A Comparative Look at X-ray Flares from Pre-main Sequence Suns and the Contemporary Sun

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AI-generated image by DALL-E: Multiple CMEs from a young star.

Thanks to many other collaborators:

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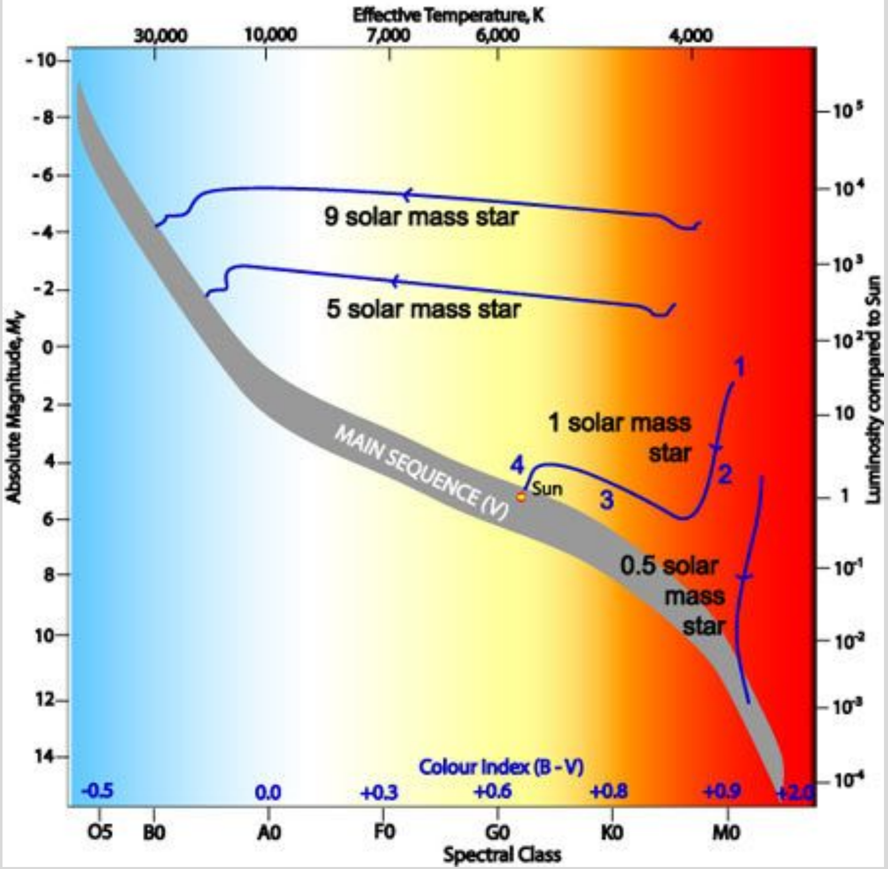
AI-generated image by Gemini.

Thanks to the Chandra Mission Operations team for scheduling observations in coordination with other multi-wavelength telescopes!

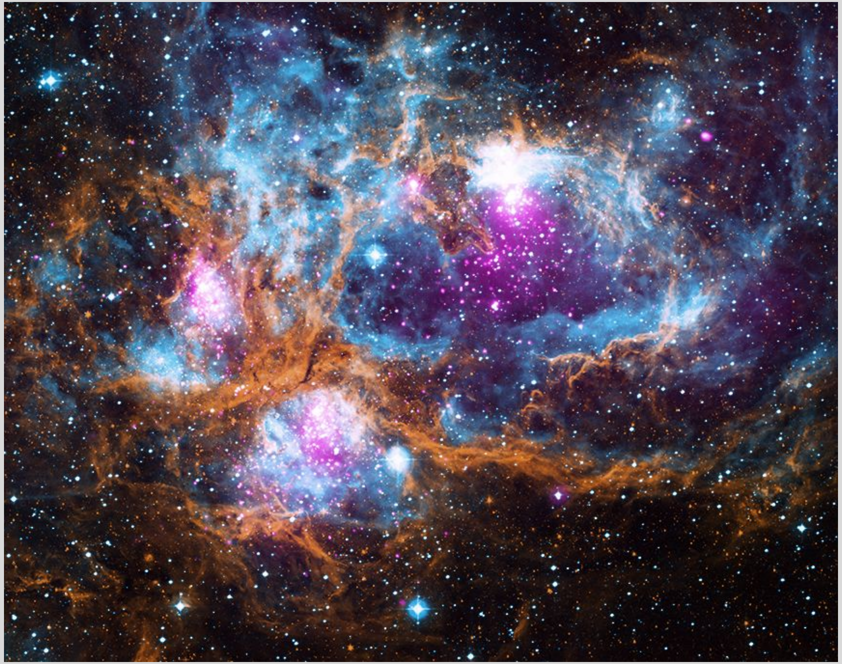
Early pre-main sequence (PMS) stars



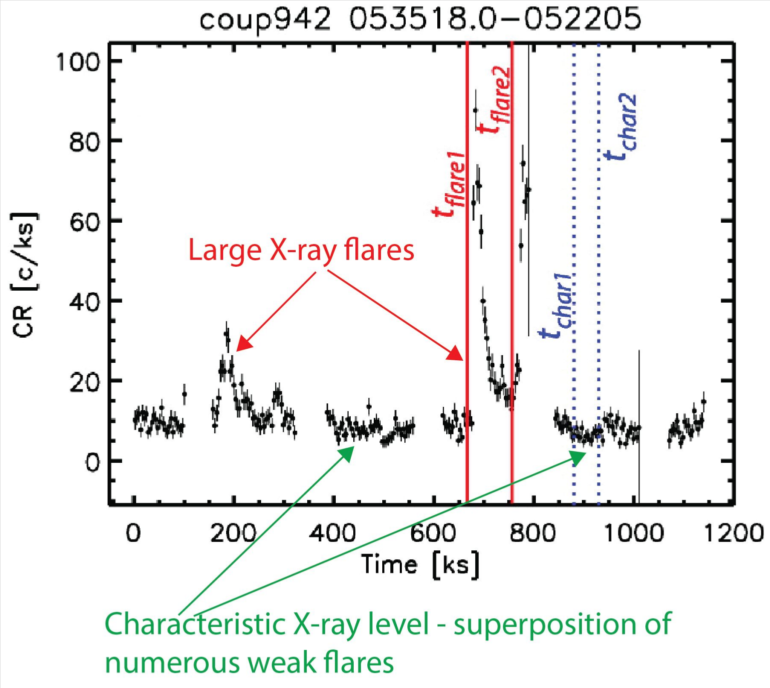
- Age range of interest: <5 Myr
- Descent along the Hayashi tracks
- Driven by gravitational contraction
- Fully convective & Fast rotating
- W/wo protoplanetary disks

Large X-ray flares from PMS stars

Chandra-ACIS-I NGC 6357



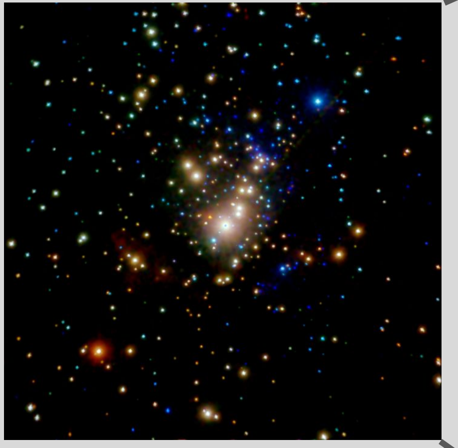
- Detection and characterization of >30,000 PMS stars in COUP (Getman+05), CCCP (Townsley+11), MYStIX (Feigelson+13), and SFiNCs (Getman+17)

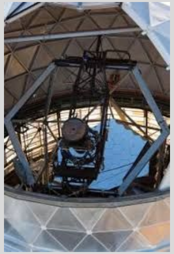


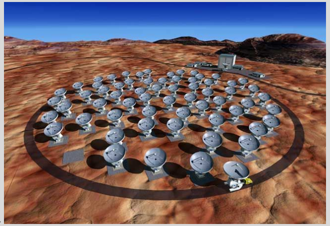
- A few thousand of large PMS X-ray flares (Wolk+2005, Favata+2005, Caramazza+2007, Albacete Colombo+2007, Flaccomio+2018, Getman+2008a,b, Getman+2021a,b, Getman+2024a,b)

After a Mega-Flare: Surface Magnetic Fields, Coronal Mass Ejections, and Disk Ionization

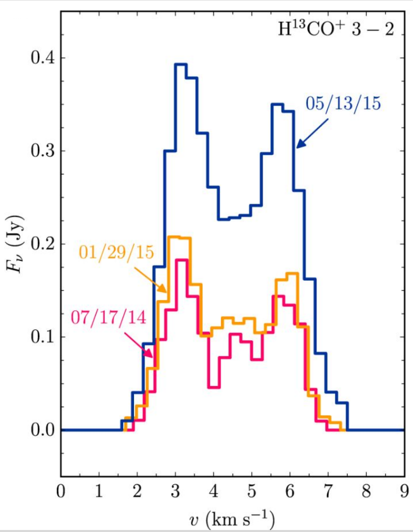
Orion Nebula Cluster







December 2023 & January 2025: Chandra + follow up observations of numerous super- and mega-flaring stars with HET-HPF, VLBA, and ALMA (Getman+24a, ApJ in press; Getman+24b, submitted)

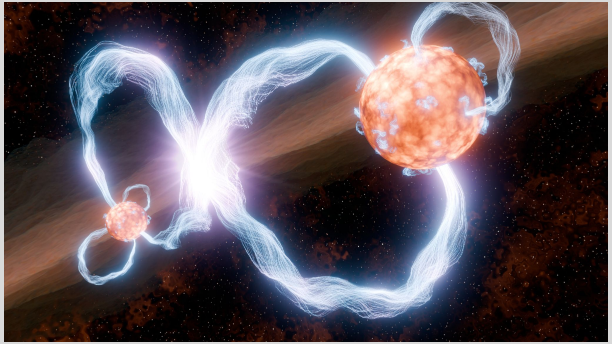


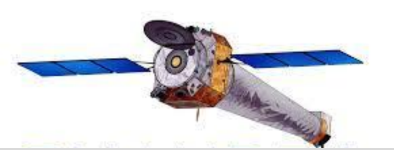
DQ Tau: A Laboratory for XUV Flare Effects on Disks

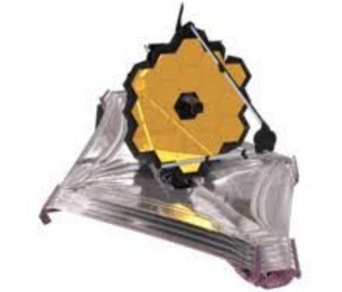
January-March 2025: Chandra, SWIFT, JWST, VLBA observations

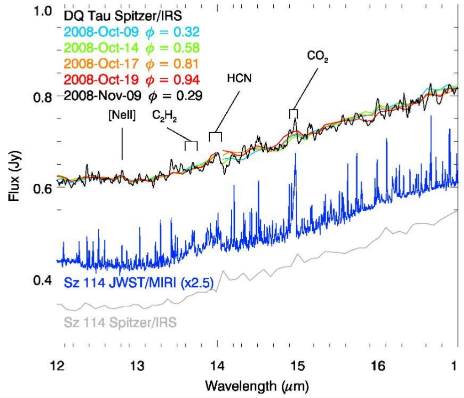
- Periastron-driven XUV outbursts
- Impact on protoplanetary disk chemistry

DQ Tau (Kospal+18, Getman+23)

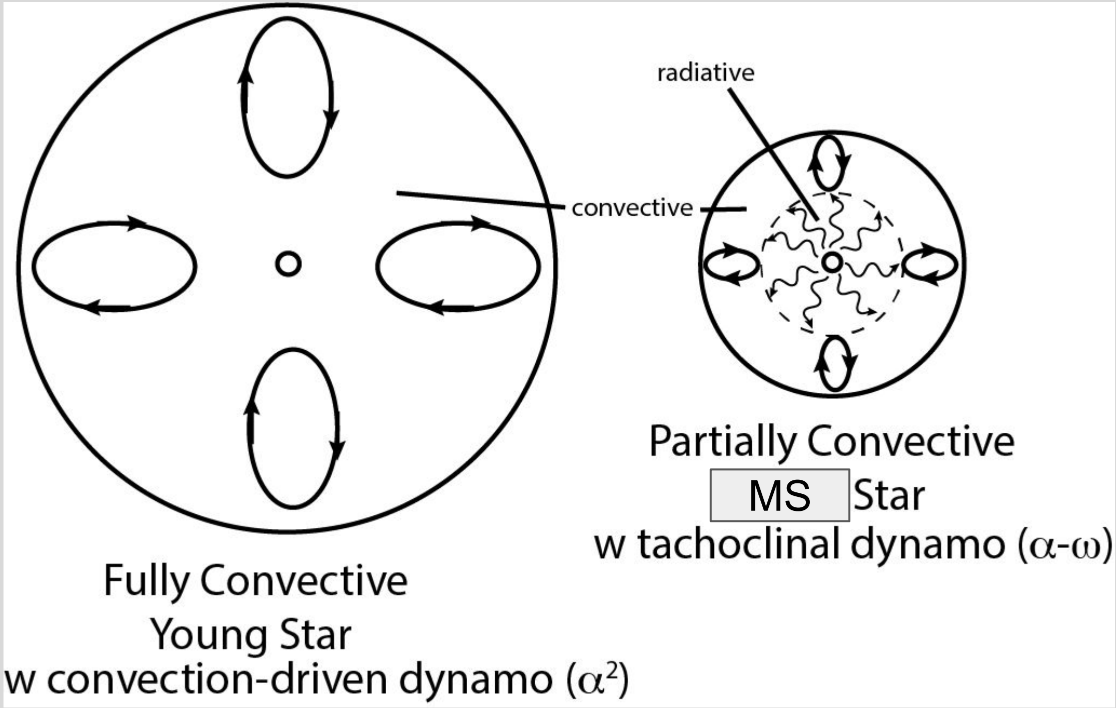






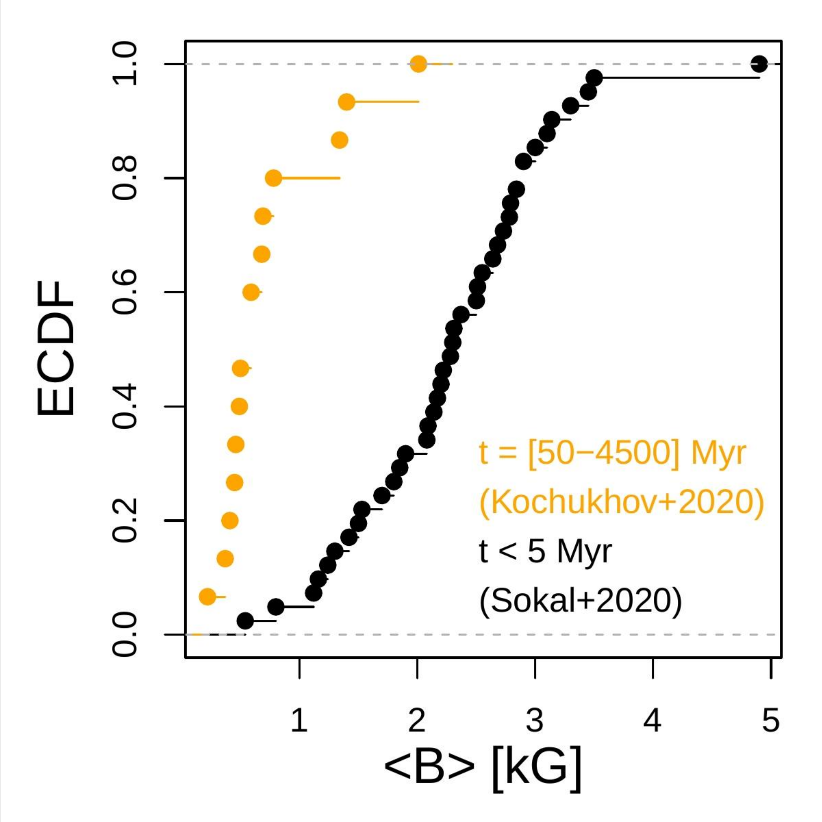


Dynamos in PMS versus MS stars



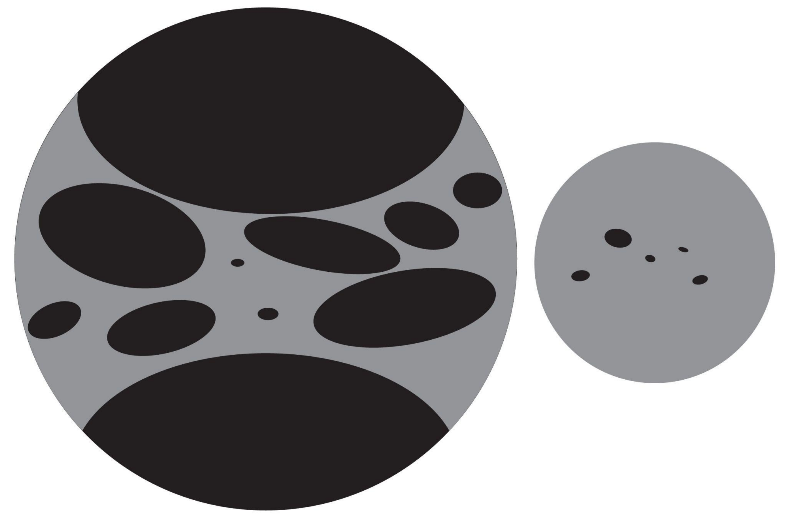
- Chabrier & Kuker 2006; Dobler+2006; Browning 2008; Kapyla+2008; Christensen+2009; Brown+2011; Yadav+2015; Kapyla+2023

Magnetic fields in PMS versus MS stars

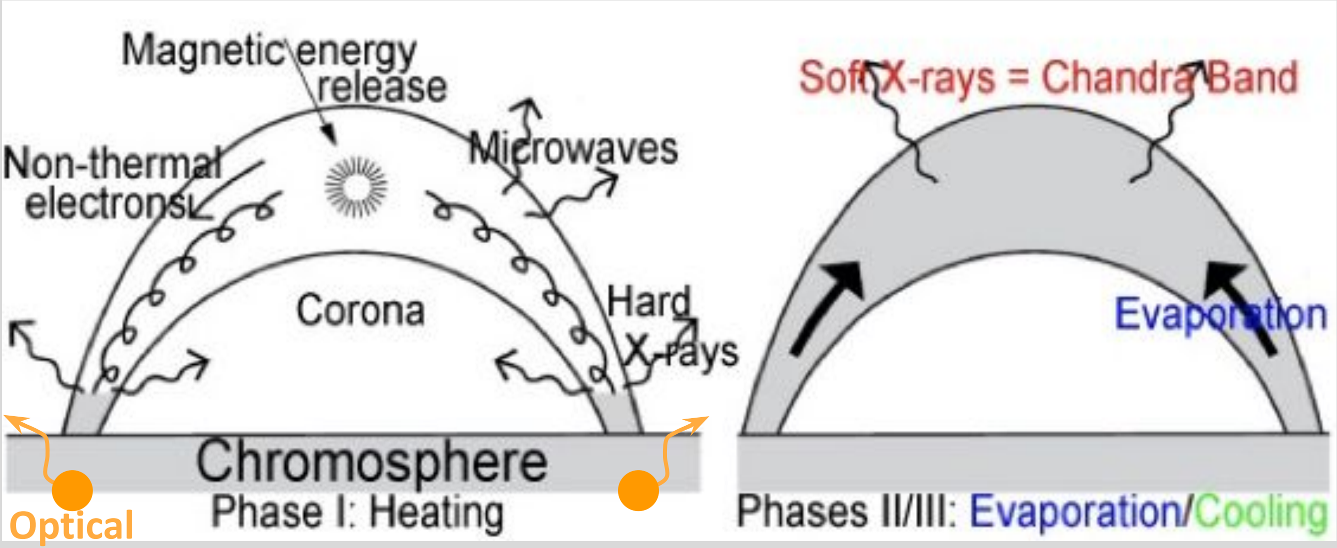


- Zeeman broadening
- $\langle B \rangle = B_{spot} \times f_{spot}$
- $B_{spot}(t) \sim const \sim 3$ kG

f_PMS > 80-90% **f_MS < 5-20%**

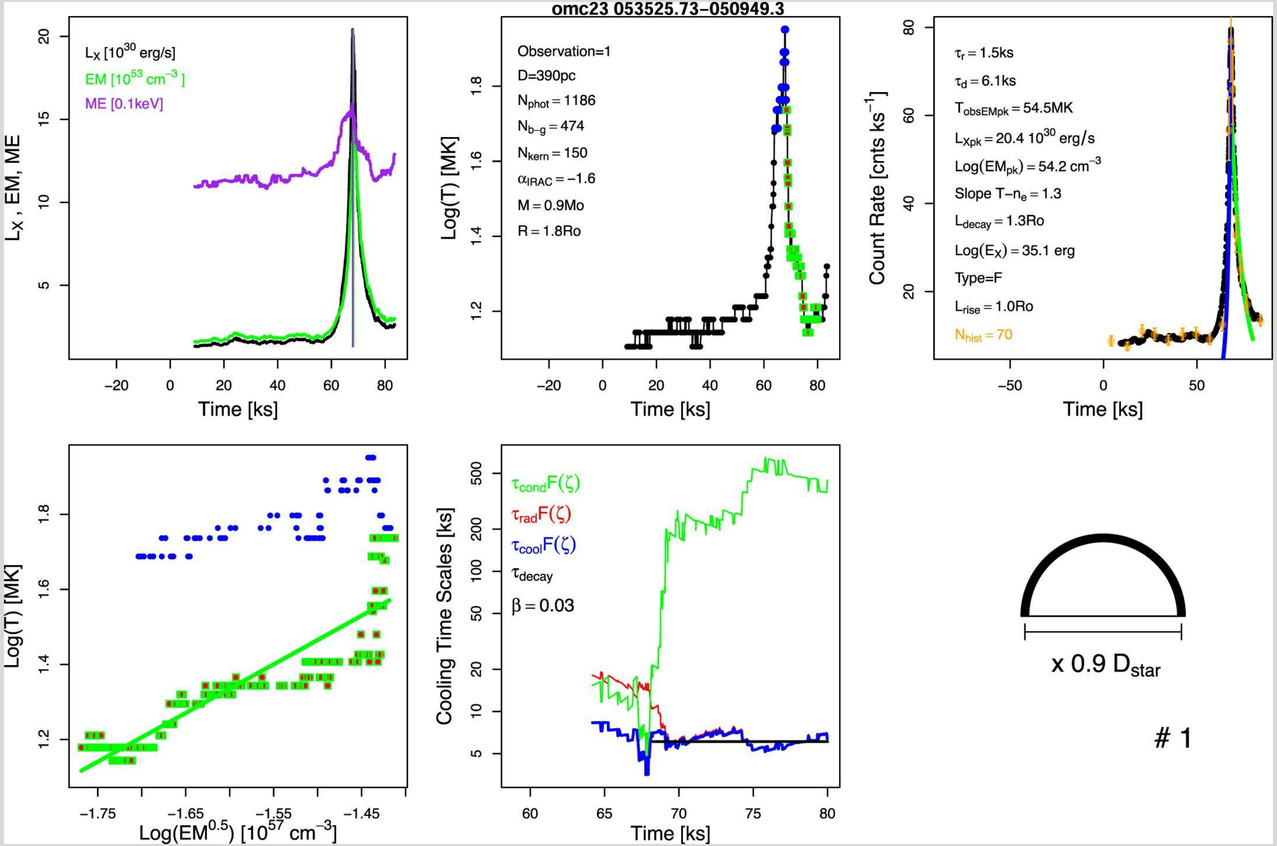


X-ray flares from PMS & MS stars

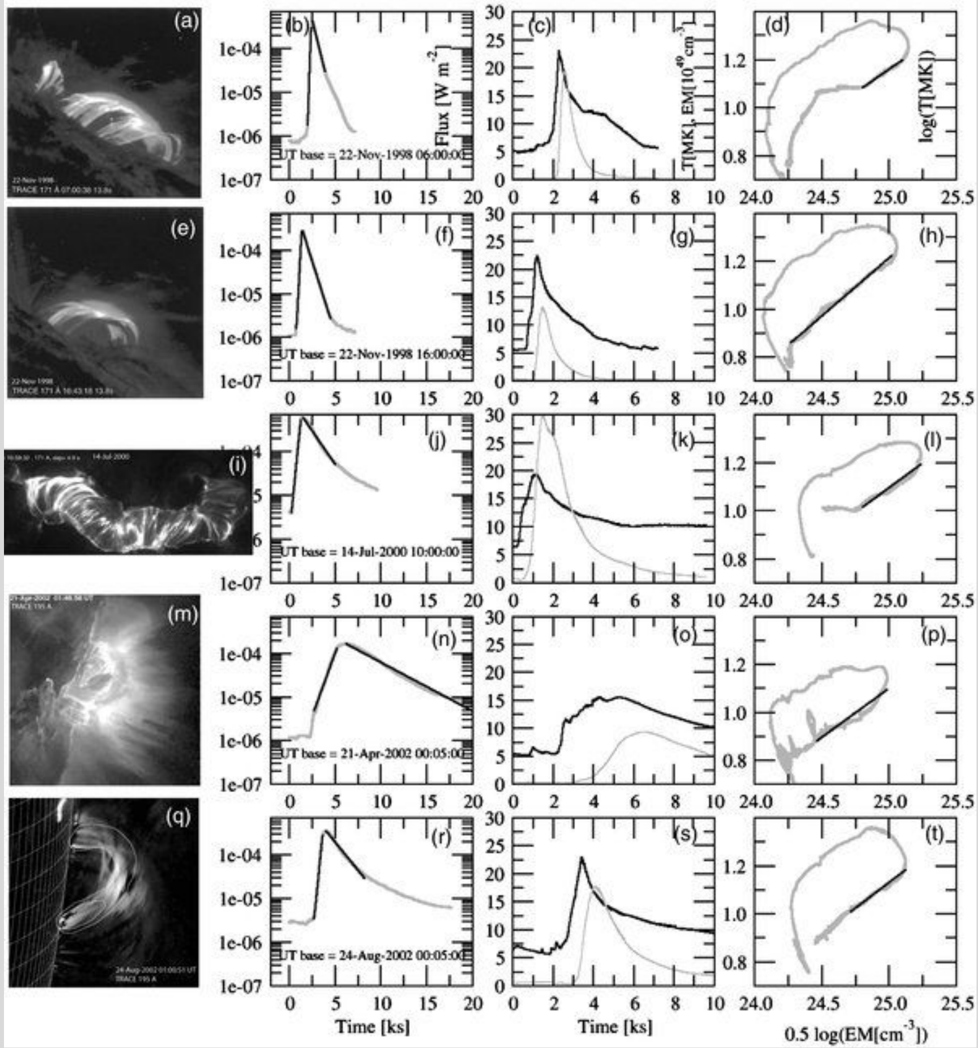


- Standard Model of a solar flare (Brown 1971, Lin & Hudson 1976, Benz 2017)
- This model is often applicable to X-ray/optical/microwave flares produced by young stars (Audard+07, Getman+11, Flaccomio+18, Getman+23b)

Modeling of large PMS X-ray flares



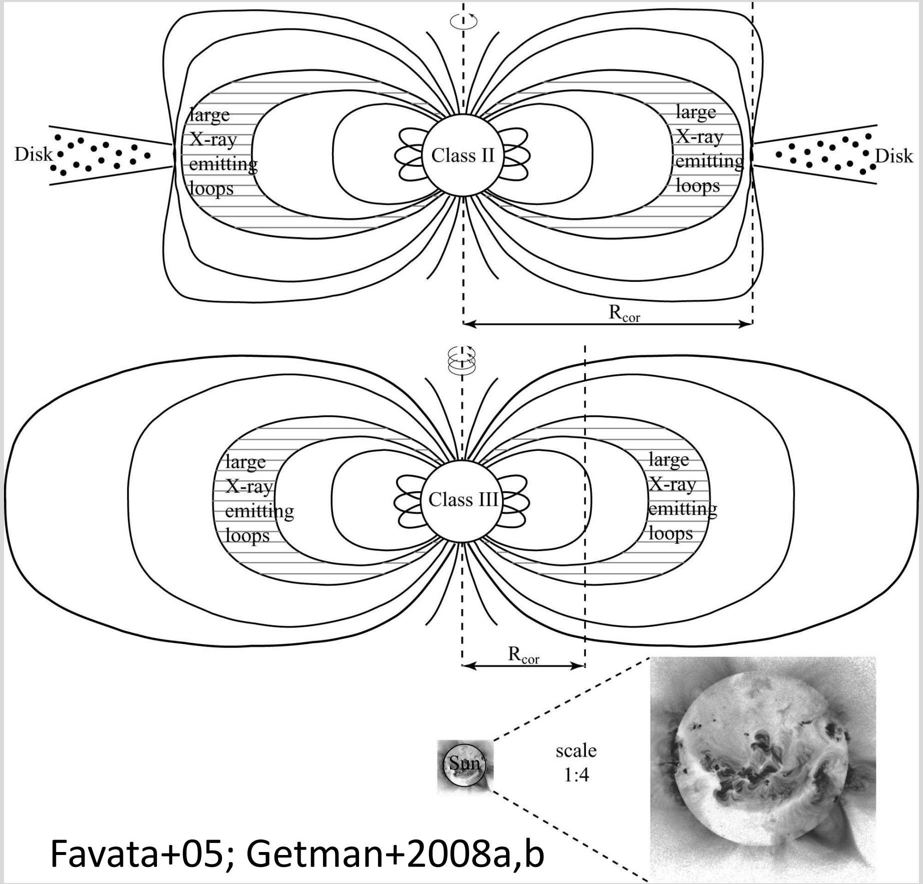
- Favata+05; Getman+08a,21b (based on the hydrodynamic stellar flare model of Reale+14)



Modeling of large Solar X-ray flares

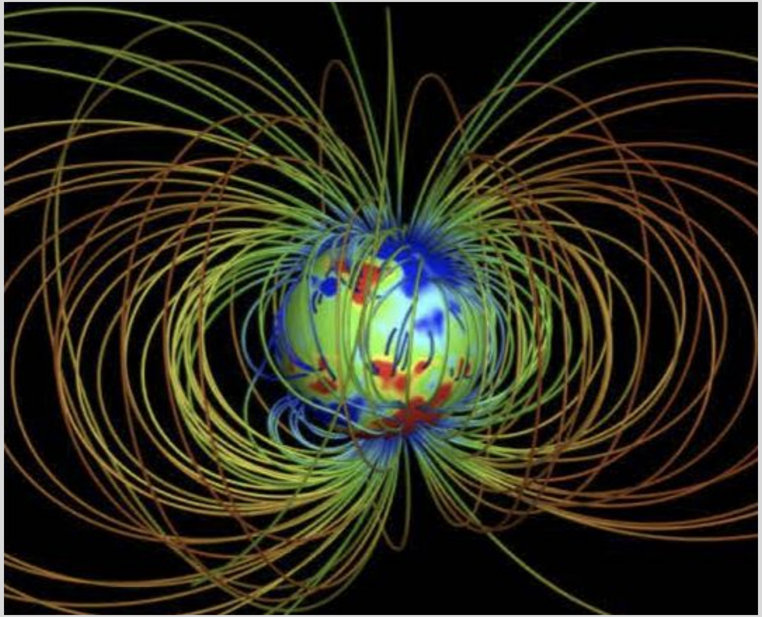
- Getman+11 (based on the hydrodynamic stellar flare model of Reale+14).
- Similar to PMS flares, U-shaped evolution in the temperature-density diagram -> **similar heating/cooling mechanisms.**
- Ignition of 20 loops within 2 minutes mimics a single dominant loop.
- Reale’s modeling yields loop sizes comparable with observations.

X-ray coronal extents in PMS stars versus the Sun



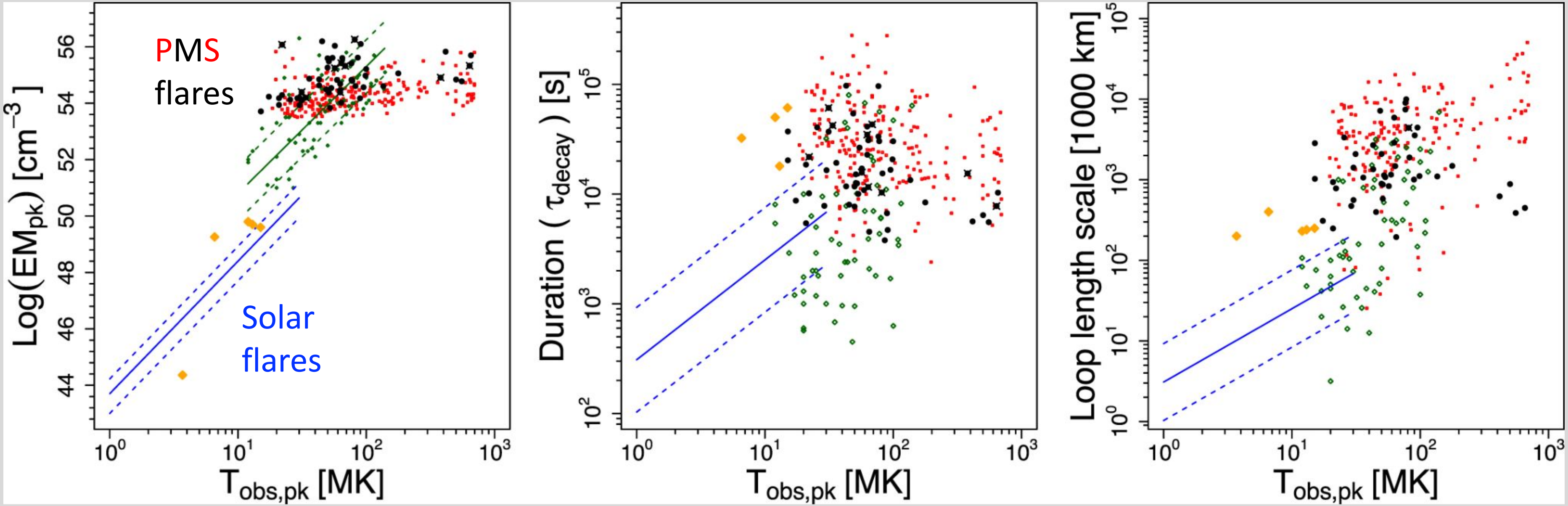
Favata+05; Getman+2008a,b

- X-ray flaring structures on PMS stars can be **immensely larger** than those on the Sun



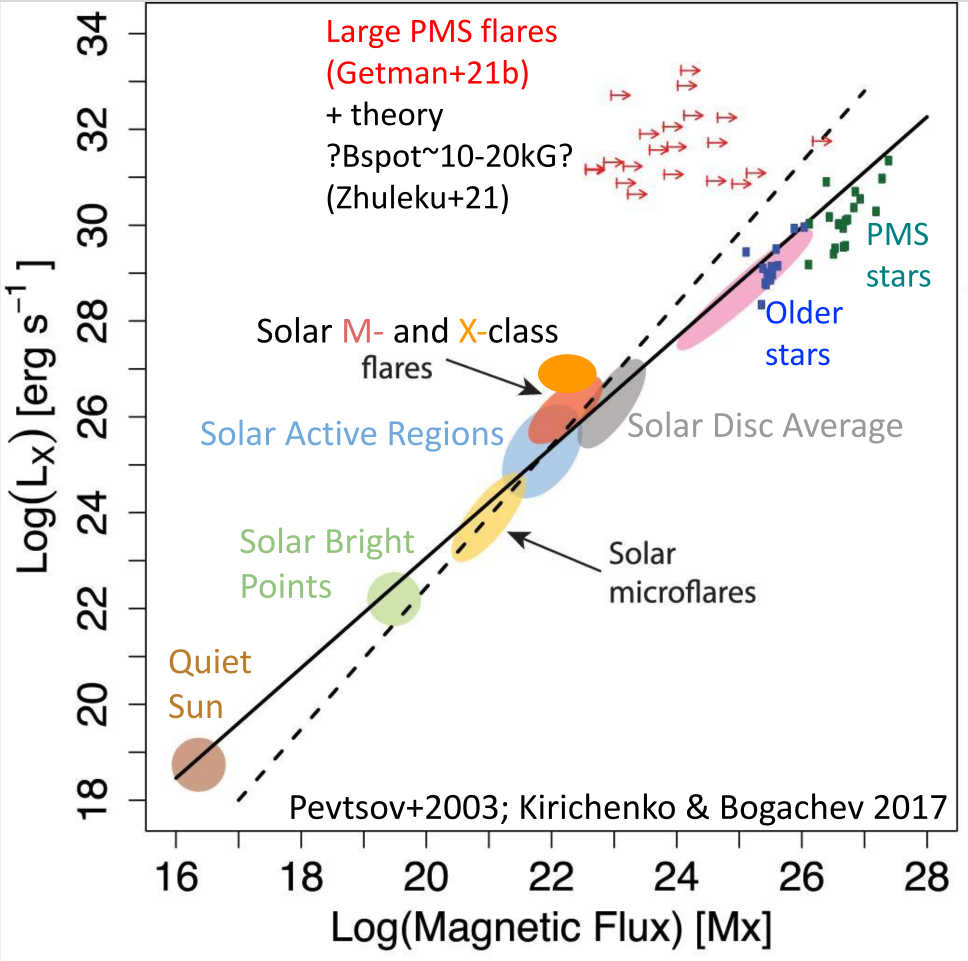
3D-MHD sims of fully convective (Cohen+17)

Flare plasma temperature, emission measure, duration, & size



- Solar flares (Aschwanden+08)
- Solar LDEs (compilation from Getman+08a)
- Flares from active stars (Gudel+04)
- Large PMS flares (Getman+08a) & Large PMS flares (Getman+21b)

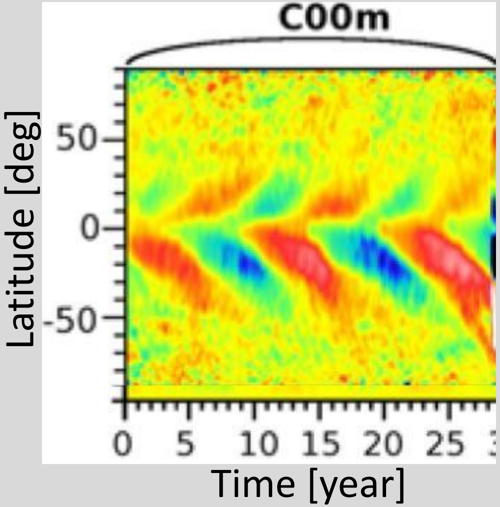
X-ray emission and surface magnetic flux



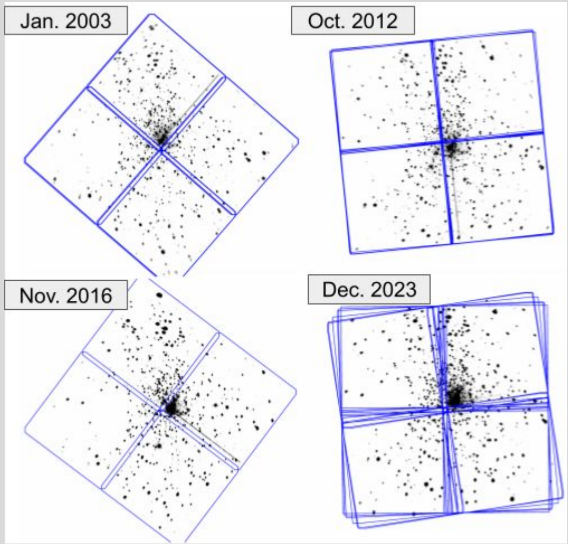
- Universality of magnetic flux propagation and dissipation

- Chandra-HPF (Getman+24b, submitted): PMS flares have B_{AR} similar to solar flares but much larger S_{AR} and V_{LOOP}. Flare Lx-Φ deviation is due to magnetic reconnection vs. Alfvén wave heating

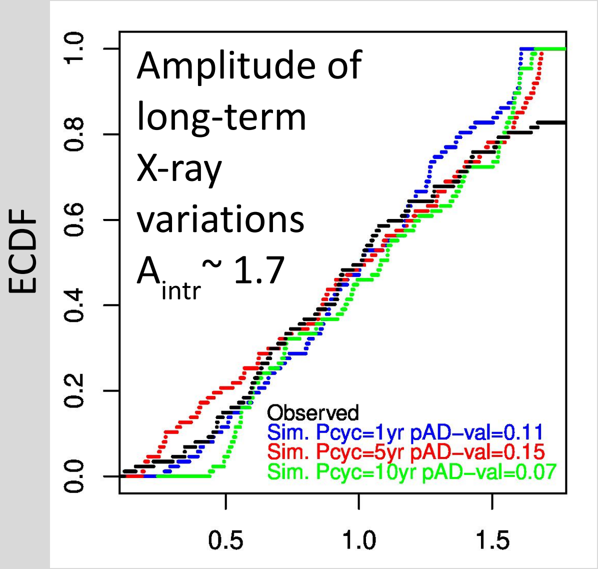
Search for Cyclical Activity in PMS stars



Emeriau-Viard & Brun 2017



Getman+24a (ApJ in press.)

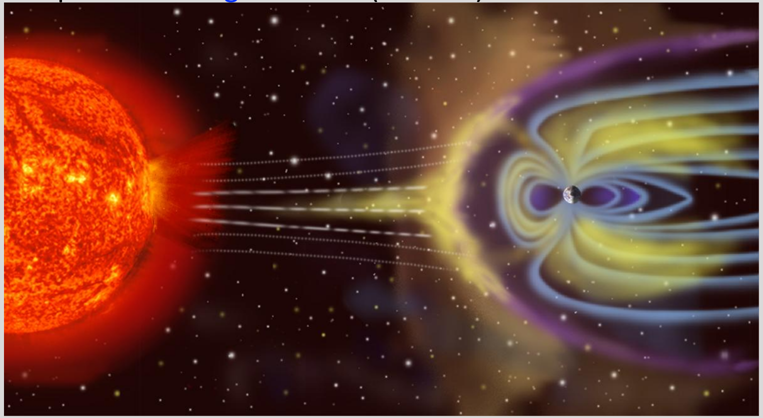


$A=(L_{Xch,max} - L_{Xch,min})/L_{Xch,min}$

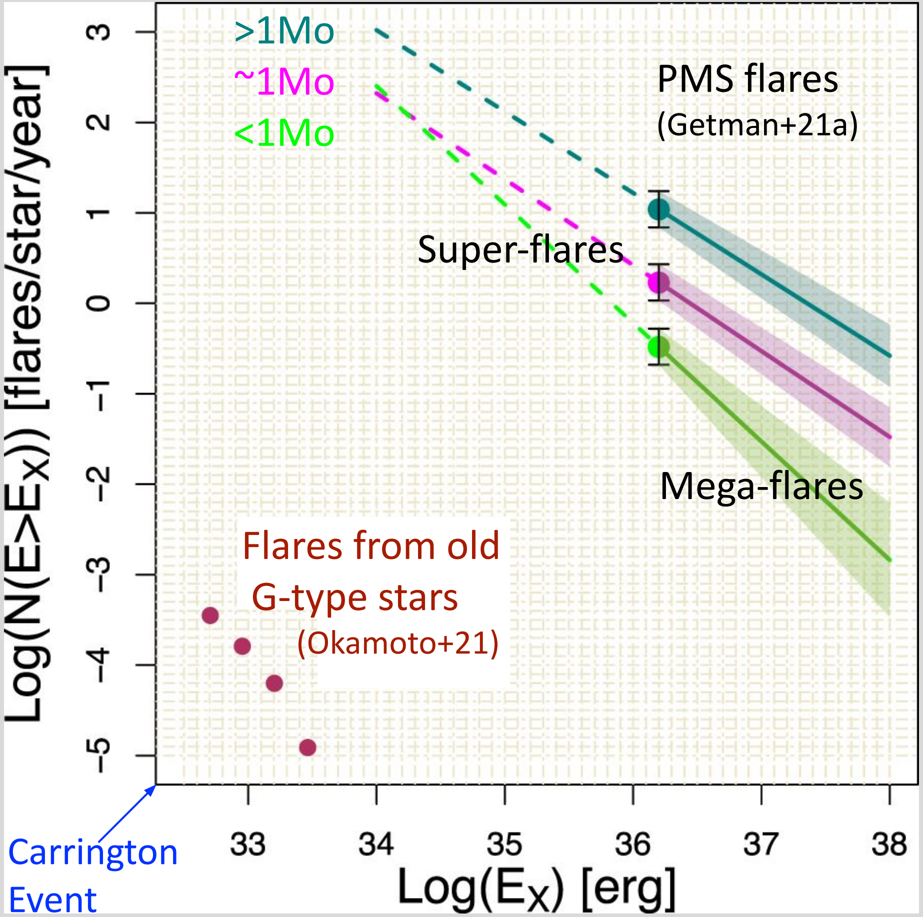
- $A_{\odot}$~(10-20) $\gg$ A_{PMS}~1.7.
- Weak PMS magnetic dynamo cycles or obs. mitigation of cycles by saturated PMS X-rays.

Flare rates: PMS vs. Solar flares

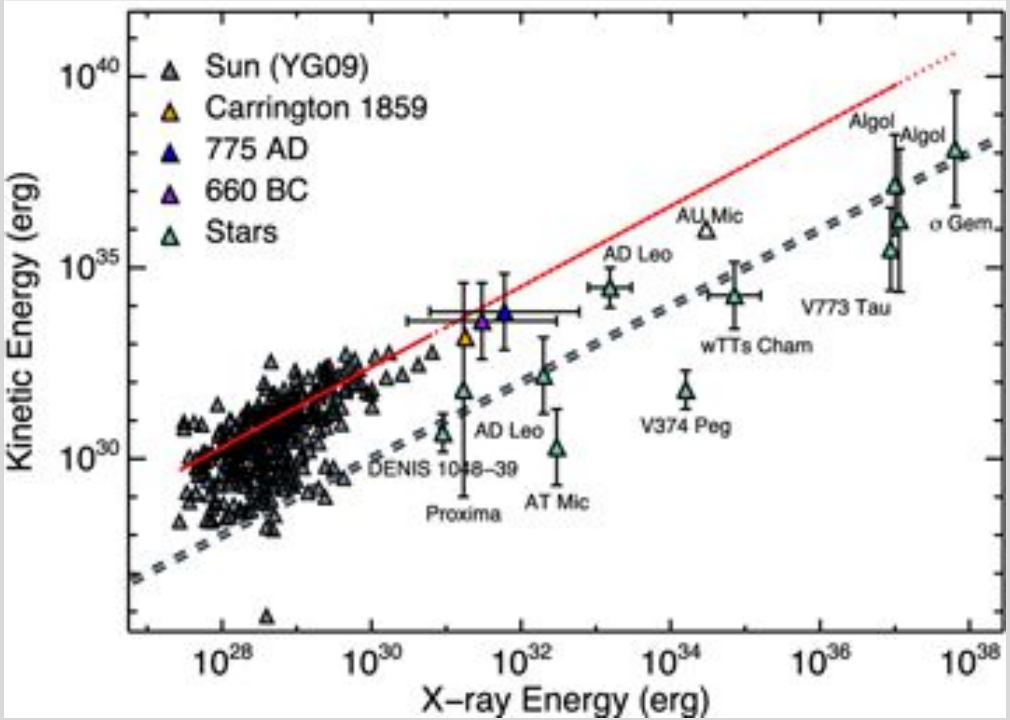
Wikipedia: Carrington Event (in 1859): Artist's rendition



- Sun: Freq.(Carrington Event) = 1/500 fl/yr. $1M_\odot$ PMS star: >25 Carrington Events per day (Getman+21a).
- $1M_\odot$ PMS star: 3 mega-flares ($E_X > 10^{36}$ erg) per yr.



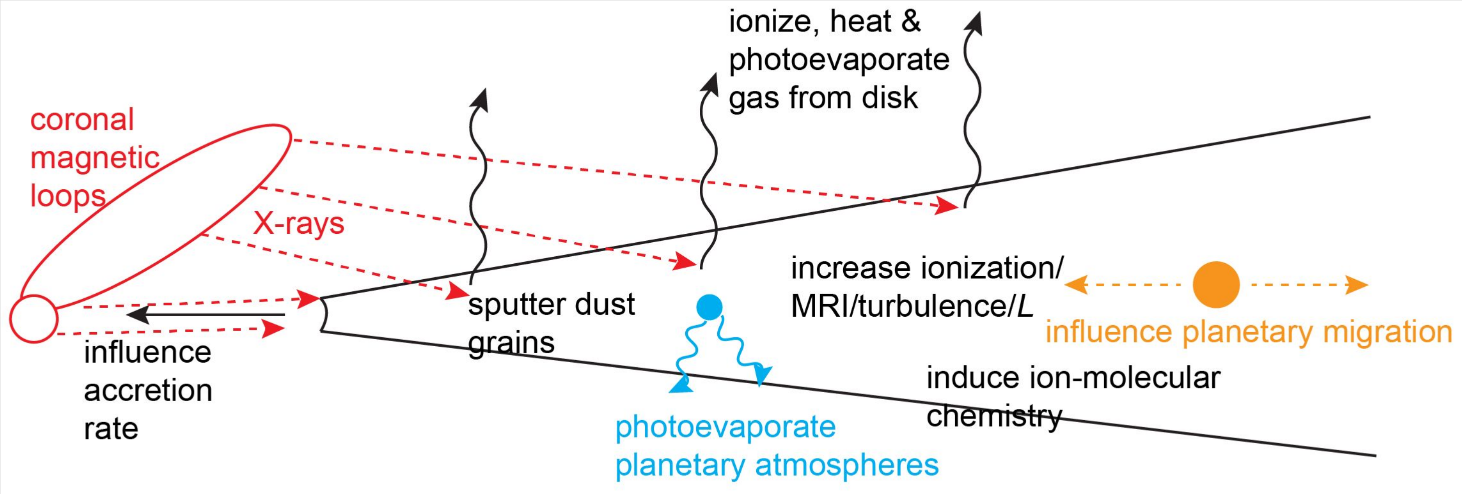
CME Energetics



Moschou+19

Indirect stellar CME signatures: Doppler shifts in emission & absorption lines, possible X-ray dimming/absorption (Argiroffi+19; Namekata+21,24; Moschou+19; Veronig+21)

Effects of PMS X-rays on environs:



- Glassgold+2000; Fromang+2002; Shang+2002; Ilgner & Nelson 2006; Williams & Cieza 2011; Owen et al. 2012,2019; Gressel+2013; Alexander et al. 2014; Cleeves+2017; Dupuy et al. 2018; Johnstone+2019; Wordsworth & Kreidberg 2022; Waggoner+2023; Ercolano & Picogna 2023; Ercolano+2023; Woitke+2024
- CMEs: Airapetian+2020, 2023; Hazra+2022; Alvarado-Gomez+2022

Summary

- The most powerful stellar flares driven by magnetic energy in non-binary systems occur during the early pre-main sequence phase.
- Overall, PMS flares are **vastly scaled-up** versions of solar flares.
- Understanding the impact of XUV outbursts and associated CMEs on PMS environments is at the forefront of modern astrophysical research.

Summary

Property	Solar Flares	Large PMS Flares
Dynamo	alpha-omega	alpha^2
<B>	<100 G	1-4 kG
f_spot	<10%	>80-90%
B_spot	few kG	few kG
X-ray-Rotation	Non-Saturation	Saturation
Standard Flare Model	yes	yes
U-shaped T-n Evolution	yes	yes
Plasma Temperature	(1-30) MK	(20-800) MK
Flare Duration	(100-6000) s	(10,000-100,000) s

Summary

Property	Solar Flares	Large PMS Flares
Flare Scale	(3000-50,000) km	(1,000,000-20,000,000) km
Flare Lx Peak	<10^28 erg/s	10^31-10^33 erg/s
dN/dE~E^-2	yes	yes
Flare Energy (E)	<10^32 erg	(10^34-10^38) erg
Freq. (Carrington Event)	1/500 fl/yr	>25 fl/day
Freq. (E > 10^34 erg)	1/100,000 fl/yr	>200 fl/yr
Freq. (E > 10^36 erg)	0 fl/yr	3 fl/yr
Lx-Magnetic Flux	yes	Might Deviate
Kinetic Energy CME	<10^33 erg	(10^34-10^38) erg