Solar Explosive Events Throughout the Evolution of the Solar System. II. Trends with Time

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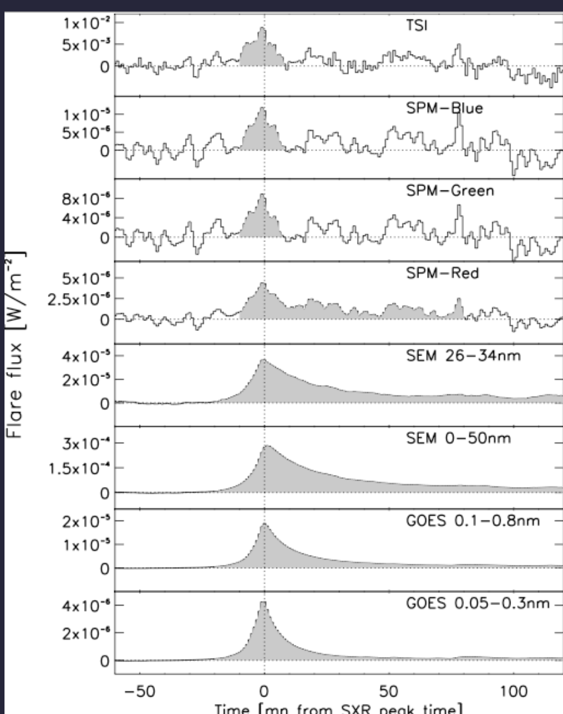
Outline

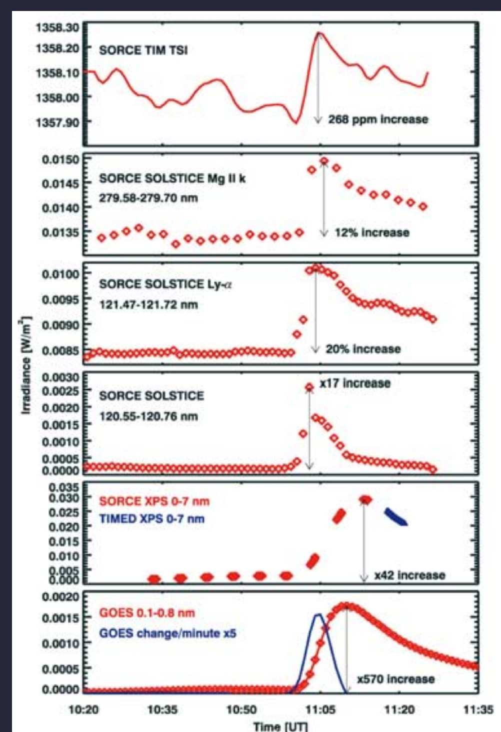
- Synthesizing event-focussed results:
  - flare spectral energy distribution, energy partition
  - frequency distributions
- Time Periods:
  - Stellar infancy: birth to Zero Age Main Sequence (ZAMS)
  - Stellar Teenage Years: ZAMS to 1 GY
  - Stellar Adulthood: 1-4.5 GY
  - Stellar Old Age: >4.5 GY

Synthesizing event-focussed results

Flare spectral energy distribution – solar



Kretzschmar et al. 2011



Woods et al. 2004

Synthesizing event-focussed results

The hot optical continuum radiation dominates over other radiative components of the flare

Mean X-ray class	Total energy TSI (ergs)	Ratio 26–34 nm/TSI	Ratio 0–50 nm/TSI	Ratio 0.1–0.8 nm/TSI	T_{bb} (°K)	S_f (arcsec^2)	Ratio Continuum/TSI
X3.2	5.9×10^{31}	0.9%–0.8%	12%–9%	1.2%–1%	9345	16.7	67%
M9.1	1.6×10^{31}	1.7%–0.4 %	23%–5%	1.0%–0.4%	8993	13.2	85%
M4.2	1.3×10^{31}	2.2%–0.5%	18%–6%	0.6%–0.3%	9244	7.3	74%
C8.7	3.6×10^{30}	1.5%–0.5%	16%–5%	0.4%–0.2%	8655	2.4	72%
M2.0	5.1×10^{30}	1.7%–0.6%	18%–6%	0.7%–0.4%	8941 K	2.8	69%

Kretzschmar et al. (2011) TSI observations of solar flares

3 filters consistent with BB at 9000 K; continuum carries most of the energy

well-studied flare on an M dwarf with multi-wavelength coverage
Hawley et al. (1995)

DERIVED QUANTITIES

Quantity	EF1	EF2	AU Mic
Optical			
T_{fl} (K)	9000	9500	...
A_{opt} (cm^2)	1.1×10^{18}	5.6×10^{17}	...
$A_{opt}/4\pi R_*^2$	1.0×10^{-4}	5.3×10^{-5}	...
E_{opt} (ergs)	$>4.6 \times 10^{33}$	2.8×10^{33}	...
Coronal			
L (cm)	3.8×10^{10}	$<1.5 \times 10^{10}$	2.6×10^{10}
N_{max} (cm^{-2})	1.3×10^{21}	$<1.0 \times 10^{21}$	1.5×10^{21}
P_{max} (dyne cm^{-2})	180	<280	350
A_{cor} (cm^2)[a]	9.1×10^{19}	1.9×10^{19}	1.7×10^{21}
$A_{cor}/4\pi R_*^2$[a]	0.0085	0.0018	0.045
V (cm^3)[a]	7.1×10^{30}	5.6×10^{29}	8.8×10^{31}
EM (cm^{-3})[a]	8.2×10^{51}	2.5×10^{51}	2.9×10^{53}
E_{th} (ergs)[a]	1.9×10^{33}	2.3×10^{32}	4.6×10^{34}

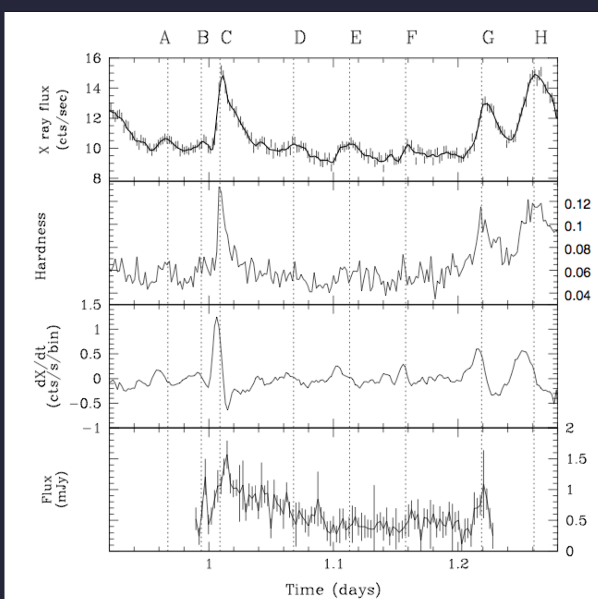
[a] The coronal area coverage, volume, emission measure, and thermal energy listed here assume no correction for possible "dead spot" effects in the AD Leo observation. If a correction factor f_{ds} is applied, each quantity should be multiplied by f_{ds}.

BB: E_{opt} comes from a flare SED with a black-body of 9000 K; 90% of the optical energy (lines + continuum) comes out in the continuum [Hawley & Pettersen]

70% of total (optical + X-ray) radiated energy comes from optical continuum

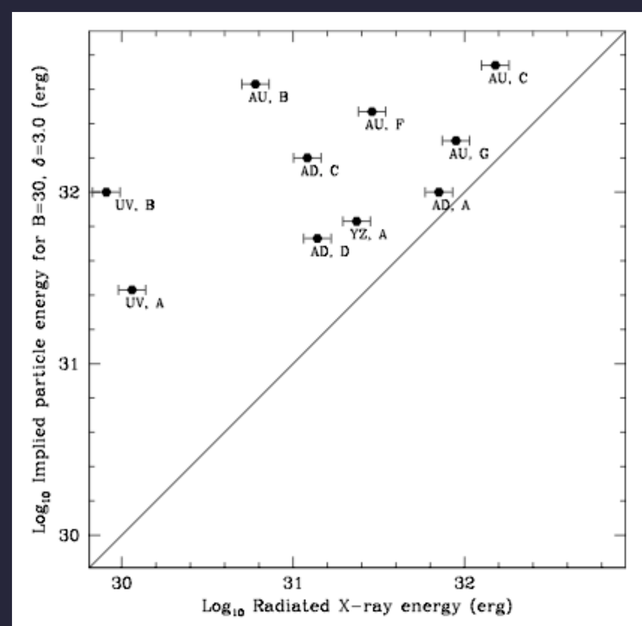
Radio-X-ray flares: energetics

Even though the radiative output of radio flares is tiny, the implied kinetic energy of the accelerated particles exceeds what is seen in the X-ray



AU Mic, Smith et al. 2005

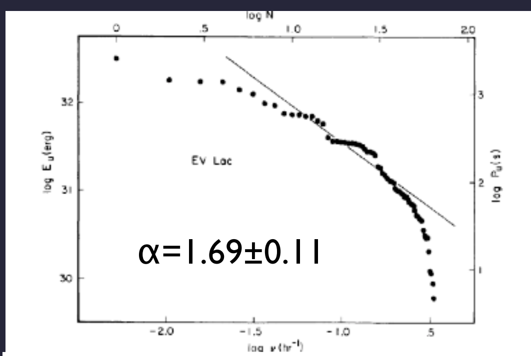
choosing one value of B, δ gives more energy in nonthermal particles than in coronal



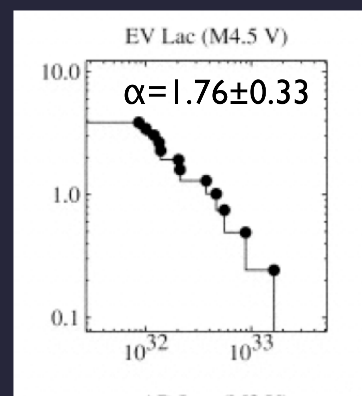
Synthesizing Event-Focussed Results

- flare frequency-energy distribution characterizes the relative numbers of small and large flares
- for flare occurrence rates $dN/dE = kE^{-\alpha}$, $\alpha>2$ implies that flares can explain the entire X-ray luminosity of the star
- for solar flare studies, α generally ~1.8, can be larger for stars

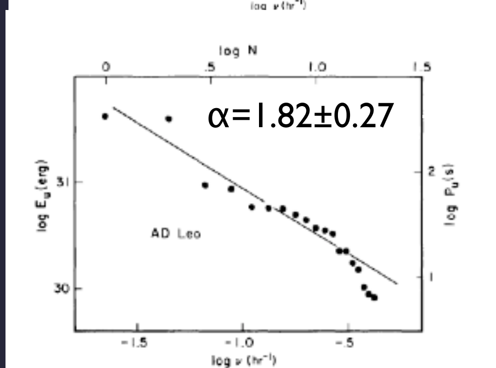
Flares measured in different wavelength regions

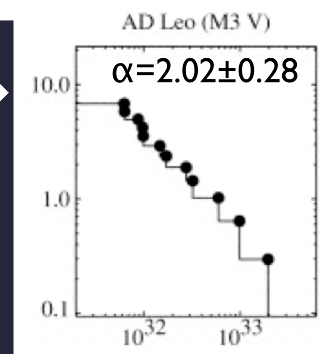


EV Lac



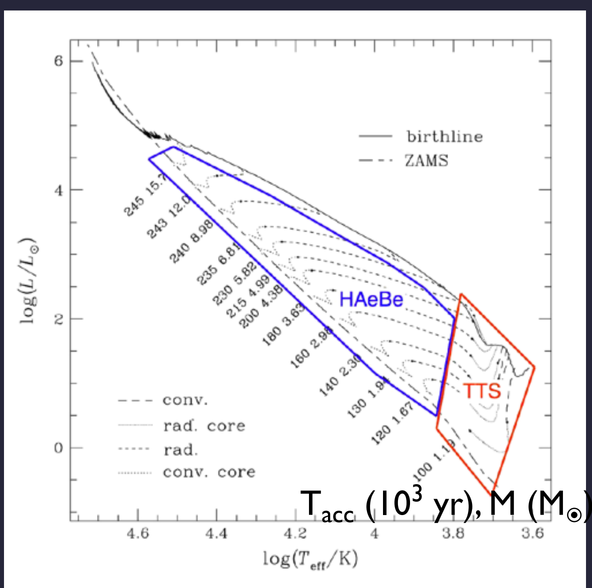
←U band
(Lacy et al. 1976)
EUVE (0.01-10 keV)
(Audard et al. 2000)→



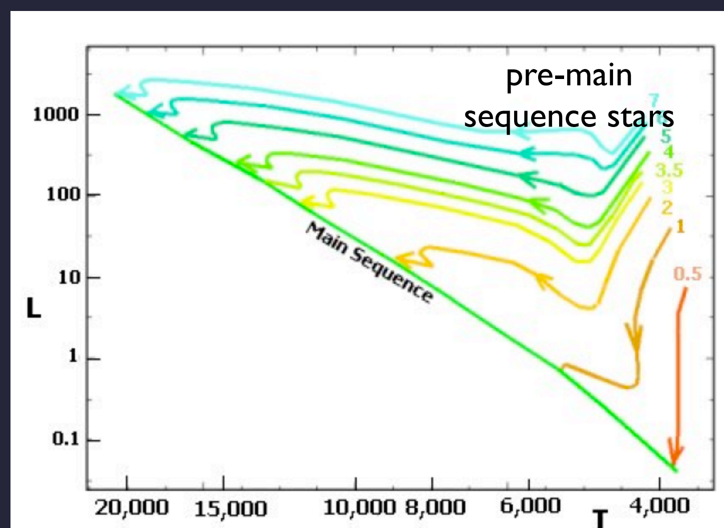


AD Leo

Stellar Infancy: Birth to Zero Age Main Sequence



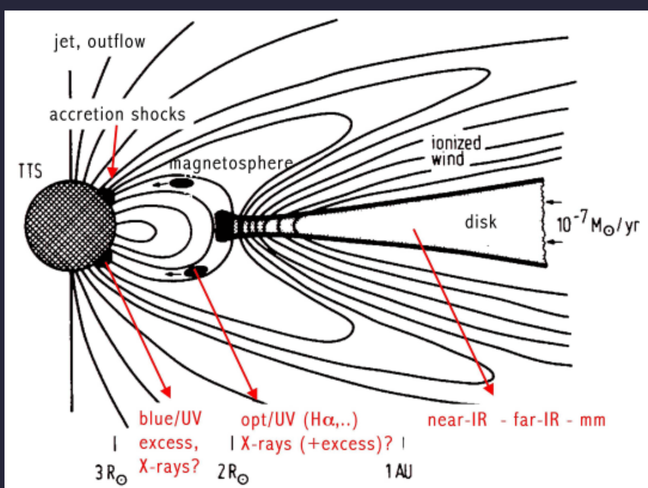
Behrend & Maeder (2001), after Alecian (2013)



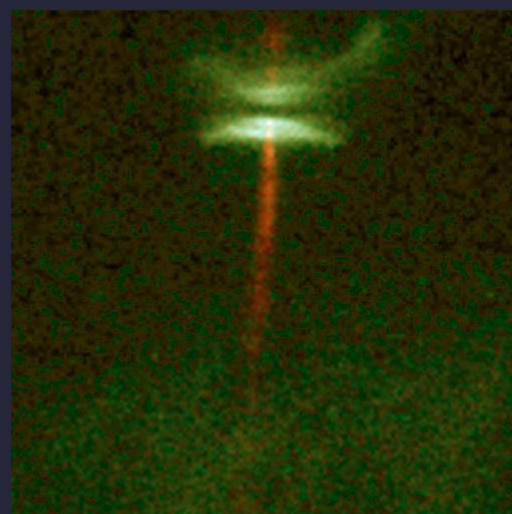
Siess et al.

- Pre-main sequence stellar evolution
- T Tauri stars: classical (cTTS) and weak-lined (wTTS). The distinction depends on the presence of a disk and importance of accretion onto the star

Stellar Infancy: Birth to Zero Age Main Sequence



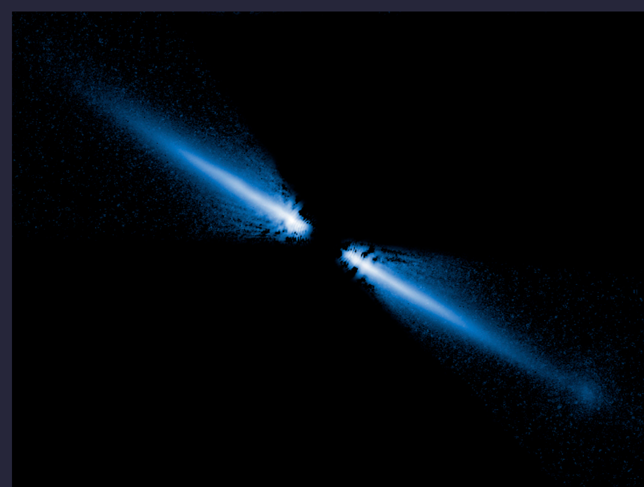
Camenzind (1990)



- interaction between the star and the disk affects the star's final rotation speed
- magnetic loops from the star can potentially reach the disk

Stellar Infancy: Birth to Zero Age Main Sequence

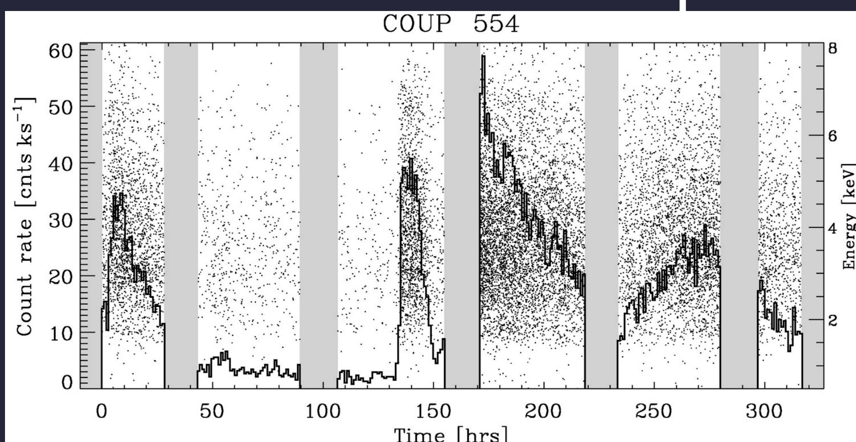
2 week-long "movie" of stellar X-ray flares from young stars in the Orion Nebula Cluster

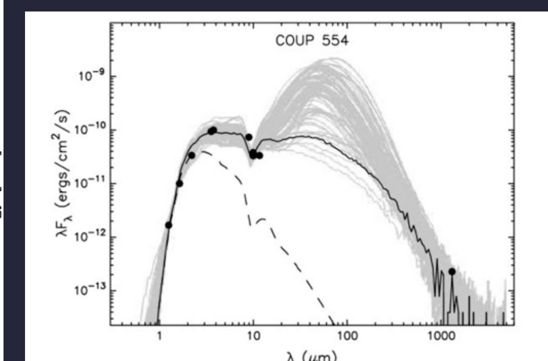


debris disk around M dwarf AU Mic

disk changes due to: accretion onto the star, ejection from the system, condensation into larger bodies; timescale is about 10 MY

Stellar Infancy: Birth to Zero Age Main Sequence





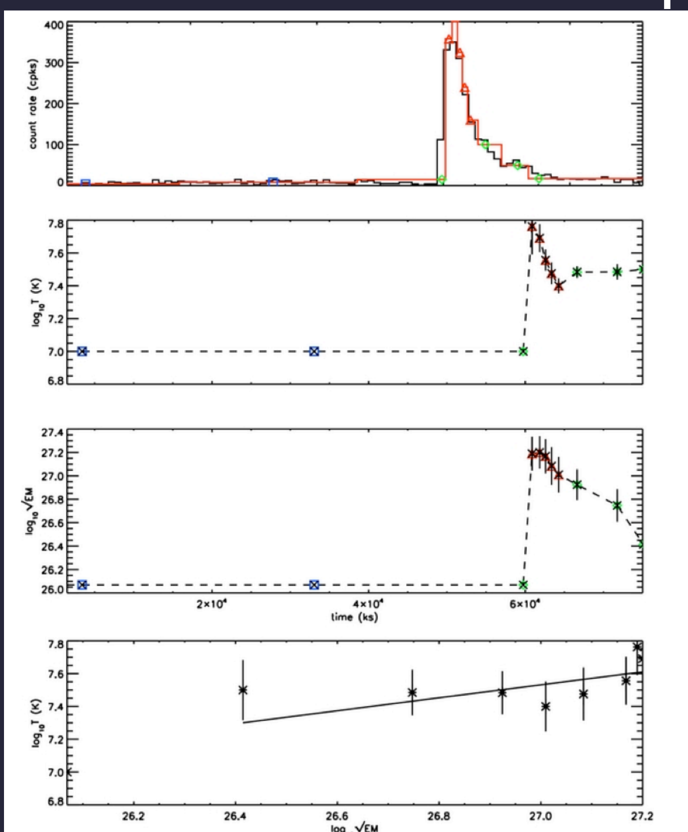
Rivilla et al. (2013)

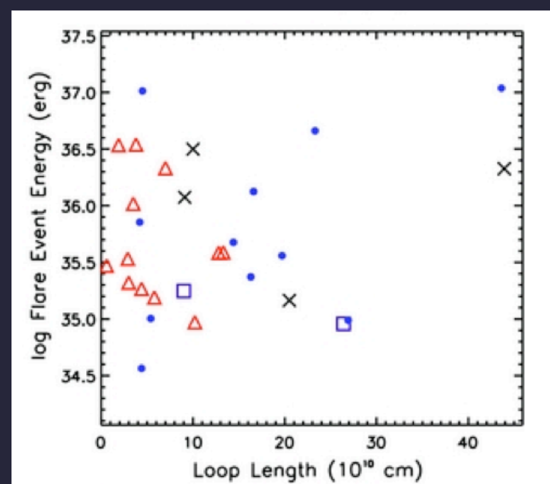
X-ray flares can be observed from stars with and without a disk

Stellar Infancy: Birth to Zero Age Main Sequence

- Hydrodynamic modelling of the decay phase of X-ray flares uses 1D models of Reale et al. (1997) first applied to solar flares. Assumes semi-circular loop, allows for heating to occur during flare decay. Models run for a range of loop lengths and timescales are applied to a specific instrument response.
- requires:
  - τ_{decay} from light curve
  - $T(t)$, $n_e(t)$ [actually VEM(t)]
- and you infer:
  - T_{max}, loop length L

Stellar Infancy: Birth to Zero Age Main Sequence





□ class I stars: embedded

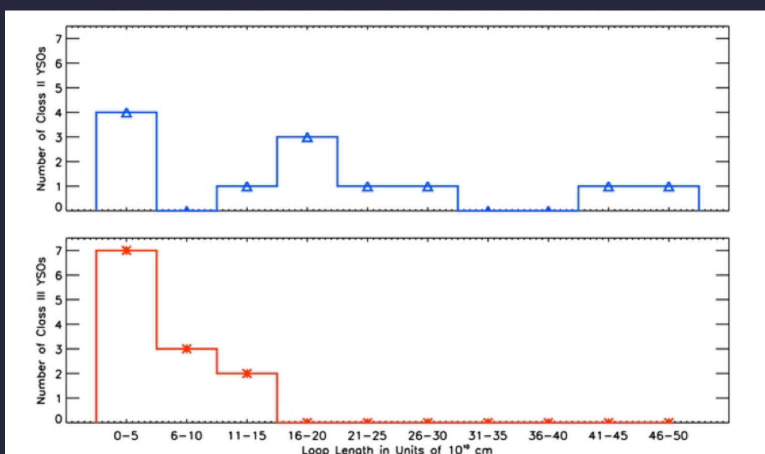
● class II stars: with disks

△ class III stars:no evidence for disks

× unclassified

McCleary & Wolk (2011)

Stellar Infancy: Birth to Zero Age Main Sequence



Distribution of flaring loop lengths on stars with a disk (top) and without (bottom)

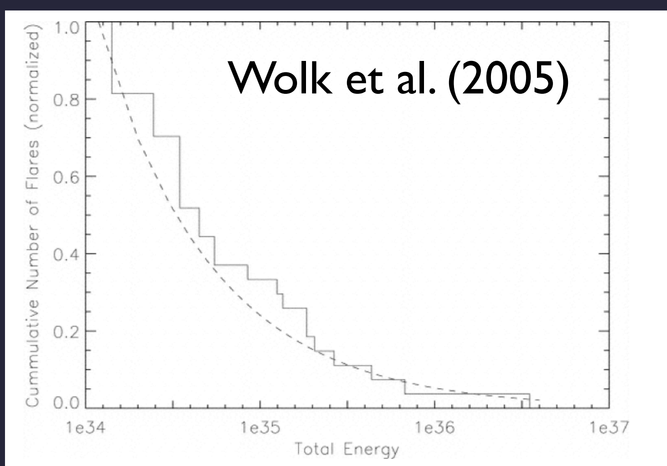
R_{star} = 1.5-4 R_{sun} for M=0.2-3 M_{sun}

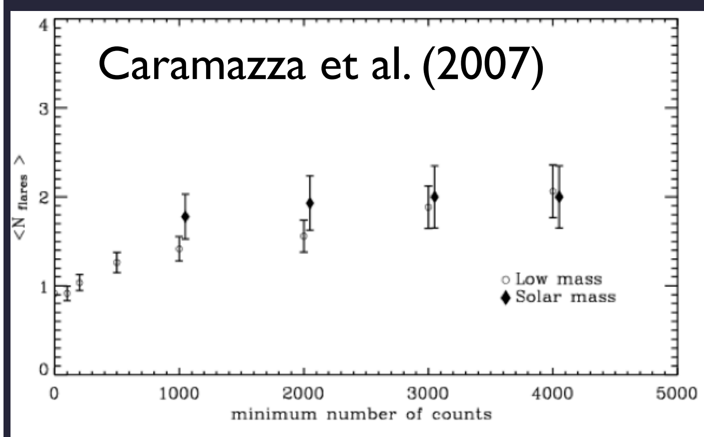
McCleary & Wolk (2011)

Can flares on these young stars connect to the planet-forming disk?

How applicable is the solar flaring loop model?

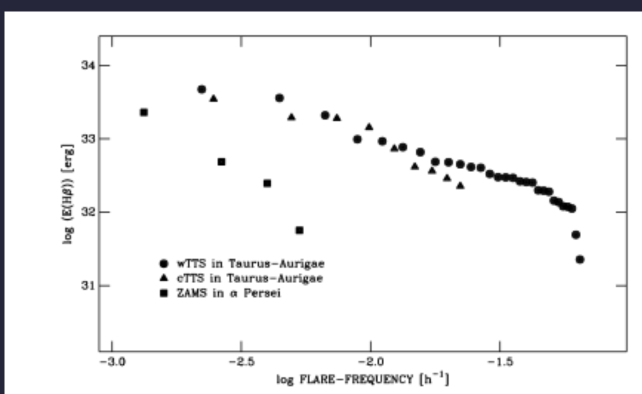
Stellar Infancy: Birth to Zero Age Main Sequence

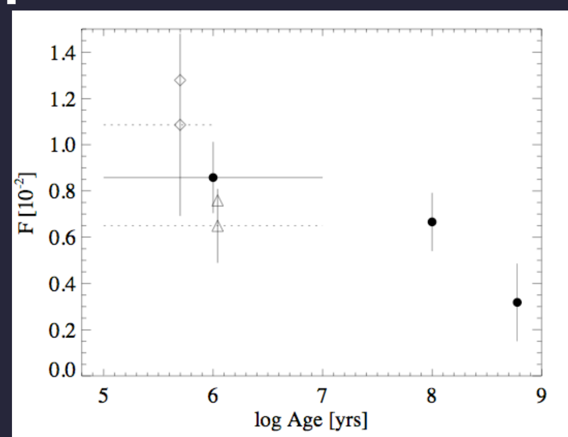




- Wolk et al. 2005 flares on young stars of solar mass (0.9-1.2 M_{sun}) at Orion age (~1 MY) have flares 1-2 times per week wtih L_x 10^{30}-10^{32} erg/s, distributed as a power-law with dN/dE~$E^{-1.7}$
- Caramazza et al. (2007) compared flare frequencies of low mass stars in Orion (0.1-0.3 M_{sun}) with solar-mass and find no difference. They get α=2.2 ±0.2

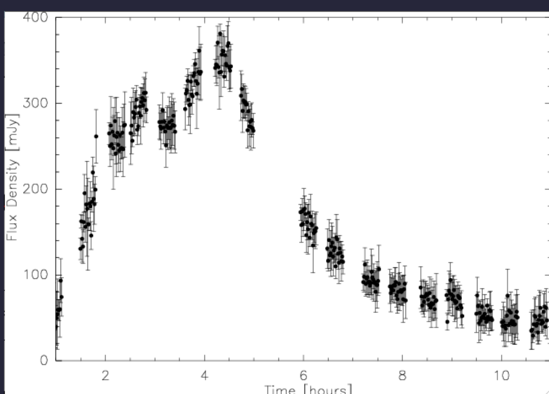
Stellar Infancy: Birth to Zero Age Main Sequence

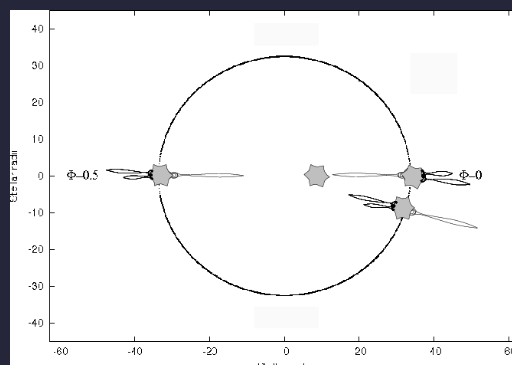




- Gunther & Ball (1999) flare frequency distribution of stars using Hβ emission line equivalent width variations. Accretion interpretation for stars with disks complicates matters
- Stelzer et al. (2000) X-ray flare rate on cTTS, wTTS maximum flare luminosities ~30 times the underlying L_x (no fluence information)

Stellar Infancy: Birth to Zero Age Main Sequence



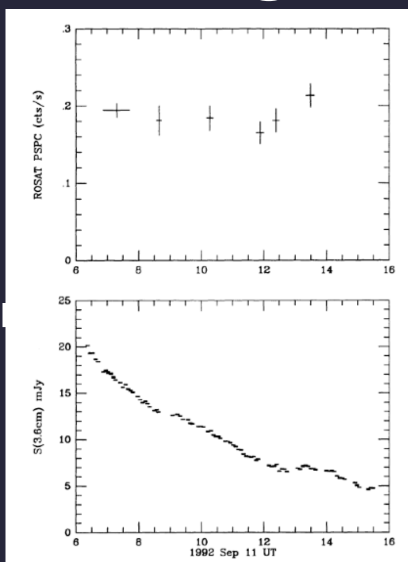


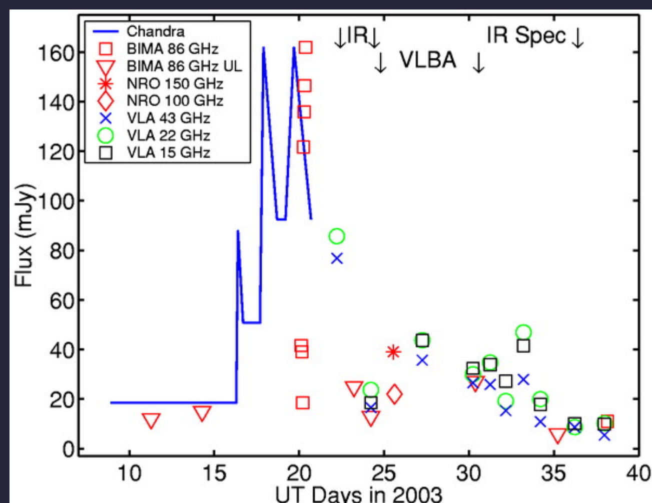
V773 Tau; Massi et al. 2006
mm flares with a periodicity on the order of the orbital period, ~52 days

- radio emission: cm wavelengths gyrosynchtron, mm from young stars usually ascribed to dust emission from disks
- for binaries, interacting magnetospheres may "provoke" flares

Stellar Infancy: Birth to Zero Age Main Sequence

Feigelson et al (1994)

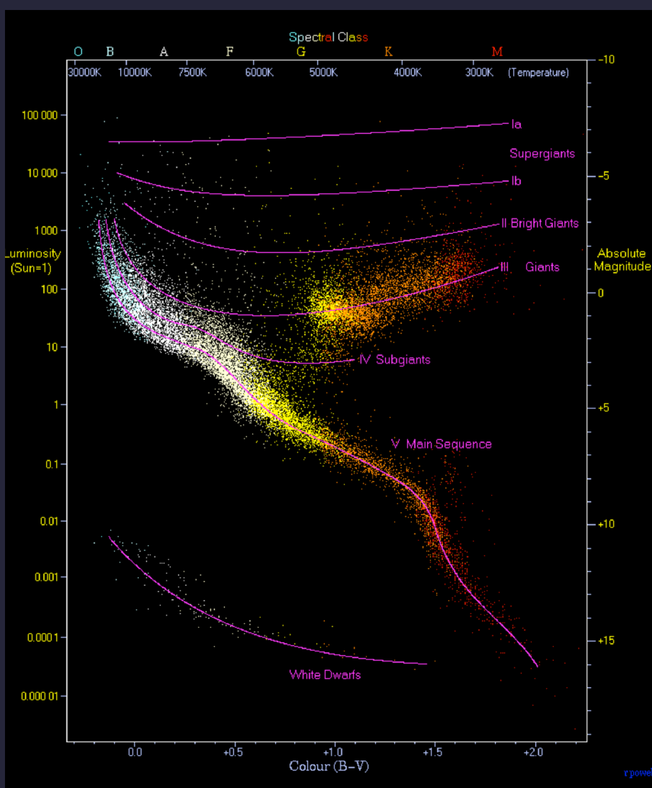




Bower et al. (2003)

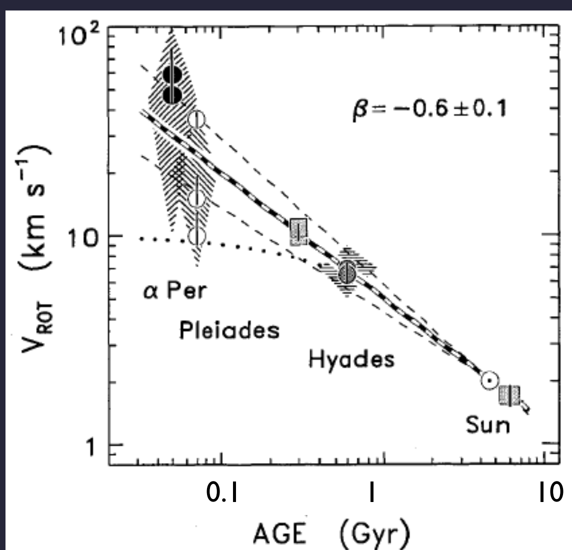
radio/X-ray flares appear to show "opposite" correlation from what is expected on the Sun

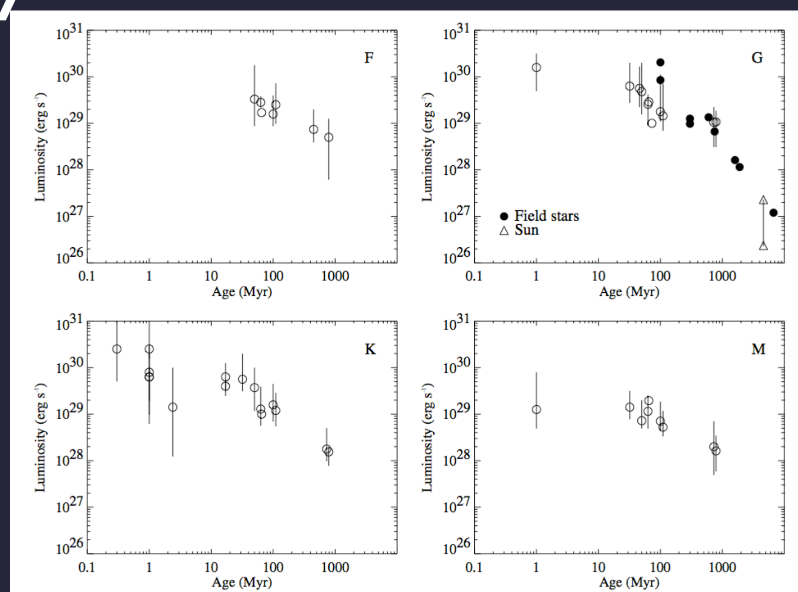
Stellar Infancy: ZAMS to 1 GY



- time to reach the ZAMS is a function of stellar mass, 100 MY for 1 M_{sun}, longer for lower mass stars
- no change in internal structure of star during this phase: star is in hydrostatic equilibrium
- time on the MS is also a function of stellar mass: $\tau_{ms} \sim 10^{10}$ yrs $(M/M_{sun})^{-2.5}$

Stellar Infancy: ZAMS to 1 GY

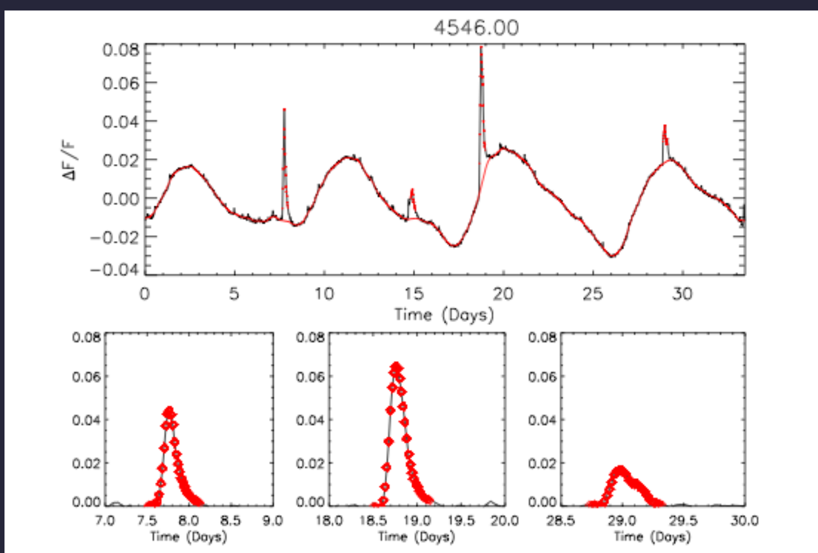




Ayres (1997), Güdel (2004)

- rotation, activity decay slowly; age is not the important parameter here, the more fundamental parameters are rotation and activity (see first presentation)
- for G stars $L_x \sim t^{-1.5}$

Stellar Infancy: ZAMS to 1 GY



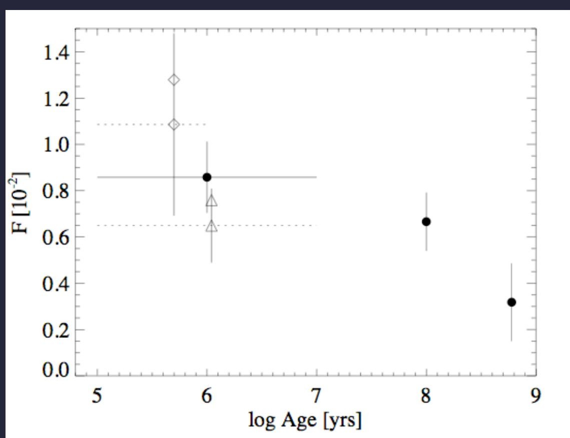
Walkowicz et al. (2011) flares on a K dwarf in the Kepler field; age is not known but likely in this age range

in the optical "commensal" flare observations can be made, often as secondary science goals (e.g. Kepler's mission to find exoplanets).

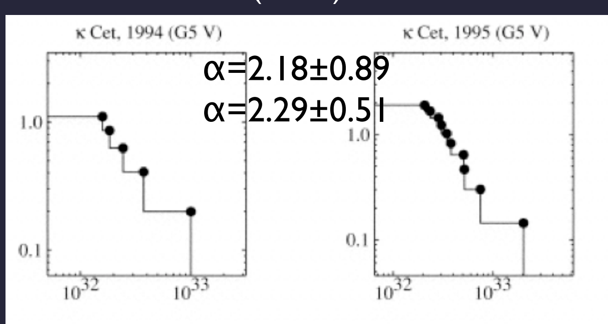
flare energies not quantified, but flare frequencies (#/hr) range from 0.03/hr to 0.5/hr

flare brightnesses up to 10 percent of the unflaring stellar brightness

Stellar Infancy: ZAMS to 1 GY



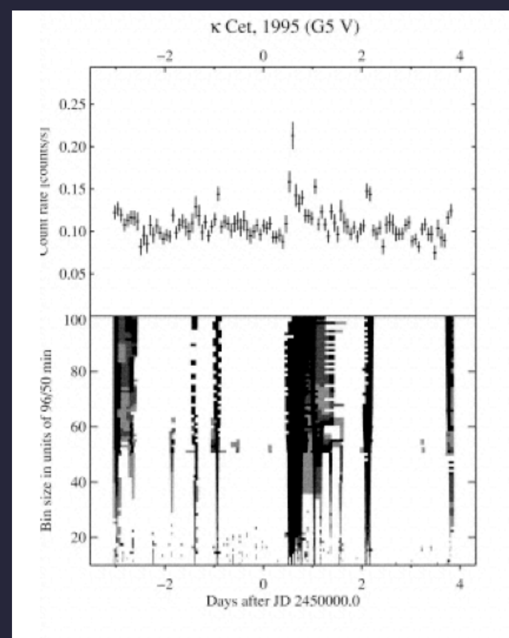
Stelzer et al. (2000)



#flares >E (day^{-1})

α=2.18±0.89
α=2.29±0.51

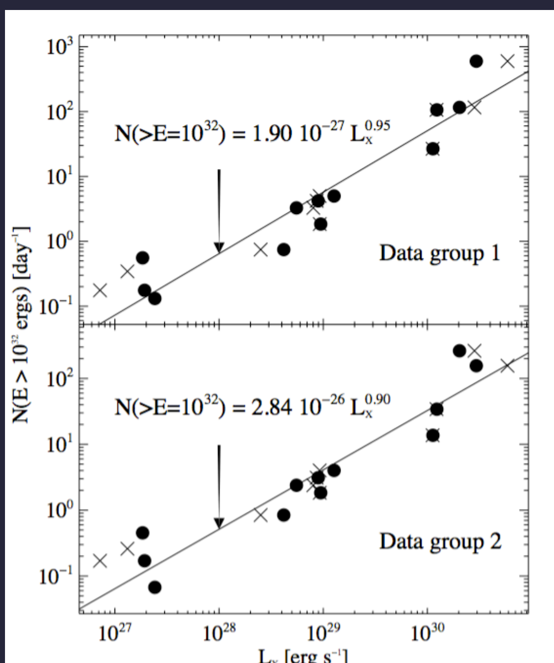
Flare coronal energy (erg)



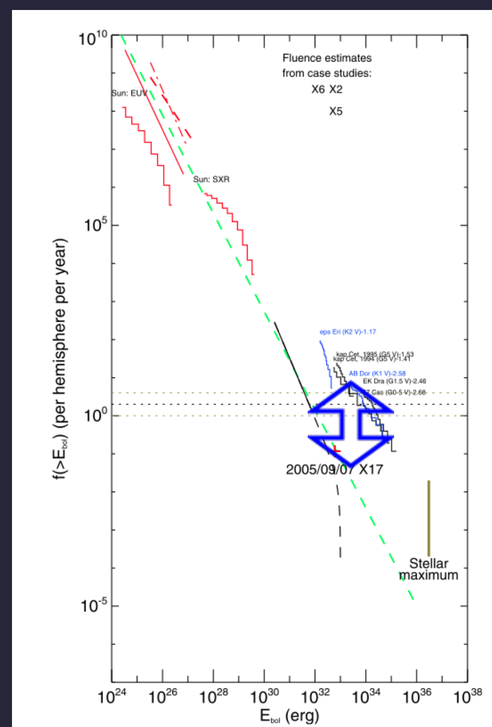
Audard et al. (2000)

EUV flares on K Cet, a G5V with an age of 300-400 MY

Stellar Infancy: ZAMS to 1 GY



Audard et al. (2000) stellar flare rate vs underlying stellar X-ray luminosity ~linear relationship



Schrijver et al. 2012

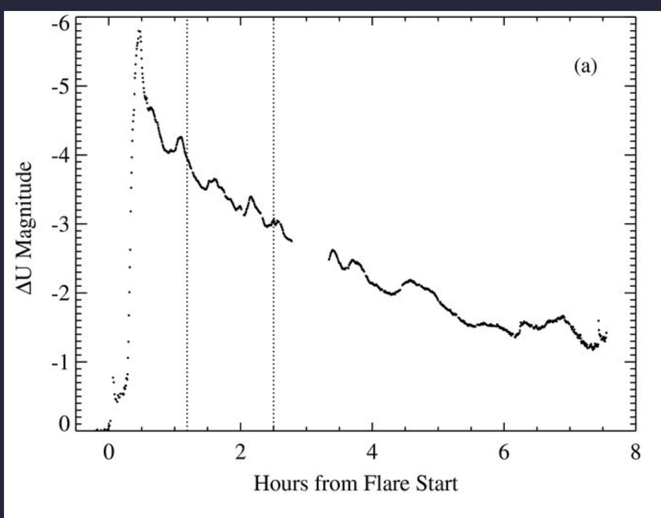
If you take the $L_X \sim t^{-1.5}$ trend, and $N(>E) \propto L_X$, suggests that you should be able to “scale” stellar flare occurrence to solar flare frequncies; but it doesn’t work!

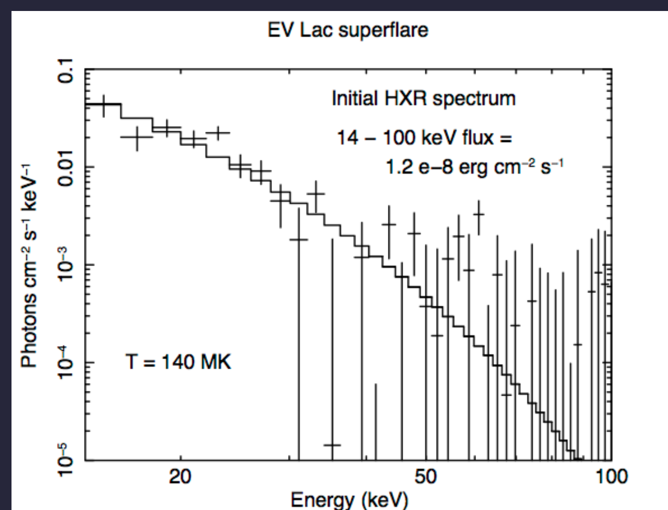
Stellar Infancy: ZAMS to 1 GY

- M dwarfs: the archetypal flare star
- most common type of star: 408 stars within 10 pc, 260 of them are M dwarfs
- many field M dwarfs have ages in this age range; flare studies of clusters in this age range tend to pick up M dwarfs as well, due to their long activity decay timescales

Stellar Infancy: ZAMS to 1 GY

$\Delta U=6$ corresponds to flux increase of ~250



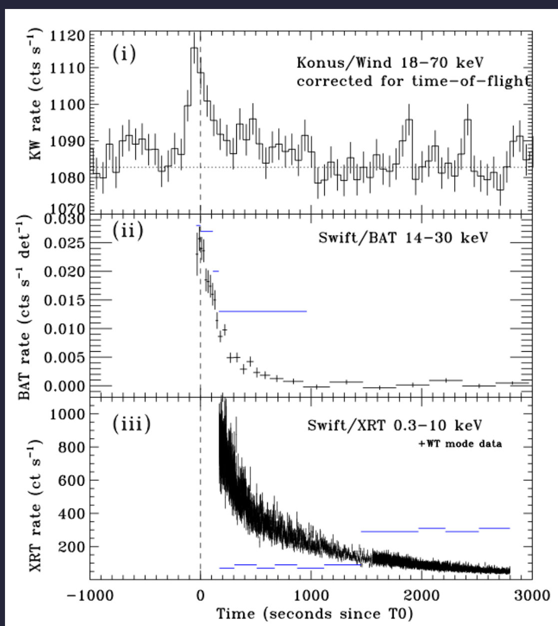


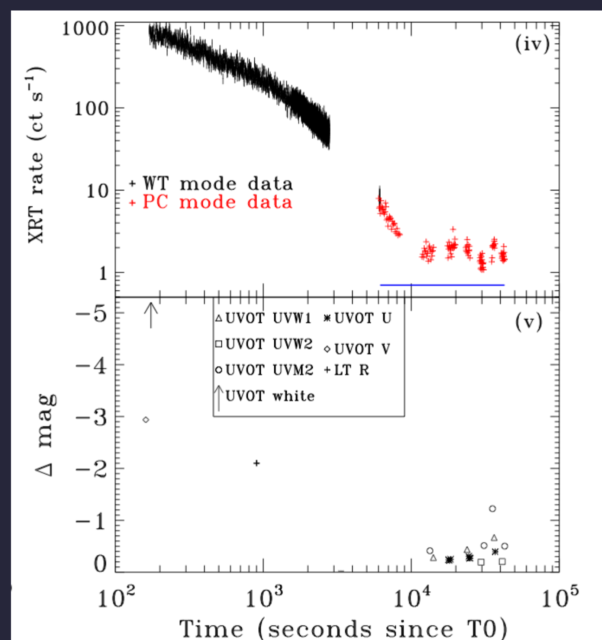
↑Kowalski et al. (2010) $E_{u,\,flare}$ >1.7×10^{34} erg at peak, L_u 8.3×10^{30} erg s^{-1}, or L_u/L_{bol} =0.37

Osten et al. (2010) peak estimated $L_{X,flare}/L_{bol}$ ~3.1, $L_{v,flare}/L_{bol}$ ~ unity ↑

Range of flare energies observed on dMe flare stars, from 10^{28} erg, comparable to M-class solar flare (Gudel et al. 2004), up to 10^{34}-10^{35} erg (Kowalski et al. 2010, Osten et al. 2010)

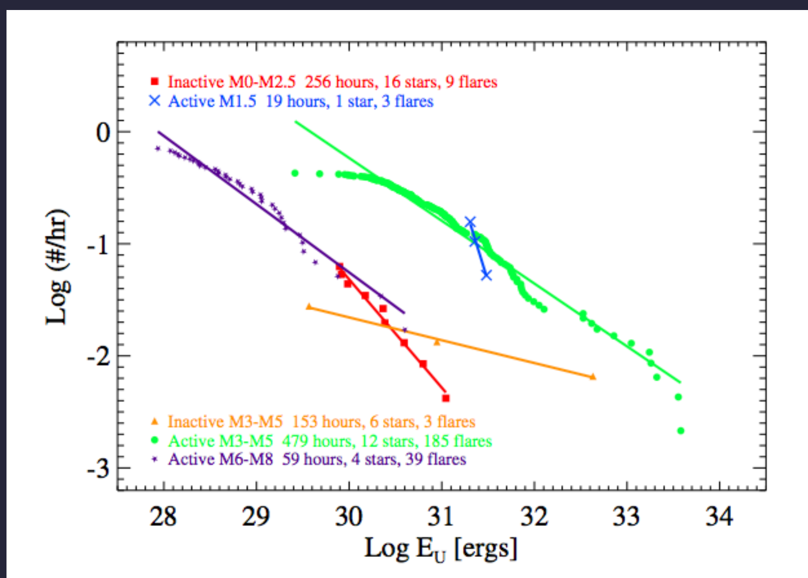
Stellar Infancy: ZAMS to 1 GY





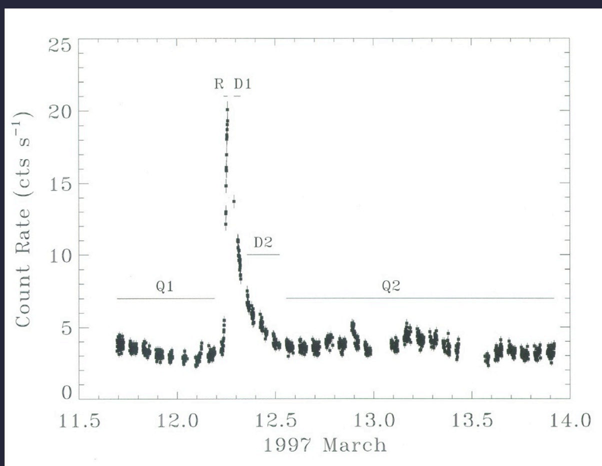
- The largest stellar flare observed to date, on an M dwarf (Osten et al 2010)
- Rate of energy release is ~10^6 times solar X-ray flare energy release
- Stellar flares ARE a minor contributor to the GRB population
- factor of 7000 increase over quiescent value
- ➜ E_{rad} (0.3-10 keV) ~ 10^{35} ergs

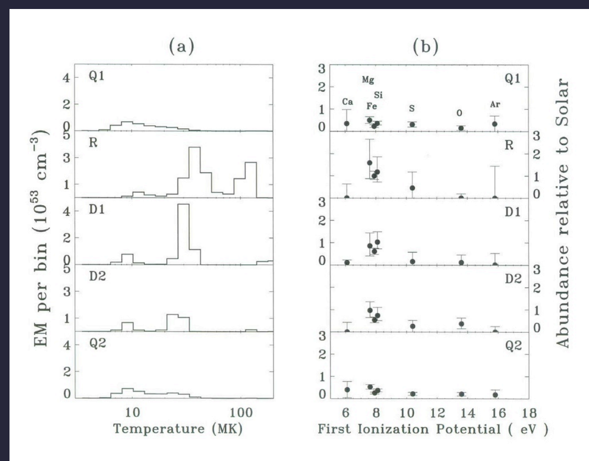
Stellar Infancy: ZAMS to 1 GY



flare rates of active & inactive M dwarfs -- Hilton (2012)
M dwarfs with spectral types M3-M5, showing evidence of chromospheric activity, have the most frequency and energetic flares (of the M dwarf classes studied)

Stellar Adulthood: 1-4.5 GY

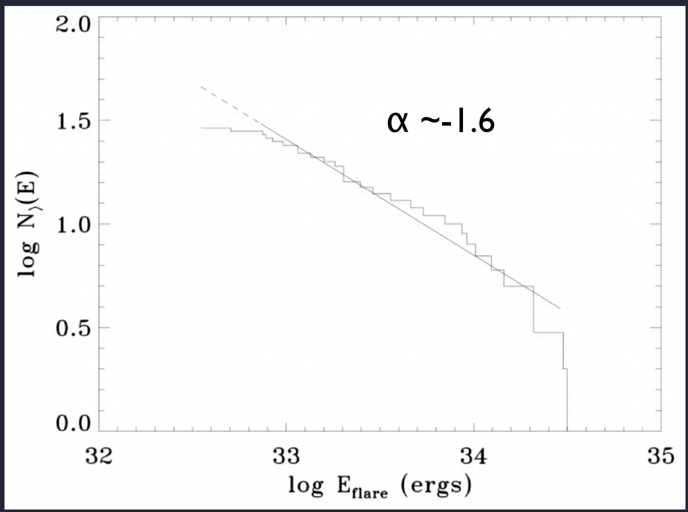




Osten et al. (2000) X-ray flare on an active binary
peak L_x 2.6×10^{31} erg s^{-1}, radiated energy 2.9×10^{35} erg

Binarity influences activity, and thus may remain high for an old star. Active binaries produce extreme outbursts, thought to be the same mechanism as for single stars

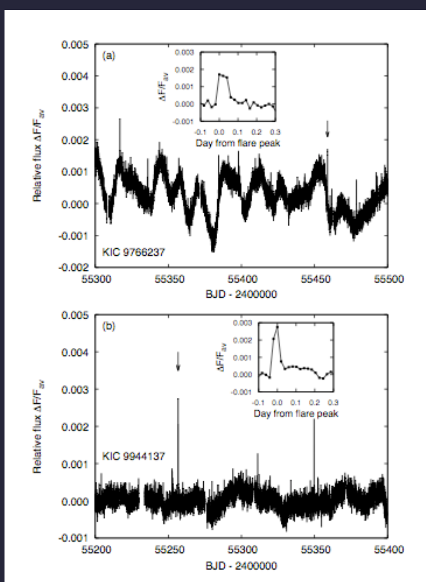
Stellar Adulthood: 1-4.5 GY



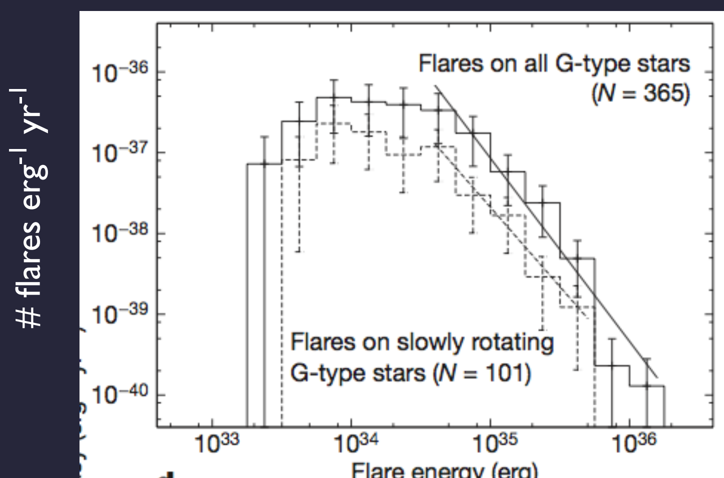
Osten & Brown (1999)

flare frequency distribution from 16 RS CVn systems, from a total of 12.2 Ms of time; these systems spend about a third of their time flaring

Stellar Adulthood: 1-4.5 GY



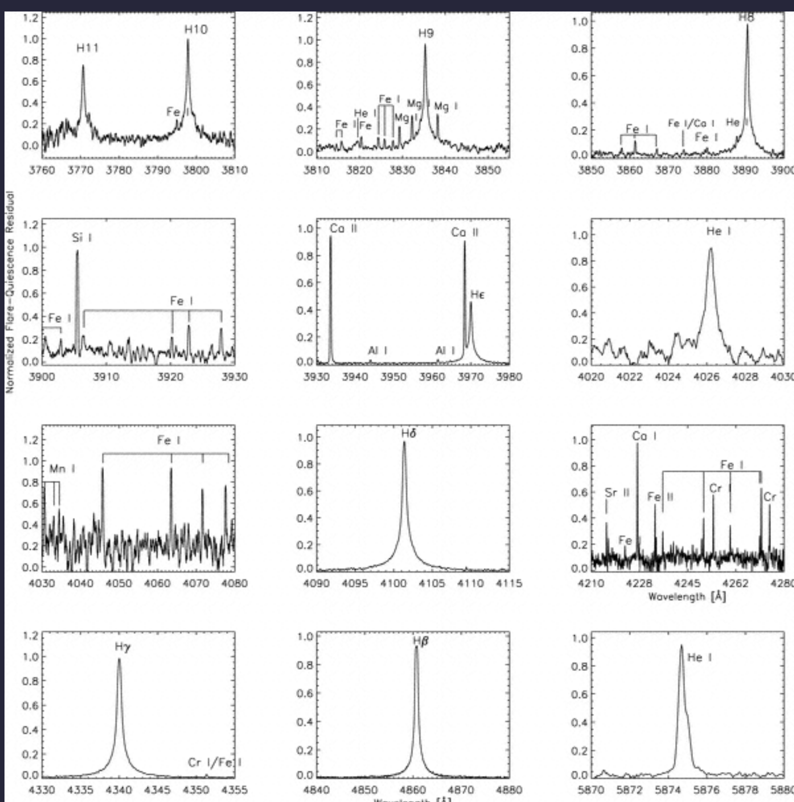
Nogami et al. (2014)
flares of 10^{34}-10^{35} erg on two Sun-like Stars with P_{rot}=21.8, 25.3 d



Maehara et al. (2012)

Shibayama et al. (2013) estimate that a superflare with energy 10^{34}-10^{35} erg occurs once in 800-5000 years in Sun-like stars (T_{eff} 5600-6000 K, P_{rot}>10d)

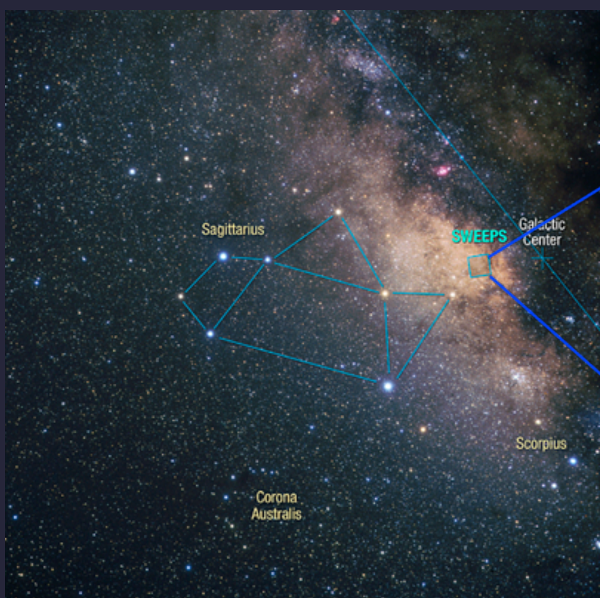
Stellar Old Age: >4.5 GY



Paulson et al. (2006)

- temperatures of >8000 K inferred from spectroscopic analysis of this flare from Barnard's star (d=1.8 pc, M4)
- limited to serendipitously detected events in isolated stars with known old ages
- frequencies not well-constrained, but: Marino et al. (2000) note X-ray measurement taken "in flare"; Robinson et al. (1990) may have observed a small flare as well

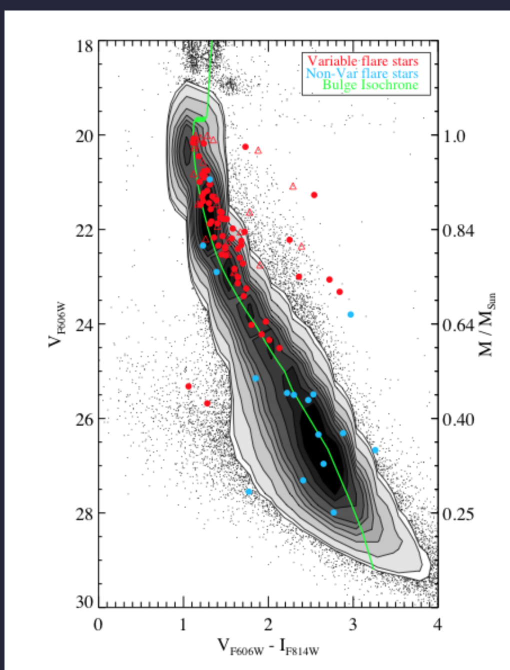
Stellar Old Age: >4.5 GY

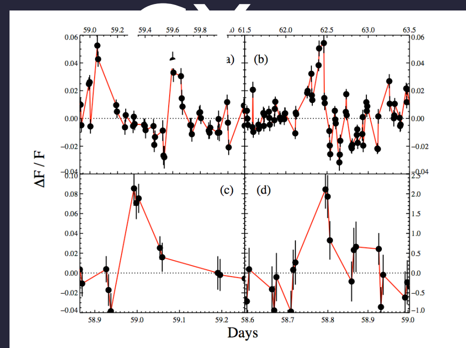


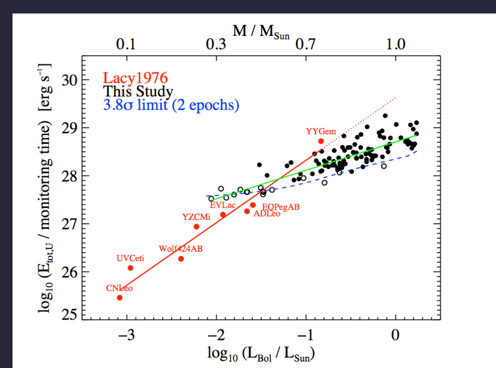
Using stellar flares to probe magnetic activity in old stellar populations

HST/ACS Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS; Sahu et al. 2006) was repurposed into a Deep, Rapid Archival Flare Transient Search (DRAFTS; Osten et al. 2012) -- serendipitous science on a 10 GY stellar population

Stellar Old Age: >4.5 GY







Osten et al. (2012) study finding evidence of flaring in 10 GY stars
These stars show enhanced flare loss rates compared to nearby M dwarfs
Based on their location in the color-magnitude diagram, they may be active binaries

Conclusions

- There are gaps in our knowledge about the behavior of stellar explosive events with time
- Solar/Stellar Connections & Disconnections:
  - studies of individual stellar flares behave like solar flares (some of the time)
  - trouble trying to put stellar, solar flares on a common scale — [T, VEM] plot of X-ray flares, [N(>E), E] —are we missing something?