2023 Sun Climate Symposium
2023 October 17th 4:25-4:40pm

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

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We acknowledge the support from the SCOSTEP/PRESTO Program Travel Award.

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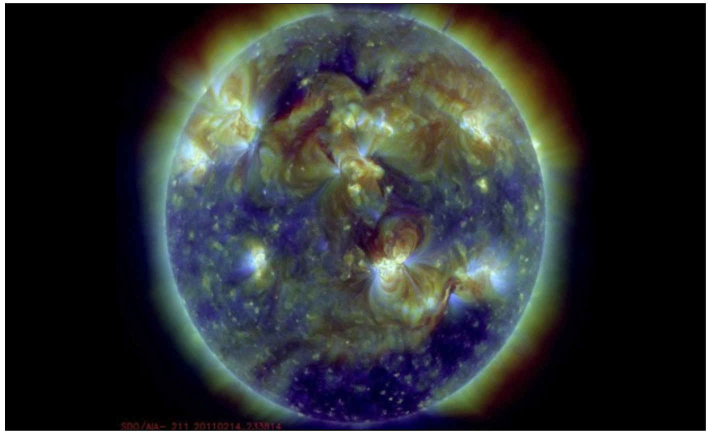
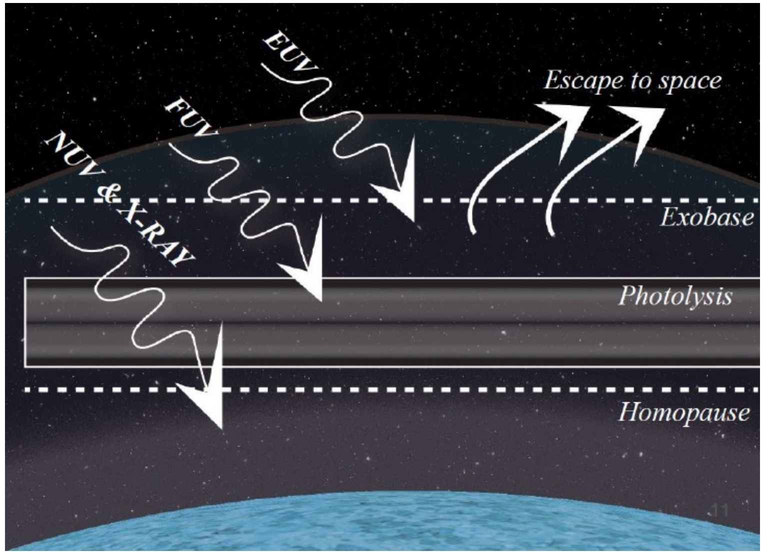
Introduction: Importance of the investigation of Stellar XUV/FUV flux/spectra

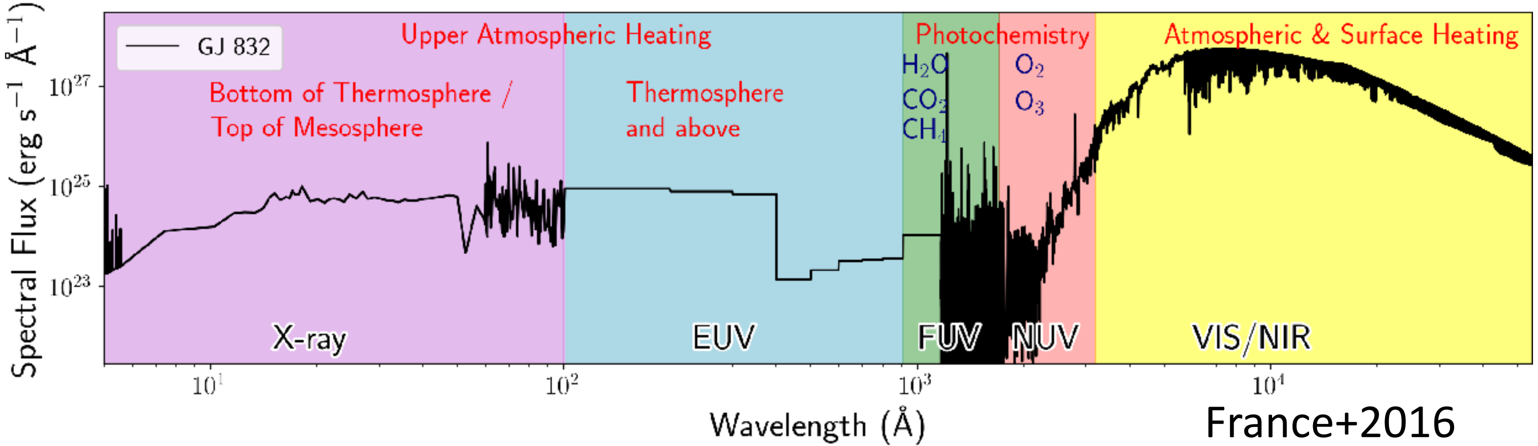
Stellar X-ray & EUV (hereafter, **XUV**) flux, and FUV fluxes are required to

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]

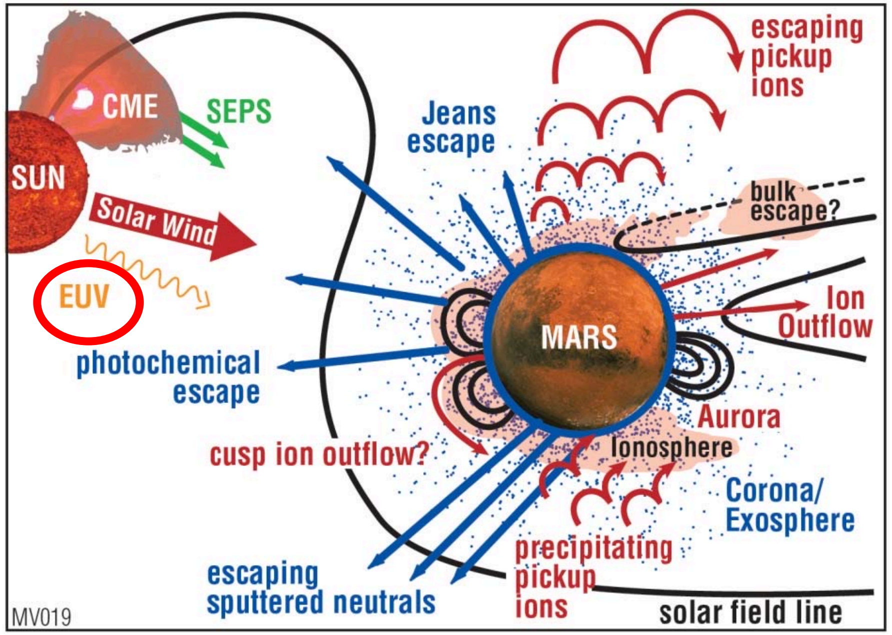






France+2016

Not only exoplanets,
but also solar-system planets !



Credit: The Lunar and Planetary Institute and LASP

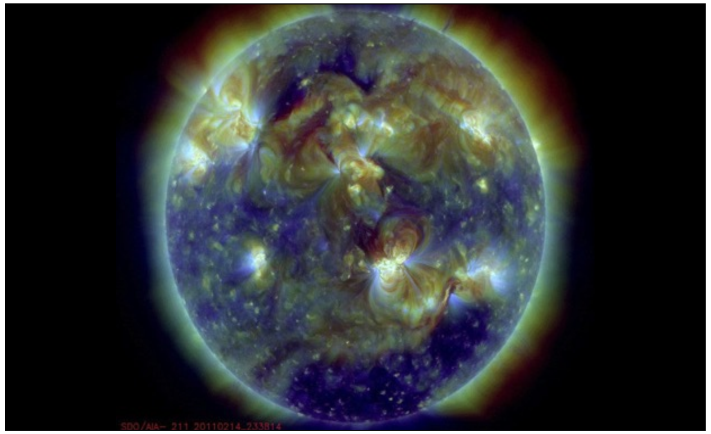
Introduction: Importance of the investigation of Stellar XUV flux/spectra

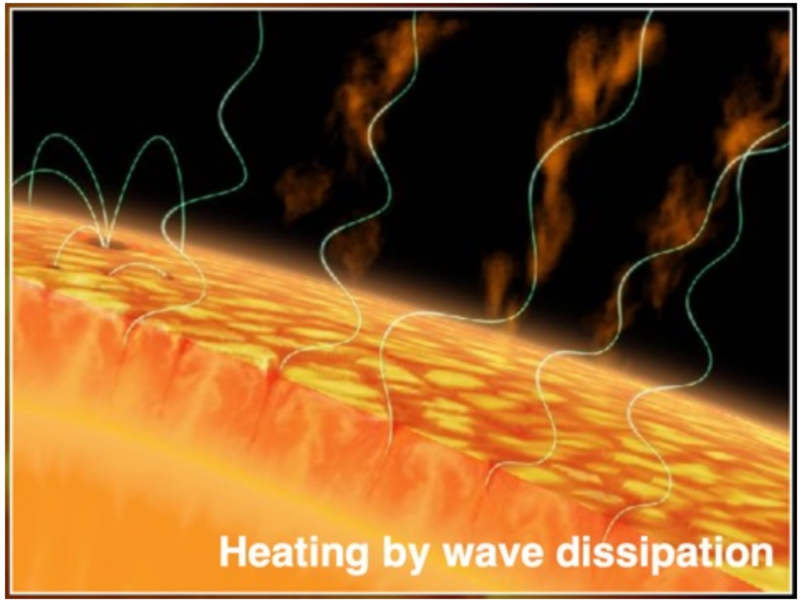
Stellar X-ray & EUV (hereafter, **XUV**) flux, and FUV fluxes are required to

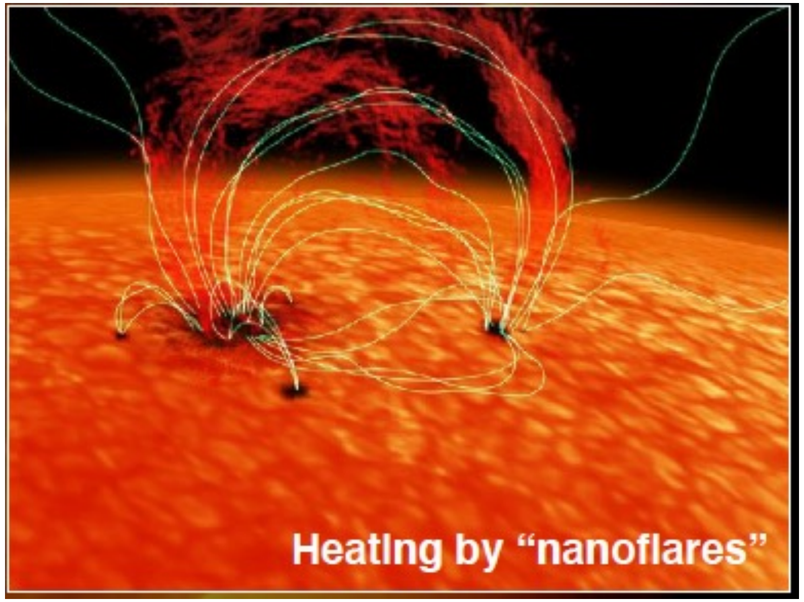
i. Constrain the effects on (exo)planetary evolution and habitable environments of rocky (exo)planets (X-ray & EUV fluxes drive planetary atmospheric escapes)

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]

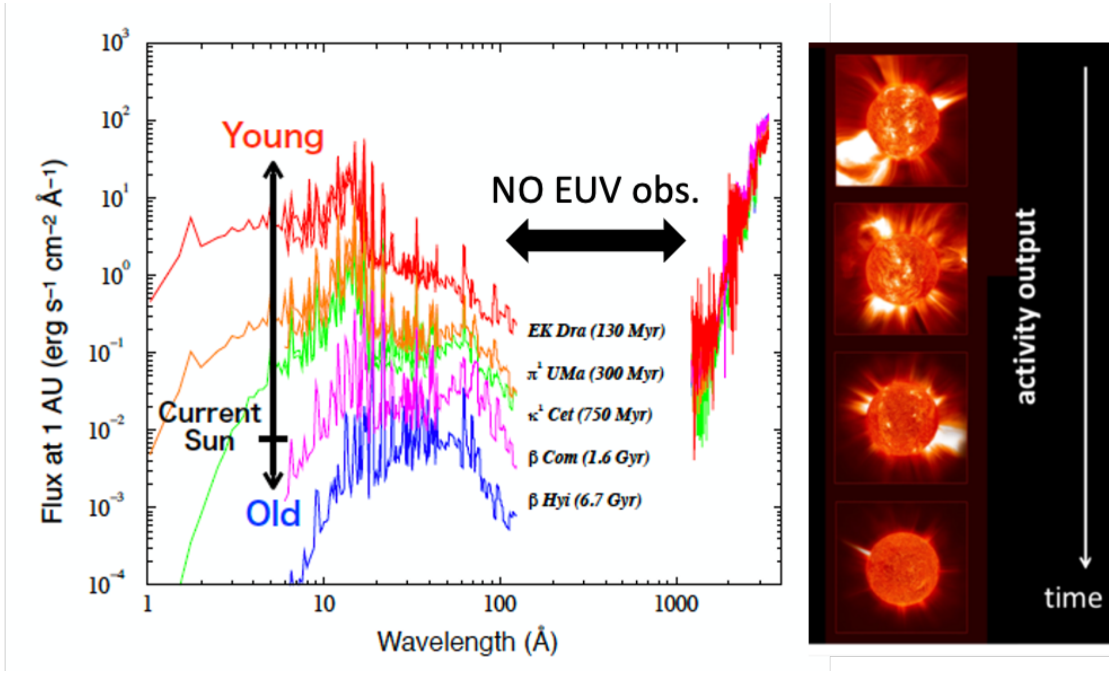






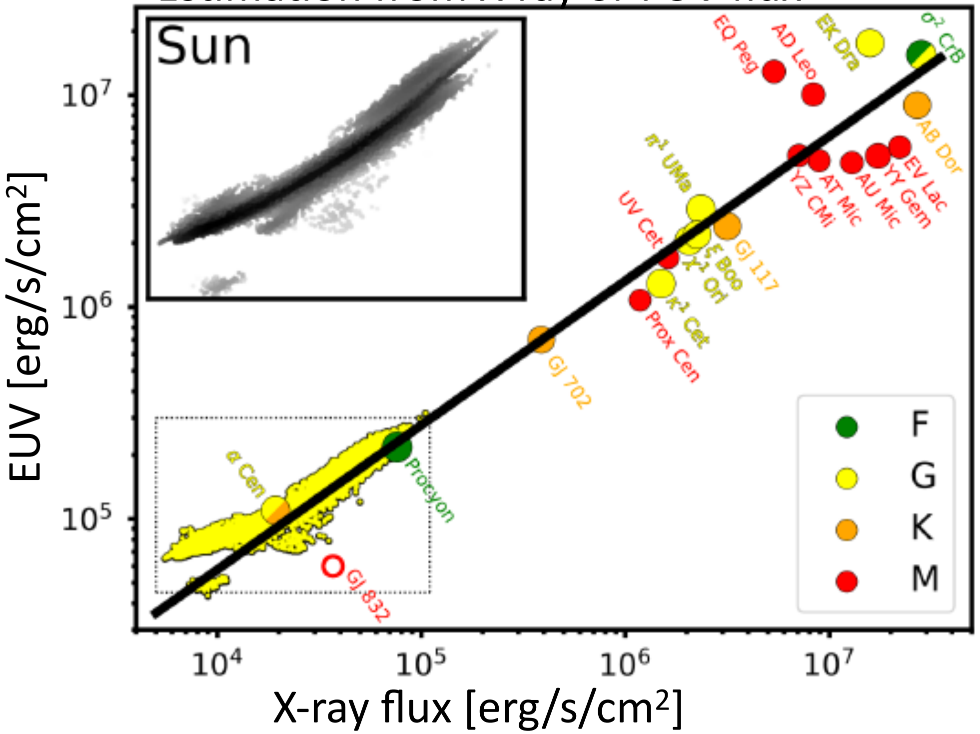
Difficulty: Stellar EUV spectrum is NOT observable (for now)

- 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]

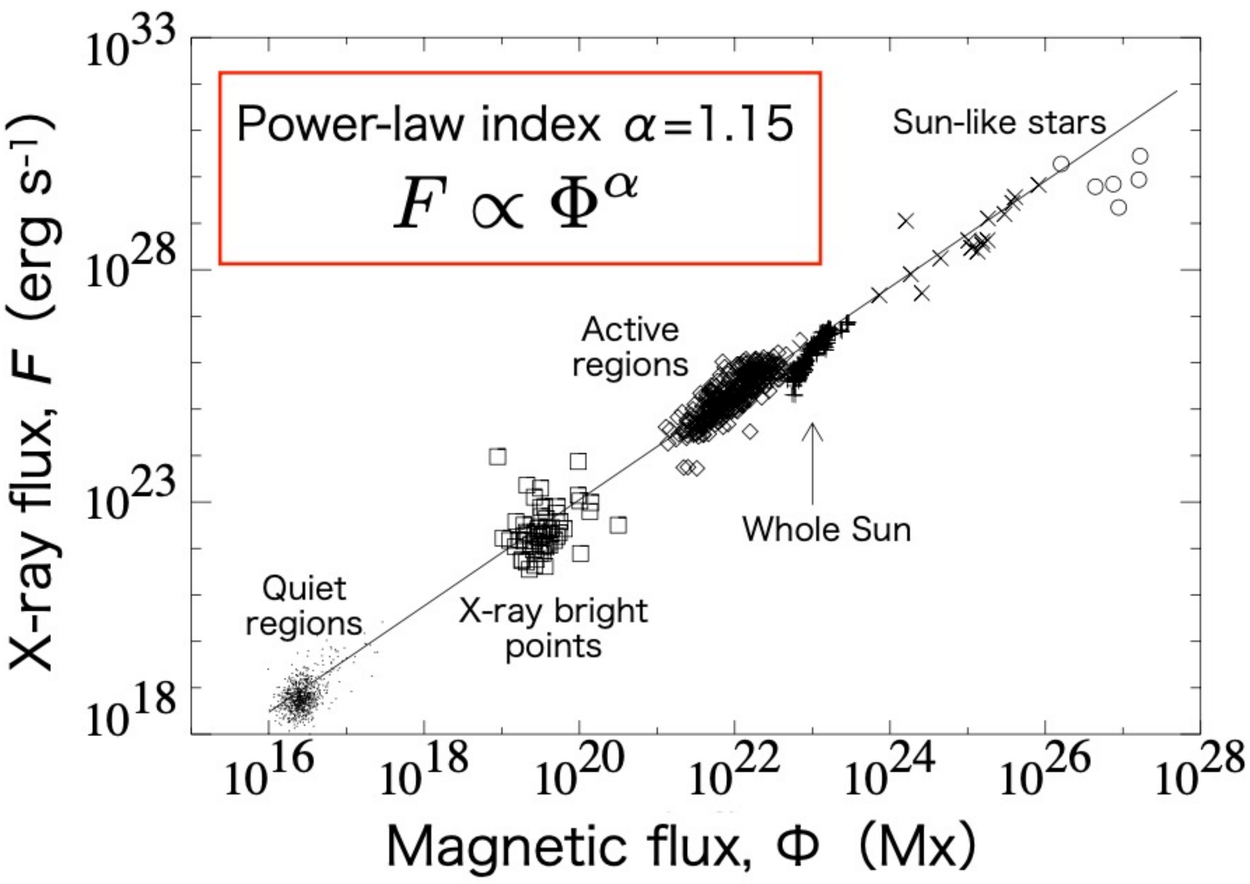
Estimation from X-ray or FUV flux



Johnstone+2020
Linsky+2014

X-ray flux - Magnetic flux scaling

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



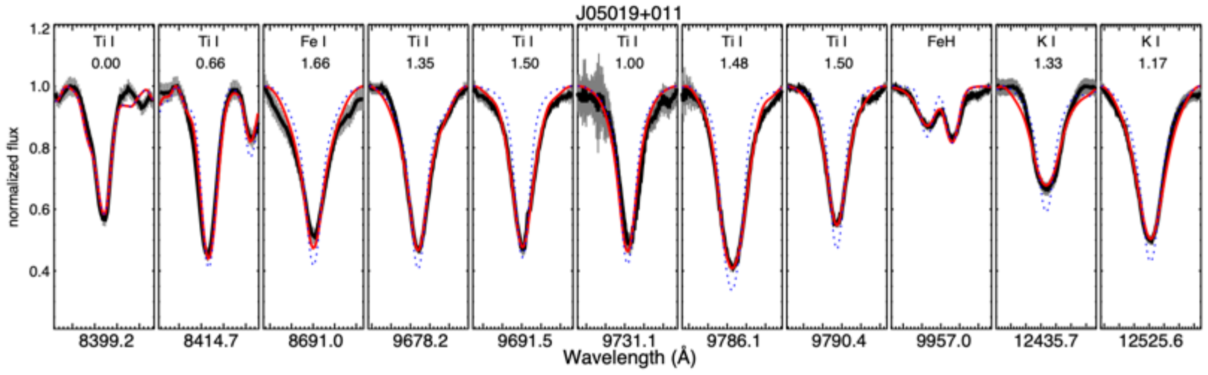
Universality of coronal heating

How about other temperature ?

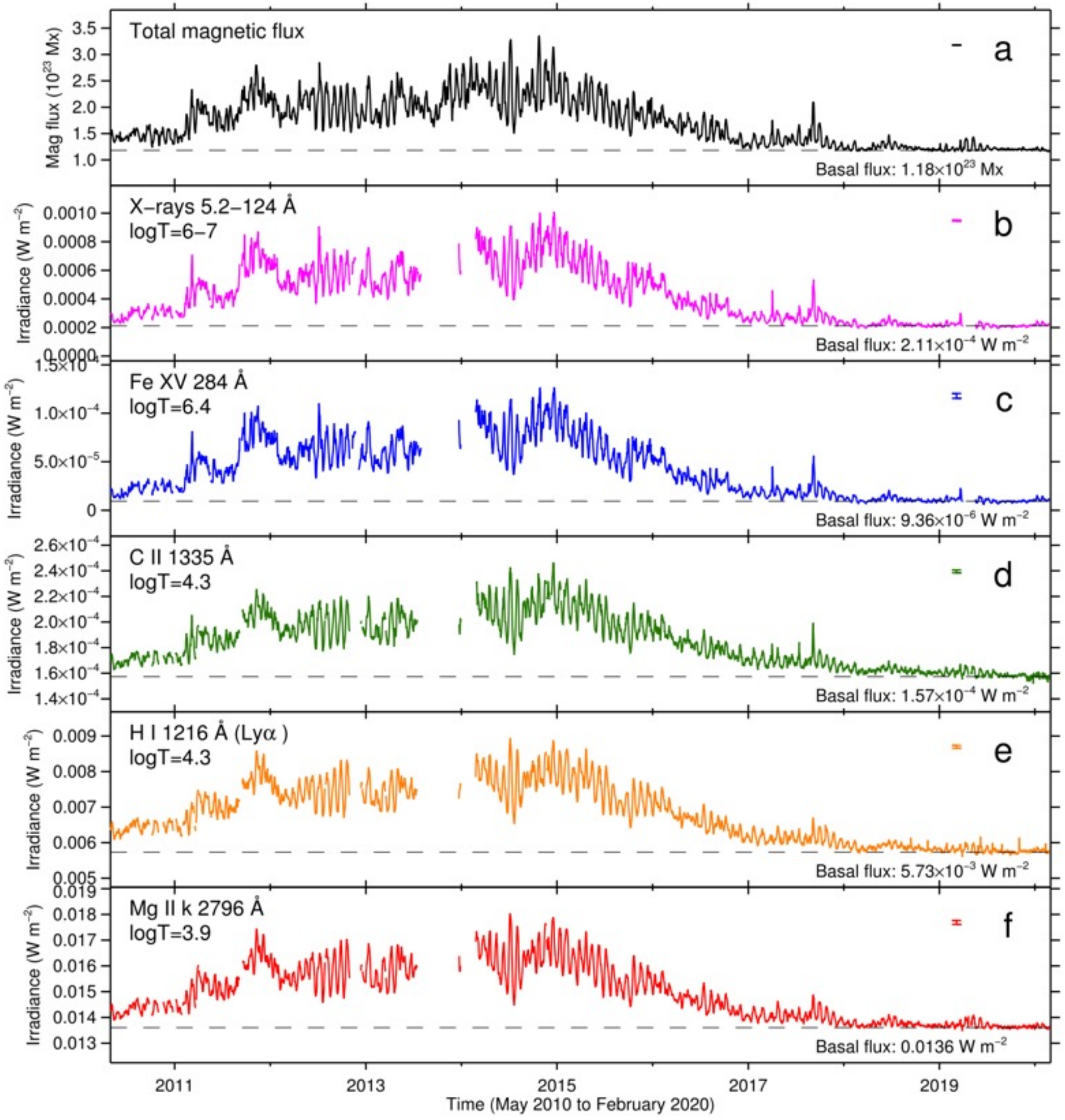
EUV ? FUV ?

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)

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



[1] 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

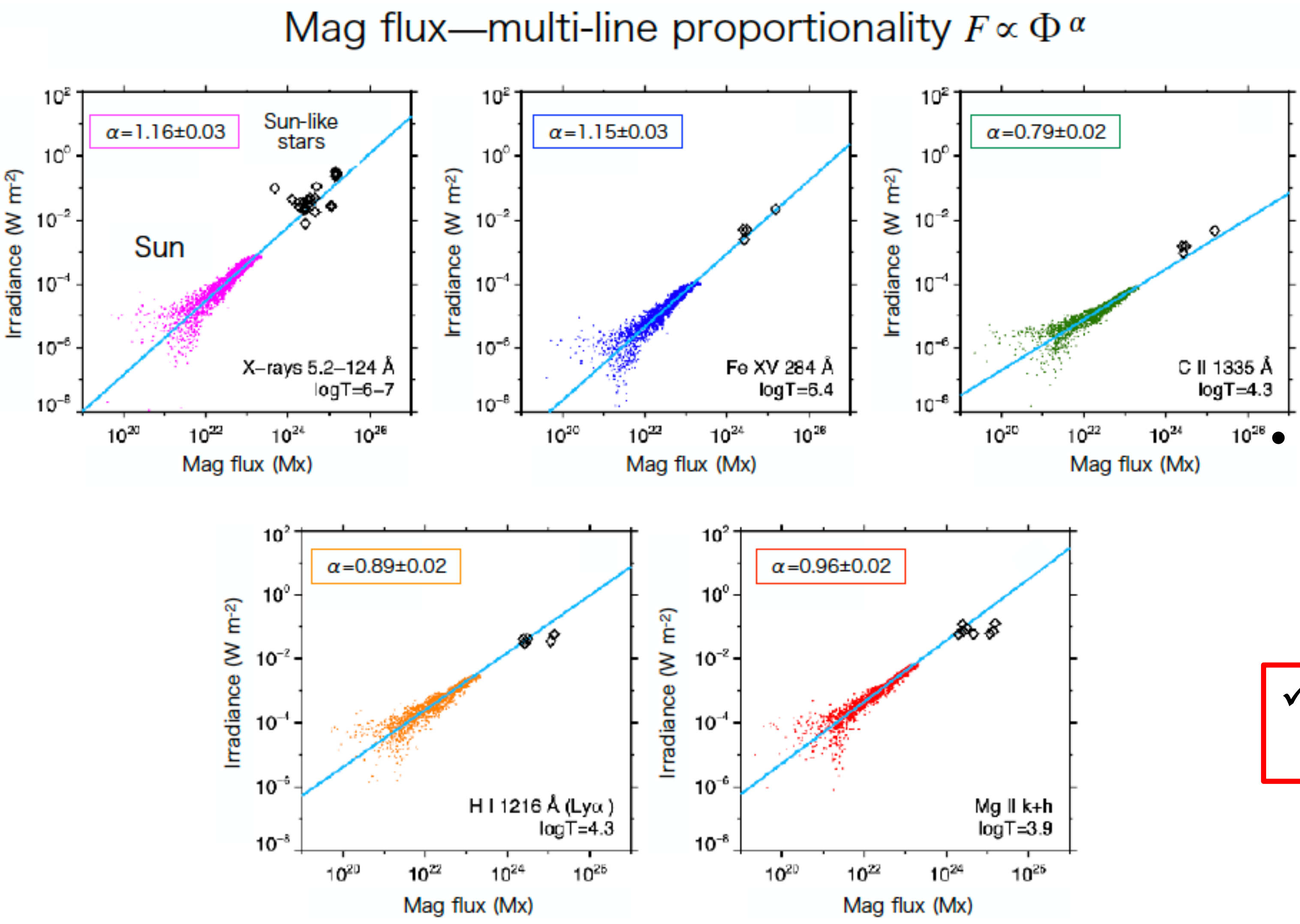
- daily value
- X-ray to radio
- logT=3.8—7

EUV:SORCE/XPS
FUV:SORCE/SOLTIS

Line centers and widths adopted from Ayres (2021)

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

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



- 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

cf. The flux – flux Relation in Tom Ayres Talk

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

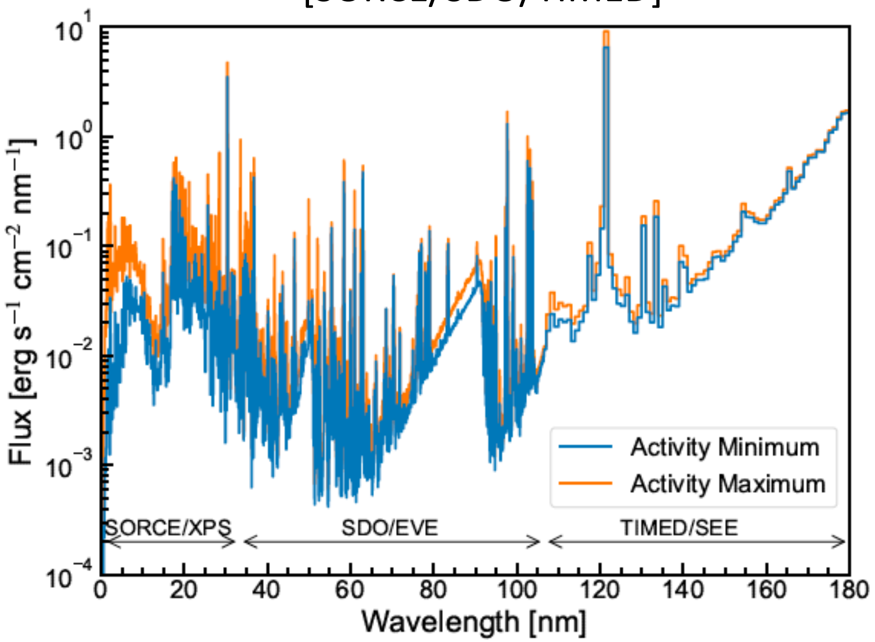
[2] Sun-as-a-star emission spectra vs magnetic flux

- 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)**

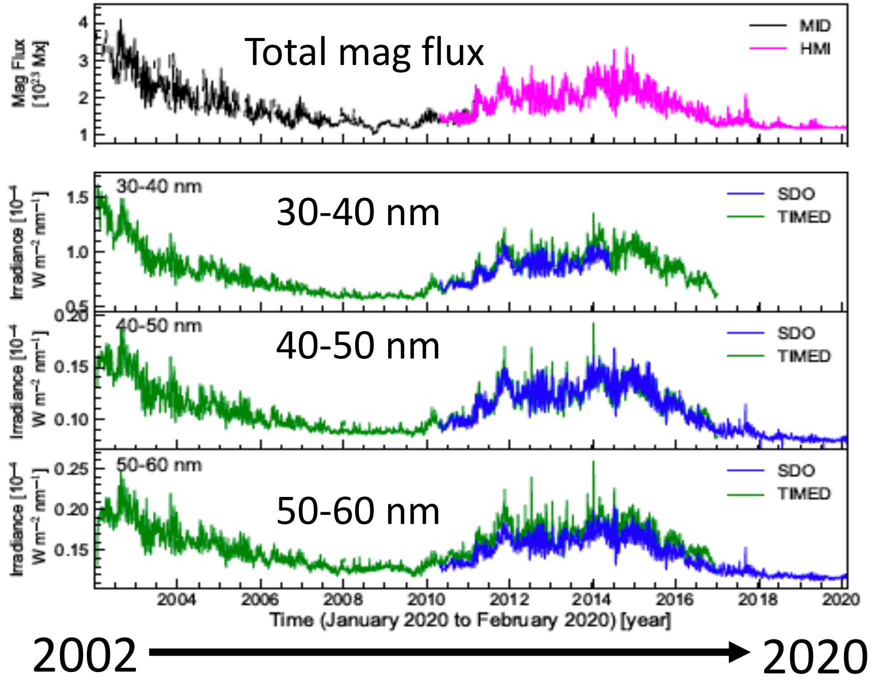
$$I(\lambda) = I_{basal}(\lambda) + \beta_\lambda \left(\phi - \phi_{basal}\right)^{\alpha_\lambda}$$

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

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

Flux [each wavelength between 0.1-180 nm]

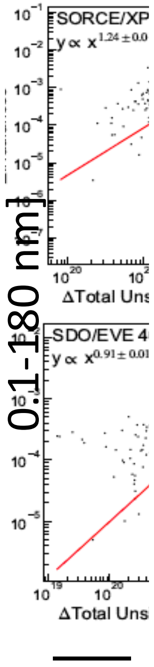
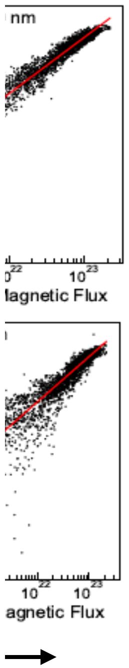


Table 3
Formula for Estimating Stellar XUV Fluxes in Best Wavelength Resolution as a Function of Total Unsigned Flux Φ of Stars (in Units of erg s^{-1} cm^{-2} nm^{-1} at 1 au)

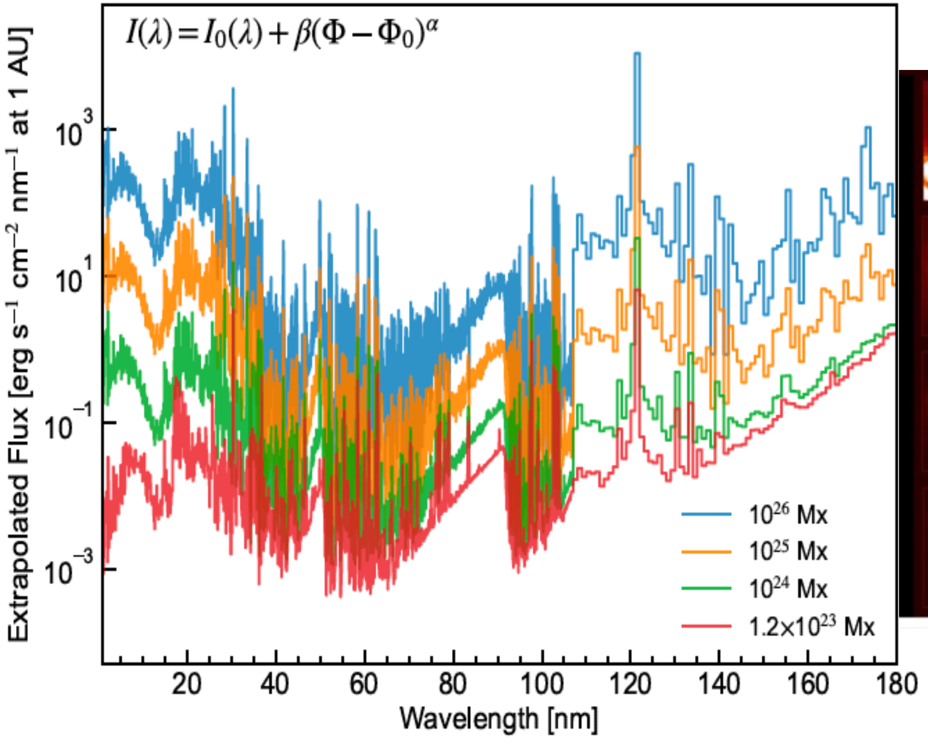
Wavelength (nm)	C.C.	$I(\lambda) = I_0(\lambda) + 10^{\beta(\lambda)}(\Phi - \Phi_0)^{\alpha(\lambda)}$		
		$I_0(\lambda)$	$\alpha(\lambda)$	$\beta(\lambda)$
0.10	0.65	1.76×10^{-15}	$11.30_{\pm 0.27}$	$-266.9_{\pm 6.20}$
0.20	0.65	2.58×10^{-10}	$7.20_{\pm 0.16}$	$-170.2_{\pm 3.67}$
0.30	0.66	8.67×10^{-8}	$4.11_{\pm 0.08}$	$-98.9_{\pm 1.92}$
0.40	0.71	1.84×10^{-6}	$2.72_{\pm 0.05}$	$-66.3_{\pm 1.08}$
0.50	0.78	1.19×10^{-5}	$1.83_{\pm 0.03}$	$-45.6_{\pm 0.57}$
0.60	0.83	5.45×10^{-5}	$1.51_{\pm 0.02}$	$-37.9_{\pm 0.40}$
0.70	0.85	2.74×10^{-4}	$1.38_{\pm 0.01}$	$-34.3_{\pm 0.33}$
0.80	0.89	2.20×10^{-4}	$1.26_{\pm 0.01}$	$-31.5_{\pm 0.23}$
0.90	0.91	4.06×10^{-4}	$1.22_{\pm 0.01}$	$-30.4_{\pm 0.21}$
1.00	0.90	1.16×10^{-3}	1.20	$-29.5_{\pm 0.21}$
170.50	0.52	6.37×10^{-1}	$1.15_{\pm 0.02}$	$-28.0_{\pm 0.41}$
171.50	0.54	6.43×10^{-1}	$1.11_{\pm 0.02}$	$-27.0_{\pm 0.38}$
172.50	0.45	7.28×10^{-1}	$1.51_{\pm 0.03}$	$-36.4_{\pm 0.74}$
173.50	0.45	7.23×10^{-1}	$1.60_{\pm 0.04}$	$-38.6_{\pm 0.81}$
174.50	0.43	8.85×10^{-1}	$1.25_{\pm 0.02}$	$-30.3_{\pm 0.54}$
175.50	0.46	1.08×10^{0}	$1.25_{\pm 0.02}$	$-30.3_{\pm 0.54}$
176.50	0.42	1.16×10^{0}	$0.99_{\pm 0.02}$	$-24.3_{\pm 0.42}$
177.50	0.36	1.43×10^{0}	$1.15_{\pm 0.02}$	$-27.7_{\pm 0.54}$
178.50	0.36	1.62×10^{0}	$1.23_{\pm 0.03}$	$-29.8_{\pm 0.66}$
179.50	0.38	1.64×10^{0}	$1.02_{\pm 0.02}$	$-24.8_{\pm 0.44}$

Useful tables included in the paper

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.)



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

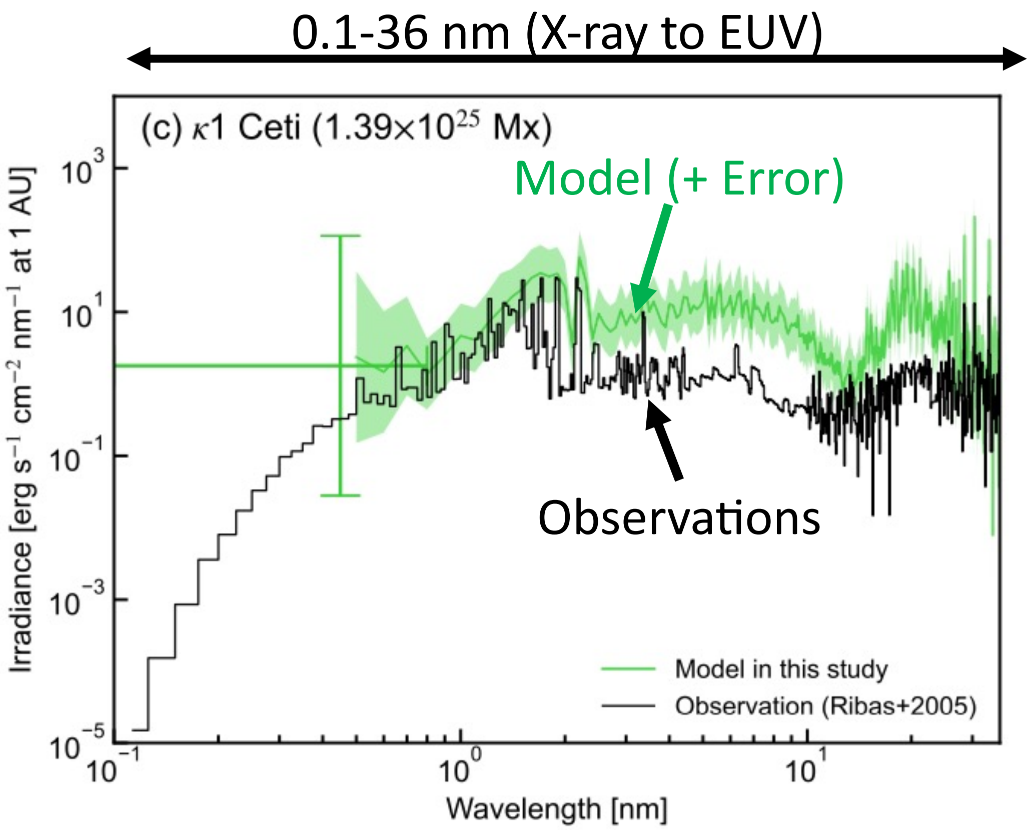


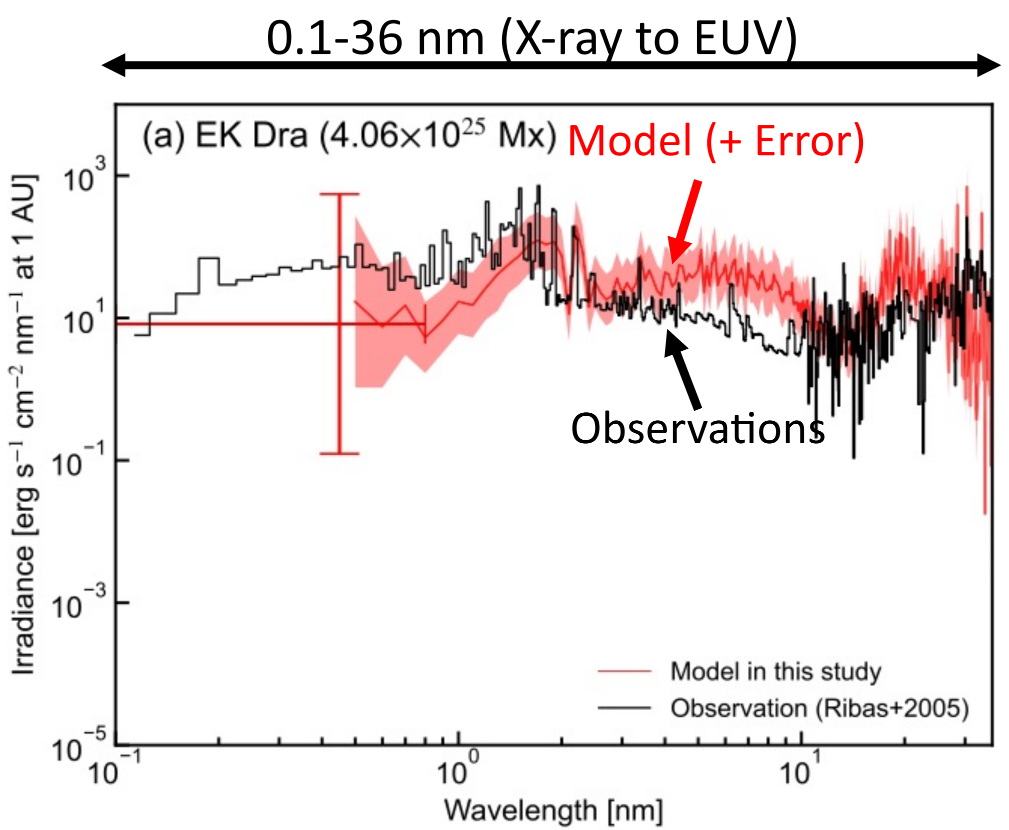
⇒ Then we compare with nearby Sun-like stars having the previous measurements of the mag. field and XUV spectra and discuss the predictability of our method!

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

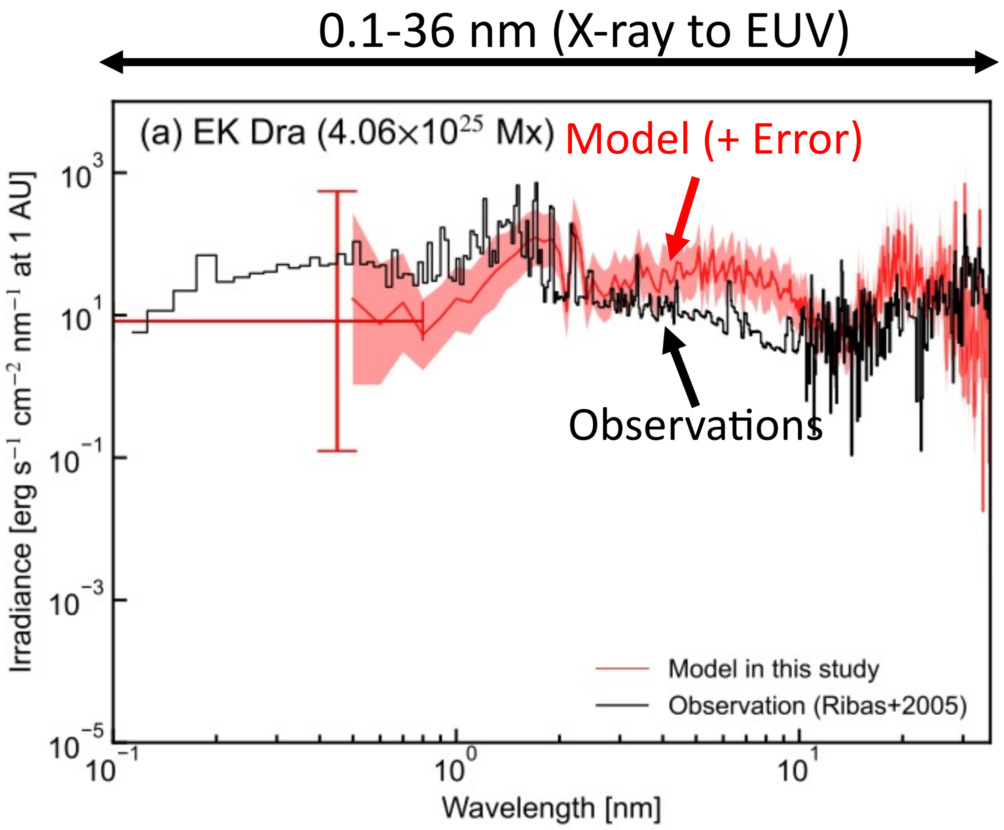
Discussion

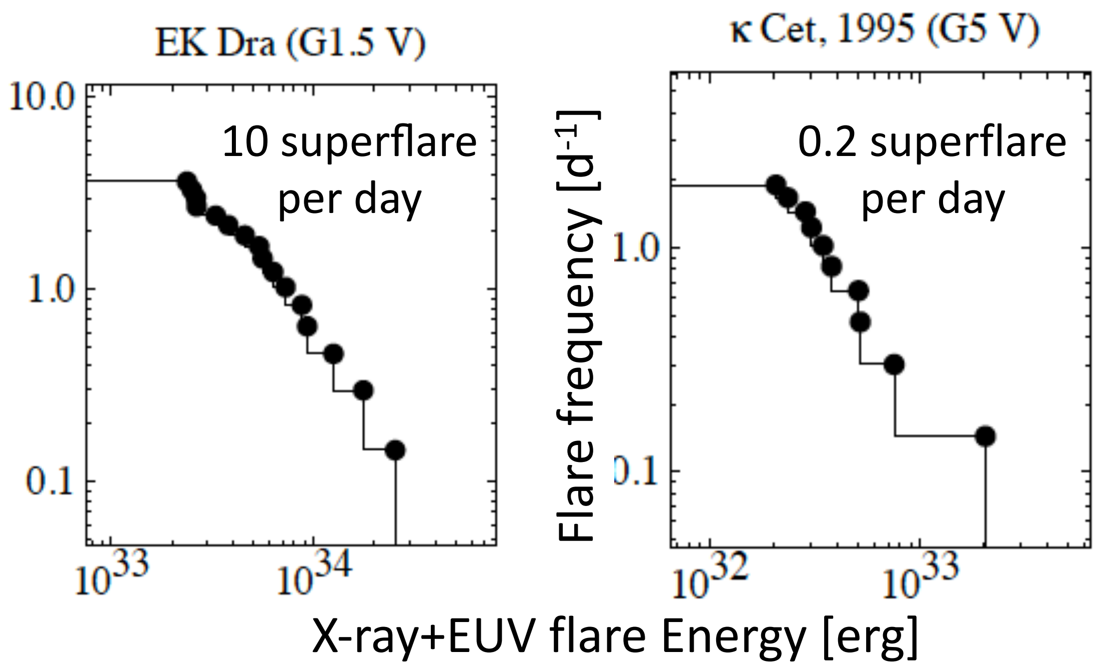
There are several factors that are not included

- 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



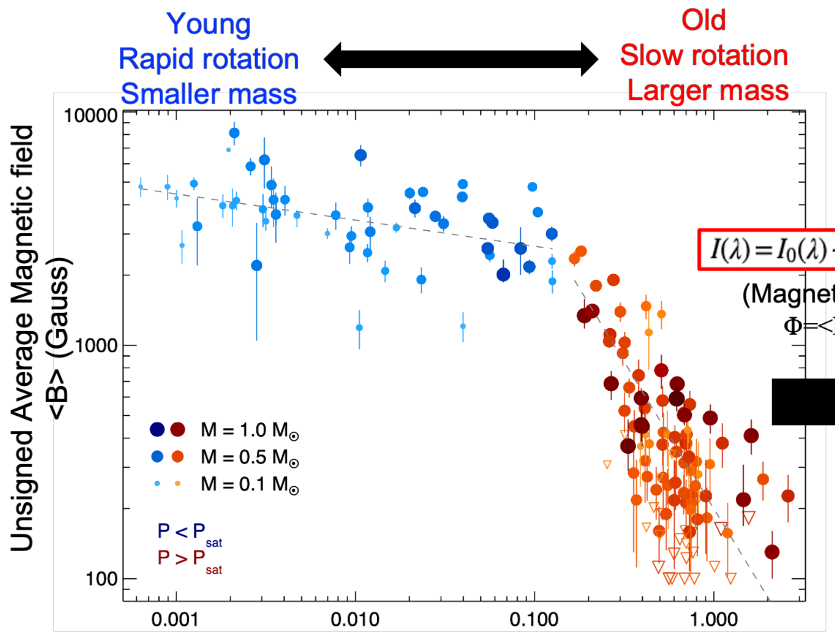


⇒ Future: establish scaling laws even for flares!

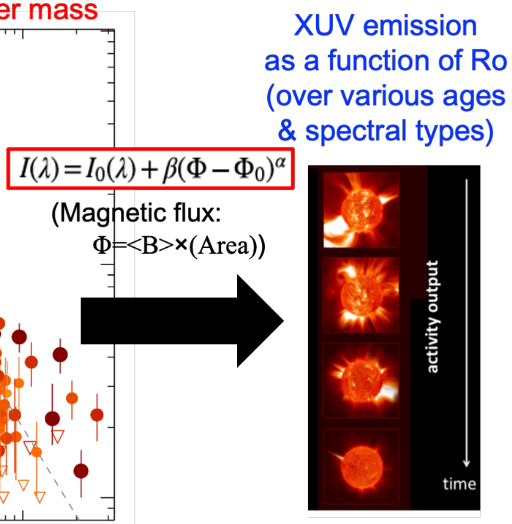
The Advantage and Applications of Our Model

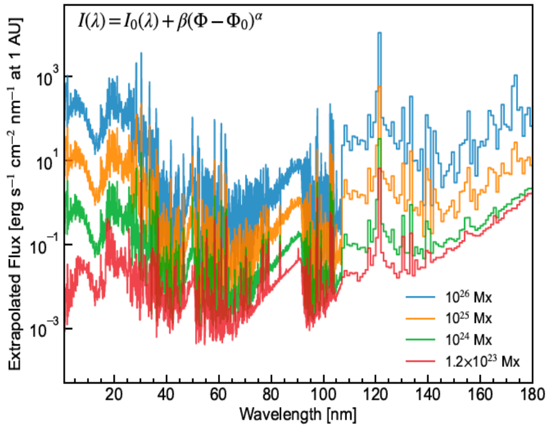
- The advantages in estimating stellar XUV+FUV spectrum
  1. Magnetic flux measurements are available from ground-based observations[1,2] ⇒ low cost
  2. Comparison with theoretical study is available [e.g. Shoda et al. 2021] ⇒ **physical understandings of ARs**

- 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]

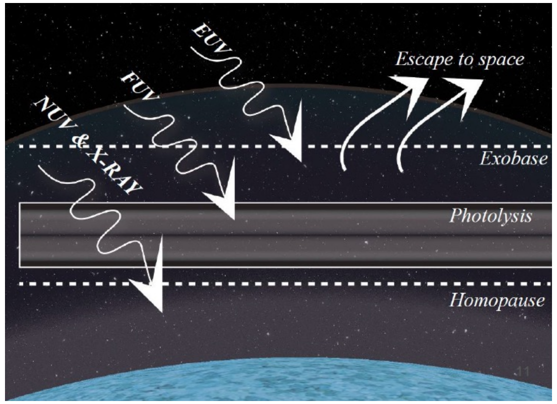


Rossby Number (Ro)
= (Rotation Period / Convective turnover time)





Contribution to exoplanet atmosphere



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 ?)

The Astrophysical Journal Supplement Series, 262:46 (20pp), 2022 October https://doi.org/10.3847/1538-4365/ac8b15

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

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]

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