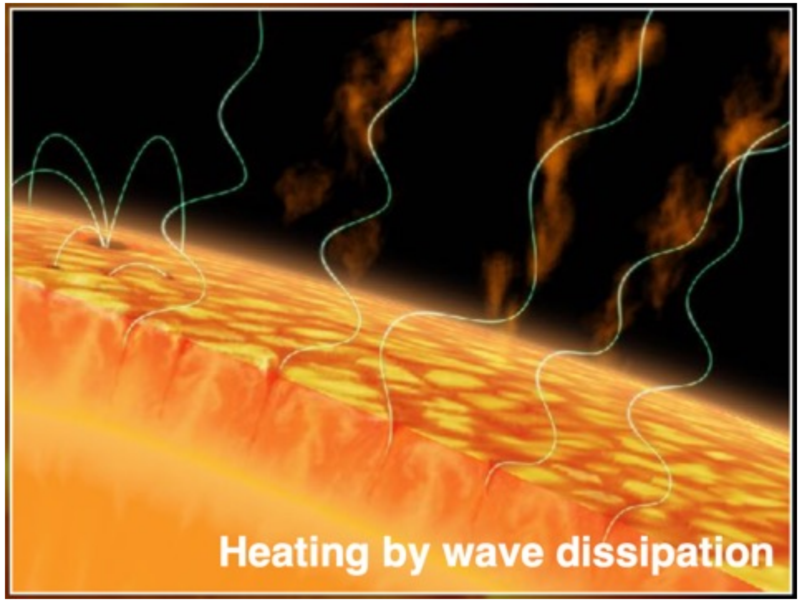
Stellar X-ray & EUV (hereafter, **XUV**) flux, and FUV fluxes are required to

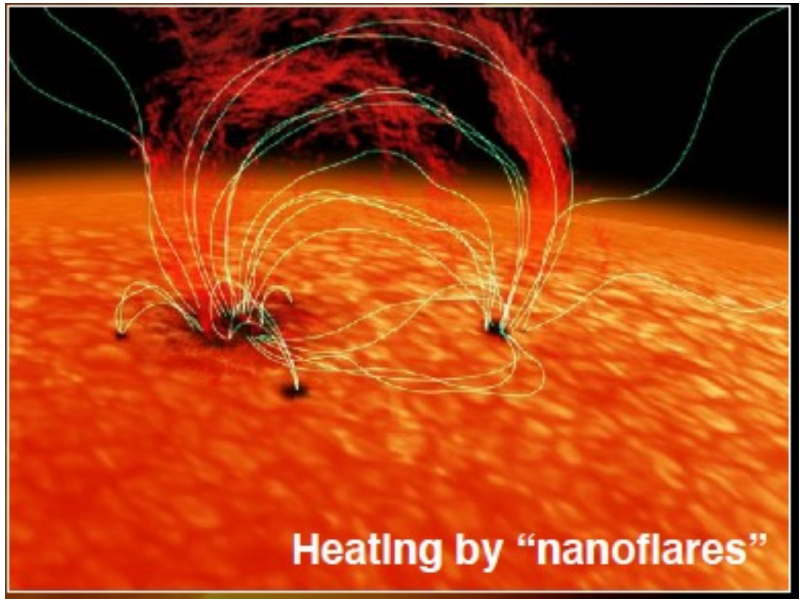
i. Constrain the effects on (exo)planetary evolution and habitable environments of rocky (exo)planets (X-ray & EUV fluxes drive planetary atmospheric escapes)

ii. Understand the heating mechanism of <u>stellar</u> hot coronae(>10^6 K)/chromosphere (10^4 K)
   - "Alfvén wave" heating or "nanoflare" heating?
   - ⇒ **Do the Sun and Sun-like stars share a common atmospheric heating mechanism ?**

Stellar XUV radiation
[from upper atmosphere]

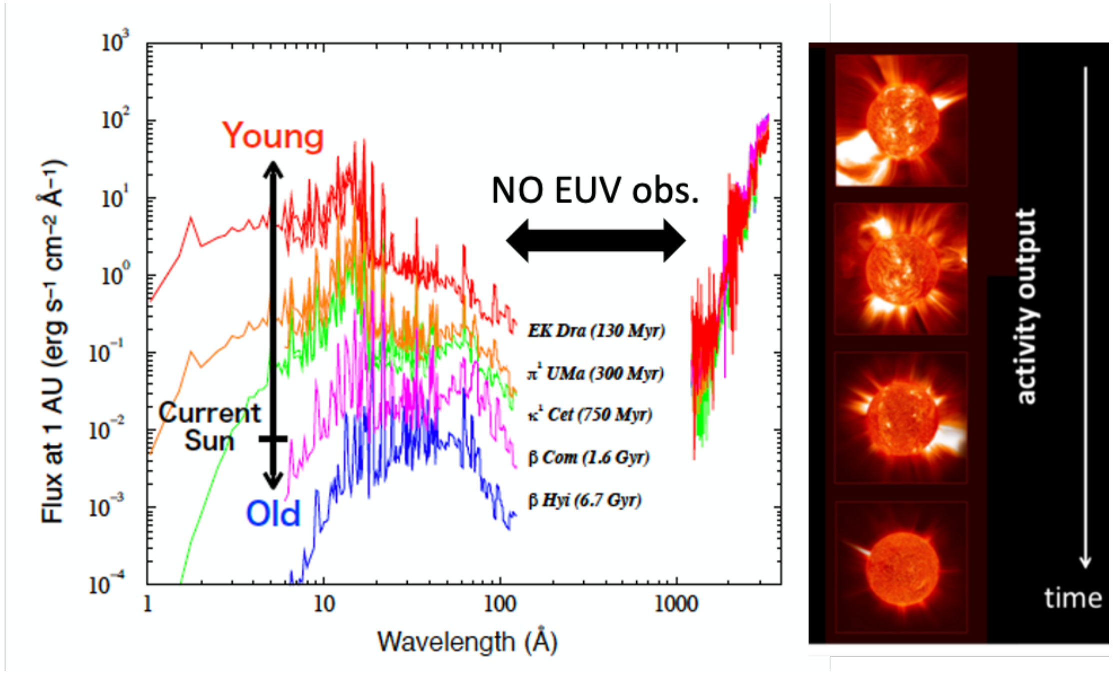




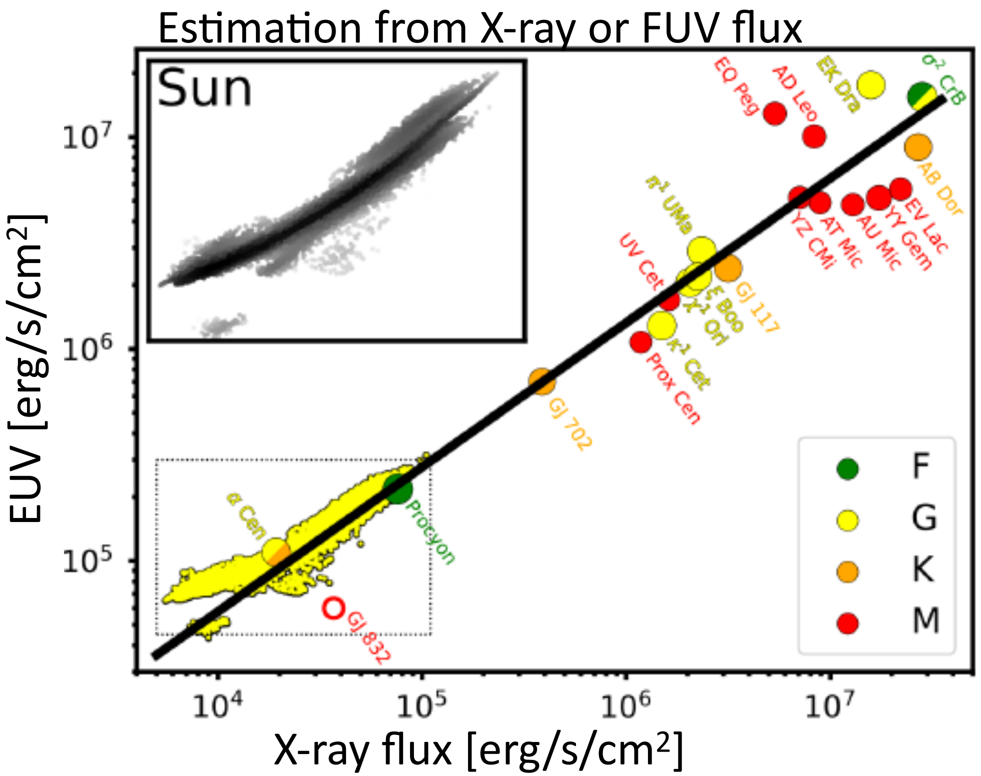


Difficulty: Stellar EUV spectrum is NOT observable (for now)

- Stellar XUV spectra are very limited, especially for EUV range [36-92nm].
  - Strong interstellar medium absorptions & Lack of EUV high sensitive instruments
    ⇒ Reconstruction of XUV spectra are important .
- Previous approaches:
  - flux-flux scaling law with X-ray/FUV flux : physical explanation
  - Differential Emission Measure Analysis (from X-ray&FUV spectra): Need high cost observations



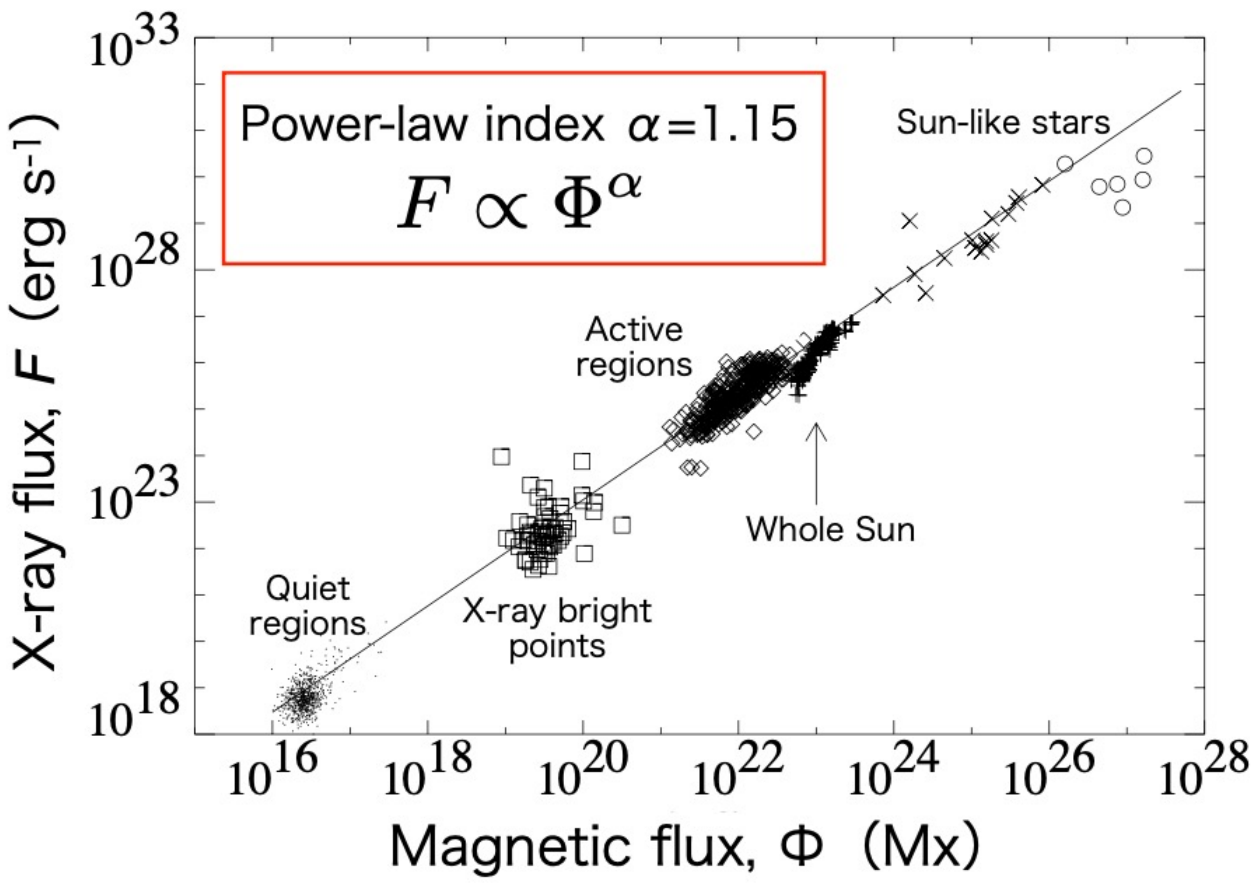
[Guinan & Ribas 2002]



Johnstone+2020
Linsky+2014

X-ray flux - Magnetic flux scaling

Mag flux—X-ray scaling [Pevtsov+ 2003]



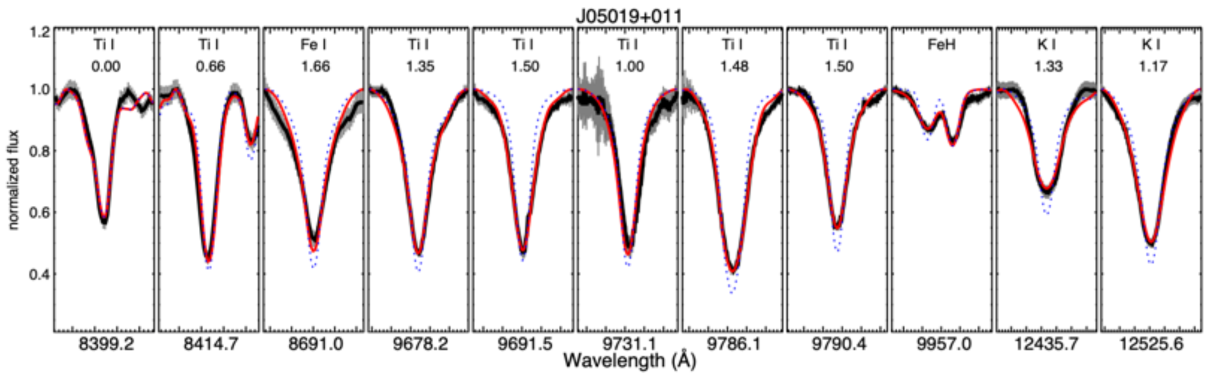
Universality of coronal heating

How about other temperature ?

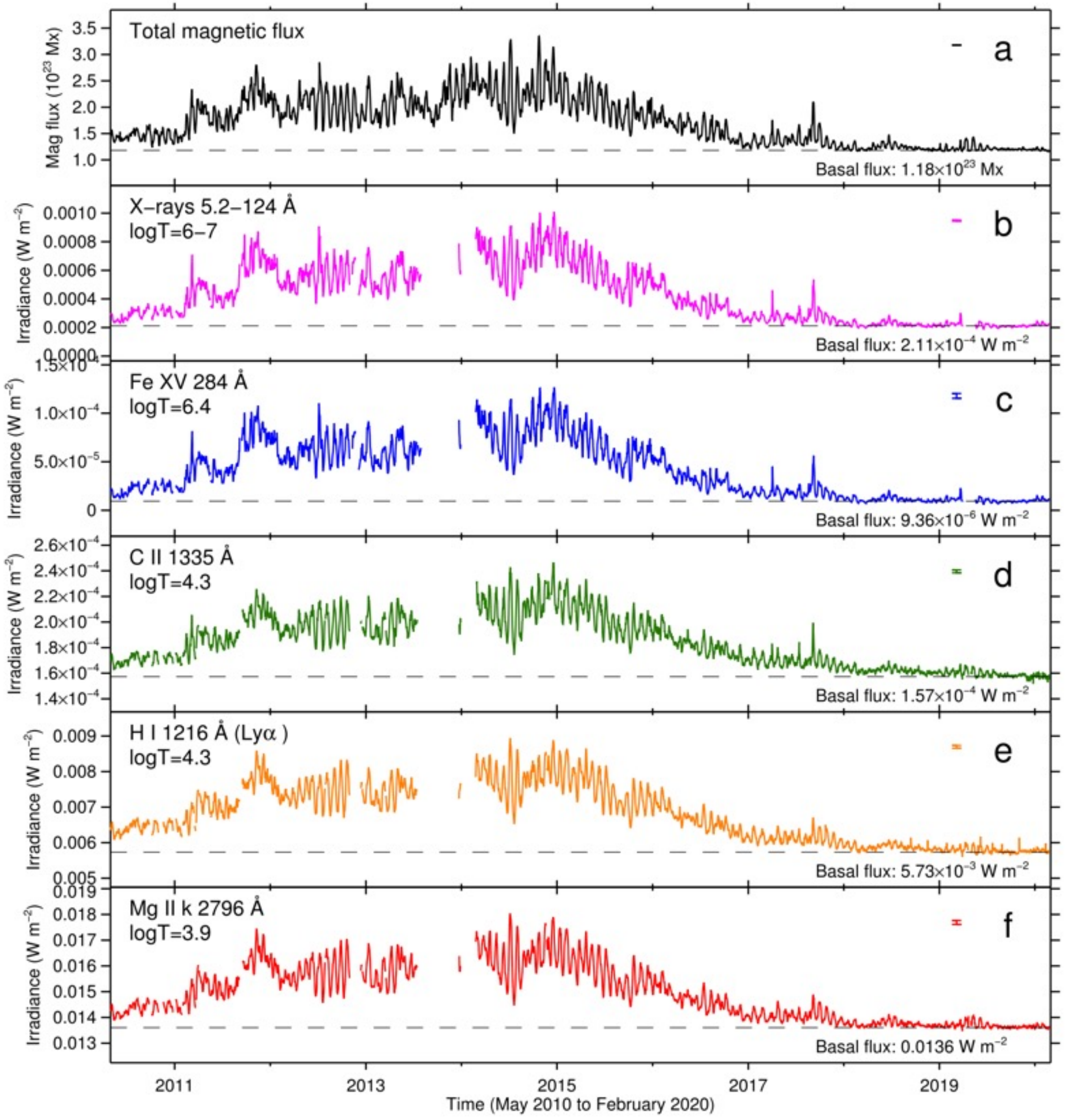
EUV ? FUV ?

NOTE: Stellar magnetic fluxes can be (relatively easily) measured with ground-based spectrosopic observations (Zeeman broadening method as in Kochukhov et al. 2020; Reiners+2022)

$$\Delta v_B = 1.4 \times 10^{-4} g_{\rm eff} \lambda B$$



X-ray flux, EUV&FUV line emission flux - Magnetic flux scaling



Total radial unsigned magnetic flux (SDO/HMI)

- daily value
- generated from four full-disk line-of-sight magnetograms per day

16 spectral lines/bands

- daily value
- X-ray to radio
- logT=3.8—7

EUV:SORCE/XPS
FUV:SORCE/SOLTIS

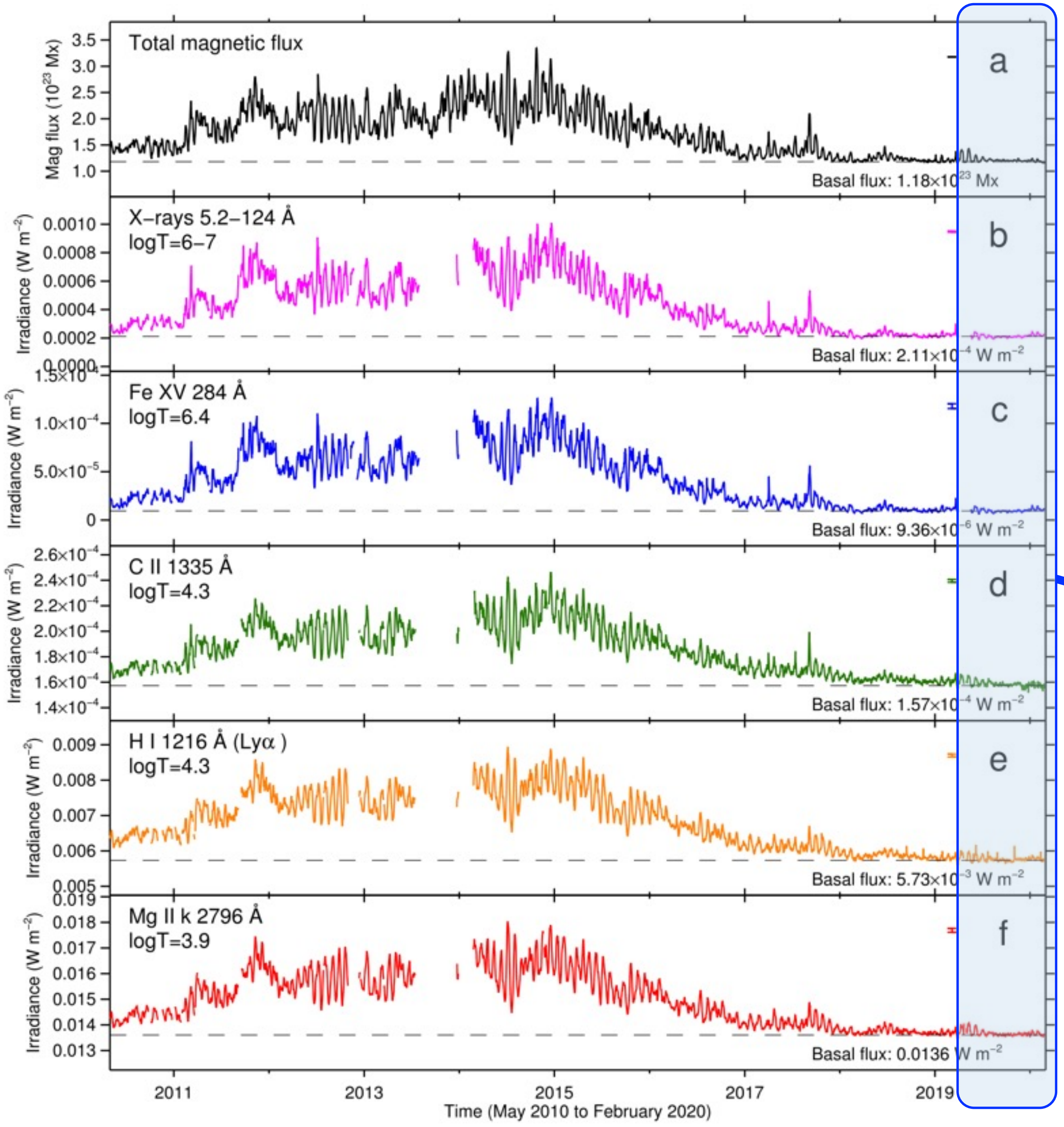
Line centers and widths adopted from Ayres (2021)

Toriumi & Airapetian (2022), Toriumi et al. (incl. Notsu) (2022)

Table 1
Summary of the Observables

Feature (1)	log(T/K) (2)	Wavelength (Å) (3)	Basal (4)	Minimum (5)	Maximum (6)	Unit (7)	Source (8)
Radial magnetic flux	3.8	6173.3	1.18×10^{23}	1.16×10^{23}	3.35×10^{23}	Mx	SDO/HMI
LOS magnetic flux	3.8	6173.3	7.02×10^{22}	6.85×10^{22}	2.52×10^{23}	Mx	SDO/HMI
Sunspot number	3.8	WL	0	0	220	⋯	WDC-SILSO (ver 2.0)
Sunspot area	3.8	WL	0	0	3120	MSH	USAF/NOAA
F10.7 cm radio	~6	10.7×10^{8}	68.83	63.67	466.57	sfu	DRAO
Total solar irradiance	3.8	WL	⋯	1358.5	1362.3	W m^{-2}	SORCE/TIM
X-rays 1–8 Å	6–7	1–8	0	1.00×10^{-9}	4.81×10^{-5}	W m^{-2}	GOES/XRS
X-rays 5.2–124 Å	6–7	5.2–124	2.11×10^{-4}	1.85×10^{-4}	1.01×10^{-3}	W m^{-2}	SORCE/XPS
Fe XV 284 Å	6.4	284.15 ± 1.50	9.36×10^{-6}	5.68×10^{-6}	1.27×10^{-4}	W m^{-2}	SORCE/XPS
Fe XIV 211 Å	6.3	211.32 ± 1.50	1.20×10^{-5}	9.88×10^{-6}	6.75×10^{-5}	W m^{-2}	SORCE/XPS
X-rays (XRT)	6.2 ± 0.1	5–60	5.00×10^{-5}	4.71×10^{-5}	1.01×10^{-3}	W m^{-2}	Hinode/XRT
Fe XII 193+195 Å	6.2	193.50 ± 2.50	6.16×10^{-5}	5.66×10^{-5}	1.72×10^{-4}	W m^{-2}	SORCE/XPS
Fe XII 1349 Å	6.2	1349.40 ± 1.00	3.64×10^{-6}	3.23×10^{-6}	5.66×10^{-6}	W m^{-2}	SORCE/SOLSTICE
Fe X 174 Å	6.1	174.53 ± 1.50	5.64×10^{-5}	5.40×10^{-5}	0.90×10^{-4}	W m^{-2}	SORCE/XPS
Fe XI 180 Å	6.1	180.41 ± 1.50	4.57×10^{-5}	4.31×10^{-5}	0.95×10^{-4}	W m^{-2}	SORCE/XPS
F10.7 cm radio	~6	10.7×10^{8}	68.83	63.67	466.57	sfu	DRAO
Fe IX 171 Å	5.9	171.07 ± 1.50	5.50×10^{-5}	5.32×10^{-5}	0.73×10^{-4}	W m^{-2}	SORCE/XPS
N V 1238 Å	5.3	1238.90 ± 1.15	1.62×10^{-5}	1.55×10^{-5}	2.39×10^{-5}	W m^{-2}	SORCE/SOLSTICE
N V 1242 Å	5.3	1242.95 ± 1.00	1.04×10^{-5}	9.89×10^{-6}	1.54×10^{-5}	W m^{-2}	SORCE/SOLSTICE
C IV 1548 Å	5.1	1548.25 ± 1.20	1.11×10^{-4}	1.07×10^{-4}	1.53×10^{-4}	W m^{-2}	SORCE/SOLSTICE
C IV 1551 Å	5.1	1550.73 ± 0.95	6.58×10^{-5}	6.38×10^{-5}	9.02×10^{-5}	W m^{-2}	SORCE/SOLSTICE
C III 1175 Å	5.0	1175.70 ± 1.75	5.52×10^{-5}	5.35×10^{-5}	8.24×10^{-5}	W m^{-2}	SORCE/SOLSTICE
He II 256 Å+blends	4.9	256.30 ± 3.00	5.53×10^{-5}	5.20×10^{-5}	1.21×10^{-4}	W m^{-2}	SORCE/XPS
He II 304 Å	4.9	304.00 ± 1.00	4.25×10^{-4}	4.09×10^{-4}	6.19×10^{-4}	W m^{-2}	SORCE/XPS
Si IV 1393 Å	4.9	1393.85 ± 1.30	4.45×10^{-5}	4.27×10^{-5}	7.66×10^{-5}	W m^{-2}	SORCE/SOLSTICE
Si IV 1402 Å	4.9	1402.85 ± 0.85	2.32×10^{-5}	2.25×10^{-5}	3.91×10^{-5}	W m^{-2}	SORCE/SOLSTICE
Si III 1206 Å	4.8	1206.60 ± 1.25	8.59×10^{-5}	8.32×10^{-5}	1.66×10^{-4}	W m^{-2}	SORCE/SOLSTICE
He I 10830 Å	4.5	10830.40 ± 0.25	0.0292	0.0270	0.0308	W m^{-2}	SORCE/SIM & SOLIS/ISS
C II 1335 Å	4.3	1335.25 ± 1.90	1.57×10^{-4}	1.52×10^{-4}	2.46×10^{-4}	W m^{-2}	SORCE/SOLSTICE
H I 1216 Å (Lyα)	4.3	1215.70 ± 2.00	5.73×10^{-3}	5.60×10^{-3}	8.94×10^{-3}	W m^{-2}	SORCE/SOLSTICE
O I 1302 Å	4.2	1302.20 ± 0.85	4.16×10^{-5}	3.93×10^{-5}	5.40×10^{-5}	W m^{-2}	SORCE/SOLSTICE
O I 1305 Å	4.2	1305.50 ± 1.75	9.14×10^{-5}	8.77×10^{-5}	1.17×10^{-4}	W m^{-2}	SORCE/SOLSTICE
Mg II k 2796 Å	(3.9)	2796.38 ± 0.78	0.0136	0.0135	0.0180	W m^{-2}	SORCE/SOLSTICE
Mg II h 2803 Å	(3.9)	2803.48 ± 0.65	0.0097	0.0096	0.0126	W m^{-2}	SORCE/SOLSTICE
Cl I 1351 Å	(3.8)	1305.50 ± 1.75	9.06×10^{-6}	8.57×10^{-6}	1.17×10^{-5}	W m^{-2}	SORCE/SOLSTICE
Ca II K 3934 Å	(3.8)	3933.66 ± 0.50	0.0114	0.0111	0.0130	W m^{-2}	SORCE/SIM & SOLIS/ISS
Ca II H 3968 Å	(3.8)	3968.47 ± 0.50	0.0139	0.0139	0.0155	W m^{-2}	SORCE/SIM & SOLIS/ISS
H I 6563 Å (Hα)	(3.8)	6562.80 ± 0.50	0.0369	0.0360	0.0448	W m^{-2}	SORCE/SIM & SOLIS/ISS
Ca II 8542 Å	(3.8)	8542.10 ± 0.50	0.0347	0.0346	0.0392	W m^{-2}	SORCE/SIM & SOLIS/ISS

X-ray flux, EUV&FUV line emission flux - Magnetic flux scaling



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16 spectral lines/bands

- daily value
- X-ray to radio
- logT=3.8—7

EUV:SORCE/XPS
FUV:SORCE/SOLTIS

Line centers and widths adopted from Ayres (2021)

- Calculate basal flux and residual
  - Basal fluxes are defined as medians of data from Mar 2019 to Feb 2020 with following criteria
    - Sunspot number = 0
    - Total sunspot area = 0
    - Magnetic flux < 5th percentile of all time

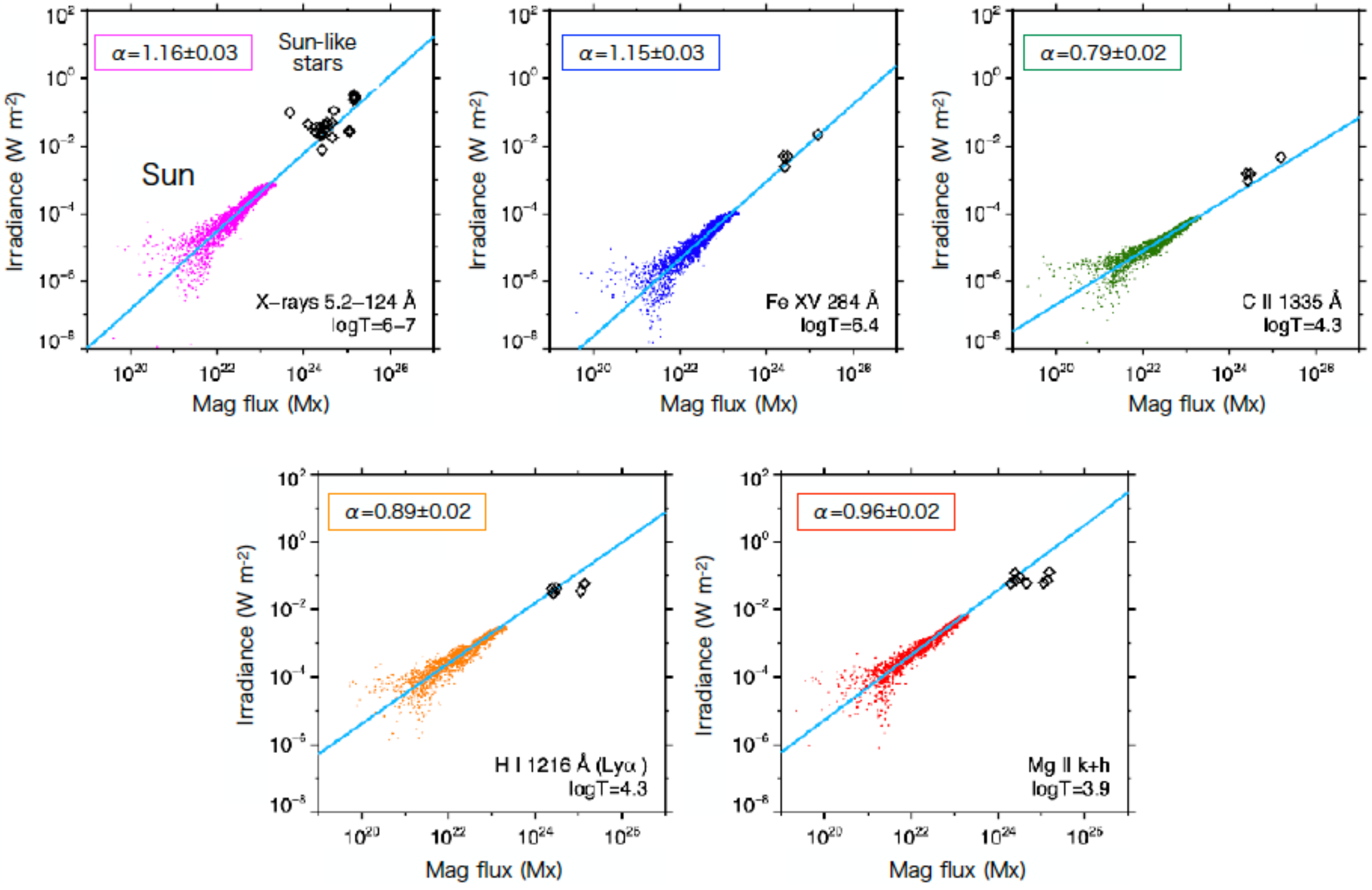
Residual = Light curve – Basal flux

- Basal flux: background heating
- Residual: heating due to magnetic elements

Toriumi & Airapetian (2022), Toriumi et al. (incl. Notsu) (2022)

X-ray flux, EUV&FUV emission line flux - Magnetic flux scaling

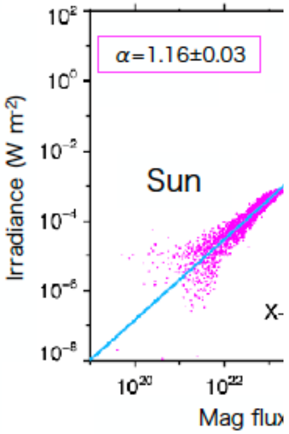
Mag flux—multi-line proportionality $F \propto \Phi^{\alpha}$



- Stellar data
  - Mainly G-dwarfs with ages from 50 Myr to 4.5 Gyr
  - Total magnetic flux based on Kochukhov et al. (2020)
  - Irradiance from published data

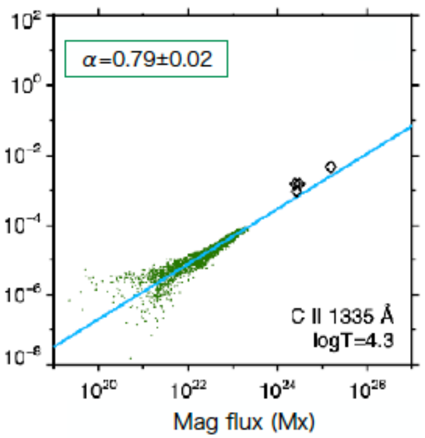
Toriumi & Airapetian (2022), Toriumi et al. (incl. Notsu) (2022)

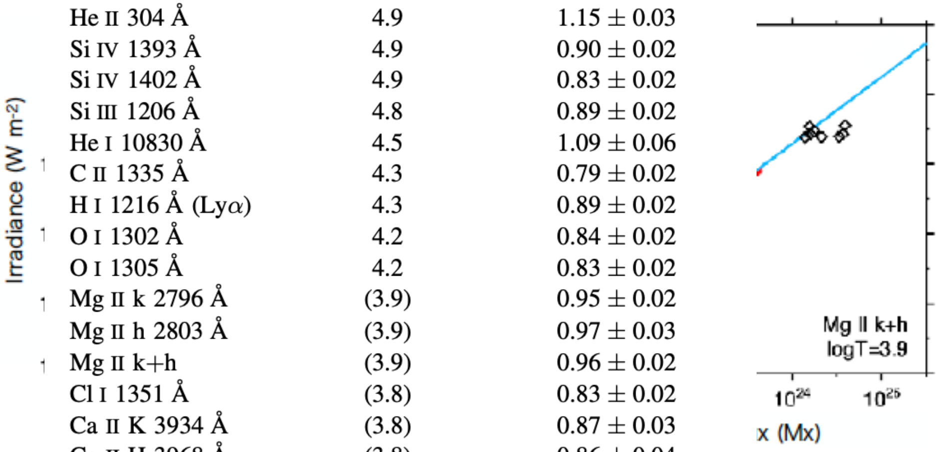
X-ray flux, EUV&FUV emission line flux - Magnetic flux scaling



Feature (1)	log(T/K) (2)	Power-law Index α (3)
X-rays 1–8 Å	6–7	1.42 ± 0.04
X-rays 5.2–124 Å	6–7	1.16 ± 0.03
Fe XV 284 Å	6.4	1.15 ± 0.03
Fe XIV 211 Å	6.3	1.15 ± 0.03
X-rays (XRT)	6.2 ± 0.1	0.95 ± 0.03
Fe XII 193+195 Å	6.2	1.14 ± 0.03
Fe XII 1349 Å	6.2	0.71 ± 0.02
Fe X 174 Å	6.1	1.15 ± 0.03
Fe XI 180 Å	6.1	1.15 ± 0.03
F10.7 cm radio	∼6	1.24 ± 0.03
Fe IX 171 Å	5.9	1.15 ± 0.03
N V 1238 Å	5.3	0.82 ± 0.02
N V 1242 Å	5.3	0.85 ± 0.02
C IV 1548 Å	5.1	0.85 ± 0.02
C IV 1551 Å	5.1	0.81 ± 0.02
C III 1175 Å	5.0	0.82 ± 0.02
He II 256 Å	4.9	1.14 ± 0.03
He II 304 Å	4.9	1.15 ± 0.03
Si IV 1393 Å	4.9	0.90 ± 0.02
Si IV 1402 Å	4.9	0.83 ± 0.02
Si III 1206 Å	4.8	0.89 ± 0.02
He I 10830 Å	4.5	1.09 ± 0.06
C II 1335 Å	4.3	0.79 ± 0.02
H I 1216 Å (Lyα)	4.3	0.89 ± 0.02
O I 1302 Å	4.2	0.84 ± 0.02
O I 1305 Å	4.2	0.83 ± 0.02
Mg II k 2796 Å	(3.9)	0.95 ± 0.02
Mg II h 2803 Å	(3.9)	0.97 ± 0.03
Mg II k+h	(3.9)	0.96 ± 0.02
Cl I 1351 Å	(3.8)	0.83 ± 0.02
Ca II K 3934 Å	(3.8)	0.87 ± 0.03
Ca II H 3968 Å	(3.8)	0.86 ± 0.04
H I 6563 Å (Hα)	(3.8)	−1.46 ± 0.14
Ca II 8542 Å	(3.8)	−1.52 ± 0.45

ty $F \propto \Phi^{\alpha}$





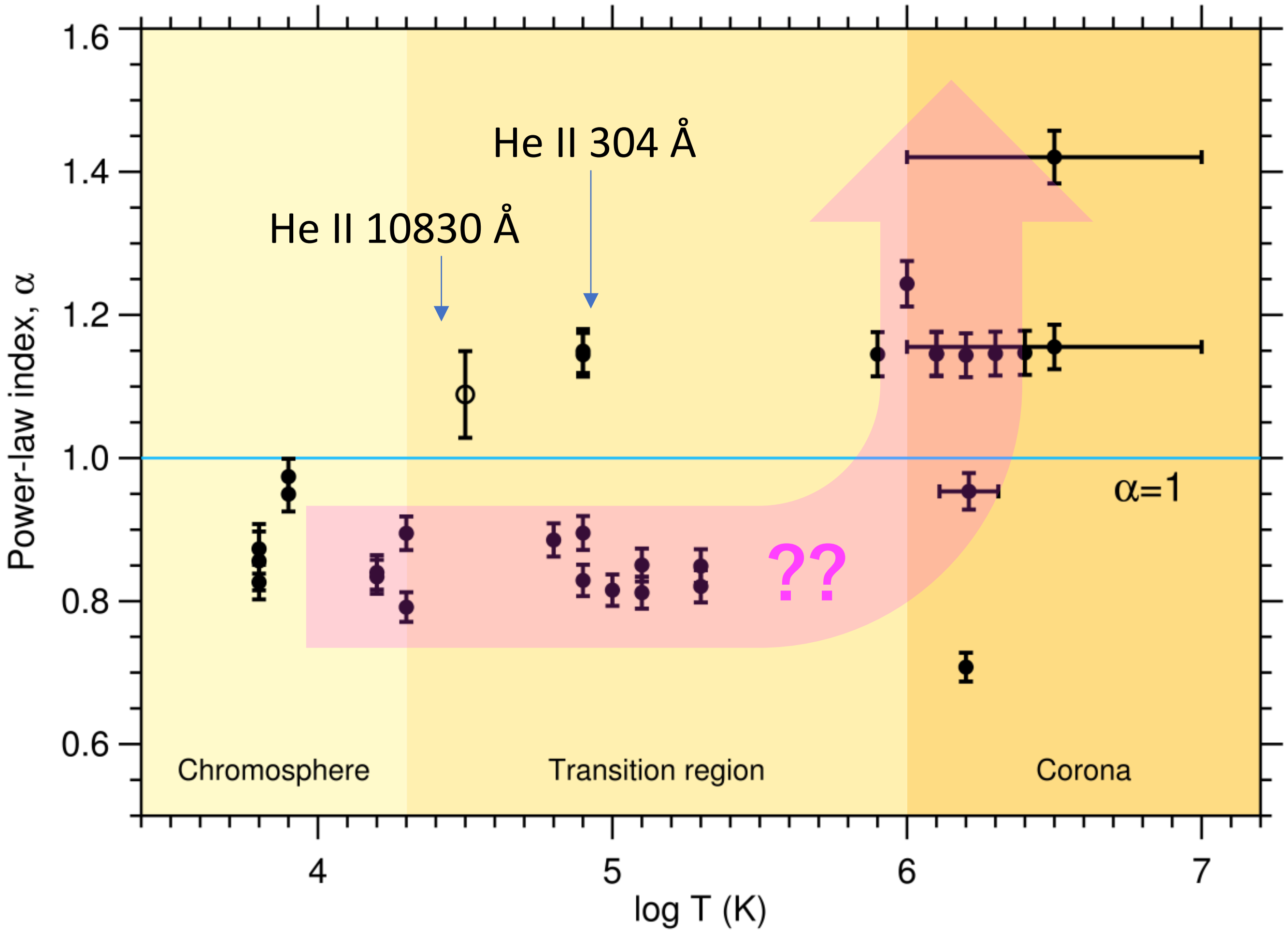
- Stellar data
  - Mainly G-dwarfs with ages from 50 Myr to 4.5 Gyr
  - Total magnetic flux based on Kochukhov et al. (2020)
  - Irradiance from published data

- The universality holds for wide range of temperature of $10^{4\text{-}7}$ K of spectral lines

✓ Heating mechanism is universal for the Sun and Sun-like stars, regardless of age or activity

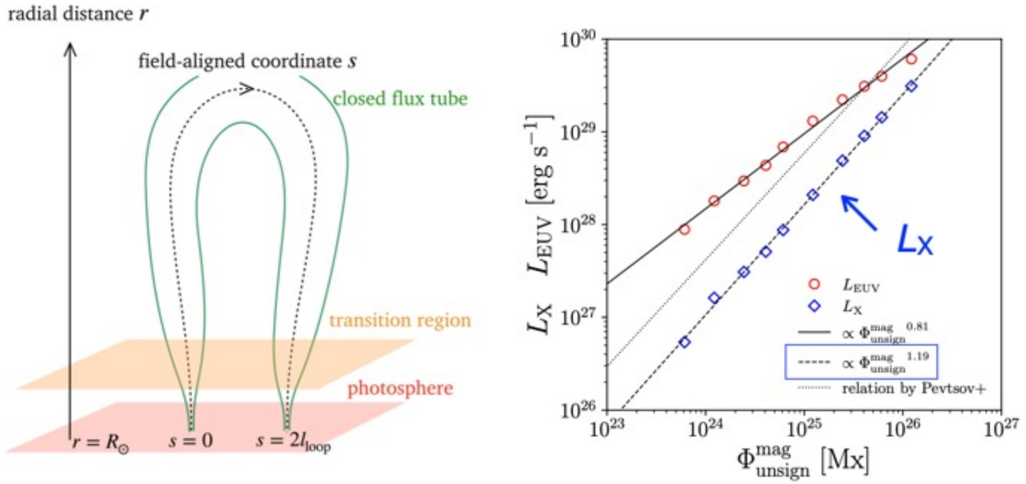
Toriumi & Airapetian (2022), Toriumi et al. (incl. Notsu) (2022)

Power-law indices of flux-flux relations



- Corona: log T > 6
  - Most of the coronal proxies show α>1 (cf. α=1.15 for X-ray from Pevtsov+2003)
  - Consistent with theoretical and Numerical models (Zhuleku+2020; also Fisher+1998, Takasao+2020)

- TR to chromosphere: log T<6
  - α<1 for many proxies, indicating that the efficiency of atmospheric heating is weaker?
  - In line with the previous studies (Skumanich+1975, Schrijver+1989, Loukitcheva+2009, Barczynski+2018)
  - For numerical modeling, radiative transfer may be needed.



[Shoda & Takasao 2020]

The Astrophysical Journal, 945:147 (18pp), 2023 March 10 https://doi.org/10.3847/1538-4357/acbe38

Reconstructing the XUV Spectra of Active Sun-like Stars Using Solar Scaling Relations with Magnetic Flux

Kosuke Namekata[1], Shin Toriumi[2], Vladimir S. Airapetian[3,4], Munehito Shoda[5], Kyoko Watanabe[6], and Yuta Notsu[7,8,9]

Table 1
Summary of Data Sets

Satellite/Instr.	Wavelength (nm)	Resl./Samp.[a] (nm)	Obs. Period (yr)	Used Period (month.yr)	Basal Period[e] (month.yr)	Ver.[d]	Lev.[d]
(1) X-ray and short EUV							
SORCE/XPS	0.1–40	0.1	2003–2020	5.2010–2.2020	3.2019–2.2020	18	4
(TIMED/SEE)[c]	0.5–180	1	2002–	1.2002–12.2016	1.2009–12.2009	12	3
(2) EUV							
SDO/EVE	33.3–106.6	0.1/0.02	2010–	5.2010–2.2020	3.2019–2.2020	7	3
(TIMED/SEE)[c]	0.5–180	0.4/1[b]	2002–	1.2002–12.2016	1.2009–12.2009	12	3
(3) FUV							
TIMED/SEE	0.5–180	0.4/1[b]	2002–	1.2002–12.2016	1.2009–12.2009	12	3
SORCE/SOLSTICE[c]	115–310	0.1/0.025	2003–2020	5.2010–2.2020	3.2019–2.2020	18	3
(4) Magnetic field							
SOHO/MDI	…	…	1996–2011	1.2002–4.2010	…	…	…
SDO/HMI	…	…	2010–	5.2010–2.2020	3.2019–2.2020	…	…

Notes.
[a] Spectral resolutions and data samplings used in our analysis.
[b] See https://lasp.colorado.edu/home/see/overview/instrument-overview/.
[c] Data indicated in parentheses were not used in the main analysis but are presented in the appendices.
[d] Data versions and data levels.
[e] We note that the different activity minima may have different flux values, although there are not consistent observations that can show the differences (see, e.g., Clette 2021).

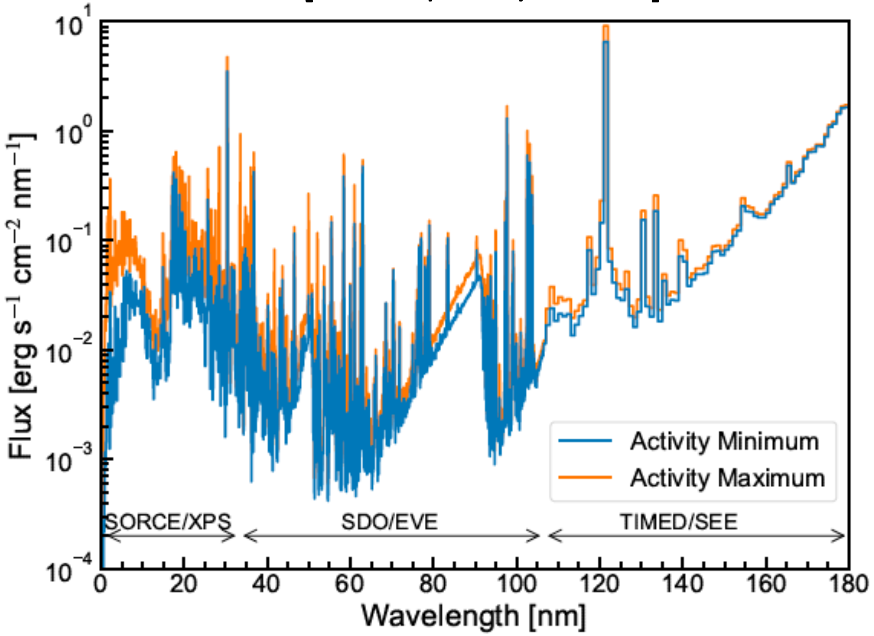
Analysis: Sun-as-a-star emission spectrum vs magnetic flux

- We analyzed a correlation between full Sun-as-a-star spectrum (0.5-180 nm, daily-averaged) and total unsigned mag flux **for each wavelength (spectral resolution is 0.1-1 nm)**

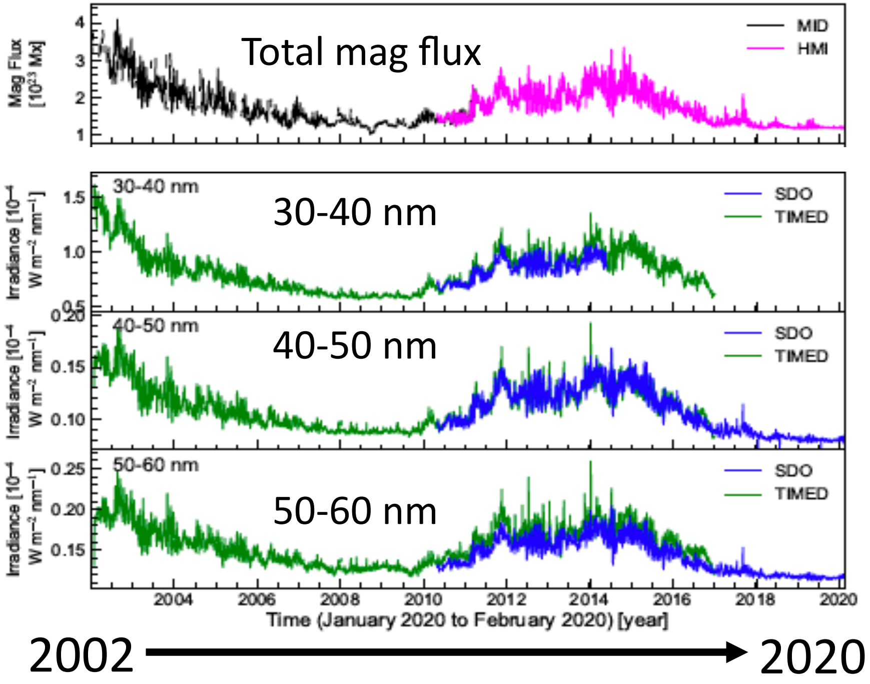
$$I(\lambda) = I_{basal}(\lambda) + \beta_\lambda \, (\phi - \phi_{basal})^{\alpha_\lambda}$$

Φ: total unsigned magnetic flux

Sun-as-a-star XUV+FUV spectrum [SORCE/SDO/TIMED]



Time series of mag flux & XUV+FUV flux



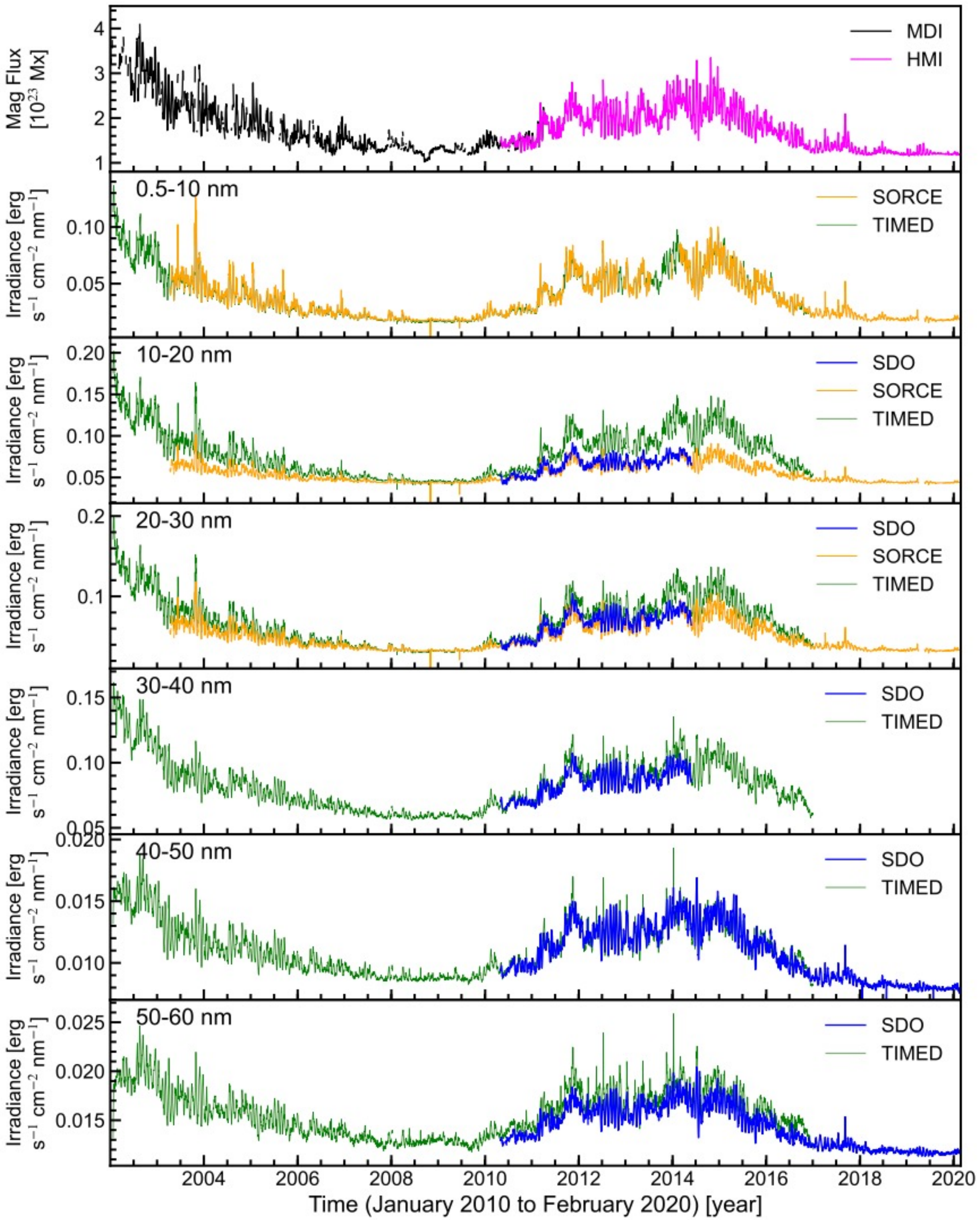
Total unsigned magnetic flux

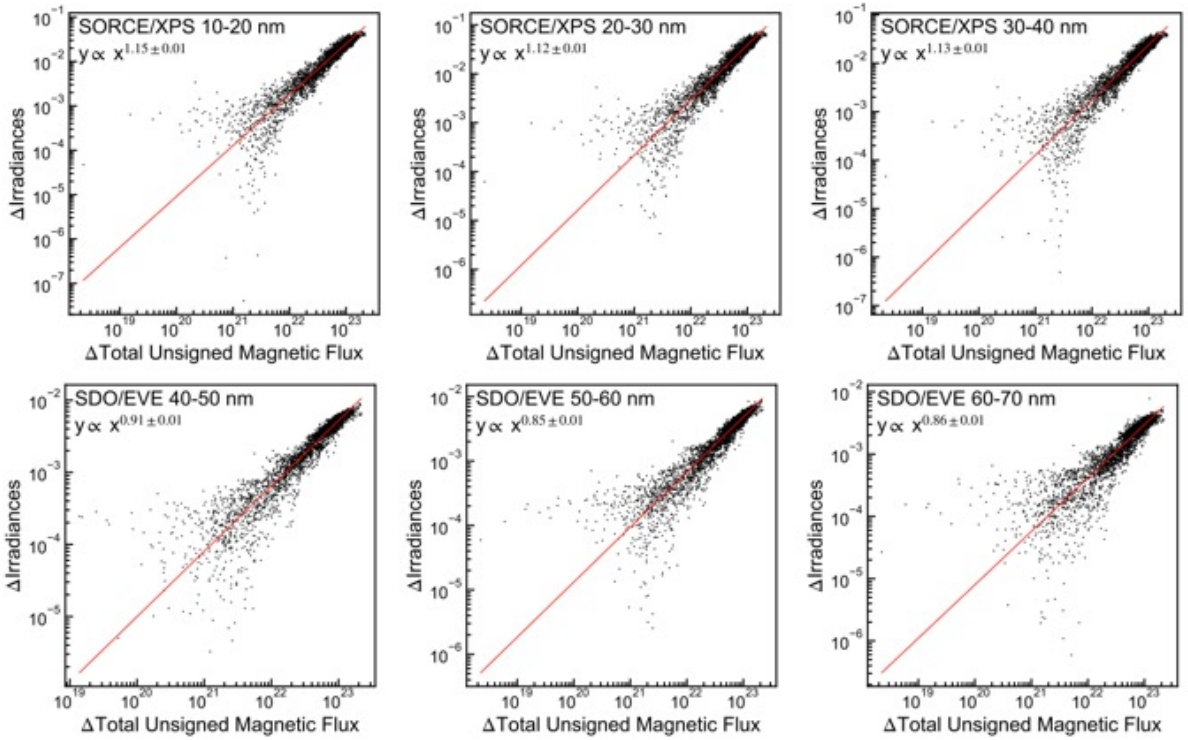
- daily value
- Full disk LOS value by SDO/HMI & SOHO MDI

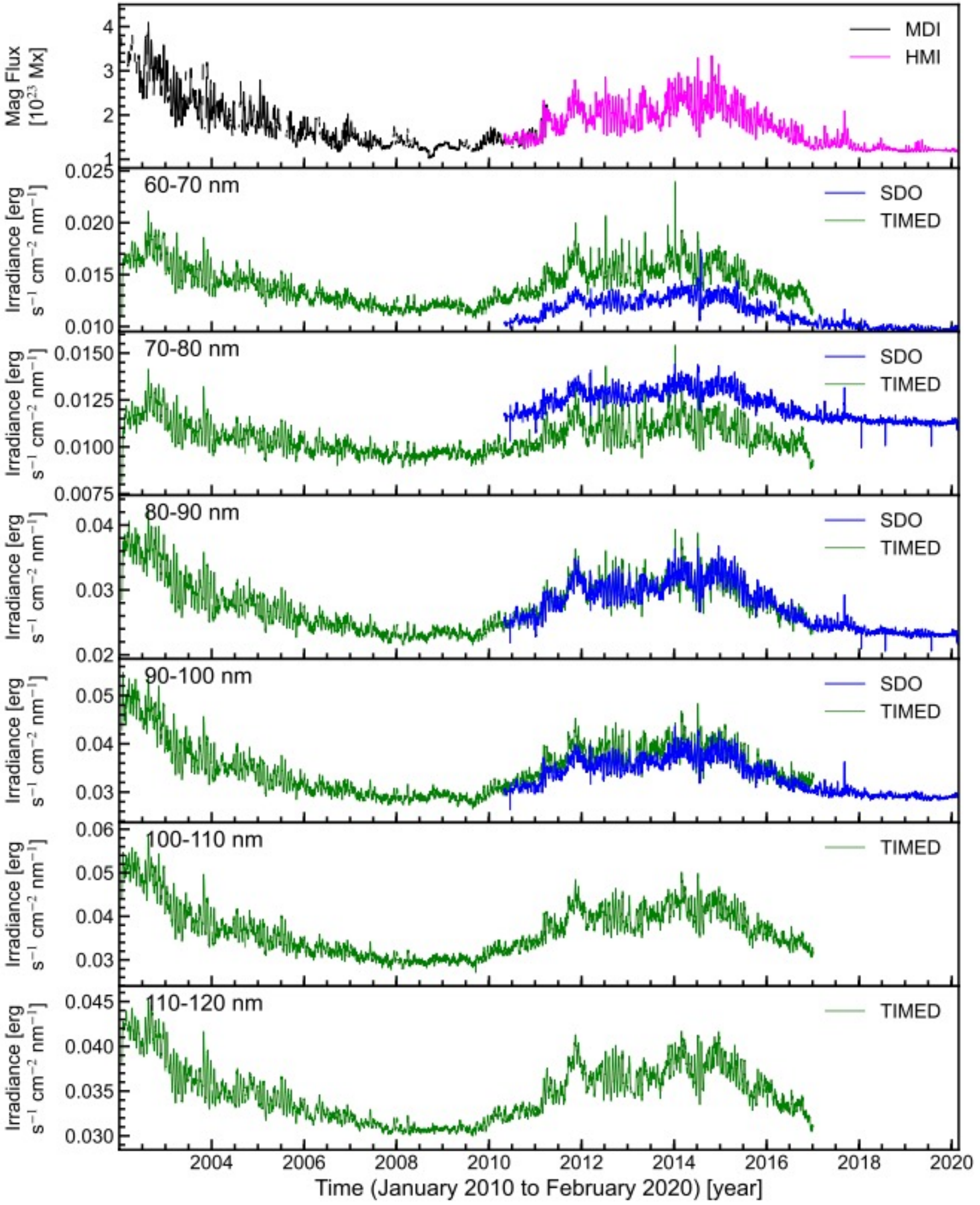
Sun-as-a-star spectrum

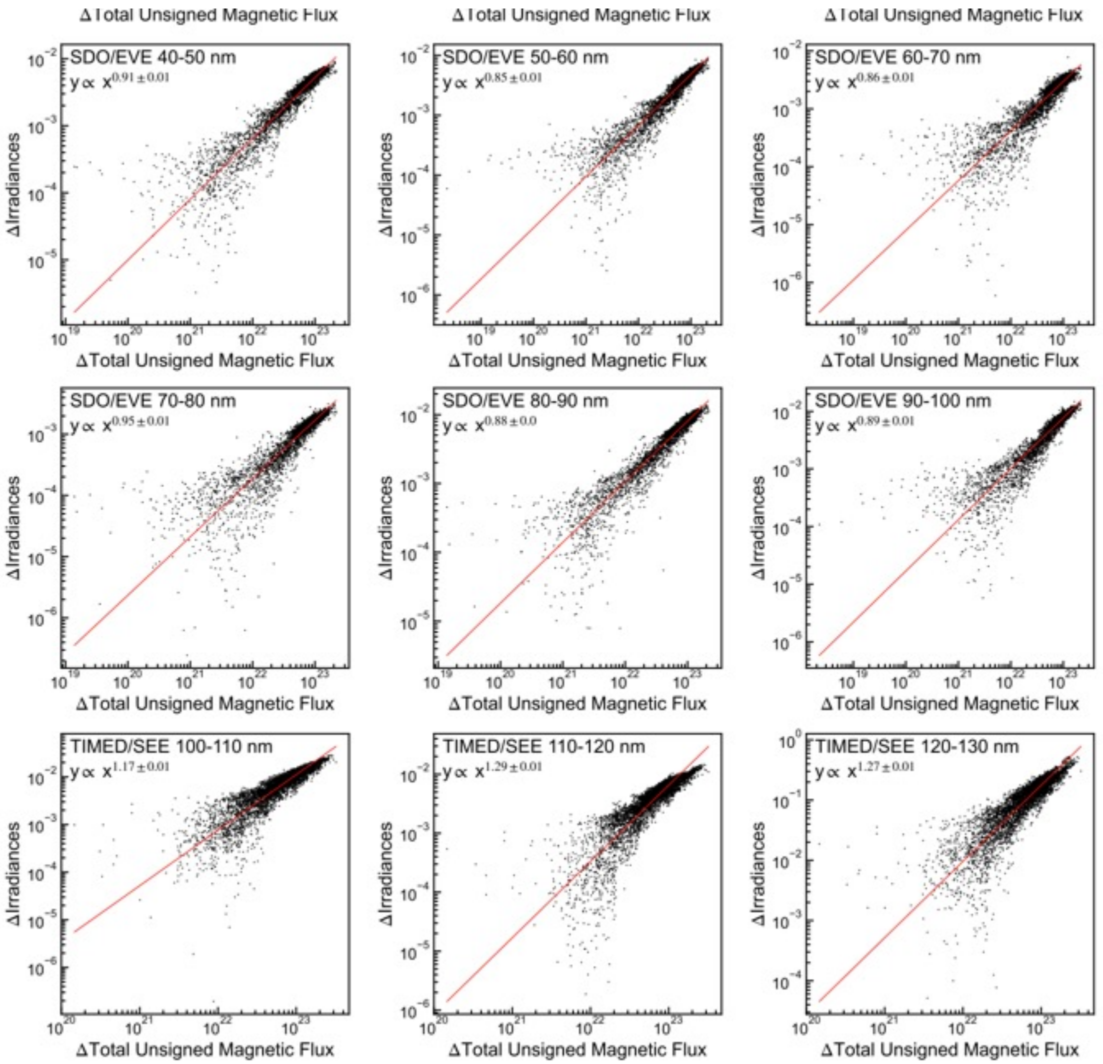
- daily value
- 0.1 – 180 nm
- SOURCE/XPS, SDO/EVE, TIMED/SEE

**The used EVE data: level 3 daily averaged spectrum of version 7


Mag Flux [10^23 Mx]
MDI
HMI
0.5-10 nm
SORCE
TIMED
10-20 nm
SDO
SORCE
TIMED
20-30 nm
SDO
SORCE
TIMED
30-40 nm
SDO
TIMED
40-50 nm
SDO
TIMED
50-60 nm
SDO
TIMED
Irradiance [erg s^-1 cm^-2 nm^-1]
Time (January 2010 to February 2020) [year]


SORCE/XPS 10-20 nm
y ∝ x^1.15±0.01
SORCE/XPS 20-30 nm
y ∝ x^1.12±0.01
SORCE/XPS 30-40 nm
y ∝ x^1.13±0.01
SDO/EVE 40-50 nm
y ∝ x^0.91±0.01
SDO/EVE 50-60 nm
y ∝ x^0.85±0.01
SDO/EVE 60-70 nm
y ∝ x^0.86±0.01
ΔIrradiances
ΔTotal Unsigned Magnetic Flux


MDI
HMI
Mag Flux [10^{23} Mx]
60-70 nm
70-80 nm
80-90 nm
90-100 nm
100-110 nm
110-120 nm
SDO
TIMED
Irradiance [erg s^{-1} cm^{-2} nm^{-1}]
Time (January 2010 to February 2020) [year]


Δ Total Unsigned Magnetic Flux
SDO/EVE 40-50 nm
$y \propto x^{0.91\pm0.01}$
SDO/EVE 50-60 nm
$y \propto x^{0.85\pm0.01}$
SDO/EVE 60-70 nm
$y \propto x^{0.86\pm0.01}$
SDO/EVE 70-80 nm
$y \propto x^{0.95\pm0.01}$
SDO/EVE 80-90 nm
$y \propto x^{0.88\pm0.0}$
SDO/EVE 90-100 nm
$y \propto x^{0.89\pm0.01}$
TIMED/SEE 100-110 nm
$y \propto x^{1.17\pm0.01}$
TIMED/SEE 110-120 nm
$y \propto x^{1.29\pm0.01}$
TIMED/SEE 120-130 nm
$y \propto x^{1.27\pm0.01}$
ΔIrradiances
ΔTotal Unsigned Magnetic Flux

Result: Scaling relations for each wavelength

- Power-low relations as a function of ϕ (total mag. flux) was derived for each wavelength

⇒ If stellar total magnetic flux is known, then we can derive stellar EUV spectrum

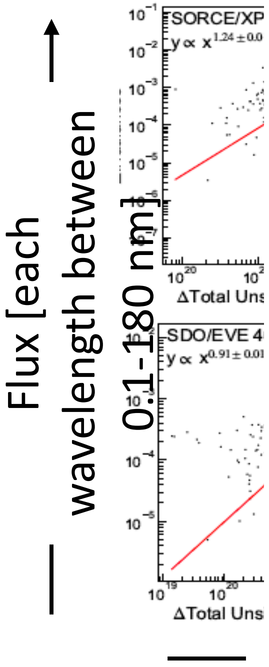


Table 3

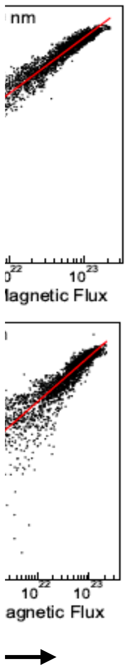
Formula for Estimating Stellar XUV Fluxes in Best Wavelength Resolution as a Function of Total Unsigned Flux Φ of Stars (in Units of erg s^{-1} cm^{-2} nm^{-1} at 1 au)

Wavelength (nm)	C.C.	$I(\lambda) = I_0(\lambda) + 10^{\beta(\lambda)}(\Phi - \Phi_0)^{\alpha(\lambda)}$ $I_0(\lambda)$	$\alpha(\lambda)$	$\beta(\lambda)$
0.10	0.65	1.76×10^{-15}	$11.30_{\pm0.27}$	$-266.9_{\pm6.20}$
0.20	0.65	2.58×10^{-10}	$7.20_{\pm0.16}$	$-170.2_{\pm3.67}$
0.30	0.66	8.67×10^{-8}	$4.11_{\pm0.08}$	$-98.9_{\pm1.92}$
0.40	0.71	1.84×10^{-6}	$2.72_{\pm0.05}$	$-66.3_{\pm1.08}$
0.50	0.78	1.19×10^{-5}	$1.83_{\pm0.03}$	$-45.6_{\pm0.57}$
0.60	0.83	5.45×10^{-5}	$1.51_{\pm0.02}$	$-37.9_{\pm0.40}$
0.70	0.85	2.74×10^{-4}	$1.38_{\pm0.01}$	$-34.3_{\pm0.33}$
0.80	0.89	2.20×10^{-4}	$1.26_{\pm0.01}$	$-31.5_{\pm0.23}$
0.90	0.91	4.06×10^{-4}	$1.22_{\pm0.01}$	$-30.4_{\pm0.21}$
1.00	0.90	1.16×10^{-3}	1.20 [illegible]	$-29.5_{\pm0.21}$
170.50	0.52	6.37×10^{-1}	$1.15_{\pm0.02}$	$-28.0_{\pm0.41}$
171.50	0.54	6.43×10^{-1}	$1.11_{\pm0.02}$	$-27.0_{\pm0.38}$
172.50	0.45	7.28×10^{-1}	$1.51_{\pm0.03}$	$-36.4_{\pm0.74}$
173.50	0.45	7.23×10^{-1}	$1.60_{\pm0.04}$	$-38.6_{\pm0.81}$
174.50	0.43	8.85×10^{-1}	$1.25_{\pm0.02}$	$-30.3_{\pm0.54}$
175.50	0.46	1.08×10^{0}	$1.25_{\pm0.02}$	$-30.3_{\pm0.54}$
176.50	0.42	1.16×10^{0}	$0.99_{\pm0.02}$	$-24.3_{\pm0.42}$
177.50	0.36	1.43×10^{0}	$1.15_{\pm0.02}$	$-27.7_{\pm0.54}$
178.50	0.36	1.62×10^{0}	$1.23_{\pm0.03}$	$-29.8_{\pm0.66}$
179.50	0.38	1.64×10^{0}	$1.02_{\pm0.02}$	$-24.8_{\pm0.44}$

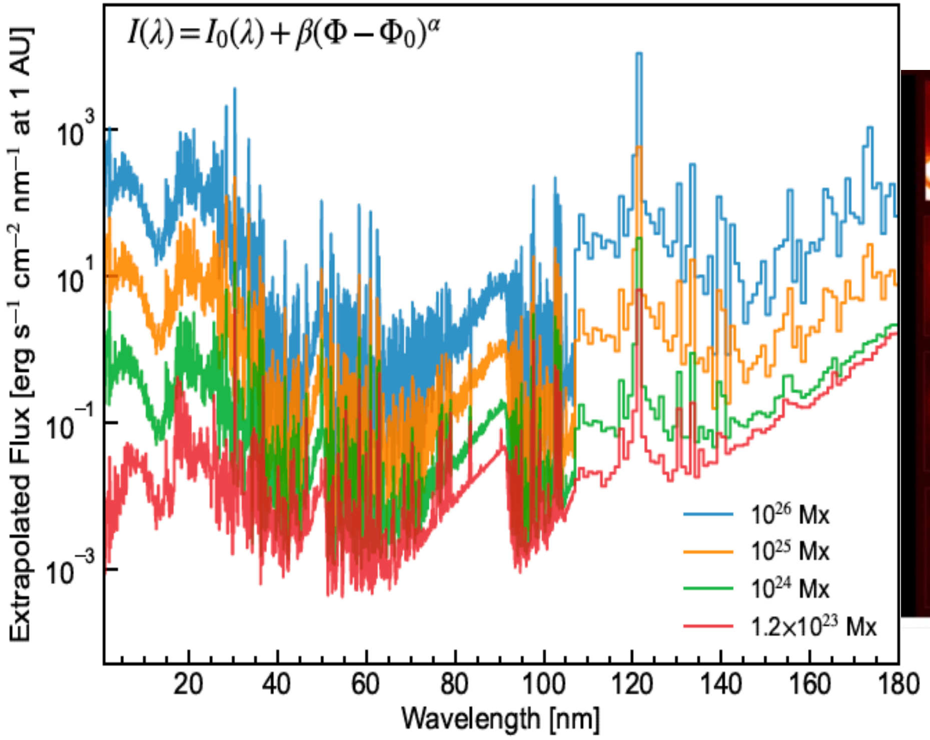
Note. The data are plotted in Figure 4 with blue lines. Φ is given in units of Mx. Φ_0 is the basal level of the magnetic flux, which is given as 1.18×10^{23} Mx.

(This table is available in its entirety in machine-readable form.)

Useful tables included in the paper



$$I(\lambda) = I_0(\lambda) + \beta(\Phi - \Phi_0)^{\alpha}$$

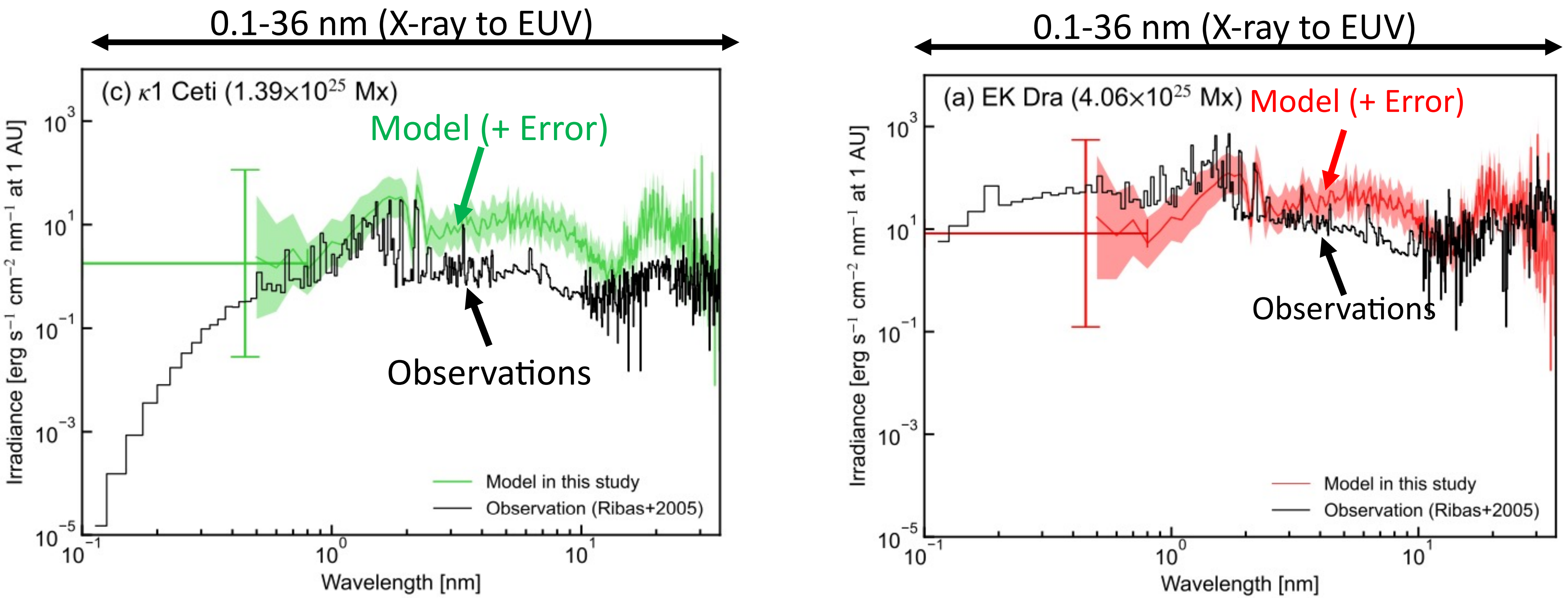


⇒ Then we compare with nearby Sun-like stars having the previous measurements of the mag. field and XUV spectra and discuss the predictability of our method!

Extended spectra vs. observations : X-ray + EUV

- Kappa 1 Ceti
- Age: 600 Myr & Teff: 5742 K
- Mag: 1.39 x 10^{25} Mx (**~40 x solar max**)

- EK Dra
- Age: 100 Myr & Teff: 5845 K
- Mag: 1.5 x 10^{25} Mx (**~120 x solar max**)

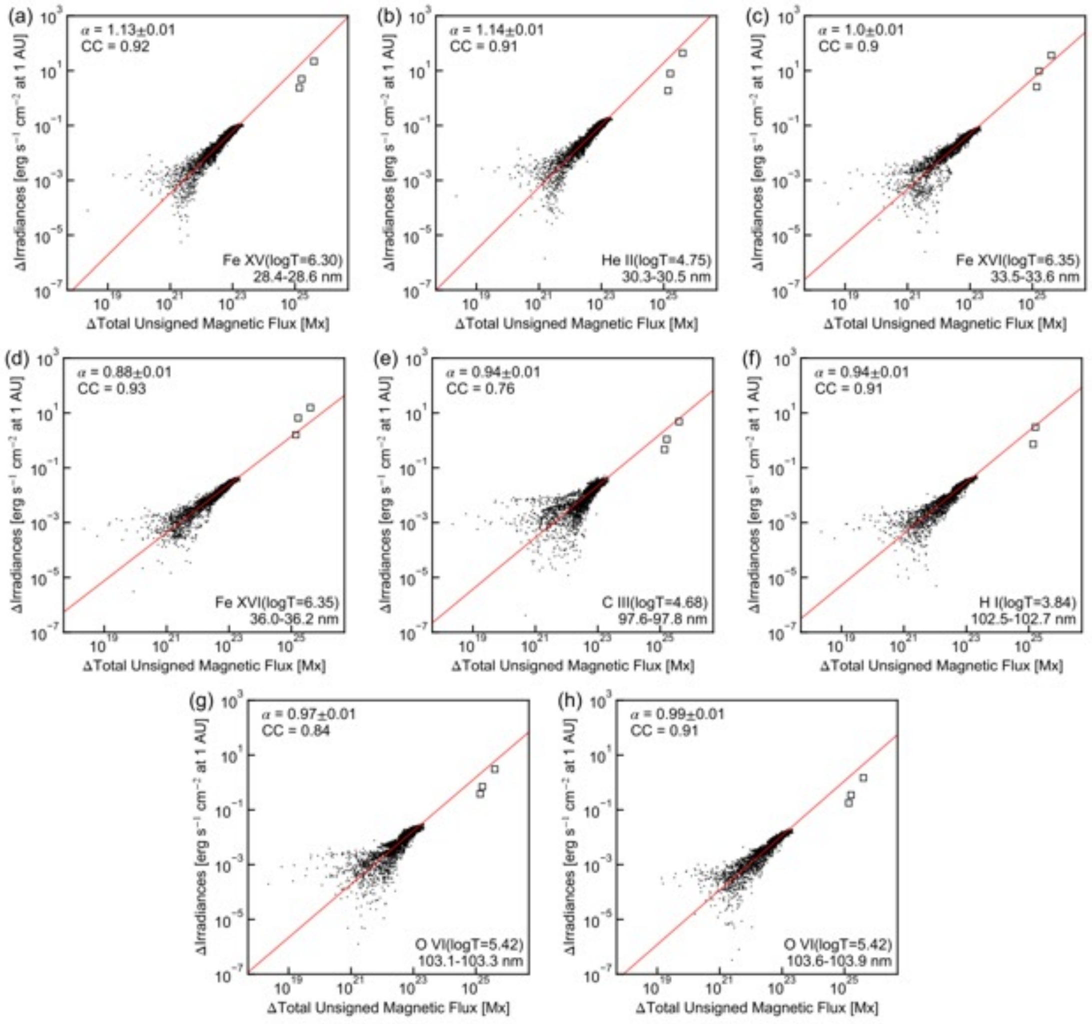


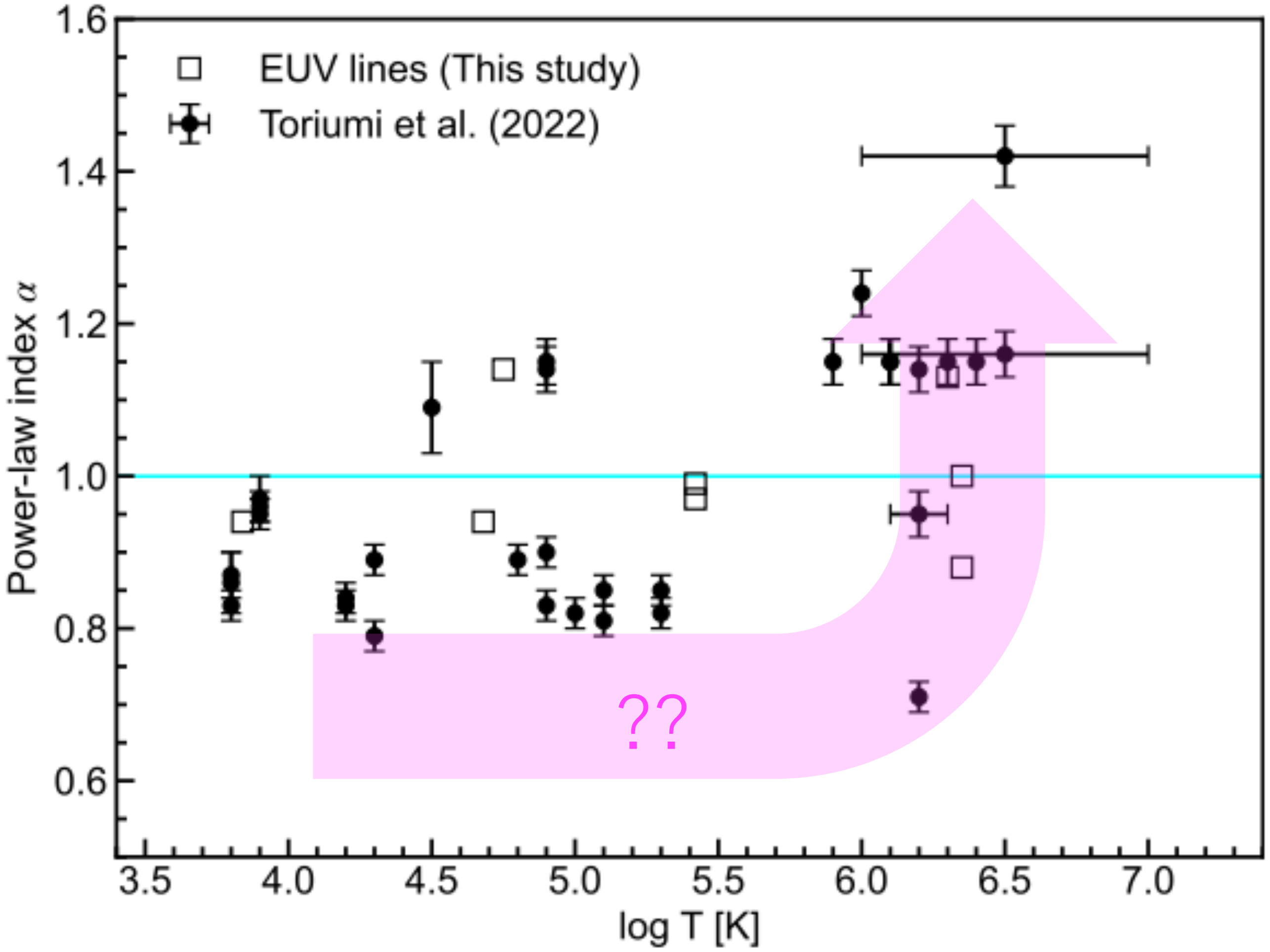
- Good agreement especially for X-ray and shortward EUV range (<36nm)

⇒ Suggests good prediction ability of our methods for estimating missing EUV range

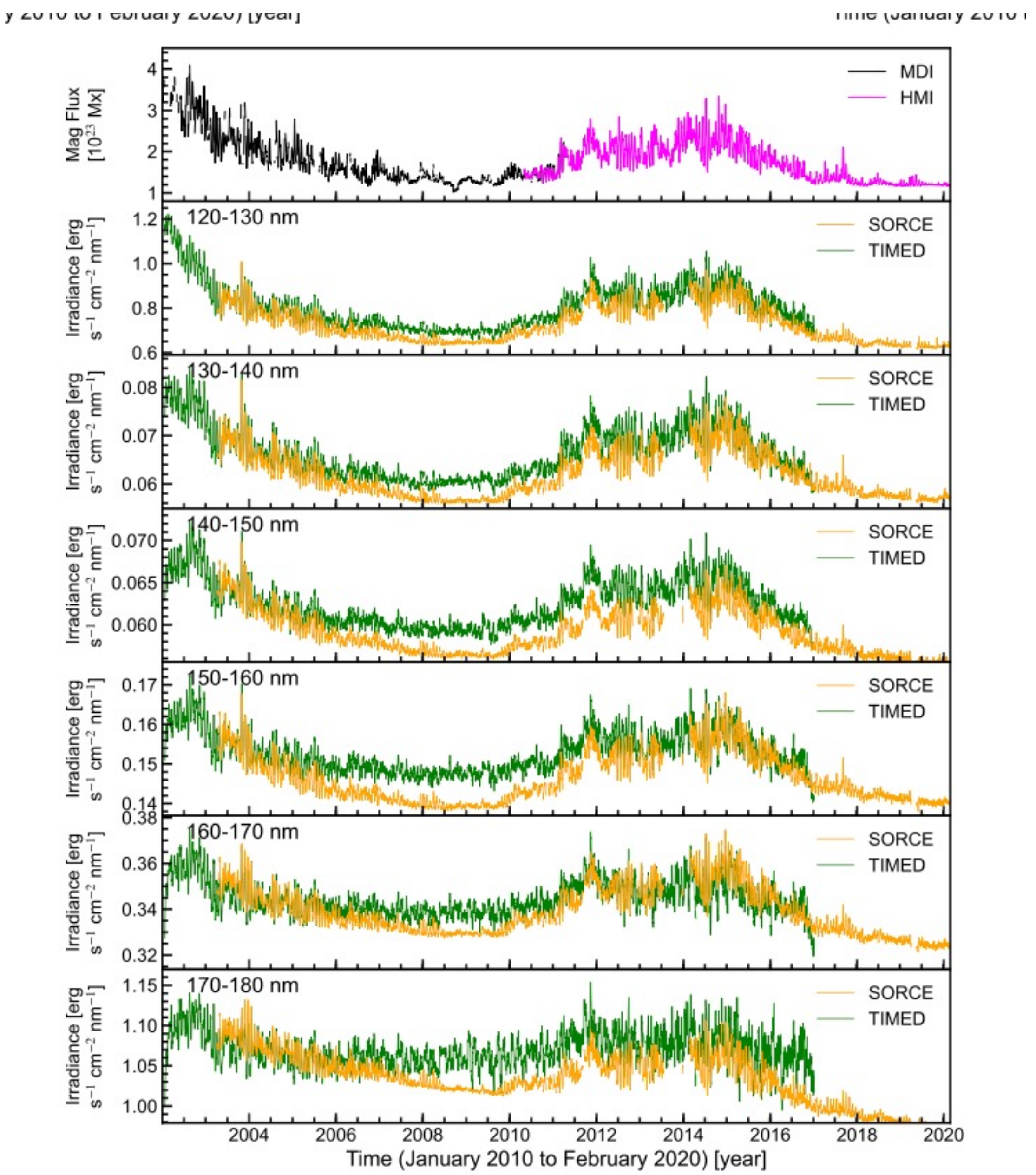
EUV Line flux vs magnetic flux

Young Sun-like stars (□) + Solar data

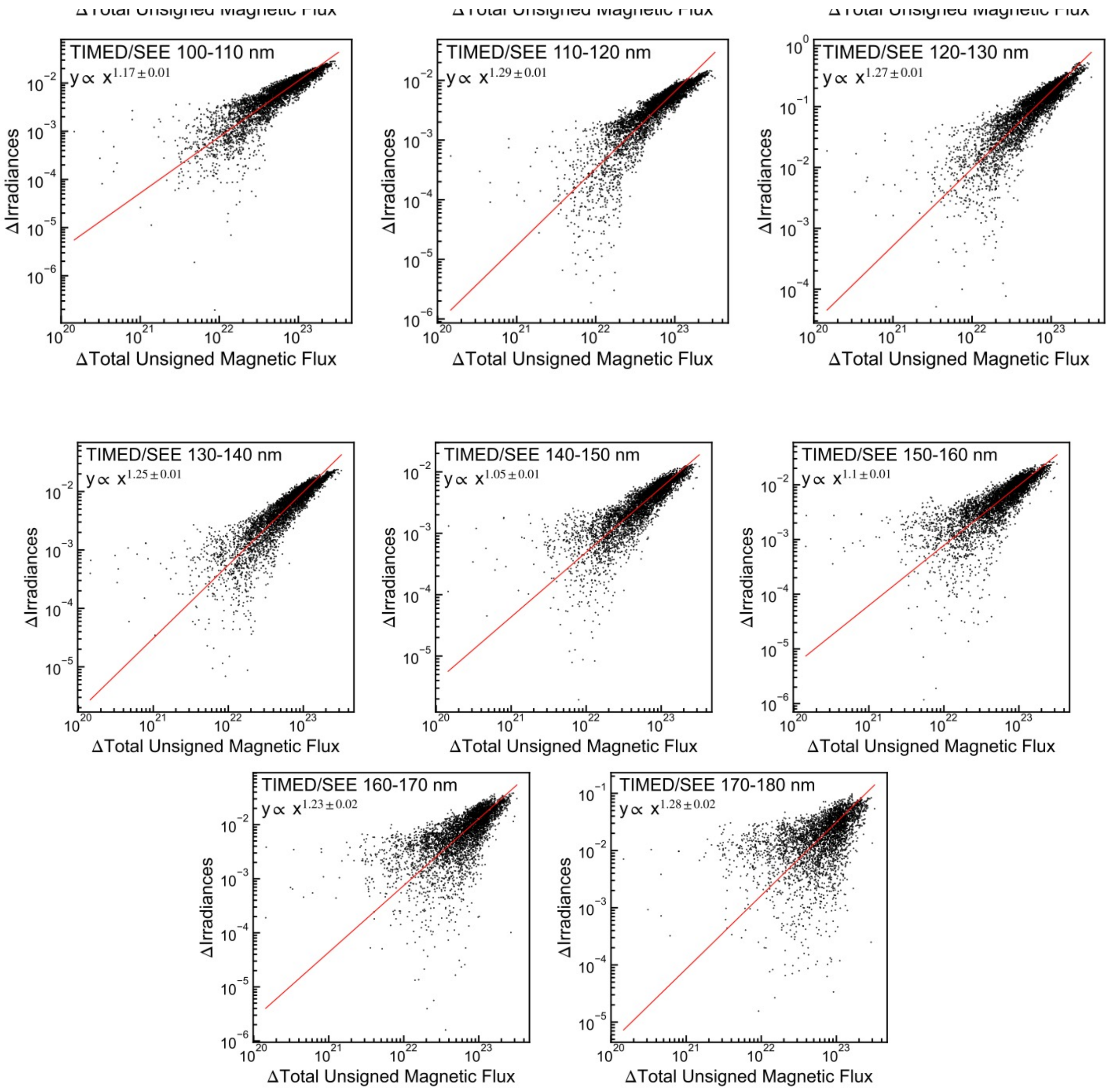




FUV

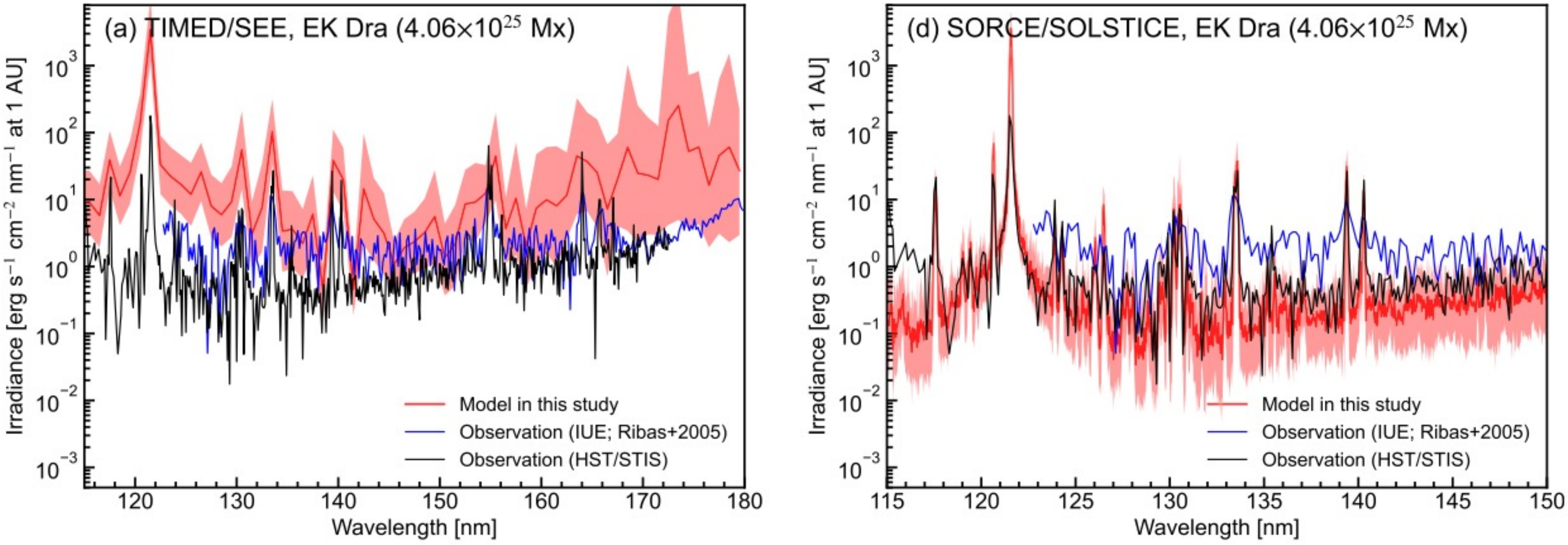


Mag Flux [10^23 Mx]
MDI
HMI
120-130 nm
130-140 nm
140-150 nm
150-160 nm
160-170 nm
170-180 nm
SORCE
TIMED
Irradiance [erg s^-1 cm^-2 nm^-1]
2004
2006
2008
2010
2012
2014
2016
2018
2020
Time (January 2010 to February 2020) [year]



TIMED/SEE 100-110 nm
y ∝ x^1.17±0.01
TIMED/SEE 110-120 nm
y ∝ x^1.29±0.01
TIMED/SEE 120-130 nm
y ∝ x^1.27±0.01
TIMED/SEE 130-140 nm
y ∝ x^1.25±0.01
TIMED/SEE 140-150 nm
y ∝ x^1.05±0.01
TIMED/SEE 150-160 nm
y ∝ x^1.1±0.01
TIMED/SEE 160-170 nm
y ∝ x^1.23±0.02
TIMED/SEE 170-180 nm
y ∝ x^1.28±0.02
ΔIrradiances
ΔTotal Unsigned Magnetic Flux

Extended spectra vs. observations : FUV



- FUV range: Within a order of magnitude difference

    SORCE/SOLSTICE data show better consistency

        with stellar FUV data than those with TIMED/SEE.

    Note: Only <150nm range is plotted here for SORCE/SOLSTICE because of the calibration issue

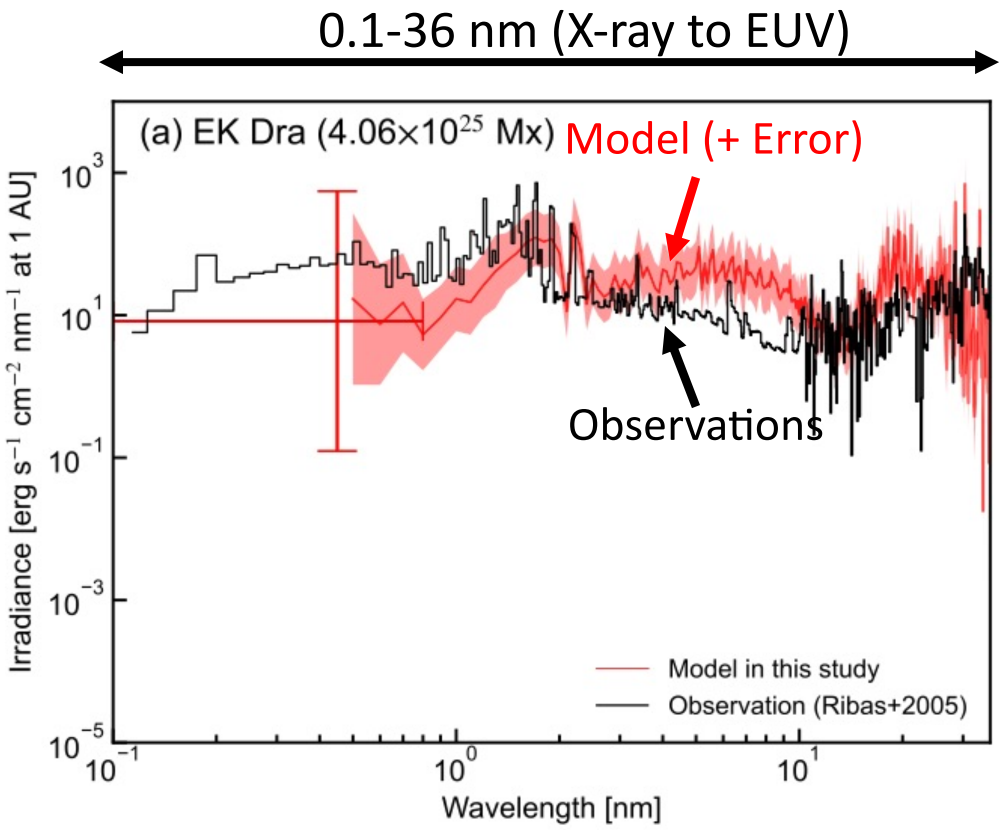
Discussion

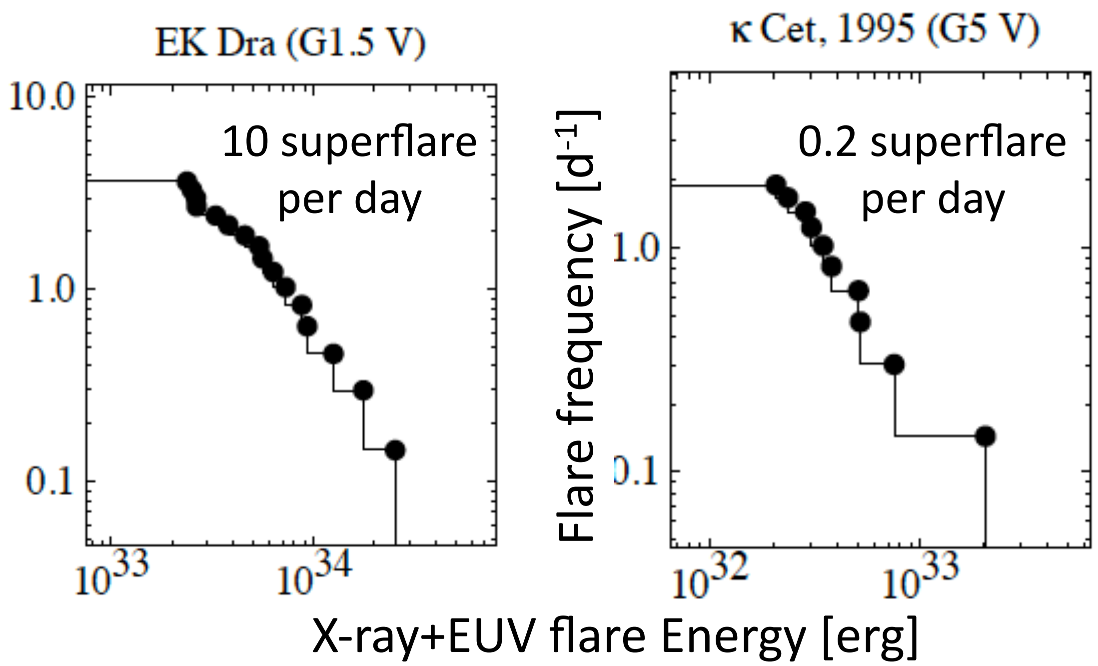
There are several factors that are not included

- Effects of Coronal Abundance (e.g., any differences between active and inactive stars ??)
- Young Stars like EK Dra produces frequent superflares [e.g., Audard+2000]

  ⇒ Flares can significantly contribute to the X-ray / EUV emission in very active Sun-like stars

  Note: our scaling is only for the quiescent XUV/FUV spectrum



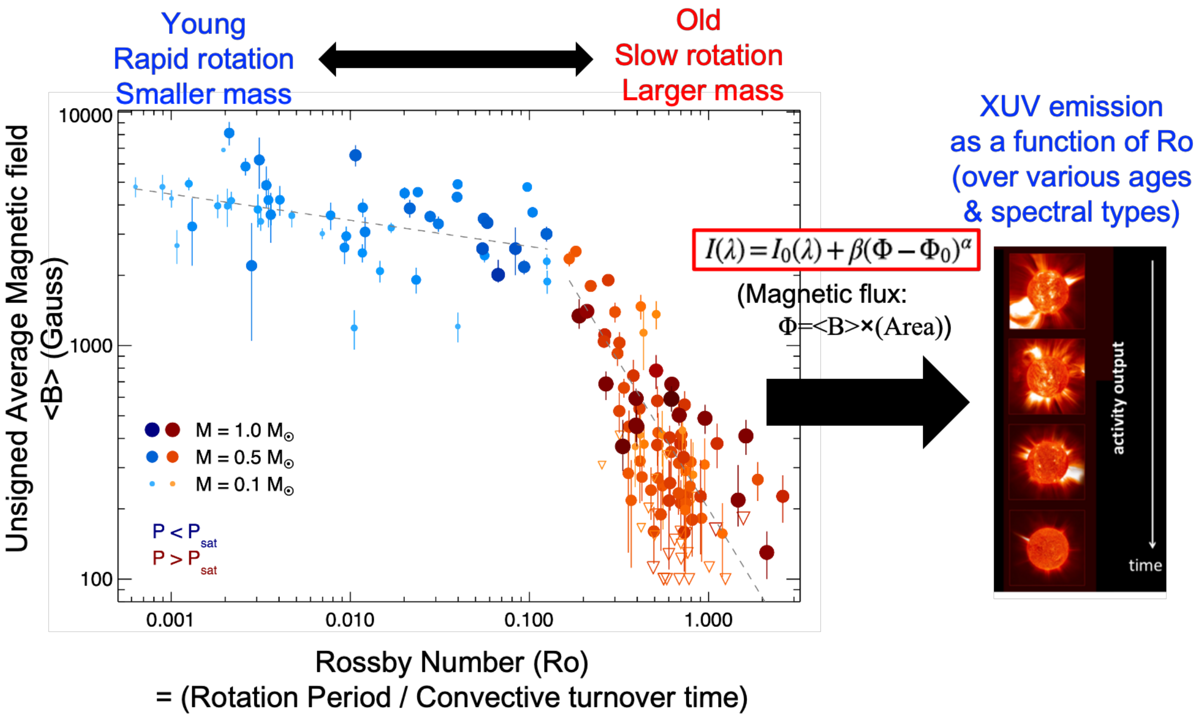


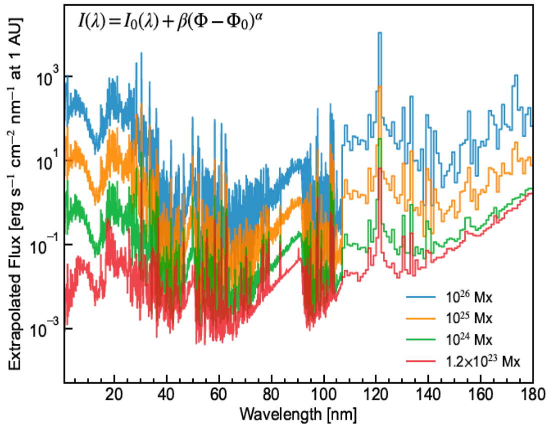
⇒ Future: establish scaling laws even for flares!

The Advantage and Applications of Our Model

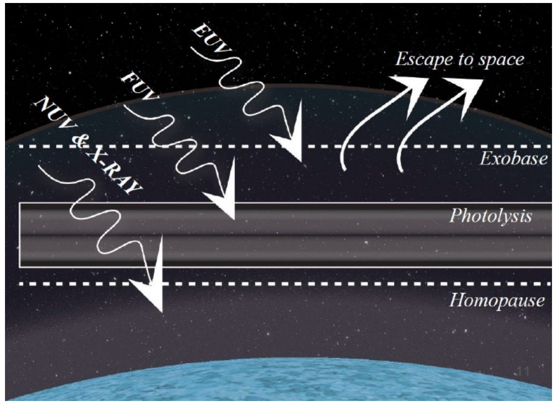
- The advantages in estimating stellar XUV+FUV spectrum
  1. Magnetic flux measurements are available from ground-based observations[1,2] ⇒ low cost
  2. Comparison with theoretical study is available [e.g. Shoda et al. 2021] ⇒ **physical understandings of ARs**

- If total unsigned magnetic flux of any given stars/ARs are obtained by observations or numerical modeling, we can easily reconstruct XUV+FUV spectrum ⇒ **This study has good synergy with your AR modellings!** [i.e., if you want stellar XUV spectrum, all you need is just to model/observe magnetic flux]





Contribution to exoplanet atmosphere



Further solar-stellar connections

- More stellar samples (G,K,M dwarfs)

  The scaling law only validated with 3 G-dwarfs.

  How about cooler M-dwarfs heating mechanism?

  Starting comparisons with more stellar

  X-ray&FUV archive data (G,K,M-dwarf from HST/XMM)

- Flare contribution on Young Sun's EUV

  SDO/EVE Sun-as-a-star flare data

  PISM-3 update ? (e.g., Chamberlin+)

- Discussions in MAVEN EUV team (LASP)

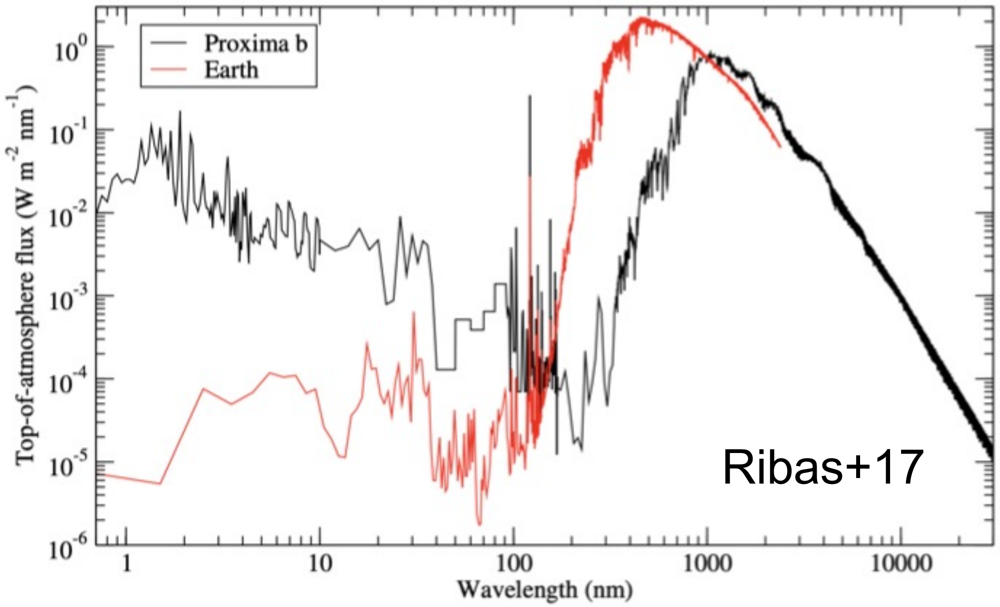
  Not only exoplanets, but also application

  to Young Sun – Young Mars interactions

- EUV dimming from SDO/EVE (e.g., Mason+16)

  Implications for Recent stellar CME study updates

  Dimming vs Line Doppler shifts (Veroning+22, Xu+22)



Top-of-atmosphere full spectral irradiance received by Proxima Cen b (black, EUV reconstructed) and the Earth (red)

Summary

- Analysis
  - Derived scaling laws $I(\lambda) \propto \Phi$ from Sun-as-a-star data and extended them to young Sun-like stars.
- Results
  - The reconstructed stellar X-ray/EUV/FUV spectrum is consistent with observed spectrum of nearby Sun-like stars.
  - To be investigated: Flare & Abundance contributions
- Conclusion
  - Our scaling flux-flux methodology can be applied to Sun-like stars with known unsigned magnetic fluxes (by observations or modellings)
  - Further studies

    More various stars (e.g., M-dwarfs)

    Flare contributions (more Sun-as-a-star data ?)

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Universal Scaling Laws for Solar and Stellar Atmospheric Heating: Catalog of Power-law Index between Solar Activity Proxies and Various Spectral Irradiances

Shin Toriumi[1], Vladimir S. Airapetian[2,3], Kosuke Namekata[4], and Yuta Notsu[5,6,7]

The Astrophysical Journal, 945:147 (18pp), 2023 March 10 https://doi.org/10.3847/1538-4357/acbe38

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$$I(\lambda) = I_0(\lambda) + \beta(\Phi - \Phi_0)^{\alpha}$$