Atmospheric Heating Mechanisms Common to the Sun and Sun-like stars

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

1: ISAS/JAXA, 2: NASA/GSFC, 3: American University, 4: NAOJ, 5: CU Boulder, 6: NSO, 7: Tokyo Tech

Atmospheric Heating Mechanisms Common to the Sun and Sun-like stars

Toriumi & Airapetian 2022, ApJ, 927, 179
Toriumi et al. 2022, ApJS, accepted

Shin Toriumi — JAXA
Kosuke Namekata — NAOJ
Vladimir Airapetian — NASA, American Univ
Yuta Notsu — CU Boulder, NSO, TITech

Hinode-15/IRIS-12 (September 19, 2022)

---

1. Introduction

- Extremely hot outer atmospheres
  - Corona > 1 MK / chromosphere ~10,000 K
  - Magnetic heating: magnetic flux transports energy from surface upwards[1]
  - Exact mechanism still unclear[2]
    - Wave dissipation?[3]
    - Nanoflares?[4]
  - Young Sun and Sun-like stars
    - Strong XUV emission due to strong magnetic fields[5]

Do the Sun and Sun-like stars share a common atmospheric heating mechanism?

How can we model the spectral line irradiances?

Young / Current Sun / Old — Flux at 1 AU (erg s⁻¹ cm⁻² Å⁻¹) — Wavelength (Å)

[Guinan & Ribas 2002]

[1: Güdel 2004; 2: Withbroe & Noyes 1977, Klimchuk 2006]
[3: van Ballegooijen et al. 2011, Cranmer & van Ballegooijen 2005; 4: Parker 1972, 1988]
[5: for further discussions, see e.g. Testa+ 2015, Brun & Browning 2017, Linsky 2019, Vidotto 2021]

2

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

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

Power-law index $\alpha = 1.15$

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

X-ray flux, F (erg s⁻¹) — Magnetic flux, Φ (Mx) — Sun-like stars — Active regions — Whole Sun — Quiet regions — X-ray bright points

- Previous studies
  - X-ray luminosity has a uniform scaling relationship with a power-law index of $\alpha = 1.15$
  - One of the key results of Yohkoh satellite
  - Barometer for efficiency of coronal heating in regard to surface magnetic flux[1]
- What about in other lines (= temperatures)?[2]
  - Analysis of Sun-as-a-star synoptic data over 10 yr
  - X-ray, EUV, UV, optical, and radio
  - corresponding to corona (logT=6-7) to chromosphere (logT=4)
  - Compare scaling with stellar data

[1: Fisher+ 1998; Pevtsov+ 2003; Vidotto+ 2014; Reiners+ 2022]
[2: Skumanich 1975; Schrijver+ 1989; Rutten+ 1991; Loukitcheva+ 2009; Barczynski+ 2018]

3

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

- Solar synoptic data over 10 yr

Total magnetic flux and representative emission lines — Total mag flux — X-ray — Fe XV 284 Å — C II 1335 Å — Ly-alpha — Mg II k

2010 May (SDO operation begins) — 2020 Feb (SORCE operation ends)

Each spike corresponds to sunspot transit [e.g. Toriumi et al. 2020]

Total radial unsigned magnetic flux
- 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

Line centers and widths adopted from Ayres (2021)

4

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

- Solar synoptic data over 10 yr

Total magnetic flux and representative emission lines — Total mag flux — X-ray — Fe XV 284 Å — C II 1335 Å — Ly-alpha — Mg II k

Each spike corresponds to sunspot transit [e.g. Toriumi et al. 2020]

- 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

5

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

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

Sun — Sun-like stars — X-rays 5.2–124 Å logT=6–7 — Fe XV 284 Å logT=6.4 — C II 1335 Å logT=4.3 — H I 1216 Å (Ly-α) logT=4.3 — Mg II k+h logT=3.9

- Solar data
  - X-rays show α=1.16, consistent with Yohkoh results
  - Other lines also show power-law scalings, although the α values are smaller for cooler temperatures
- 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
- Comparison of Sun and stars
  - Stellar data points are located at extensions of solar scaling laws for all spectral lines (= all temperatures)

✓ Heating mechanism is universal among the Sun and stars, regardless of age or activity

6

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

Table 3
Characteristics of the Sun-like Stars

HD	Name	Sp. Type	T_{eff} (K)	log g	Age (Myr)	P_{rot} (days)	R ($R_\odot$)	Φ (Mx)	X-rays 5.2–124 Å (W m⁻²)	Fe XV 284 Å (W m⁻²)	C II 1335 Å (W m⁻²)	Lyα (W m⁻²)	Mg II k+h (W m⁻²)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1835	BE Cet	G3V	5837	4.47	600	7.78	1.00	4.55×10^{18}	4.80×10^{-7}, 1.78×10^{-2}	···	···	···	6.04×10^{-2}
20630	κ^1 Cet	G5V	5742	4.49	600	9.3	0.95	2.61×10^{18}	2.19×10^{-7}, 2.56×10^{-2}	2.40×10^{-3}	9.50×10^{-4}	3.01×10^{-2}	7.09×10^{-2}
39587	χ^1 Ori	G0V	5882	4.34	500	4.83	1.05	2.47×10^{18}	3.48×10^{-7}, 3.73×10^{-2}	5.00×10^{-3}	1.52×10^{-3}	4.16×10^{-2}	1.18×10^{-1}
56124	···	G0V	5848	4.46	4500	18	1.01	4.78×10^{18}	9.79×10^{-2}	···	···	···	···
72905	n^1 Uma	G1.5V	5873	4.44	500	4.9	0.95	3.08×10^{18}	4.48×10^{-7}, 2.96×10^{-2}	5.00×10^{-3}	1.52×10^{-3}	4.22×10^{-2}	8.93×10^{-2}
73350	V401 Hya	G5V	5802	4.48	510	12.3	0.98	2.43×10^{18}	2.05×10^{-2}	···	···	···	···
76151	···	G3V	5790	4.55	3600	20.5	1.00	2.62×10^{18}	7.78×10^{-3}	···	···	···	···
82558	LQ Hya	K1V	5000	4.00	50	1.601	0.71	1.39×10^{18}	3.24×10^{-7}, 2.43×10^{-1}	···	···	5.91×10^{-2}	7.27×10^{-2}
129333	EK Dra	G1.5V	5845	4.47	120	2.606	0.97	1.52×10^{18}	3.03×10^{-7}, 2.52×10^{-1}	2.20×10^{-2}	4.70×10^{-3}	···	1.26×10^{-1}
131156	ξ Boo A	G7V	5570	4.65	200	6.4	0.83	1.13×10^{18}	2.58×10^{-7}, 2.83×10^{-2}	···	···	3.53×10^{-2}	6.19×10^{-2}
166435	···	G1IV	5843	4.44	3800	3.43	0.99	4.94×10^{18}	1.12×10^{-1}	···	···	···	···
175726	···	G0V	5998	4.41	500	3.92	1.06	1.26×10^{18}	4.48×10^{-2}	···	···	···	···
190771	···	G2V	5834	4.44	2700	8.8	1.01	3.48×10^{18}	4.80×10^{-2}	···	···	···	···
206860	HN Peg	G0V	5974	4.47	260	4.55	1.04	1.92×10^{18}	3.56×10^{-7}, 2.52×10^{-2}	···	···	···	5.90×10^{-2}
Sun	(mean)	G2V	5777	4.44	4600	25.4	1.00	1.73×10^{18}	4.24×10^{-4}	4.12×10^{-5}	1.84×10^{-4}	6.77×10^{-3}	2.55×10^{-2}
	(median)							1.67×10^{18}	3.87×10^{-4}	3.59×10^{-5}	1.82×10^{-4}	6.69×10^{-3}	2.52×10^{-2}
	(max)							3.35×10^{18}	1.01×10^{-3}	1.27×10^{-4}	2.46×10^{-4}	8.94×10^{-3}	3.06×10^{-2}
	(min)							1.16×10^{18}	1.85×10^{-4}	5.68×10^{-6}	1.52×10^{-4}	5.60×10^{-3}	2.32×10^{-2}

Note. The HD number, name, spectral type, effective temperature, surface gravity, age, rotation period, and radius of the stars are shown in Columns 1–8. Column 9 shows the total hemispheric magnetic flux estimated based on the Zeeman broadening of the spectral lines. Columns 10–14 show the irradiances of X-ray 5.2–124 Å, Fe XV 284 Å, C II 1334.5 + 1335.7 Å, Lyα, and Mg II k+h (combined) in the literature, all converted to the values at 1 au from the stars. For X-rays, multiple observations are shown (if they exist).

References. Turon et al. (1993), Valenti & Fischer (2005), McDonald et al. (2012), Gonzalez et al. (2010), Cole et al. (2015), Allende Prieto & Lambert (1999), Vidotto et al. (2014), Roén et al. (2016), Olah et al. (2016), See et al. (2019), Kochukhov et al. (2020), Telleschi et al. (2008), Ribas et al. (2005), Takeda et al. (2007), Wood & Linsky (2010), Güdel et al. (1997), Wood et al. (2005), Schmitt et al. (1990), Dorren & Guinan (1994).

7

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

Power-law index α as a function of T

GOES SXR — F10.7cm — 5.2-124 Å — Fe XV 284 Å, Fe XV 211 Å, FeXII 193+195Å — α=1

Chromosphere — Transition region — Corona — Power-law index, α — Temperature, logT(K)

- Corona: logT > 6
  - Not only X-rays but also other coronal proxies consistently show α >1
  - Explained by theoretical and numerical models [Zhuleku et al. 2020; also Fisher+1998; Takasao+ 2020]

[Shoda & Takasao 2020]

8

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

Power-law index α as a function of T

He II 256 Å — Mg II k 2796 Å, Mg II h 2803 Å — Ca II K 3949 Å, Ca II H 3968 Å — Si IV 1393 Å, Si IV 1402 Å — Lyα — C II 1335 Å — α=1

Chromosphere — Transition region — Corona — Power-law index, α — Temperature, logT(K)

- TR to chromosphere: logT < 6
  - Power-law exponents fall below unity, α <1, indicating that the efficiency of chromospheric heating is weaker than the corona
  - In line with the previous studies [Skumanich et al. 1975; Schrijver et al. 1989; Loukitcheva et al. 2009; Barczynski et al. 2018]
  - Geometrical model by Schrijver et al. (1989) :

Intensity I_{chrom} — Mag flux density B — $F_{chrom} \propto \Phi$

- Because (super)granules push the flux tubes near enough to each other, the free fanning is restricted and the effective area of the chromosphere is reduced, leading to a sub-linear proportionality, $F_{chrom} \propto \Phi^{\alpha}$ (α<1)

Convective flows — $F_{chrom} \propto \Phi^{\alpha}\ (\alpha < 1)$

- Flux tube expansion is also a key for Alfven wave reflection [Cranmer & van Ballegooijen 2005]
- May require numerical modeling to understand why α<1

9

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

Solar cycle dependence of α

X-rays 5.2-124 Å — Fe XV 284 Å — C II 1335 Å — H I 1216 Å (Lyα) — Mg II k & h — Power-law index, α — I. Rising — II. Max — III. Declining — IV. Min — Solar cycle phase

- α is smallest at solar maximum
  - At minimum, the Sun has few active regions.
  - At maximum, the Sun is filled with magnetic fluxes and loops. Therefore, the atmosphere is not effectively heated any more even if the new mag flux is supplied to the surface via flux emergence.

Coronal loops — Flux emergence

- Requires global effect in numerical modeling?

10

---

2. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

Conclusion

Atmospheric heating mechanism is common to the Sun and Sun-like stars, regardless of age or activity

11

---

3. Reconstruction of Irradiances

[Toriumi et al. ApJS, accepted]

Activity proxy

- Radial magnetic flux

Irradiance (3.8 < logT < 7)

- X-rays 1–8 Å
- X-rays 5.2–124 Å
- Fe XV 284 Å
- Fe XIV 211 Å
- X-rays (XRT)
- Fe XII 193+195 Å
- Fe XII 1349 Å
- F10.7cm radio
- Fe IX 171 Å
- N V 1938 Å
- N V 1242 Å
- C IV 1548 Å
- C IV 1551 Å
- C III 1175 Å
- He II 256 Å +blends
- He II 304 Å
- Si IV 1393 Å
- Si IV 1402 Å
- Si III 1206 Å
- He I 10830 Å
- C II 1335 Å
- H I 1216 Å (Lyα)
- O I 1302 Å
- O I 1305 Å
- Mg II k 2796 Å
- Mg II h 2803 Å
- C II 1351 Å
- Ca II K 3934 Å
- Ca II H 3968 Å
- H I 6563 Å (Hα)
- Ca II 8542 Å

Catalog of power-law index

Line number increased!

12

---

3. Reconstruction of Irradiances

[Toriumi et al. ApJS, accepted]

Previous result — Updated catalog: line number increased

Power-law index, α — Temperature, logT(K) — Chromosphere — Transition region — Corona — α=1

✓ Similarity of heating efficiencies (mechanisms) of transition region and chromosphere

13

---

3. Reconstruction of Irradiances

[Toriumi et al. ApJS, accepted]

Activity proxy

- Radial magnetic flux
- LOS magnetic flux
- Sunspot number
- Sunspot area
- F10.7 cm radio

Irradiance (3.8 < logT < 7)

- X-rays 1–8 Å
- X-rays 5.2–124 Å
- Fe XV 284 Å
- Fe XIV 211 Å
- X-rays (XRT)
- Fe XII 193+195 Å
- Fe XII 1349 Å
- F10.7cm radio
- Fe IX 171 Å
- N V 1938 Å
- N V 1242 Å
- C IV 1548 Å
- C IV 1551 Å
- C III 1175 Å
- He II 256 Å +blends
- He II 304 Å
- Si IV 1393 Å
- Si IV 1402 Å
- Si III 1206 Å
- He I 10830 Å
- C II 1335 Å
- H I 1216 Å (Lyα)
- O I 1302 Å
- O I 1305 Å
- Mg II k 2796 Å
- Mg II h 2803 Å
- C II 1351 Å
- Ca II K 3934 Å
- Ca II H 3968 Å
- H I 6563 Å (Hα)
- Ca II 8542 Å

Catalog of power-law index

Proxy number increased!

14

---

3. Reconstruction of Irradiances

[Toriumi et al. ApJS, accepted]

Conclusion

Catalog of power-law index can be used for reconstruction of irradiances from various proxy data

16

---

3. Reconstruction of Irradiances

[Toriumi et al. ApJS, accepted]

Historical solar observations — Sunspot number — Sunspot area — F10.7 cm radio — Year

Catalog of α

$$F^{line}(t) = 10^{\beta}\,[P(t) - P_0]^{\alpha} + F_0^{line}$$

Irradiances can be reconstructed from
- Historical solar observations
- Stellar observations
- Surface flux transport simulations
- Dynamo models
- etc.

Pros: Relative differences between the proxies are less than 20% 👍
Cons: Scalings are measured only for the "very weak" cycle 24 👎

Sample reconstructed irradiances over centuries — X-rays 5.2-124 Å — Fe XV 284 Å — H I 1216 Å (Lyα) — Mg II k 2796 Å — Year

✓ Catalog provides ways to empirically synthesize line irradiances

15

---

4. Reconstruction of XUV Spectra

[Namekata et al. in prep]

Preliminary

Observation: solar spectra — Reconstruction: spectra for G dwarfs

- Toriumi et al: Mag flux vs irradiance for each line

$$I^{line} = 10^{\beta}\,(\Phi - \Phi_0)^{\alpha} + I_0^{line}$$

- Namekata et al: Mag flux vs irradiance for the whole XUV spectrum with a wavelength resolution of 1~10 Å bin
- XUV spectra: 1 Å ~ 1800 Å

$$I(\lambda) = 10^{\beta}\,(\Phi - \Phi_0)^{\alpha} + I_0(\lambda)$$

- Provide synthesized XUV spectra for G-dwarfs based on observed magnetic fluxes
- Maybe utilized as inputs for, e.g. chemical calculations of exoplanetary atmospheres

17

---

4. Reconstruction of XUV Spectra

[Namekata et al. in prep]

Preliminary

- Comparison 1: κ¹ Ceti

X-ray to EUV (0.1—36 nm) — Reconstruction — Observation — Model in this study — Observation (Ribas+2005)

FUV (123—180 nm) — Reconstruction — Observation

✓ Active young Sun-like star with magnetic flux of ~10x solar maximum
✓ Reconstruction is overall in good agreement with observation

18

---

4. Reconstruction of XUV Spectra

[Namekata et al. in prep]

Preliminary

- Comparison 2: EK Dra

X-ray to EUV (0.1—36 nm) — Reconstruction — Deviation of ~1 order — Observation

FUV (123—180 nm) — Reconstruction — Observation

✓ Very active young Sun-like star with magnetic flux of ~50x solar maximum
✓ Still shows excellent predictive capability but with small deviations for X-ray range

19

---

4. Reconstruction of XUV Spectra

[Namekata et al. in prep]

Preliminary

Conclusion

Empirical XUV spectral modeling shows excellent predictive capability of stellar spectra

20

---

5. Summary and Perspective

- Universal atmospheric heating
  - Comparison of scaling laws $F \propto \Phi^{\alpha}$ between the Sun and Sun-like stars with ages from 50 Myr to 4.5 Gyr
  - The heating mechanism is universal among the Sun and Sun-like stars, regardless of age or activity
- Reconstruction of irradiances
  - Updated catalog of power-law index can be used for reconstruction of irradiances from various proxy data
  - Proxy can be: historical solar observation, stellar data, and simulated Sun-like stars
- Reconstruction of XUV spectra
  - Empirical XUV spectral modeling shows excellent predictive capability of stellar spectra
  - Can be used as inputs for, e.g. chemical calculations of exoplanetary atmospheres

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

Toriumi & Airapetian 2022, ApJ, 927, 179
Toriumi et al. 2022, ApJS, accepted

21