X-ray Super-Flares From Pre-Main Sequence Stars: Flare Energetics, Frequency, and Loop Geometry

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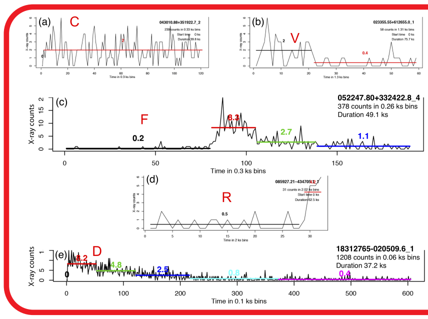
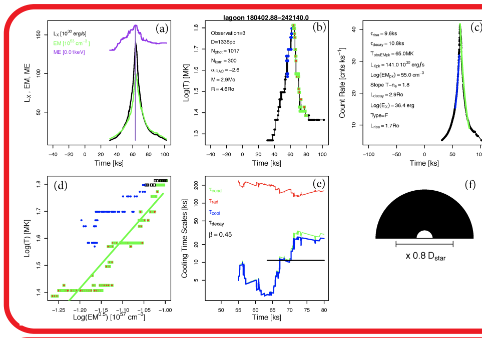
Solar-type stars exhibit their highest levels of magnetic activity during early convective pre-main sequence (PMS) phase of evolution. The most powerful PMS flares, super-flares (SFs), have total energies 10^{34}-10^{38} erg. Among 24,000 young (t < 5 Myr) X-ray-selected members of 40 star-forming regions emerged from our Chandra MYStIX/SFiNCs surveys, we identify and analyze 1,086 X-ray SFs, the largest sample ever studied. These are considerably more powerful than optical flares detected on older stars. We find that X-ray SFs are produced by young stars of all masses over a range of evolutionary stages from protostars to diskless stars with the occurrence rate positively correlated with stellar mass. A powerlaw slope in the flare energy distributions is consistent with those of optical/X-ray flaring from older stars. SFs contribute >10-20% to the total PMS X-ray energetics. PMS SFs may have implications for X-ray driven photoevaporation of the protoplanetary disk, variable ionization in disk gas, production of spallogenic radionuclides in disk solids, and hydrodynamic escape of young planetary atmospheres. We fit plasma models to the 55 brightest X-ray SFs and compare them with published SFs from young ONC and older stars. Several more results emerge. First, most PMS SFs resemble solar long duration events associated with coronal mass ejections. Second, the properties of PMS SFs are independent from the presence or absence of protoplanetary disks, supporting the solar-type model of PMS flaring magnetic loops with both footpoints anchored in the stellar surface. Third, strong correlations of SF peak emission measure and plasma temperature with the stellar mass are similar to established correlations for the PMS X-ray emission composed of numerous smaller flares. Fourth, a new correlation of loop thickness or geometry is linked to stellar mass. Finally, the slope of a long-standing relationship between the X-ray luminosity and magnetic flux of various solar-stellar magnetic elements appears steeper in PMS SFs than for solar events.

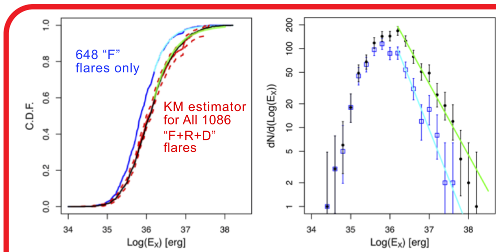
Based on 2 papers submitted to ApJ: "X-ray Super-Flares From Pre-Main Sequence Stars: Flare Energetics And Frequency" by Getman & Feigelson, 2021; "X-ray Super-Flares From Pre-Main Sequence Stars: Flare Modeling" by Getman, Feigelson, & Garmire, 2021. Full paper drafts are available at: http://personal.psu.edu/kug1/RESEARCH/RESEARCH.htm



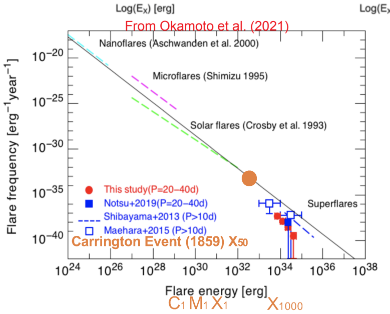
Application of the Poisson regression model with multiple changepoints to >24,000 MYStIX/SFiNCs X-ray YSOs resulted in 1086 F (full flare), R (rise part), and D (decay part) super-flare events.

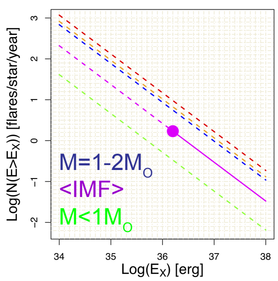


For 55 brightest MYStIX/SFiNCs super-flares, modeling results include temporal profiles of X-ray count rate, median energy, X-ray luminosity, emission measure, plasma temperature, and cooling timescales, as well as the slope on the temperature-density diagram. Based on these quantities, loop heights (Reale 2014) and loop thicknesses (Getman et al. 2011) are estimated.



Fitting the Kaplan-Meier super-flare energy estimator with the Pareto distribution function gives the energy distribution $dN/dE_X \sim E_X^{-2}$, close to the solar-flare one.





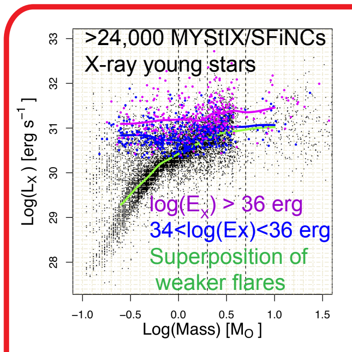
For the Sun, Okamoto et al. (2021) predict:

$Freq_{Sun}(E_{Xray}>1.6e33erg) \sim 1$ flare per 6000 years.

Inferred PMS super-flare occurrence rate is roughly:

$\log(N[E>E_{Xray}])=34.62-0.95\cdot\log(E_{Xray})$ [flares/star/year].

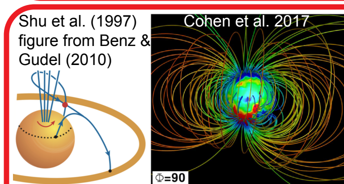
$Freq_{PMS}(E_{Xray}>1.6e33erg) \sim 1000$ flares per star per 1 year.



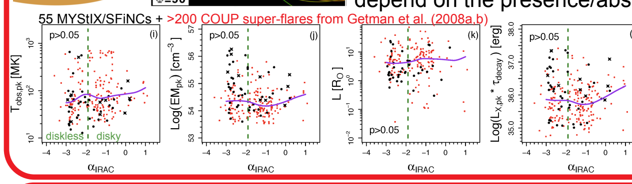
Contribution of mega-flares to the total X-ray PMS energetics is >10-20%.

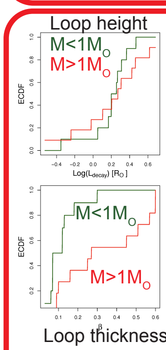
Primordial atmosphere of a planet near 1M$_O$ PMS star or gas in the disk around 1M$_O$ PMS star can be removed within ~5 Myr by photoevaporation from characteristic X-ray emission. X-ray mega-flares ($E_X>10^{36}$ erg) alone may speed up this process by >0.5 Myr (assuming a linear reponse to the flare events).

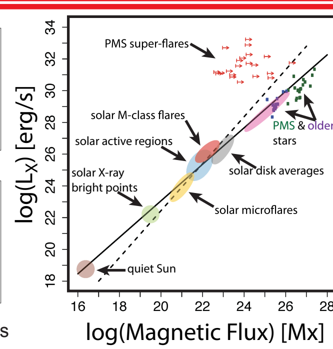
However, more astrophysical modeling is needed to understand whether the response to flares is linear or not.



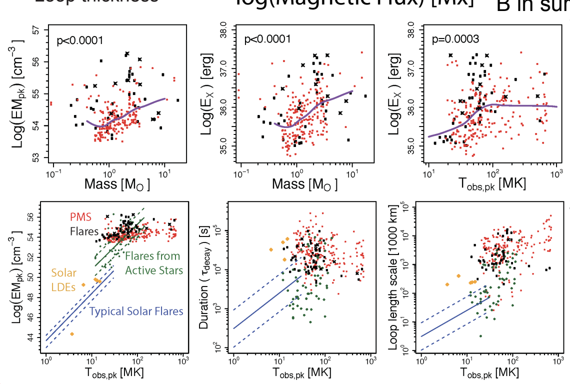
Shu et al. (1997) predict star-disk flaring coronal loops on disky PMS stars. Getman et al. (2008b) find large flaring loops on both disky and diskless stars. Here, we report that loop geometry, super-flare duration, peak emission measure and plasma temperature, and flare energy do not depend on the presence/absence of disks. Which agrees e.g., with the 3-D MHD simulations of Cohen et al. of large, hot loops in fast rotating, fully convective M stars.







MYStIX/SFiNCs SFs' loop thickness positively correlates with stellar mass, indicating larger surface foot-prints for more X-ray luminous flares. SF positions on the L_X-magnetic flux diagram [8;10;14], with the latter as a product of loop thickness and minimum equipartition magnetic field strength, indicate that SFs either deviate from the universal slope and/or have extremely high B in surface spots, of >10-20 kG.



Solar-stellar flares from Aschwanden et al. (2008) & Gudel (2004)

We report various flare scaling relationships indicating that more energetic (more X-ray luminous) flares are associated with hotter plasma and often higher flare duration and larger loop scales. [1;14] suggest that $L_X \sim$ mag.flux^m & EM~T^a can be linked to the long-standing RTV scaling laws for solar static coronal loops [12]. PMS SFs are analogs of Solar LDEs.

[1]Aschwanden et al. 2008, ApJ, 672, 659
[2]Benz & Gudel 2010, ARAA, 48, 241
[3]Cohen et al. 2017, ApJ, 834, 14
[4]Getman et al. 2008a, ApJ, 688, 418
[5]Getman et al. 2008b, ApJ, 688, 437
[6]Getman et al. 2011, ApJ, 730, 6
[7]Gudel 2004, A&ARev, 12, 71
[8]Kirichenko & Bogachev 2017, SoPh, 292, 120
[9]Okamoto et al. 2021, ApJ, 906, 72
[10]Pevtsov et al. 2003, ApJ, 598, 1387
[11]Reale 2014, LRSP, 11, 4
[12]Rosner et al. 1978, ApJ, 220, 643
[13]Shu et al. 1997, Science, 277, 1475
[14]Zhuleku et al. 2020, A&A, 640, 119

Future goals:
*** Measure average surface magnetic field strengths near PMS super-flare epochs;
*** Populate the flare scaling plots with weaker PMS flares;
*** Study super-flares from older (t= [5-100] Myr) PMS/MS stars.