Who's Afraid of a Stellar Superflare?

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"Normal" Flares

- solar flares T_{max} ~20-30 MK
- NT HXR emission lasts ~minutes, accompanied by impulsive nonthermal gyrosynchrotron emission
- flare rate function of energy: alpha~-1.8
- "typical" flare energy release ~10^{29} erg, largest X-ray flares flux of 10^{-3} W/m^2

- stellar flares: T_{max} "usually" 50-80 MK
- SXR flares can be accompanied by radio gyrosynchrotron
- flare rate f'n of energy; alpha ≈-1.7 for RS CVns, >-2 for dMe stars?
- flare energies range from ~10^{33}-10^{35} erg

scaling of solar, stellar X-ray flares: $EM \propto T^5$ (Feldman & Doschek) so

stellar flares are just scaled-up solar flares?

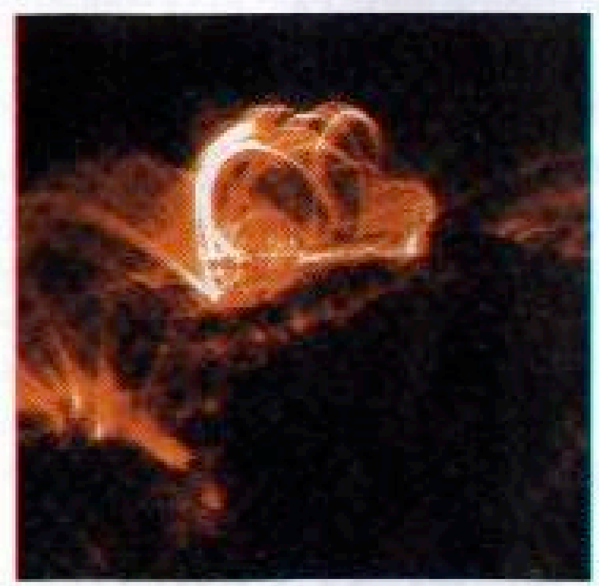
Superflares in the News

Old Star Unleashes Monster Flare

On December 16, 2005, Rachel Osten (University of Maryland) and six colleagues had the good fortune to observe one of the most powerful stellar flares ever. Energetic X-rays from the active binary star II Pegasi (HD 224085) triggered sensors on NASA's Swift satellite.

Located about 135 light-years from Earth, II Peg is at least a billion years older than our Sun and has only about 80% of its mass. These characteristics would normally suggest a quiescent star. But tidal forces exerted by the nearby companion cause the star to rotate quickly (once every seven days), generating a dynamo capable of igniting powerful flares. The December 2005 outburst released 100 million times more energy than a typical solar flare — a similar event from our Sun would extinguish much of life on Earth. The "superflare" gives scientists insight into the physics of stellar flares that they cannot obtain from the Sun alone.

Thanks to the flare's strength, Osten's team identified direct evidence of charged particles being accelerated along the star's magnetic-field lines — an early stage of a stellar flare. While a full-blown flare releases a burst of radiation across a wide swath of the spectrum, the particle-acceleration signatures are fainter and isolated to just a few spectral regions, including high-energy X-rays. According to Osten, "Previous generations of X-ray telescopes haven't had the sensitivity or the energy coverage to collect enough photons" to reveal the spectroscopic signature of particle acceleration.



NASA's TRACE satellite captured this solar flare at X-ray wavelengths in 2005. Such events can cause power blackouts and satellite failures at Earth. Now imagine scaling this up 100 million times; such was the power of II Pegasi's flare.

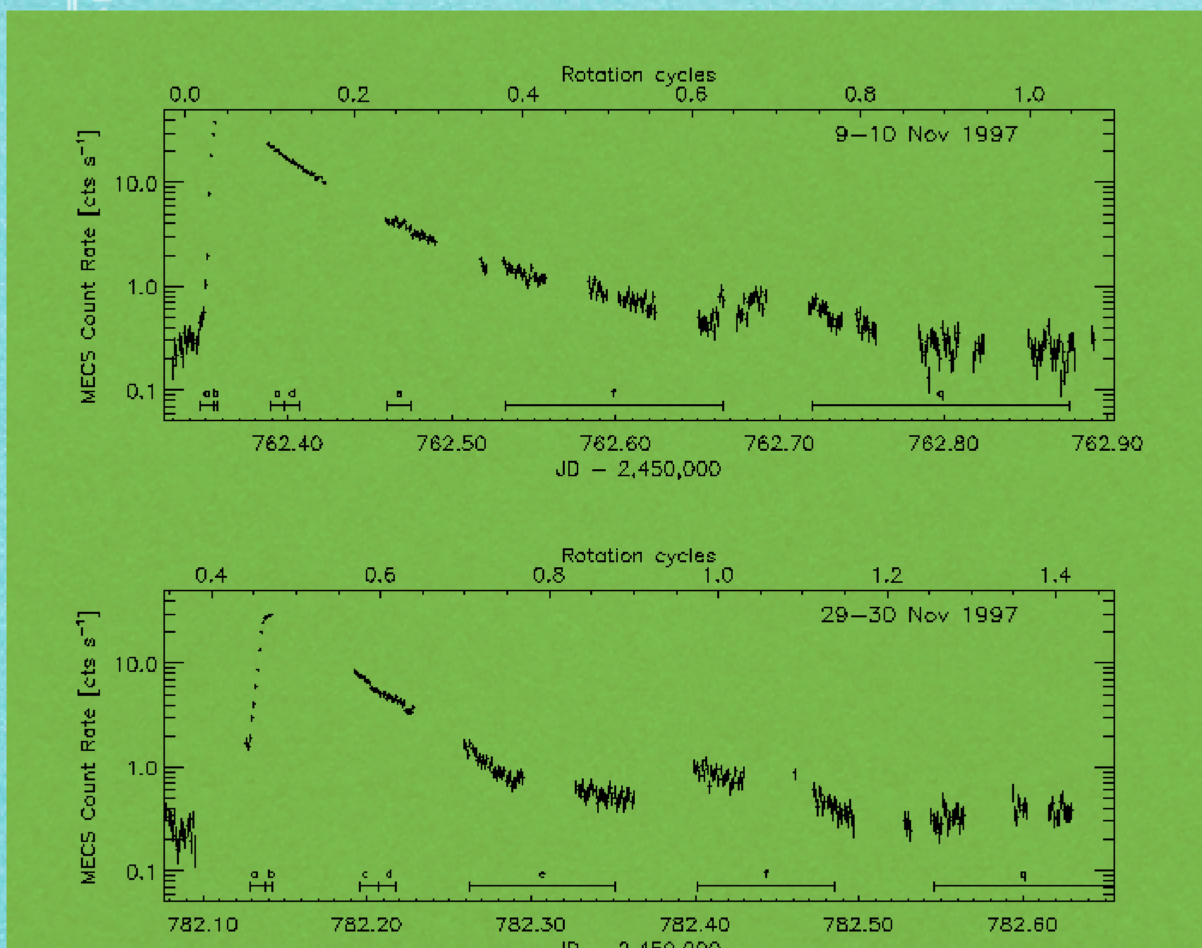
Many flares, like a record-setting burst from the red dwarf Gliese 3685A in 2004 (*S&T:* September 2005, page 17), had been observed in visible or ultraviolet light. But such emission "is only the tip of the iceberg of flare energetics," says Eric Feigelson (Penn State University). With the detection of high-energy X-rays, says Feigelson, Osten and her team "found the iceberg."

Osten's group reports its results in the January 1st *Astrophysical Journal.*

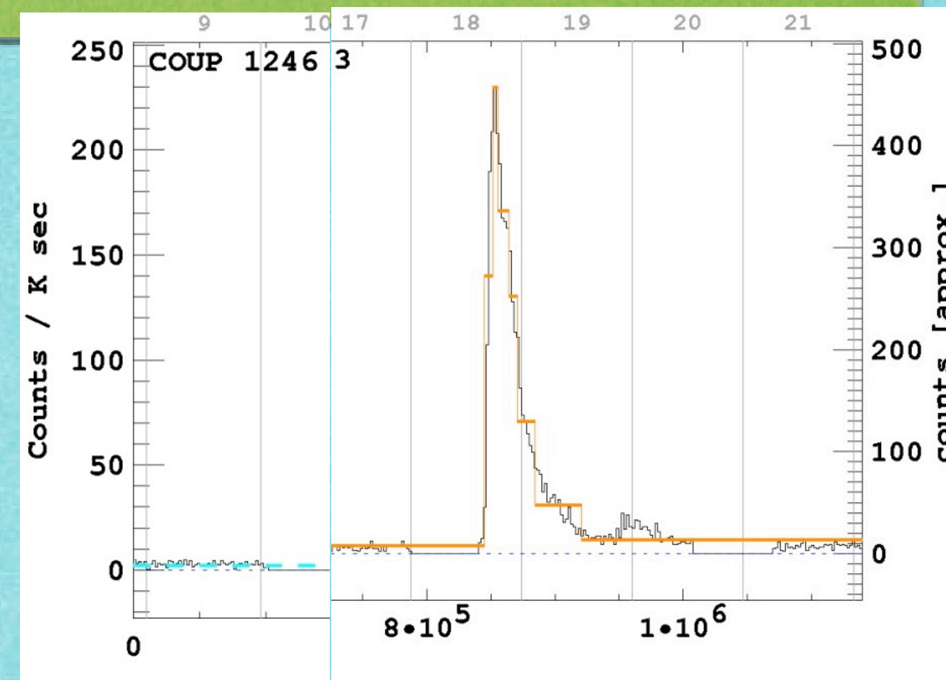
— Kate Becker

22 *February 2007* **Sky & Telescope**

Gallery of X-ray superflares



Superflares on AB Dor observed with BeppoSAX; Maggio et al. 2000



superflare on young star in Orion observed with Chandra; Favata et al. 2005

key characteristics:

L_X increases by ~100 over pre-flare values

hot plasma ~10^8K

EM >10^2-10^3 typical values

large energy releases (E_{rad} >10^{36})

How to make a flare

1. magnetic reconnection/ energy release
2. particle acceleration
3. plasma heating
4. mass motions

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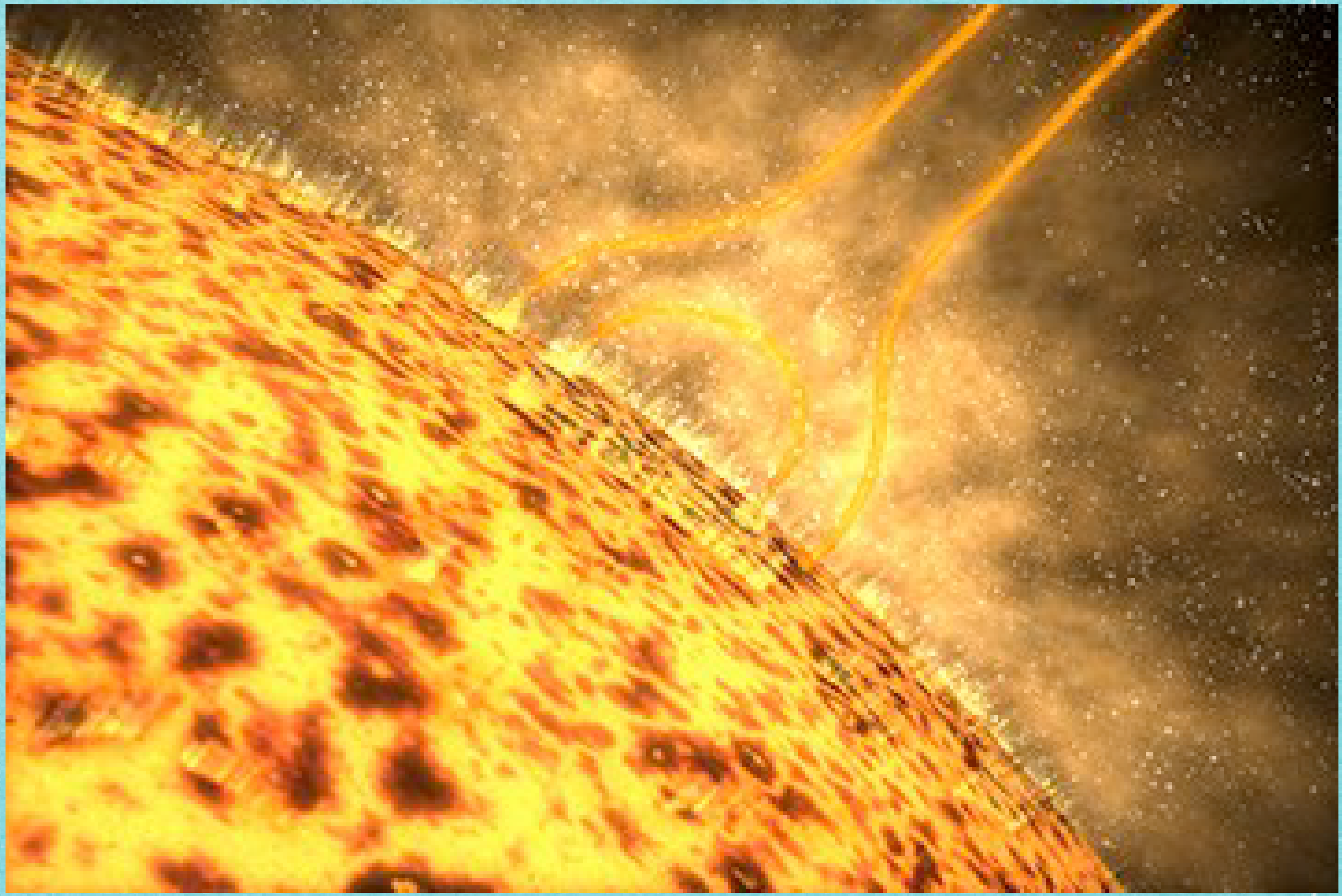
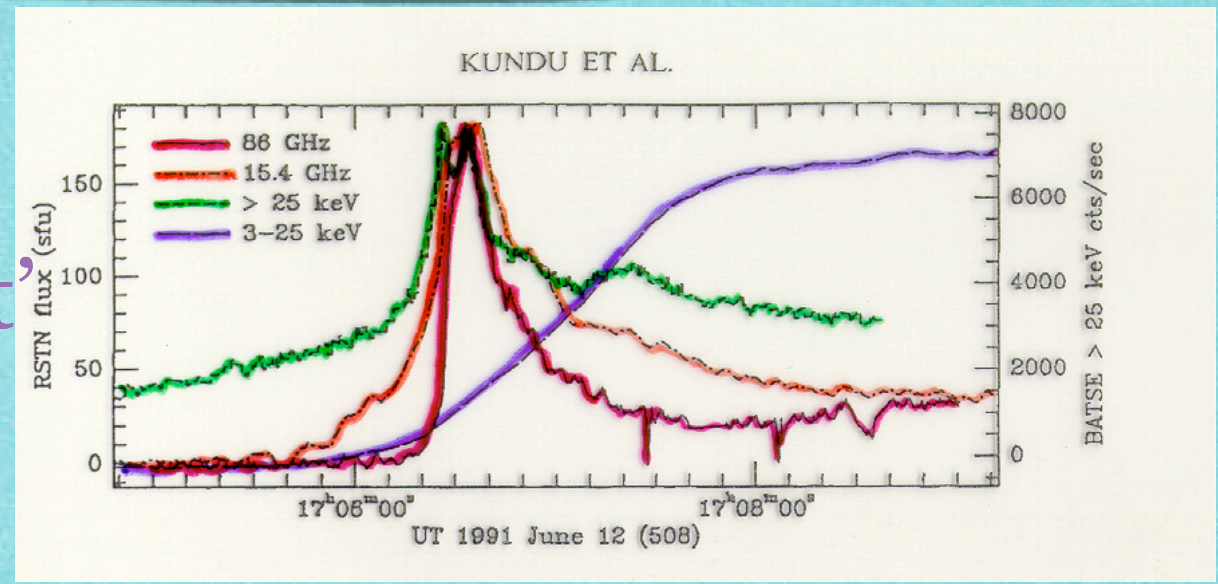
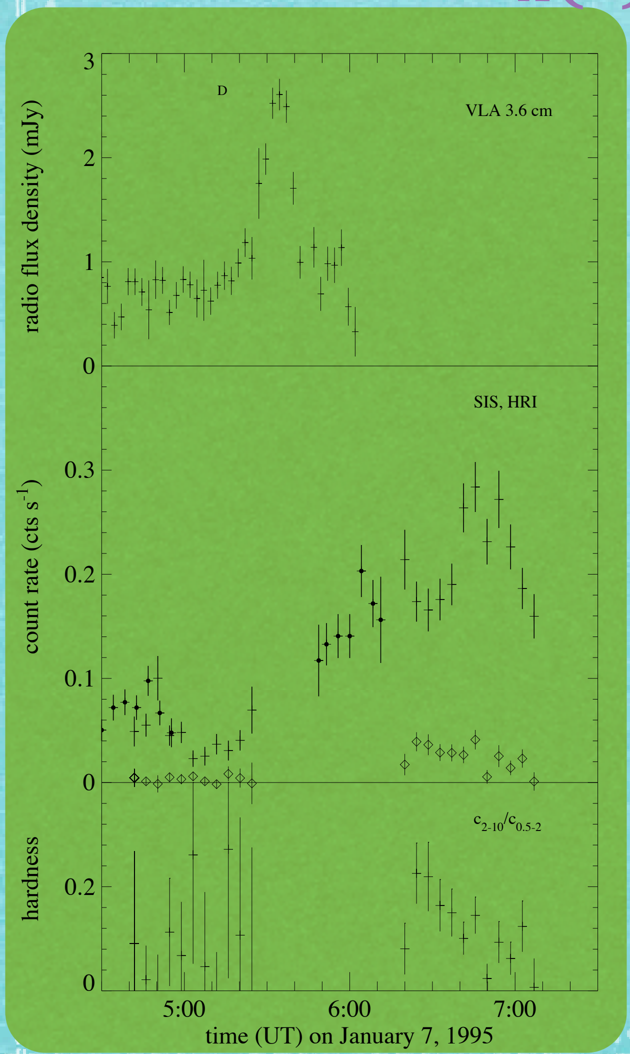


Flares involve particle acceleration

Neupert effect = observational relationship between signatures of particle acceleration and plasma heating

$L_x(t) \propto \int L_{nt}(t')dt'$



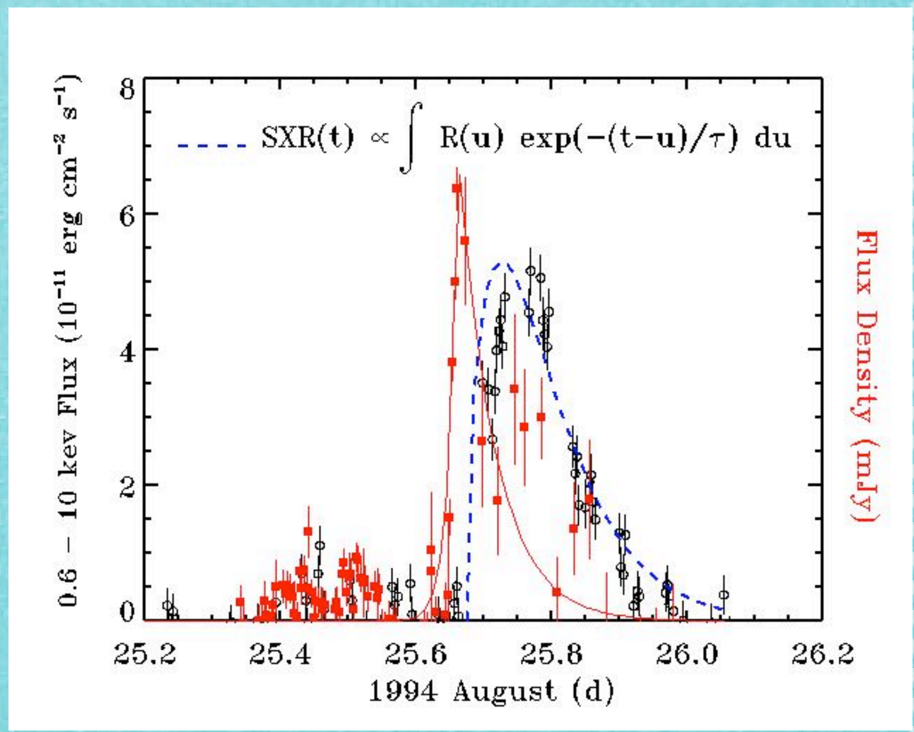


Gudel et al. 1996

-White light solar flares correlated with nonthermal HXR emission (Neidig & Kane 1978)

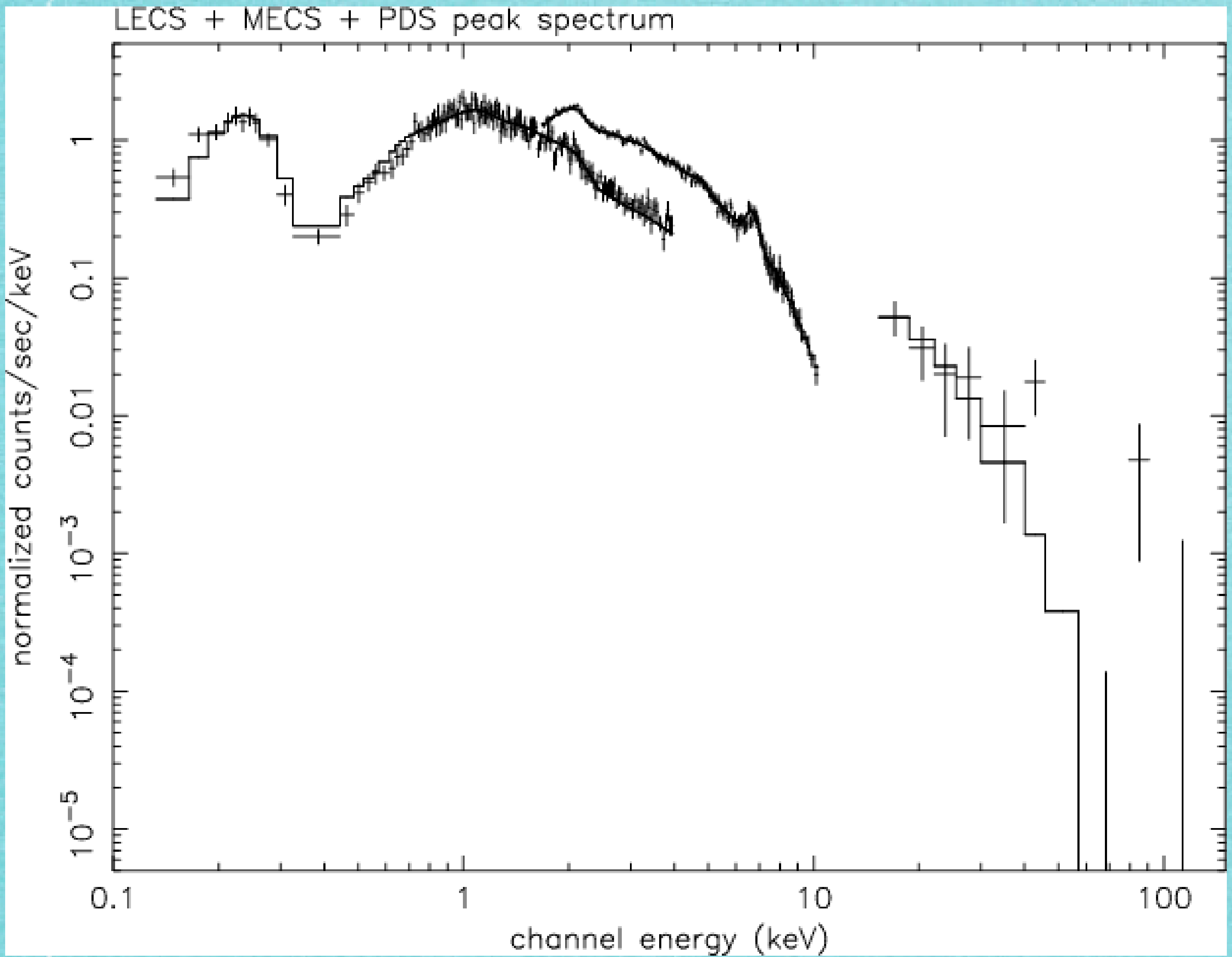
-modelling of white light solar & stellar flares involves energy input from acc. ptcls (Allred et al. 2005,6)

-gyrosynchrotron radio flares detail transient particle accel. episodes (Gudel 2002)



Osten et al. 2004

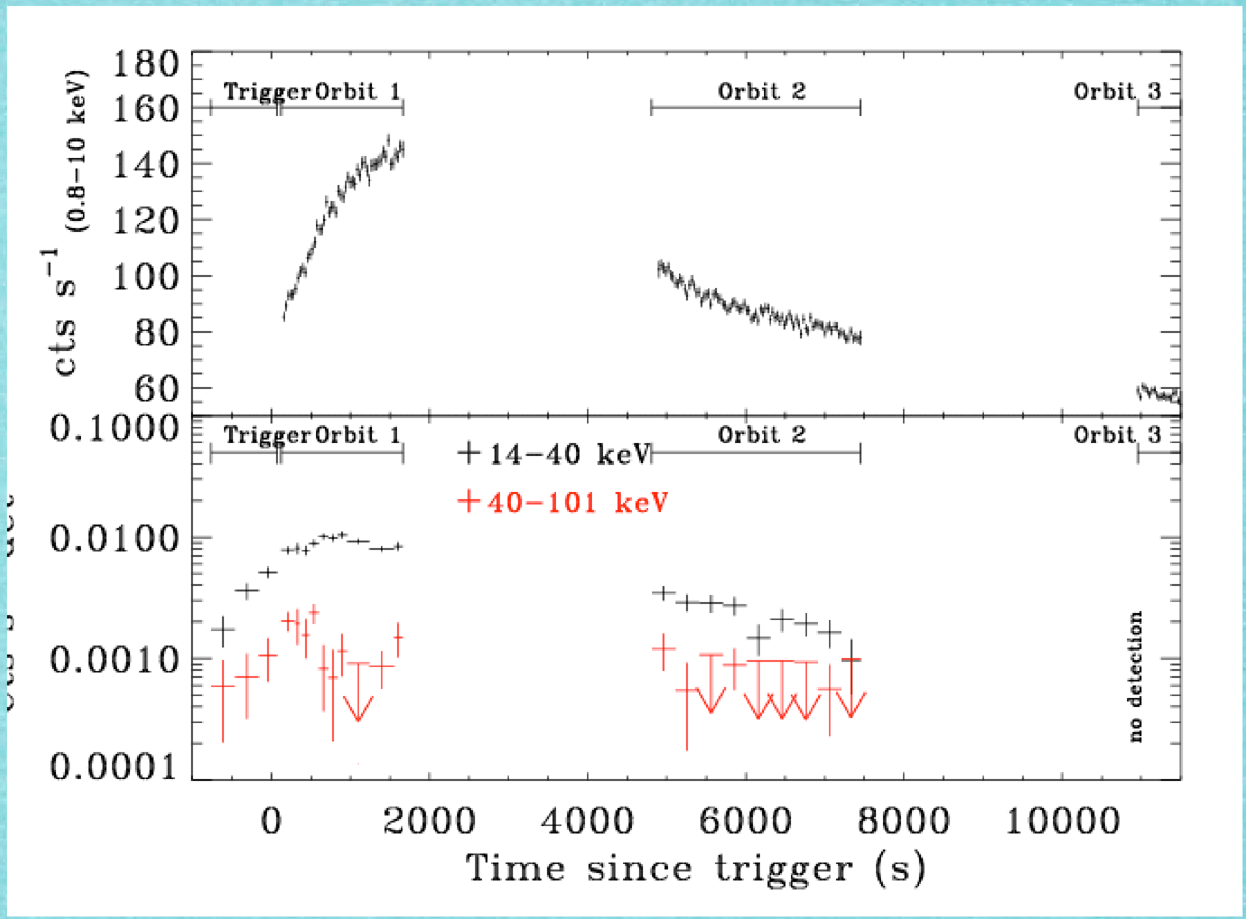
Previous Superflares & Nonthermal Emission



Franciosini et al. (2001); large long-duration flare on UX Ari (G5V+K0IV; Porb=6.44d) seen by BeppoSAX

- previous HXR detections inconclusive as to presence of NT emission
- HXR spectra could be explained by thermal tail of superthermal plasma
- detections out to <100 keV

Swift & II Peg ($K2IV+dM$, $P_{orb}=6.7d$); 12/16/05

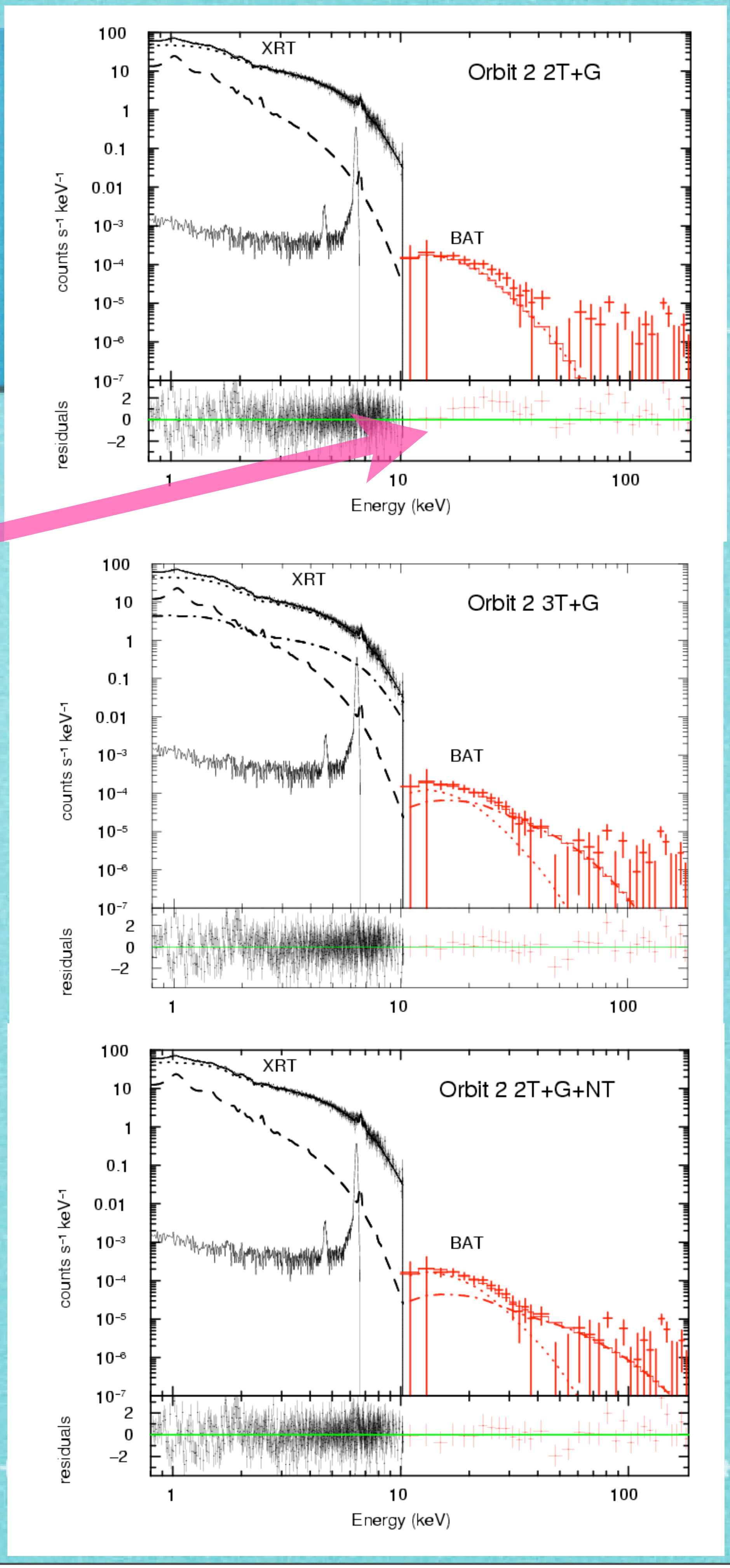


Osten et al. 2007

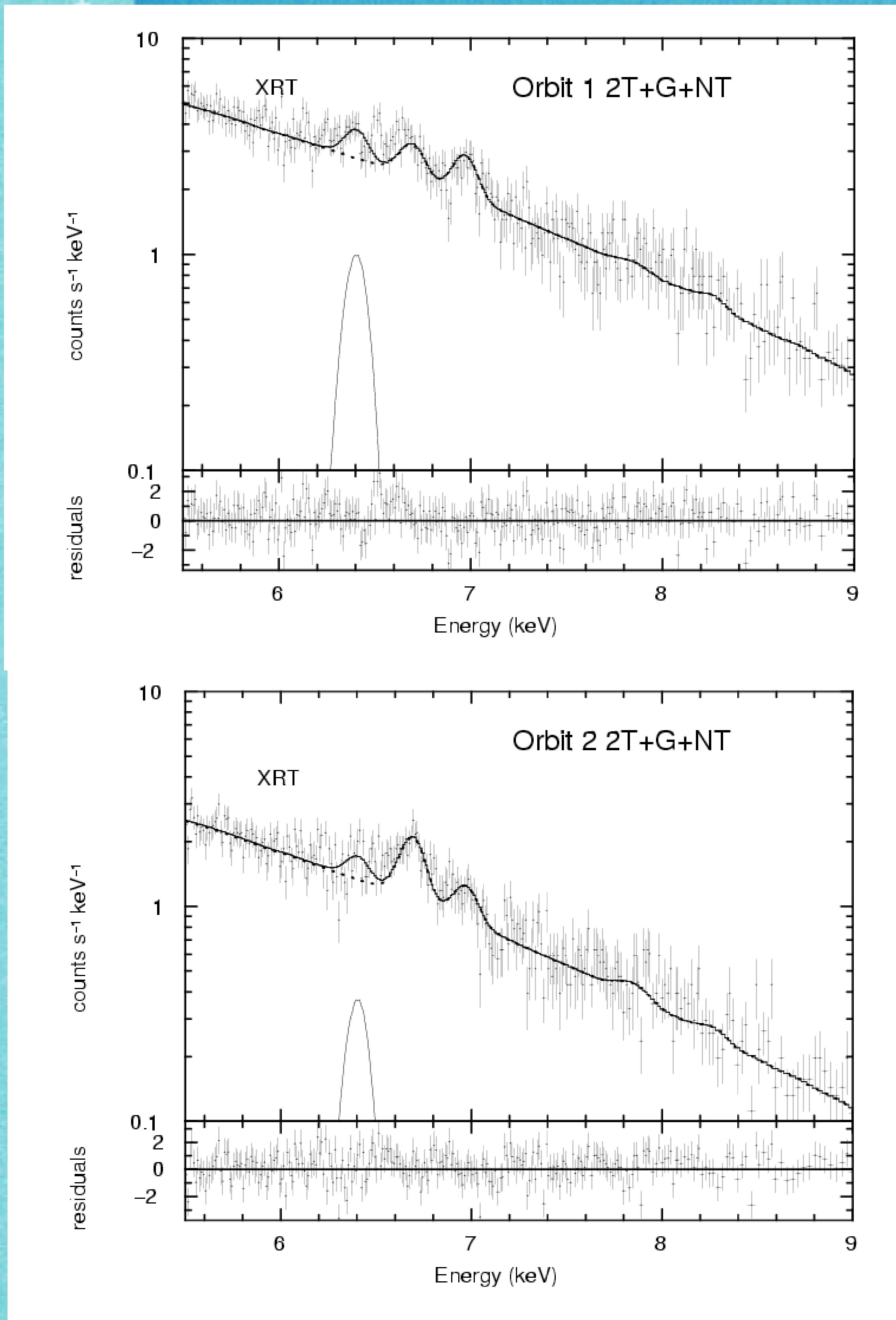
- *HXR emission out to 200 keV*
- *Fe Ka emission 6.4 keV*
- *thermal plasma > 120 MK*
- *L_x/L_{bol} (0.8-200 keV) at peak 38%*
- *L_x ~10^{33} erg/s (0.8-10 keV)*
- *E_{rad} ~10^{37} erg*

XRT+BAT

- during Orbits 1 and 2, XRT+BAT spectral analysis requires more than 2 thermal components: excess continuum emission E>30 keV
- can be fit by high T bremsstrahlung (300 MK) or NT thick-target bremsstrahlung
- reject thermal explanation for hard X-ray emission:
  - $\tau_{relax}/\tau_{cond} = 200\ T_8^4/(n_{10}^2\ L_9^2)$ requires high densities and/or large length scales
  - Neupert effect behavior relating hardest X-rays/soft X-rays
  - $E_{NT} \sim E_{thermal}$ rough equipartition around 10^{40} erg
  - would indicate lack of cooling plasma in flare decay (T_3 in orbit 2 ~T_3 in orbit 1)



XRT spectra &Fe K emission



- reality of 120 MK plasma in orbit 1 (2nd temperature component) confirmed by He-, H-like Fe (changing ratio in 2nd orbit shows temperature decay)
- also see emission at 6.4 keV in orbits 1 and 2; no detection in orbit 3 when HXR emission is undetectable

Interpreting the Kα emission

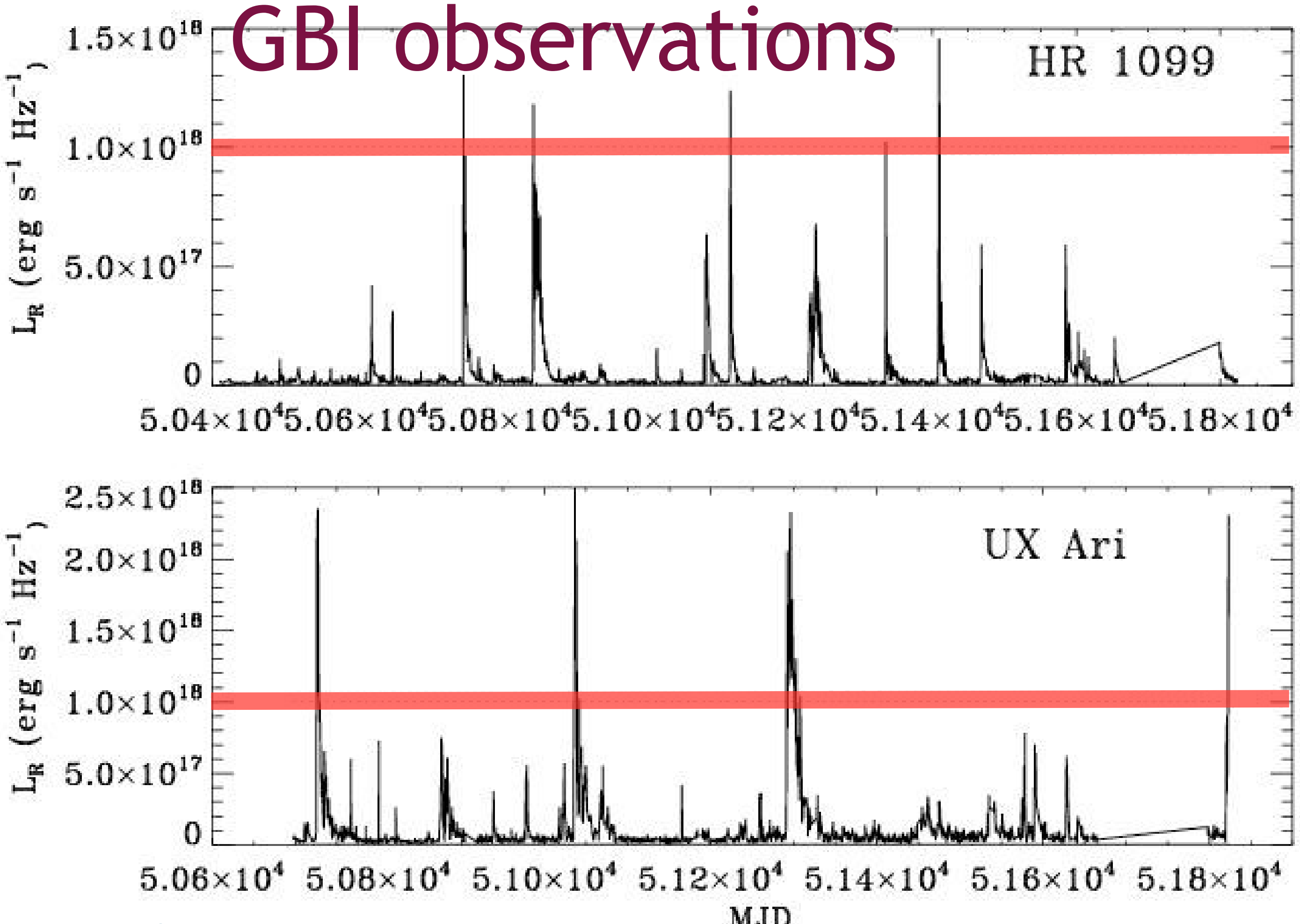
- in solar flares, produced by fluorescence off cold iron in photosphere; probe of both photospheric abundance and height of irradiating structure (e.g. Bai 1979)
- possibly also collisional ionization (Emslie et al. 1986)
- Osten et al. (2007) favored collisional interpretation due to reaching Compton scattering depths in II Peg's atmosphere, non-negligible optical depth effects for fluorescence
- recent work by Drake et al. (2007) suggests that fluorescence efficiencies of ~1% can explain the equivalent widths observed here

Sub-threshold Swift events on HR 1099

- HR 1099 (V711 Tau), K1IV+G5IV, Porb=2.8d event 11/29/06
- 3 detections in ~4 min 10-50 keV, SNR~7
- intensity ~400 mCrab, 1/2 peak flux of II Peg event, Lx 1032 erg/s
- XRT TOO took place 40 hours later
- also detected in March '06 at ~8 times lower intensity
- superhot thermal plasma only? NT emission? Kα emission? radio response?

Radio Superflares

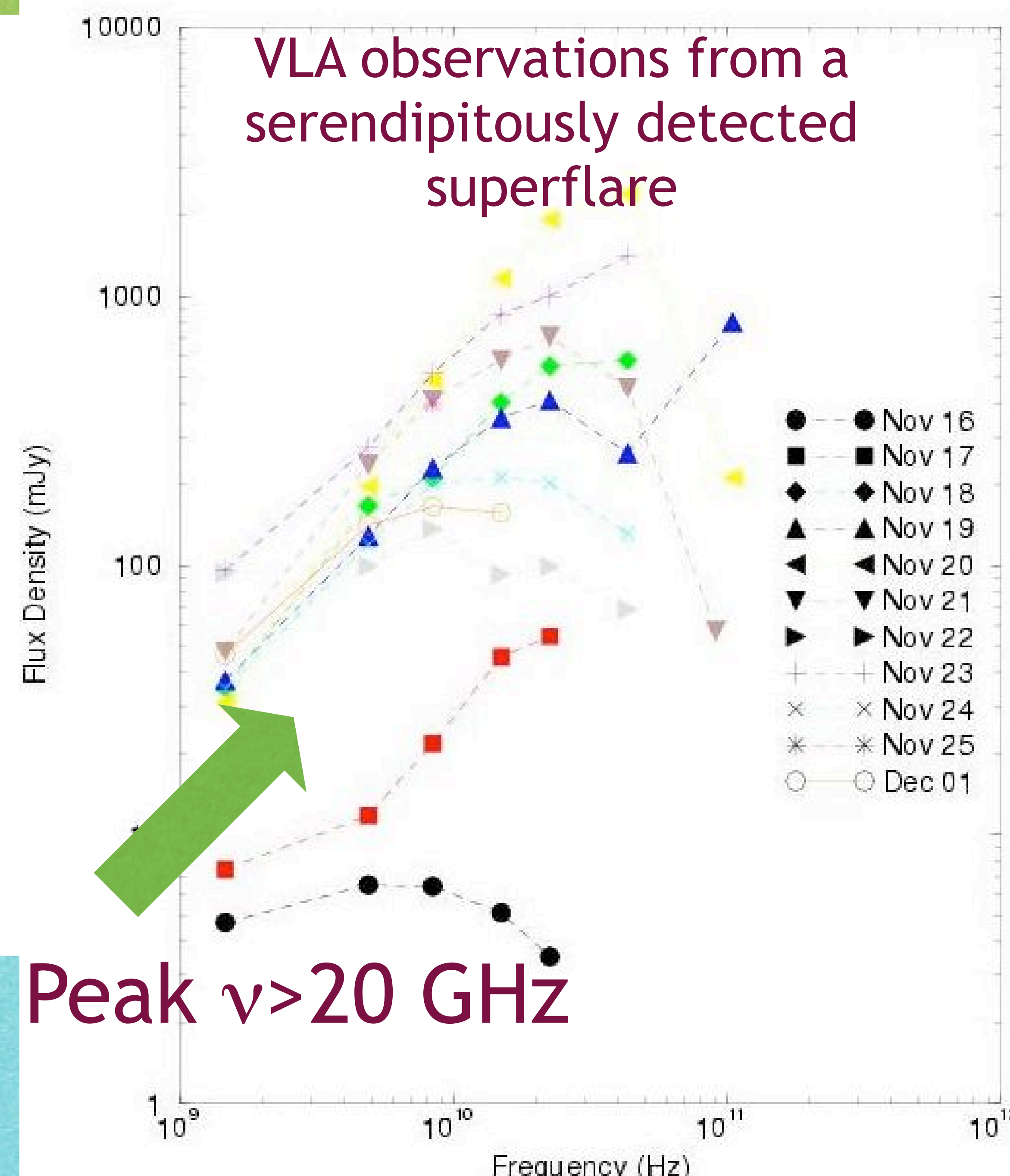
GBI observations



10^{18} erg/s/Hz ~10^{33}-10^{34} erg/s using GB L_x-L_r

Primarily at cm and shorter wavelengths; recurrence time once every several months-year

VLA observations from a serendipitously detected superflare



Peak ν>20 GHz

Planning for the next "big one"

- catalog of ~60 sources: "usual suspects" mix of active binaries, dMe flare stars, other active stars
- VLA TOO program
  - triggers off GCN notice, on source within 0.5 hr, multi-frequency (1.4-40 GHz) observations
- importance of XRT+BAT+other wavelengths
  - incidence of XR superflares with superhot plasma +NT emission
    - Fe Kα emission
    - radio/NT HXR correlation

Superflares in Other Stars

- young stars are known to produce large impulsive transient X-ray flares
  - Favata et al. (2005) studied these in the COUP, found hydrodynamically modelled loop lengths consistent with star-disk interaction in some cases
- Kashyap et al. (2006) superflaring in old active binary systems in globular clusters, super-bolometric X-ray luminosities
- superflaring in normal stars -- Schaefer et al. (2000) normal solar-like stars undergoing flaring events with energy releases 10^{33}-10^{38} ergs, occurring roughly once every 100 years or so

Killer flares?

- Gehrels et al. (2003) and others have investigated the putative effects of a SNe; gamma rays and cosmic rays can cause significant disruption of terrestrial ozone for d<8 pc. Based on SN rate, this is an unlikely mass extinction mechanism
- Thomas et al. (2005) estimated that a galactic GRB with fluence 100kJ m^{-2} could deplete the ozone layer on Earth globally to 38%: Late Ordovician mass extinction caused by GRB?

•what about stellar flares? II Peg flare scaled to 1 AU would produce a X4400000 flare
•planets might be unlikely to form around 1 star in an active binary, but Quintana & Lissauer (2006) demonstrate that planetary systems can form around close binary stars

Smith et al. (2004) show that while incident ionizing radiation from stellar flares won't penetrate terrestrial atmosphere, redistribution of radiation to UV is orders of magnitude larger and can be a significant effect

Conclusions

- pointed observations of stellar superflares will be able to determine more complete information about superflare process (esp. precursor activity)
- due to their rare nature, ptd obsn's also have small probability of actually catching one; autonomous fast triggers of spacecraft with large E range (and accompanying multi-wavelength coverage) are therefore ideal
- superflares have the potential to reveal answers to several important questions about dynamics of stellar flares not available with normal flares

Unanswered Questions

- Further examples of nonthermal hard X-ray emission: was this a singular event?
- Evolution of particle acceleration/ injection during flares
- Further evidence for Kα emission
- How do these things compare to relatively well-studied solar flares?

Occurrence rates

- radio surveys: HR 1099 2.4/yr, UX Ari 12/yr
- flare frequency distributions from EUVE (Osten & Brown 1999):
  - 0.08 flares/yr/star above 100x min. flare EUV luminosity or 1031 erg/s HXR
  - II-Peg level flares 0.003/yr/star
- X-ray surveys:
  - Ariel-V (Schwartz et al. 1981) 11/yr >6e-10 erg/cm2/s II Peg (1032 erg/s)
  - Pye & McHardy (1983) all-sky 23/yr above 4e-10, 2.3/yr above 4e-9