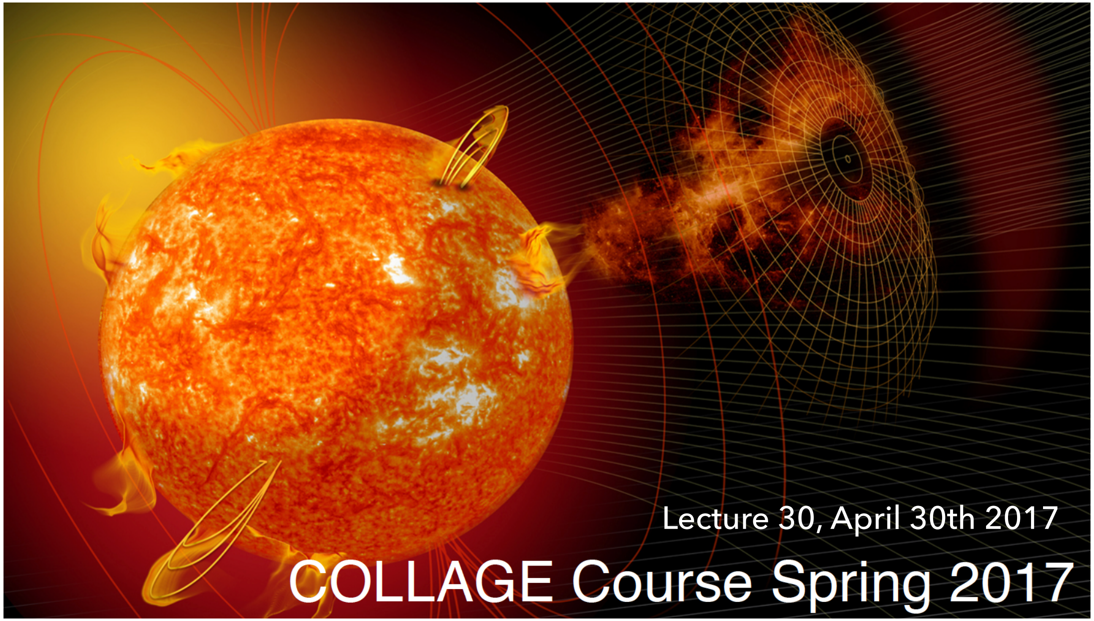
STELLAR FLARES

Adam Kowalski (CU/NSO/LASP)

With significant contributions from Suzanne Hawley & Rachel Osten



Recommended reading: Hawley & Pettersen 1991, Osten et al. 2016, ApJ 832, 174

TYPES OF STARS THAT FLARE: AN OVERVIEW

- Stellar flares ~10^{28} erg to 10^{38} in radiated energy

- The Sun would not be a 'flare star' at a distance: largest few x 10^{32} erg, 250 x10^{-6} in white-light
- Rapidly rotating, young G-type, K-type stars
  - EK Dra, Superflare stars in *Kepler,* AB Dor
- Active binaries (RS CVn) tidally locked, main sequence early-type star (BV-GV) and later type sub-giant (KIV) star
  - II Peg, HR1099, UX Ari, Algol (eclipsing), CC Eri
- Some single red clump giants
- Pre-main sequence stars (T Tauri), some of which are in eccentric binary and flare at periastron (active accretion)
  - V773 Tau, DQ Tau
- Active late-type main sequence stars in tidally locked binary
  - BY Dra, YY Gem
- M dwarf stars, not tidally locked, but most are probably young, rapidly rotating, and main-sequence / non-accreting
  - YZ CMi, AD Leo, EV Lac, UV Ceti, CN Leo, EQ Peg, DT Vir, AU Mic, Proxima Centauri

TYPES OF STARS THAT FLARE: AN OVERVIEW

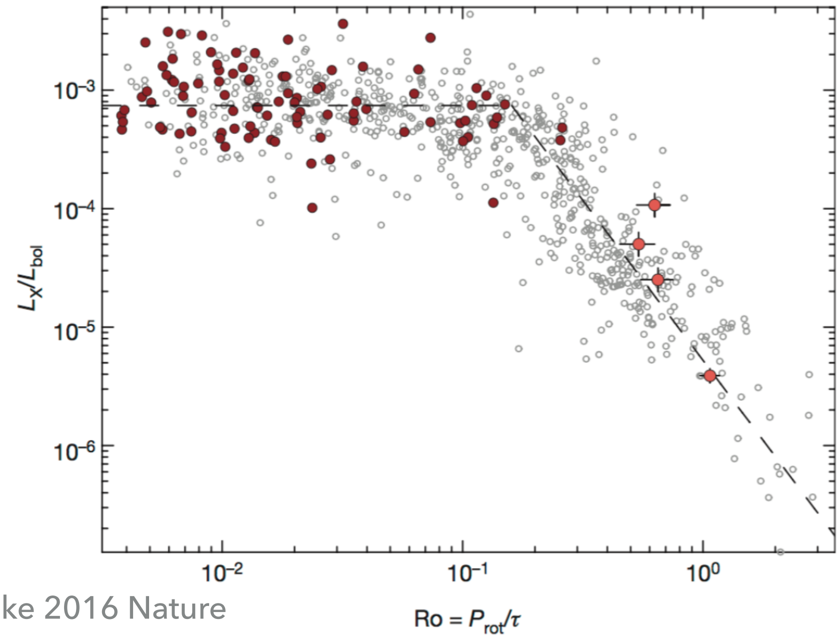
- Stellar flares ~10^{28} erg to 10^{38} in radiated energy

- The Sun would not be a 'flare star' at a distance: largest few x 10^{32} erg, 250 x10^{-6} in white-light
- Rapidly rotating, young G-type, K-type stars
  - EK Dra, Superflare stars in *Kepler,* AB Dor
- Active binaries (RS CVn) tidally locked, main sequence early-type star (BV-GV) and later type sub-giant (KIV) star
  - II Peg, HR1099, UX Ari, Algol (eclipsing), CC Eri
- Some single red clump giants
- Pre-main sequence stars (T Tauri), some of which are in eccentric binary and flare at periastron (active accretion)
  - V773 Tau, DQ Tau
- Active late-type main sequence stars in tidally locked binary
  - BY Dra, YY Gem
- M dwarf stars, not tidally locked, but most are probably young, rapidly rotating, and main-sequence / non-accreting
  - YZ CMi, AD Leo, EV Lac, UV Ceti, CN Leo, EQ Peg, DT Vir, AU Mic, Proxima Centauri

- Share the property of convection in outer layers or fully convective, and can be enhanced by binarity

THE ACTIVE M DWARFS

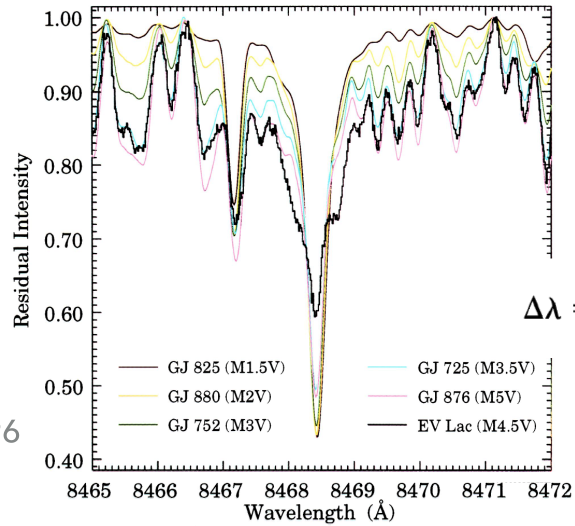
- By "active" we mean H alpha in emission when not flaring
  - most are rapidly rotating, near fully convective regime (M3-M6)
  - most are near saturated activity regime ($L_{X\text{-ray}}$ / L_{Bol} ~ 0.001)



Wright & Drake 2016 Nature

THE ACTIVE M DWARFS

- By "active" we mean H alpha in emission when not flaring
  - most are rapidly rotating, near fully convective regime (M3-M6)
  - most are near saturated activity regime ($L_{X\text{-}ray}$ / L_{Bol} ~ 0.001)
  - average surface magnetic field strength ~4 kG with 50% coverage fraction ("filling factor", *f* or *X*)



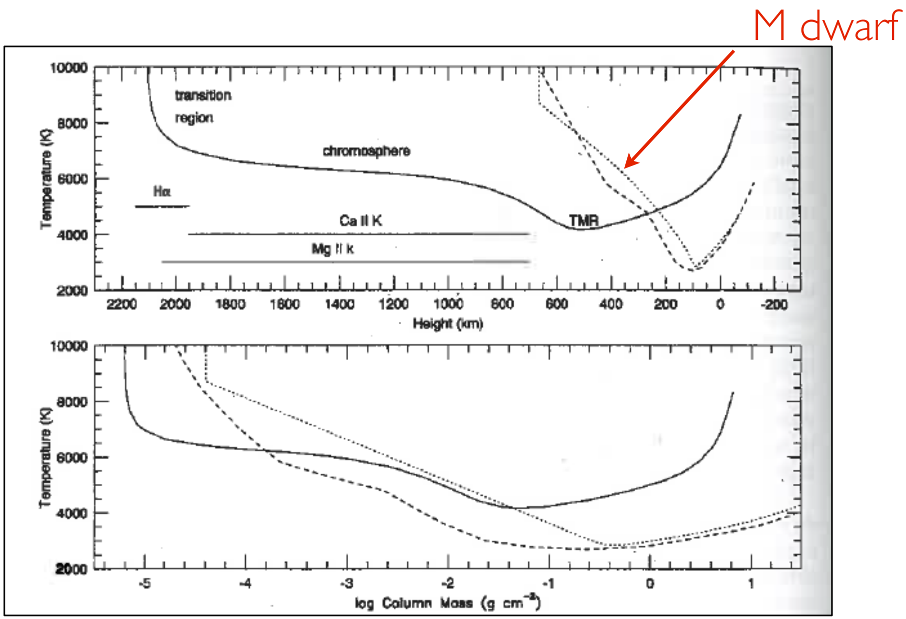
Johns-Krull & Valenti 1996

- broadening due to Zeeman effect of Fe I 8468.4 A (splitting of m_l in magnetic field):

$$\Delta\lambda = \frac{e}{4\pi mc^2}\lambda^2 g_{\text{eff}}|\boldsymbol{B}| = \pm 83.7\,|\boldsymbol{B}|\text{ mÅ kG}^{-1},$$

M DWARFS HAVE 2–3.5X HIGHER GRAVITY THAN THE SUN

M dwarf vs. G dwarf (semi-empirical models)

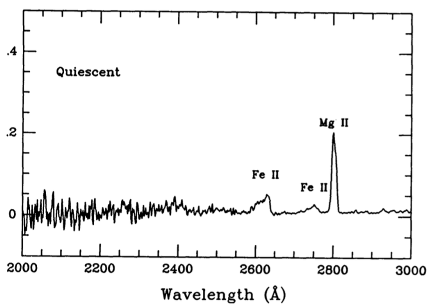


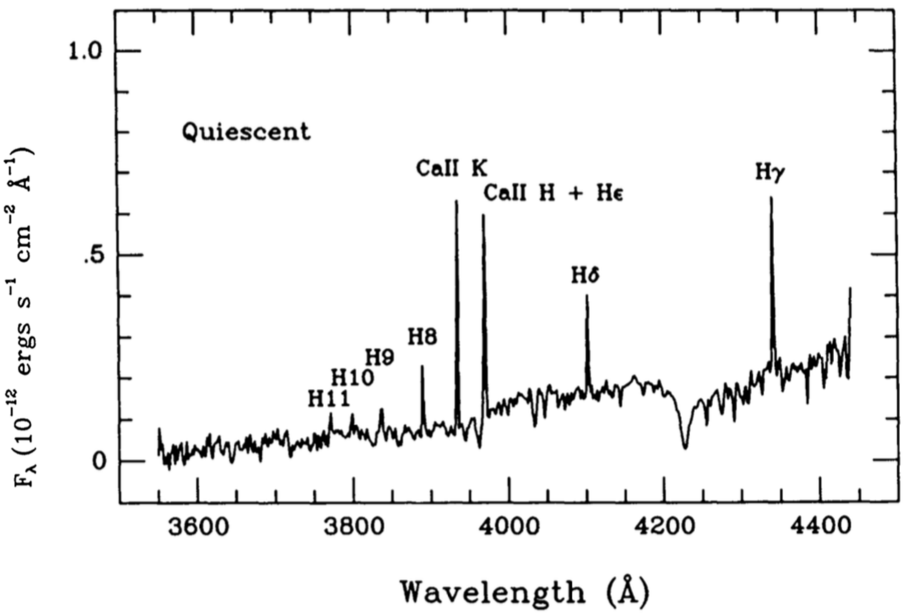
Reid and Hawley (1995)

- Also have hotter, denser non-flaring coronae (e.g., Osten et al. 2006)

Active M Dwarf Chromospheres

- The dM3e star AD Leo





Hawley & Pettersen 1991

SO WHAT?

- larger B (but: *what is the B-field environment in the corona of an M dwarf?*), higher coronal density: more energy released into the footpoints, more NT particles if n_{NT}/n_0 ~ 1 (Kowalski et al. 2015)
- Lecture 22: from Prof. Chen:

Alternative view: ALT HXR source **is** the primary acceleration site

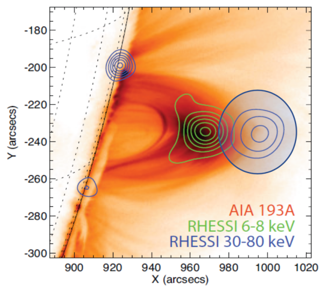
Krucker & Battaglia 2014:

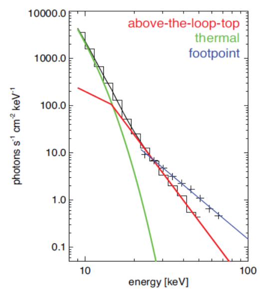
RHESSI imaging spectroscopy to infer density of accelerated electrons: n_{nt}~10^9 cm^{-3}

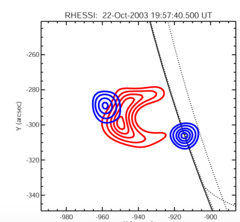
SDO/AIA DEM analysis to determine ambient thermal density n_0

→ ratio n_{nt}/n_0 is close to 1
→ bulk acceleration takes place within the ALT HXR source?

Similar findings were reported for partially occulted flares (Krucker et al. 2010)

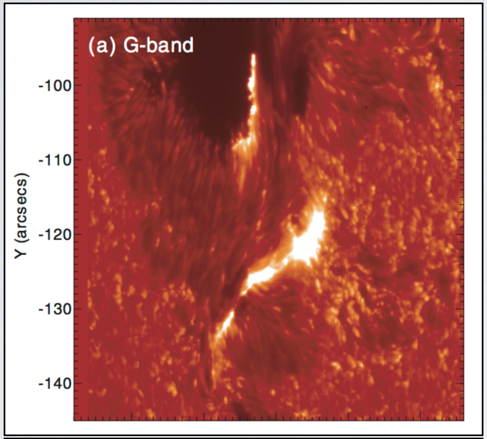


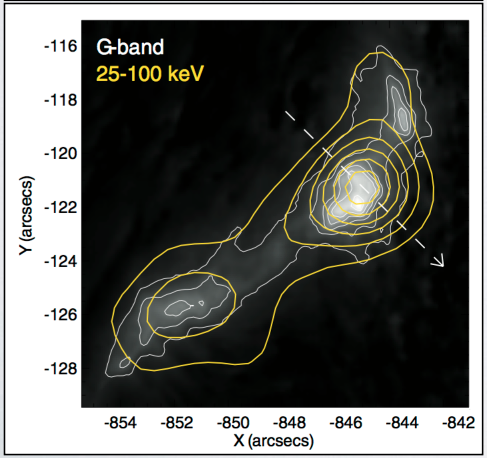


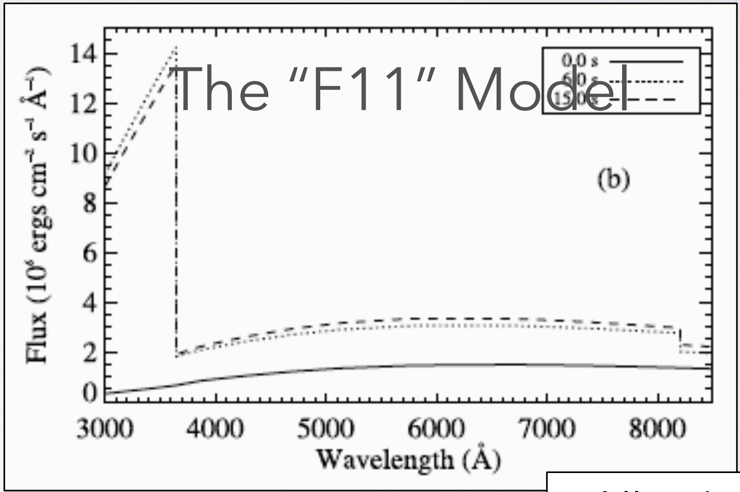


High spatial resolution footpoint "kernels" have inferred beam energy fluxes of 3×10^{11} - 5×10^{12} erg s^{-1} cm^{-2} (3F11-5F12)

Krucker et al. 2011 (with Hinode), Kleint et al. 2016 (with IRIS)







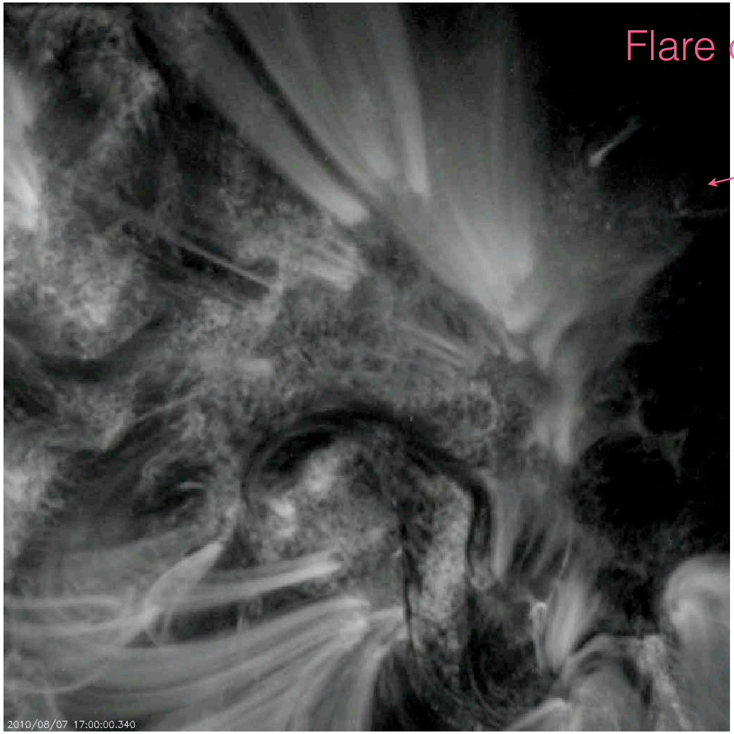
F11 e- beam (10^{11} erg s^{-1} cm^{-2})

Allred et al. 2005, 2006

Should consider higher beam fluxes (larger F-numbers) for M dwarf flares

↳ F13 (Kowalski + 2015, 2016, 2017)

THE TWO-RIBBON SOLAR FLARE ANALOGY FOR STELLAR FLARES



Flare classification:

X

M

C

B

SDO/AIA 171, T~800,000 K (see Prof. Qui's Lecture #12)

THE TWO-RIBBON SOLAR FLARE ANALOGY FOR STELLAR FLARES

Flare classification:

X

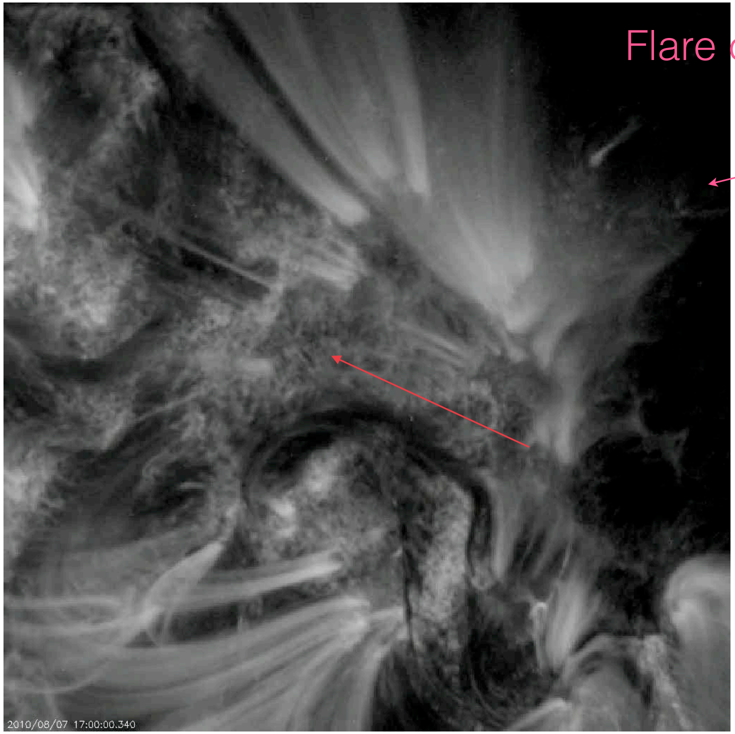
M

C

B

SDO/AIA 171, T~800,000 K (see Prof. Qui's Lecture #12)

THE TWO-RIBBON SOLAR FLARE ANALOGY FOR STELLAR FLARES

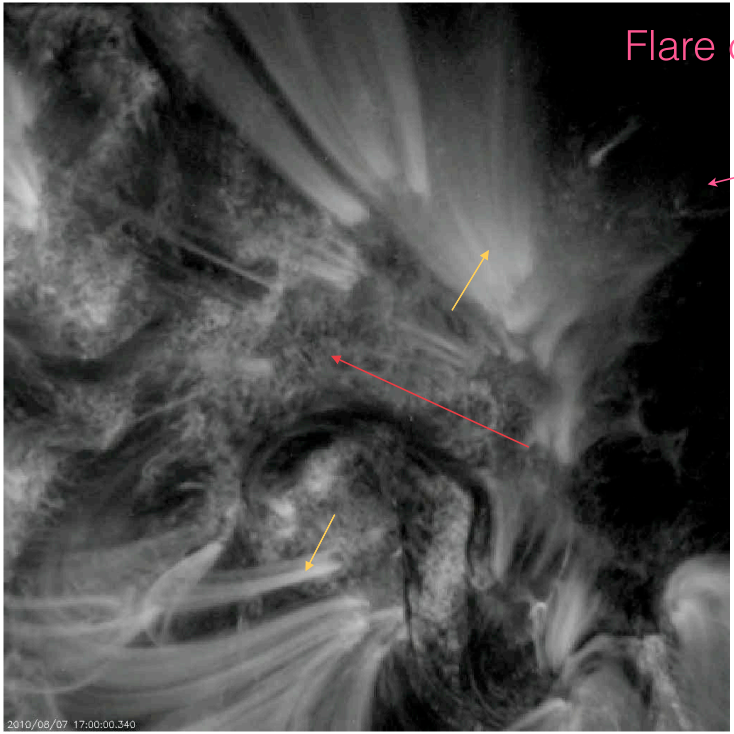


Flare classification:

X
M
C
B

SDO/AIA 171, T~800,000 K (see Prof. Qui's Lecture #12)

THE TWO-RIBBON SOLAR FLARE ANALOGY FOR STELLAR FLARES



Flare classification:

X

M

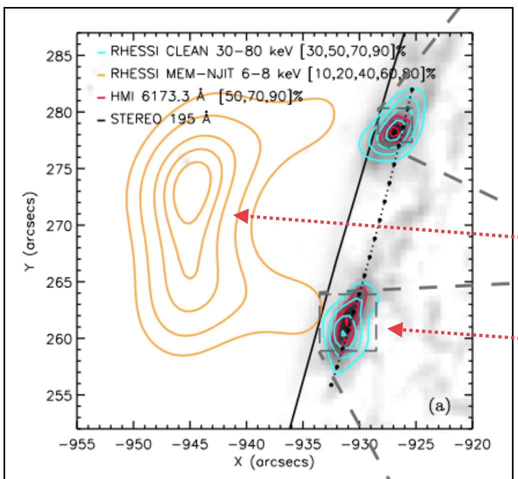
C

B

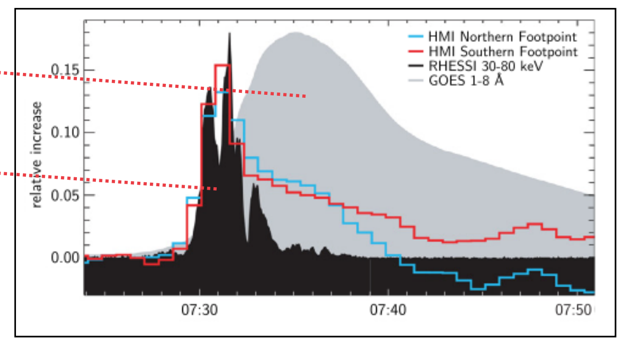
SDO/AIA 171, T~800,000 K (see Prof. Qui's Lecture #12)

WHITE LIGHT A PROXY OF IMPULSIVE PHASE HEATING

- white-light: observed continuum radiation from near-UV through optical (sometimes far-UV, IR)
  - proxy for white-light on Sun is optical intensity at 6173Å (SDO/HMI)
  - proxy for white-light on M dwarfs is the Johnson U-band, but also have broad wavelength coverage spectra for detailed characterization



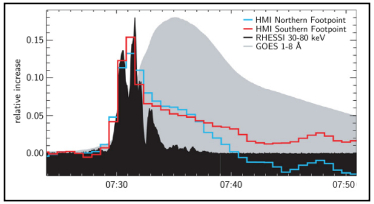
Observations of solar flares on the limb:
Martinez-Oliveros et al. 2012, Krucker et al. 2015



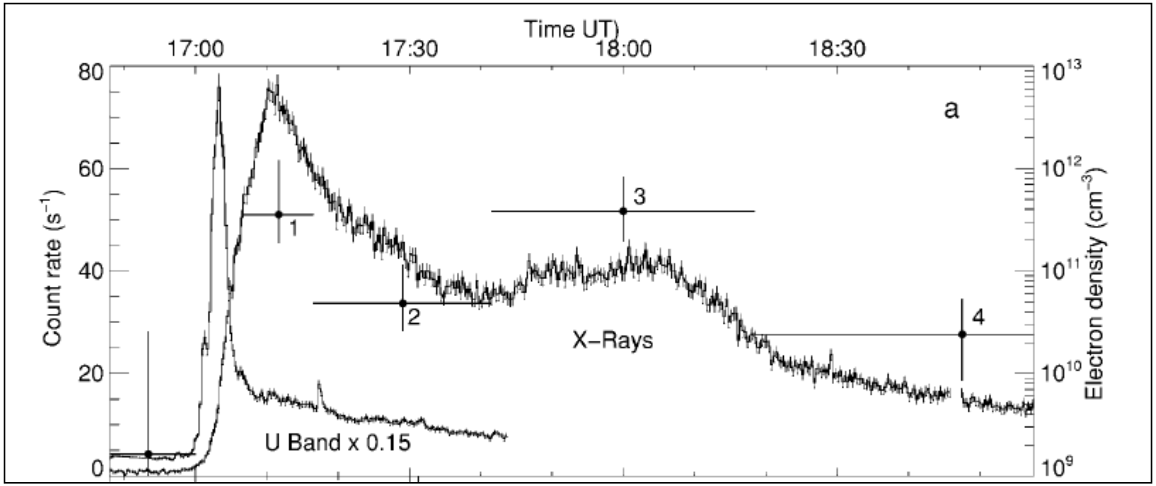
Time (UT)

WE OFTEN INVOKE THE TWO-RIBBON SOLAR FLARE ANALOGY

The Neupert Effect



Solar flare from Martinez-Oliveros et al. 2012

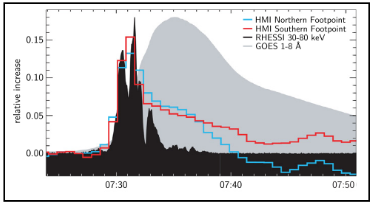


Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)

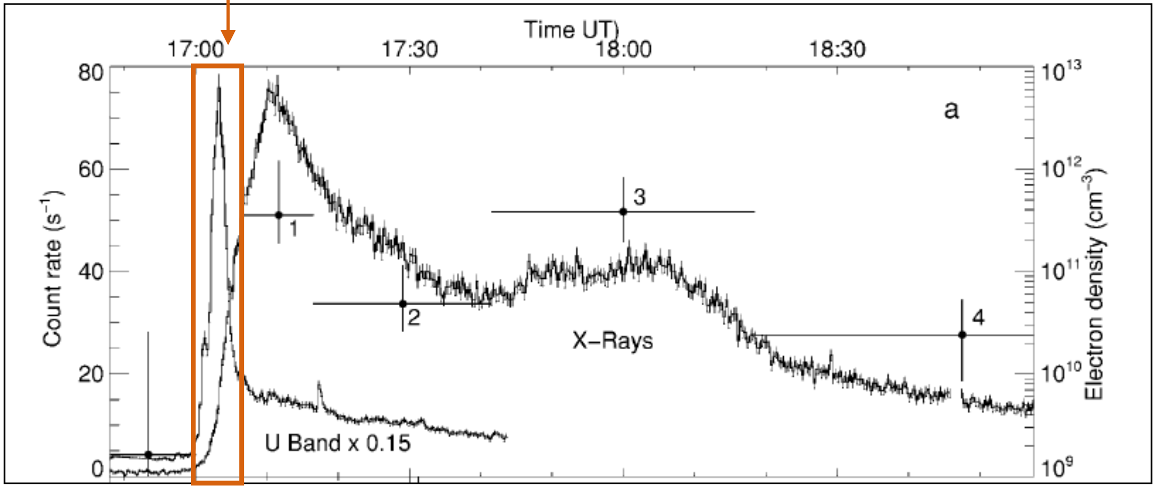
WE OFTEN INVOKE THE TWO-RIBBON SOLAR FLARE ANALOGY

The Neupert Effect

Impulsive phase (U-band is white-light, proxy for hard X-rays), 10,000 K "footpoints"



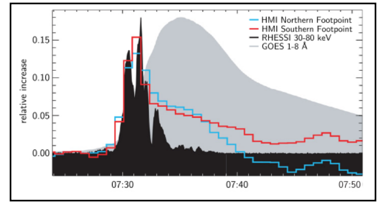
Solar flare from Martinez-Oliveros et al. 2012



Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)

WE OFTEN INVOKE THE TWO-RIBBON SOLAR FLARE ANALOGY

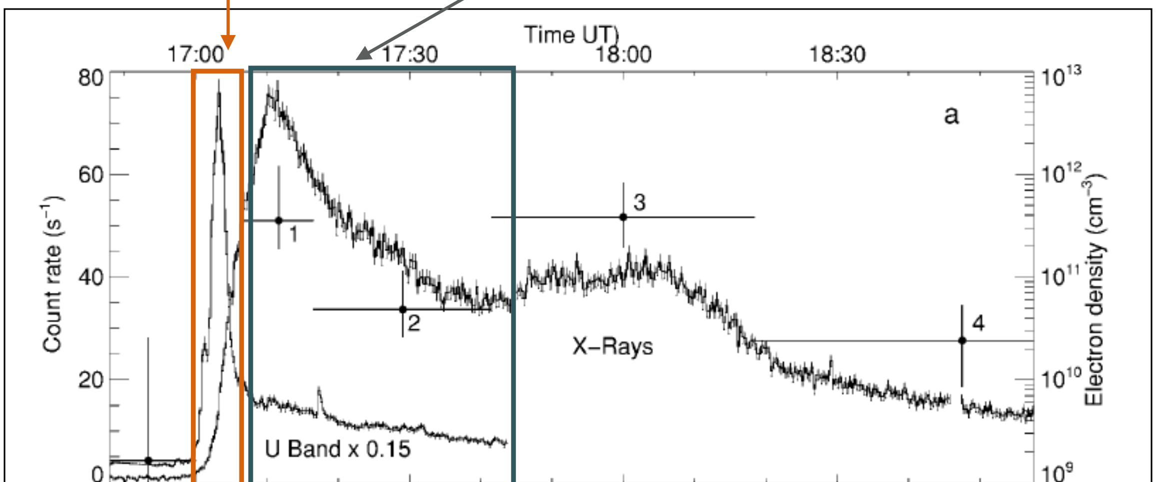
The Neupert Effect



Solar flare from Martinez-Oliveros et al. 2012

Impulsive phase (U-band is white-light, proxy for hard X-rays), 10,000 K "footpoints"

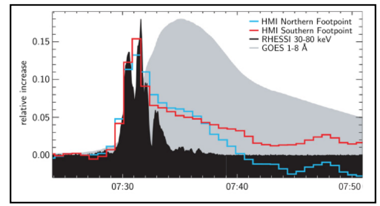
Gradual phase (bright soft X-rays), 10 MK "loops"



Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)

WE OFTEN INVOKE THE TWO-RIBBON SOLAR FLARE ANALOGY

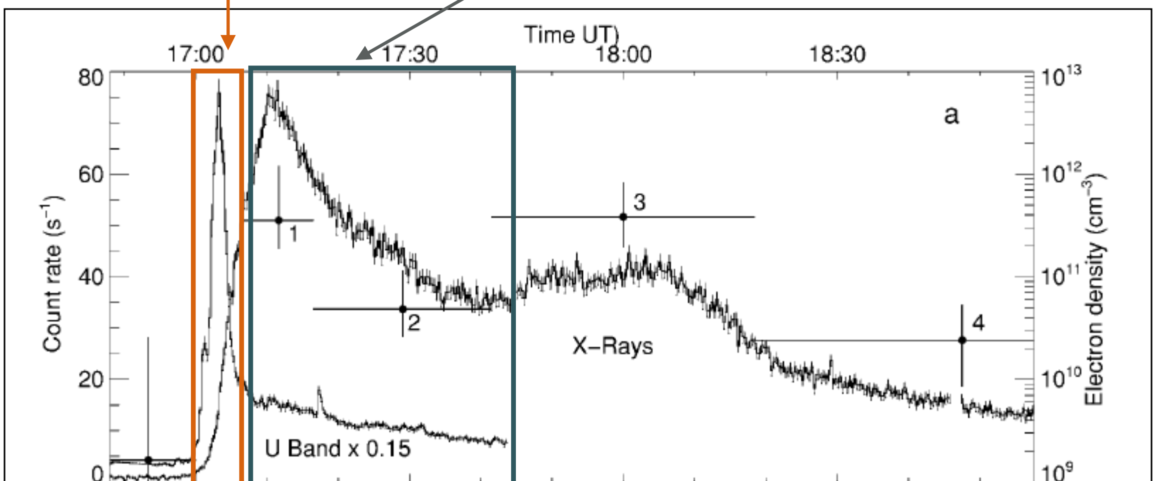
The Neupert Effect



Solar flare from Martinez-Oliveros et al. 2012

Impulsive phase (U-band is white-light, proxy for hard X-rays), 10,000 K "footpoints"

Gradual phase (bright soft X-rays), 10 MK "loops"



Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)

- Note: this flare ~10^{32} erg in radiated energy

NEUPERT EFFECT IN STELLAR FLARES

- Microwave (gyrosynchrotron), HXR, or white-light proportional to SXR derivative
- Hawley et al. 1995, Gudel et al. 1996, ….
- Observed in flares with energies > 10^{36} erg!

The Neupert Effect: when is the heating?

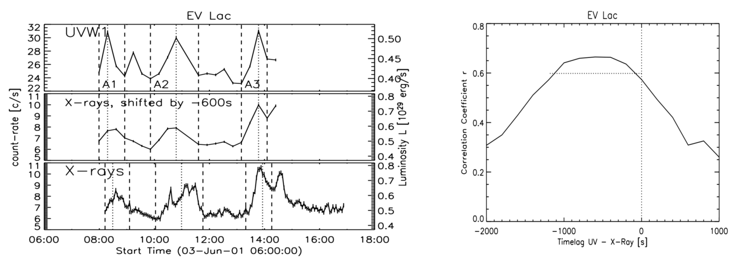
Neupert (1968), "Comparison of Soft X-ray Line Emission with Microwave Emission During Solar Flares", states that the time integral of microwave burst corresponds best to X-ray line emission from rise to maximum.

The Astrophysical Journal, Vol. 153, July 1968

COMPARISON OF SOLAR X-RAY LINE EMISSION WITH MICROWAVE EMISSION DURING FLARES

Werner M. Neupert
Goddard Space Flight Center, Greenbelt, Maryland

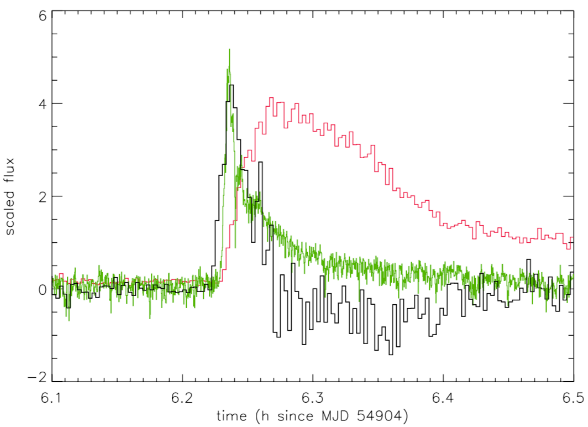
Received April 18, 1968; revised June 3, 1968



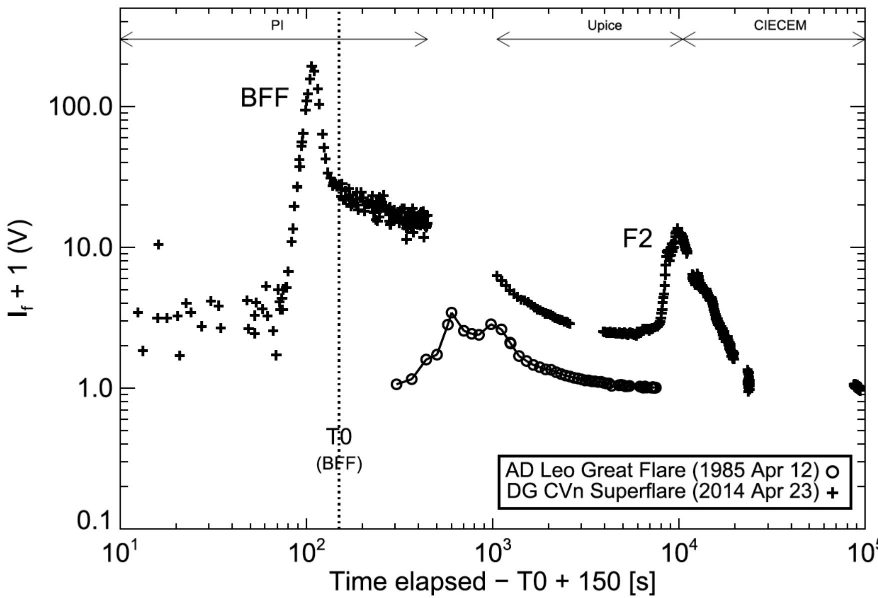
Mitra-Kraev et al. 2005 M dwarfs

NEUPERT EFFECT EVEN IN VERY LARGE FLARES

- From the relatively small flares of Proxima Centauri to giant flares of DG CVn



Fuhrmeister et al. 2011; medium-sized flare on Prox Cen

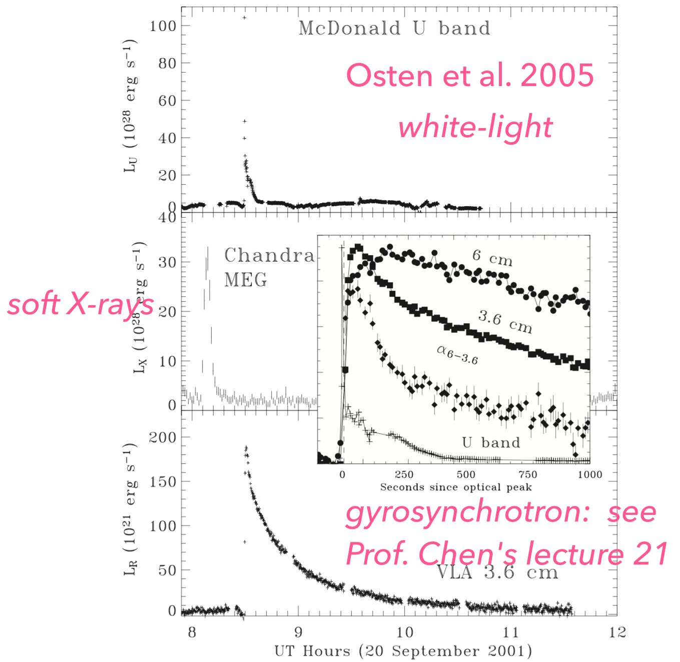


Osten et al. 2016; the soft X-ray lags the optical and HXR peak by ~40 seconds (Caballero-Garcia et al. 2015); superflare on DG CVn

LIKE FOR THE SUN, THERE ARE ALSO INTERESTING EXCEPTIONS

- But very little statistics! See Prof. Qiu Lecture 12: about 20% of solar flares don't exhibit Neupert-like correlations

- Great amounts of X-ray / EUV data for the Sun, great amounts of optical data for M dwarfs



- Multi-wavelength data in NUV continuum (U-band), soft X-rays (Chandra), and microwave (VLA 3.6 cm, 6 cm) from Osten et al. 2005

- Neupert effect not always observed in stellar flares

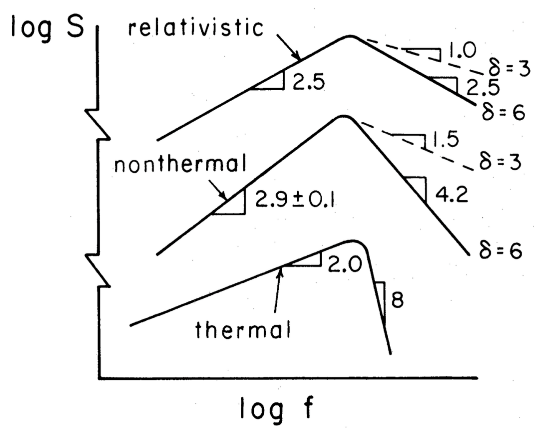
  - One possibility: deep heating with a high low-energy cutoff does not cause (observable) evaporation (e.g., Warmuth e al. 2009, Kowalski et al. 2017, Ayres 2015)

  - Why?

NONTHERMAL PARTICLES IN STELLAR FLARES

- radio gyrosynchrotron (VLA): the best diagnostic of nonthermal electrons in stellar flares
    - must assume frequencies are optically thin to relate radio emission spectrum to nonthermal particle energy spectrum (if peak not constrained)

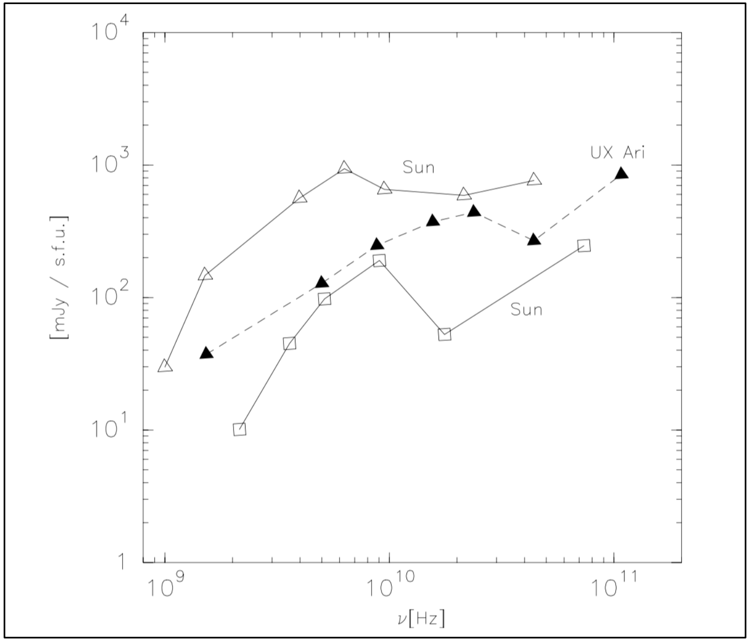
Lecture 21:



- Hard X-ray emission (>25 keV) too faint except during largest "superflares" detected by *Swift/BAT* (Osten et al. 2007, 2010, 2016) or *Chandra* (Getman et al. 2008)
    - degeneracy in superhot (50-300 MK) thermal fit and nonthermal bremsstrahlung fit at E > 25 keV
    - thermal interpretation favored (see Osten et al. 2016)

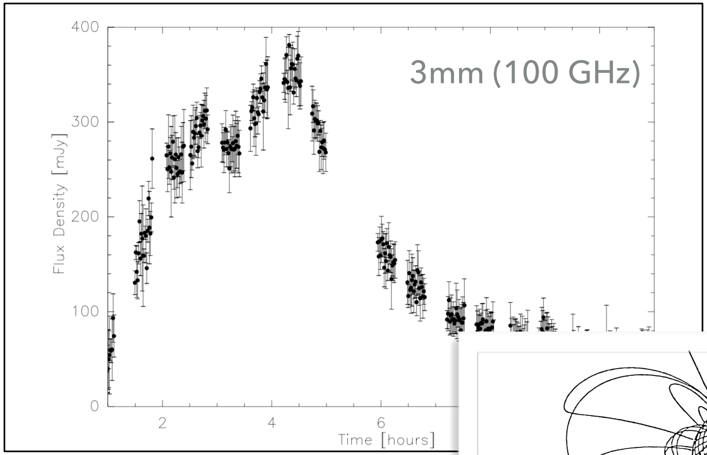
My only slide on RS CVn's (see Osten et al. 2004)

SUB-THZ COMPONENT IN STELLAR FLARES

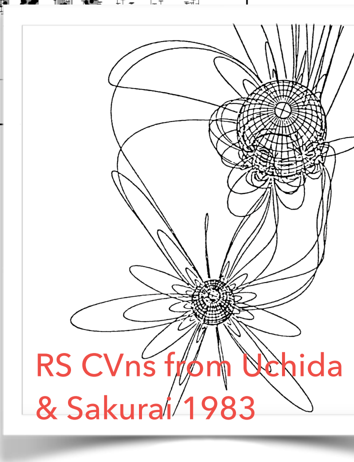


Beasley & Bastian 1998

V773 Tau



Massi et al. 2006

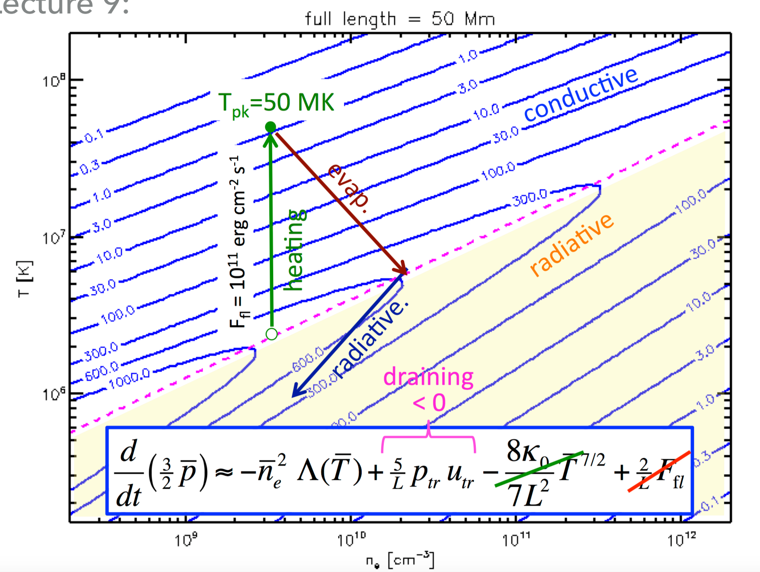


RS CVns from Uchida & Sakurai 1983

- Synchrotron emission often invoked to explain this emission in stellar flares
- Krucker et al. 2013: review article of the "sub-THz" component in solar flares; as many possibilities as for "Tabby's Star" (but not aliens!)

FROM DECAY TIME OF X-RAYS, CAN OBTAIN LOOP LENGTHS

Lecture 9:



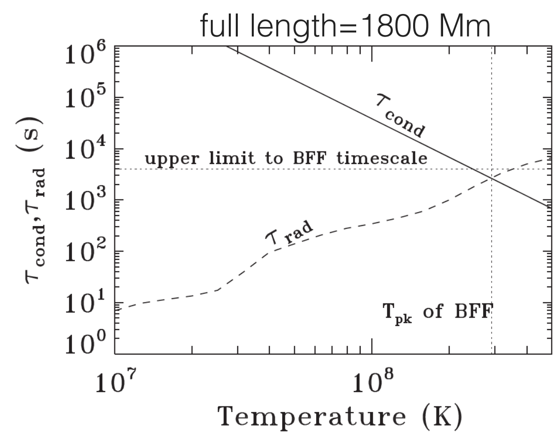
$$\tau_{\rm rad} = \frac{3k_{\rm B}T_e}{n_e\psi(T_e)}$$

$$\tau_{\rm cond} = \frac{3n_e k_{\rm B} l^2}{\kappa T_e^{5/2}}$$

Cooling rate:

$$\frac{1}{\tau_{cool}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{cond}}$$

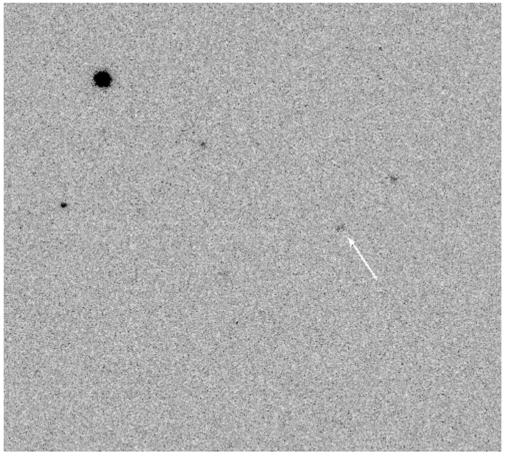
- Loop lengths of several stellar radii!
- see Reale et al. 1997 (VEM(t) vs. T(t))
- VEM 10^{54} cm^{-3} for large flares! (compared to 10^{50} cm^{-3} for solar flares)

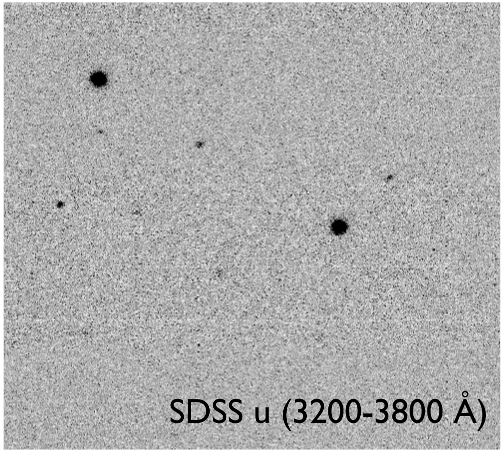


- 300 MK flare from Osten et al. 2016

RED DWARF FLARES ARE CONSPICUOUS IN THE BLUE

Flares on nearby active M dwarfs (dMe)



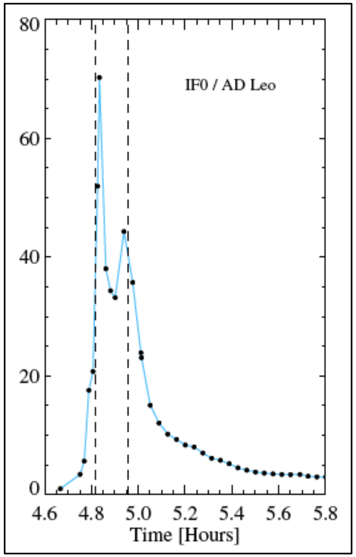


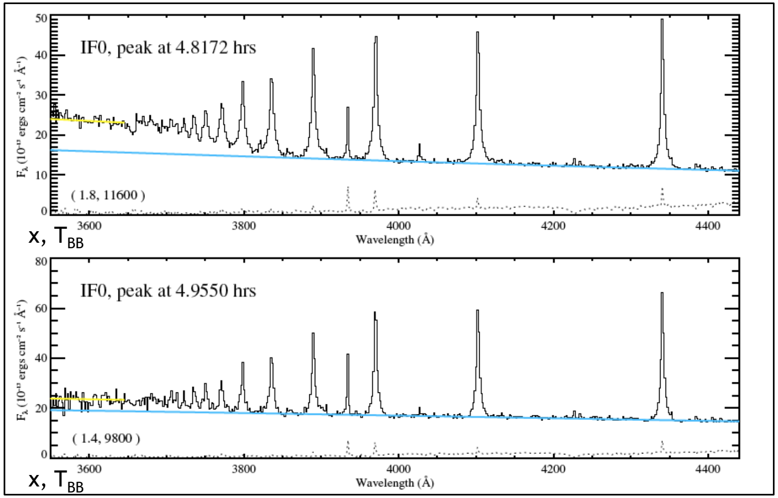
Quiescence Flaring

Sloan Digital Sky Survey Stripe 82

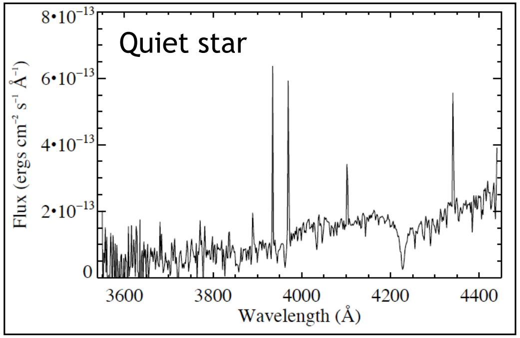
- *<u>Flare visibility</u>: earlier spectral types have lower flare visibility. For the same fractional change, flares on early type stars have larger energy/ luminosity.*

The Great Flare on AD Leo





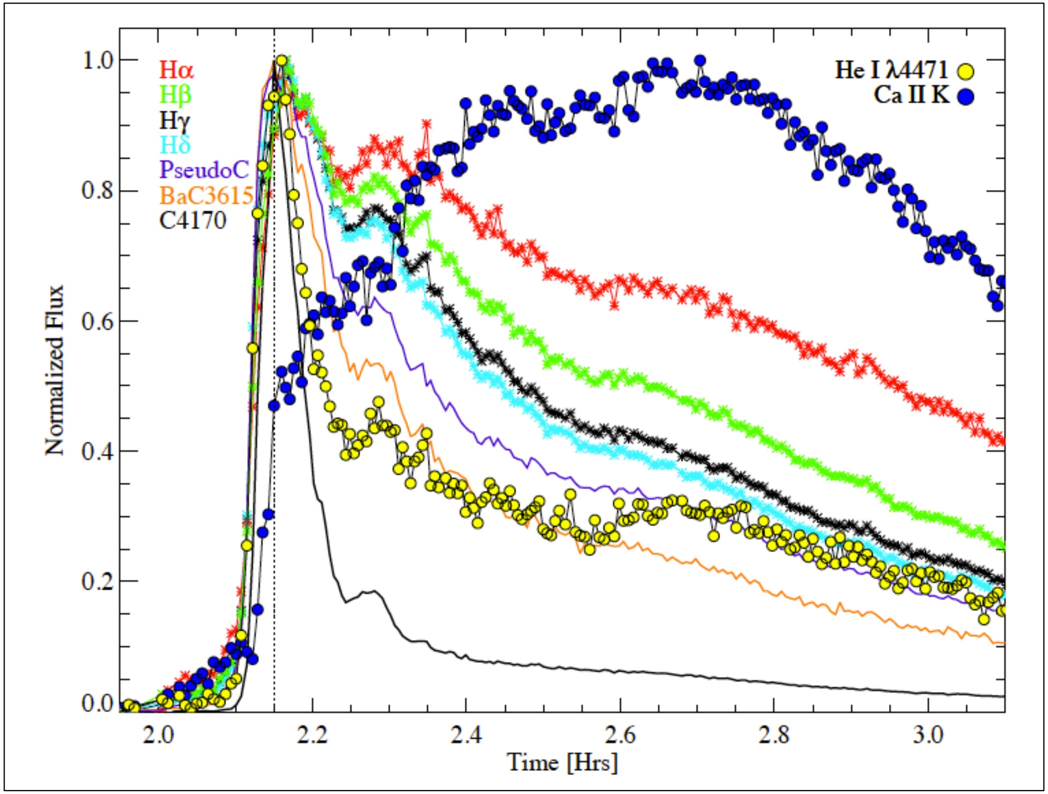
- 1) Broad hydrogen Balmer lines, 2) ~10% of the radiated energy compared to continuum, 3) U-band about 1/6 of continuum energy, 4) white-light continuum about 60-70% of total radiated energy.
- T~10,000 K blackbody roughly explains the continuum distribution from far-UV, near-UV, and optical



TIME EVOLUTION OF CHROMOSPHERIC LINES

Emission line evolution in dMe flares

Continuum fastest to decay, then Balmer lines, then Ca II K

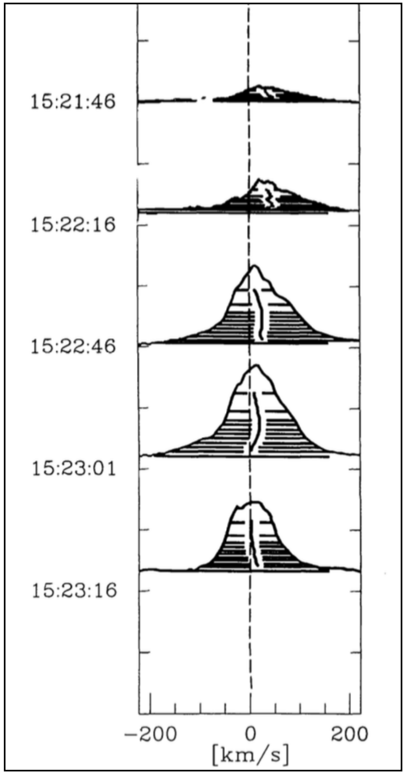


Kowalski et al. 2013

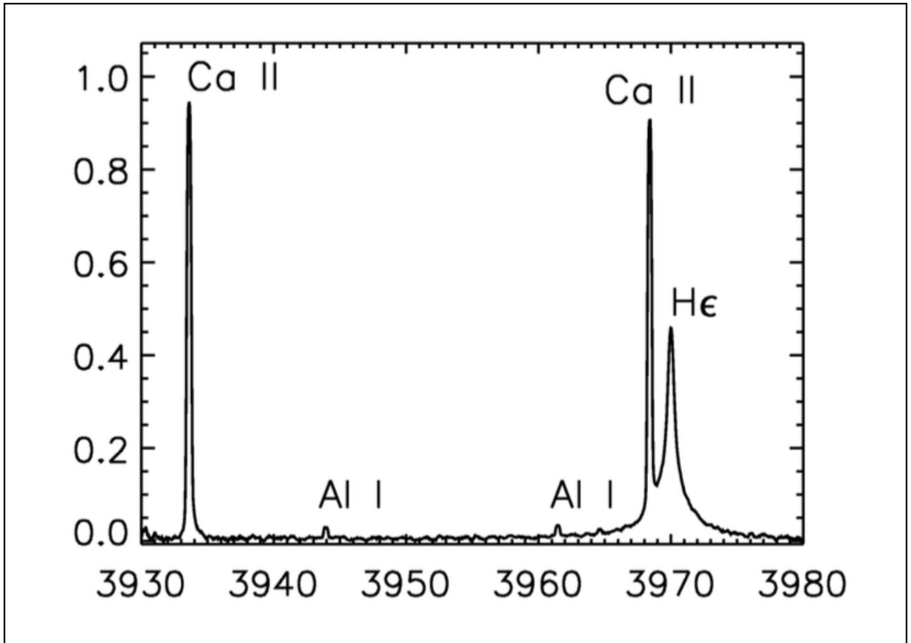
SYMMETRIC BROADENING OF THE HYDROGEN LINES

Solar flare

M dwarf flare



Canfield et al. 1990



Paulson et al. 2006

SYMMETRIC BROADENING OF THE HYDROGEN LINES

Broadening of Hydrogen Lines

Electric pressure broadening of energy levels of hydrogen

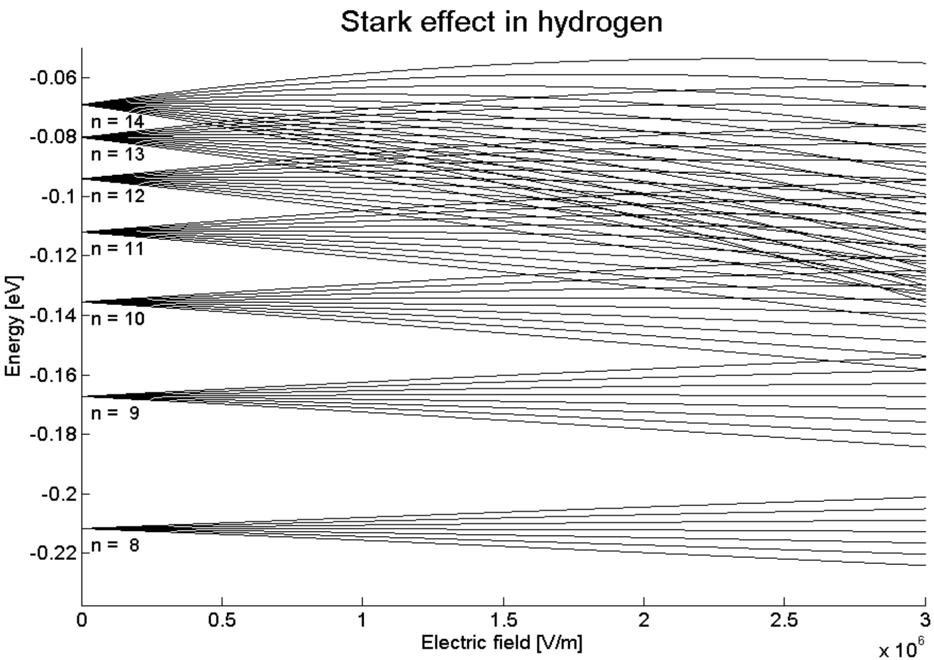


Figure credit: P.-E. Tremblay

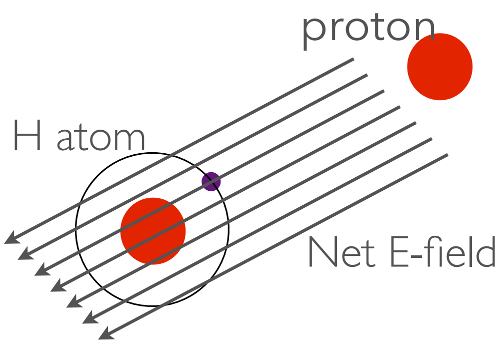
SYMMETRIC BROADENING OF THE HYDROGEN LINES

A. Thermal and turbulent broadening

B. Electric pressure broadening due to fluctuations in ambient charge density

a. protons are quasi-static perturbers
b. electrons are dynamic perturbers

Unified theory of pressure broadening: Vidal et al. 1971, 1973



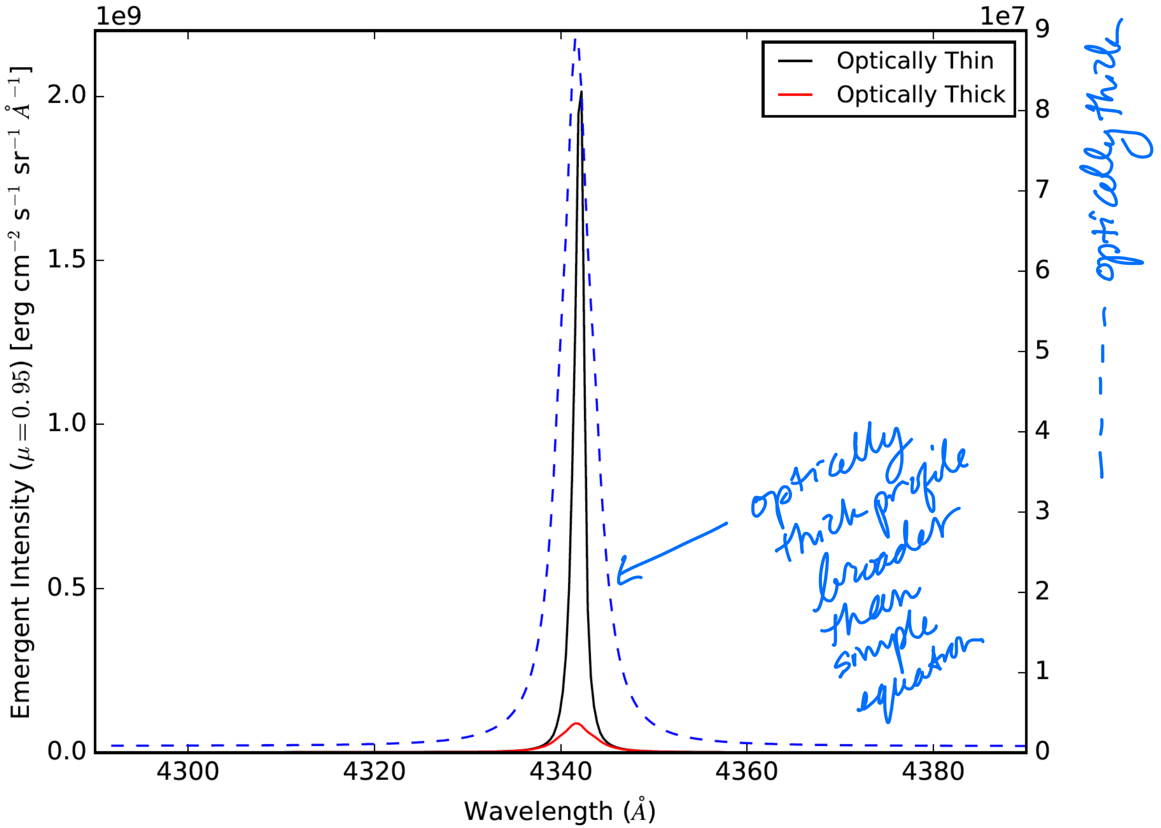
Linear energy splitting:

$$\Delta E^1_{n,m,q} = \frac{3ea_0F}{2}nq\,.$$

(F is the perturbing electric field strength)

optically thin width → $\Delta\lambda \propto n_e^{2/3}\{\frac{n^2}{n^2-4}\}^2[n(n-1)+2]$

OPTICALLY THICK VS. OPTICALLY THIN



FILLING FACTOR OF WHITE-LIGHT

$$f_{\lambda,flare,Earth} = F_{\lambda,flare,surface} \frac{R^2_{flare}}{d^2}$$

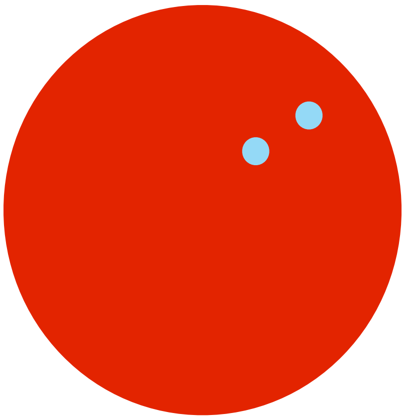
X = filling factor
= fraction of visible stellar hemisphere

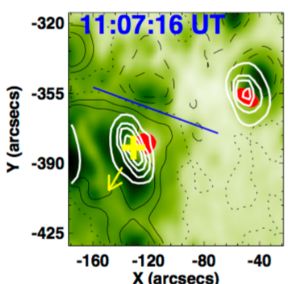
$$X_{flare} = \frac{\pi R^2_{flare}}{\pi R^2_{star}}$$ one circular kernel

$$X_{flare} = \frac{2\pi R^2_{flare}}{\pi R^2_{star}}$$ two circular kernels

$$f_{\lambda,flare,Earth} = F_{\lambda,flare,surface} X_{flare} \frac{R^2_{star}}{d^2}$$

$F_{\lambda,surface}$ { 1) Blackbody
2) Spectrum from RHD model





Maurya & Ambastha 2009; optical flare kernels/ribbons on the Sun

FILLING FACTOR OF WHITE-LIGHT

$$f_{\lambda,flare,Earth} = F_{\lambda,flare,surface} \frac{R^2_{flare}}{d^2}$$

X = filling factor

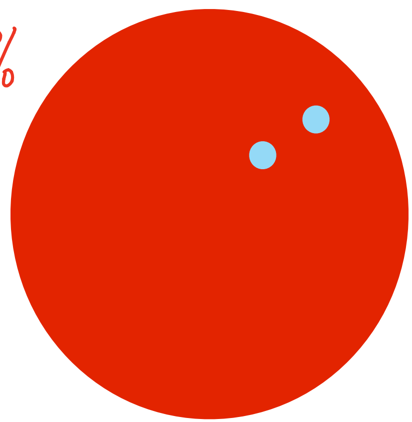
$$X_{flare} = \frac{\pi R^2_{flare}}{\pi R^2_{star}}$$ one kernel

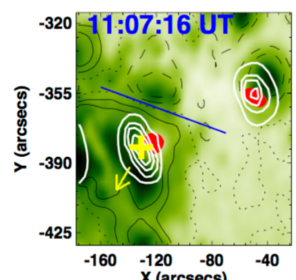
$$X_{flare} = \frac{2\pi R^2_{flare}}{\pi R^2_{star}}$$ two circular kernels

$$f_{\lambda,flare,Earth} = F_{\lambda,flare,surface} X_{flare} \frac{R^2_{star}}{d^2}$$

⇒ X_{flare}: 0.005% to 0.5%

⇒ white-light emitting regions are compact like kernels on the Sun.

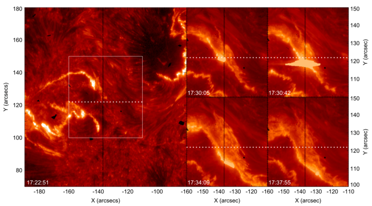




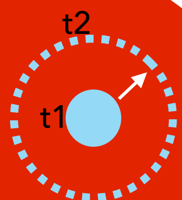
Maurya & Ambastha 2009; optical flare kernels/ribbons on the Sun

RATE OF WHITE-LIGHT AREAL INCREASE

- Areal coverage of white-light increases with color temperature approximately constant in the rise phase of stellar flares

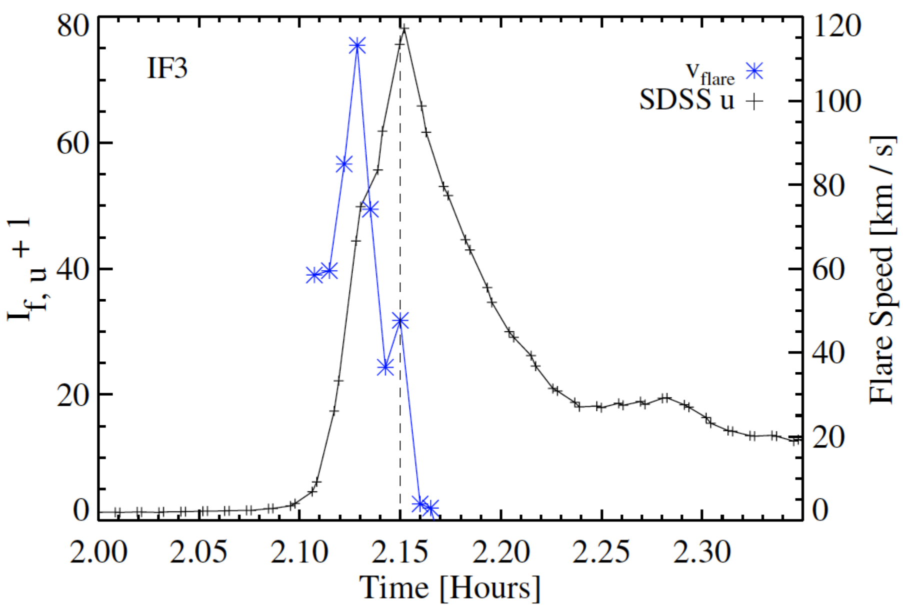


Graham & Cauzzi 2015



A simplistic "expanding circle" model of separating flare ribbons

$$v(t)_{\rm flare} = \frac{dr(t)_{\rm flare}}{dt} = 0.5\frac{dX(t)}{dt}\frac{1}{r(t)_{\rm flare}}R^2_{\rm Star},$$



Kowalski et al. 2013

THE BALMER JUMP RATIO (χ)

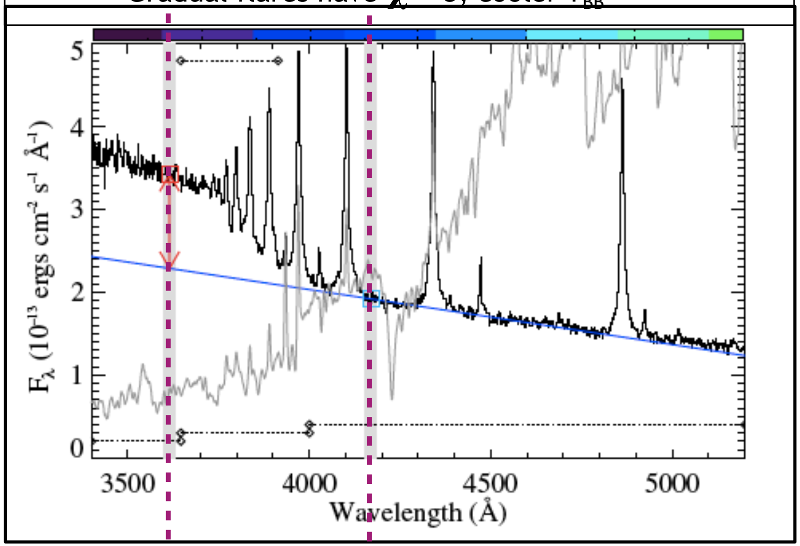
Observations

Measure importance of Balmer continuum relative to hot blue(blackbody-like) continuum using χ = flux(3615)/ flux(4170)

Impulsive flares have χ ~ 1-2, hotter T_{BB}

Hybrid flares have χ ~ 2-3, intermediate T_{BB}

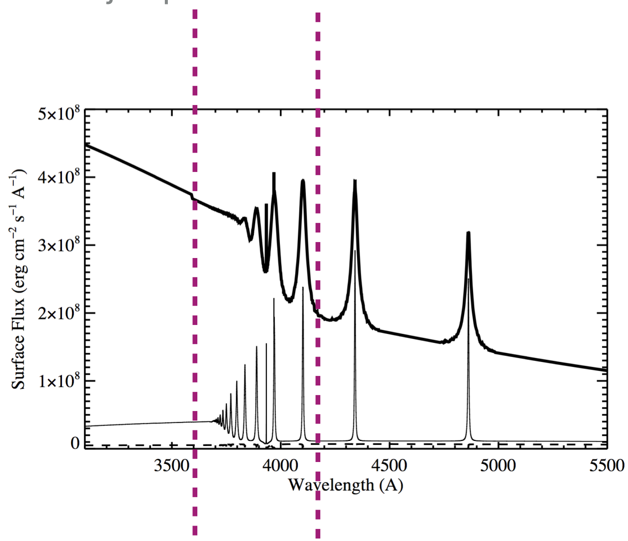
Gradual flares have χ > 3, cooler T_{BB}



*Stellar atmospheres do not produce perfect blackbodies, even during flares.

Models

- For hydrogen recombination radiation over high optical depth and T~10,000 K, Balmer jump ratio is ~2 or lower
- For hydrogen recombination radiation over low optical depth and T~10,000 K, Balmer jump ratio is close to 9-10

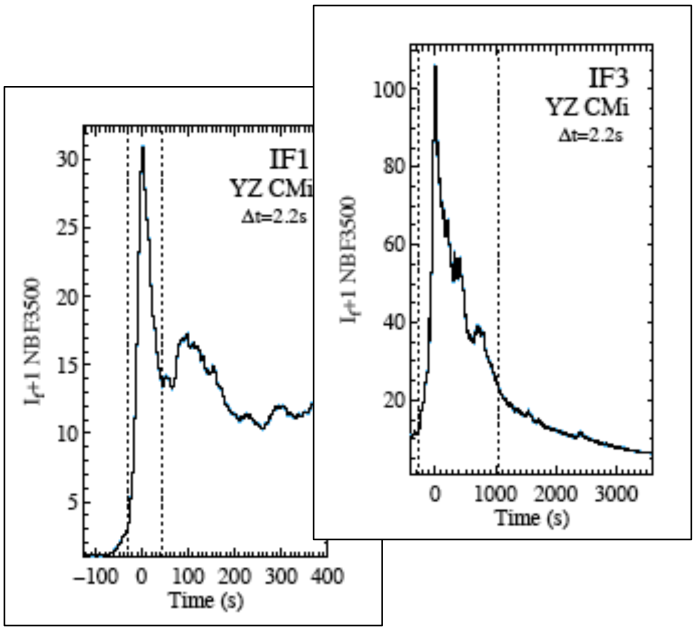


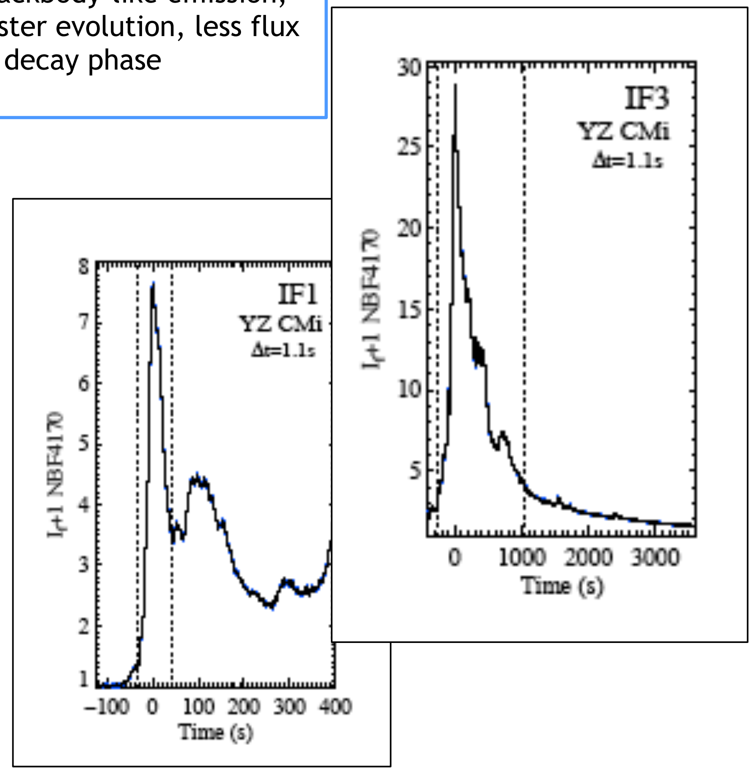
BALMER JUMP RATIO TIME EVOLUTION

ULTRACAM light curves of flares on YZ CMi

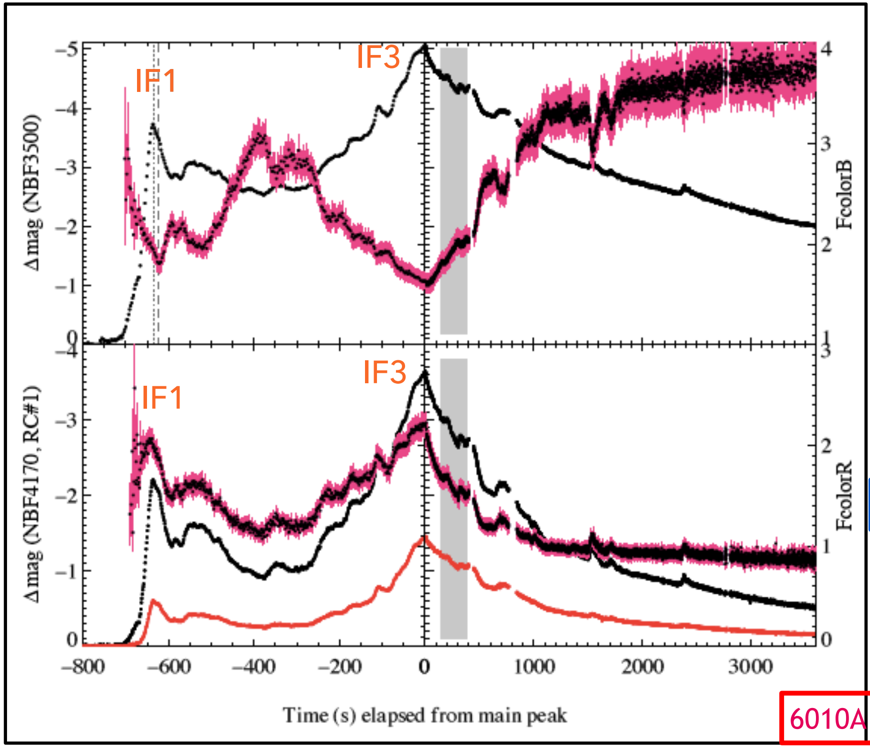
Balmer continuum filter 3500A,
Slower evolution, more flux
in decay phase

Blue continuum filter
4170A Measures hot
blackbody-like emission,
faster evolution, less flux
in decay phase





BALMER JUMP RATIO TIME EVOLUTION



3500A light curve

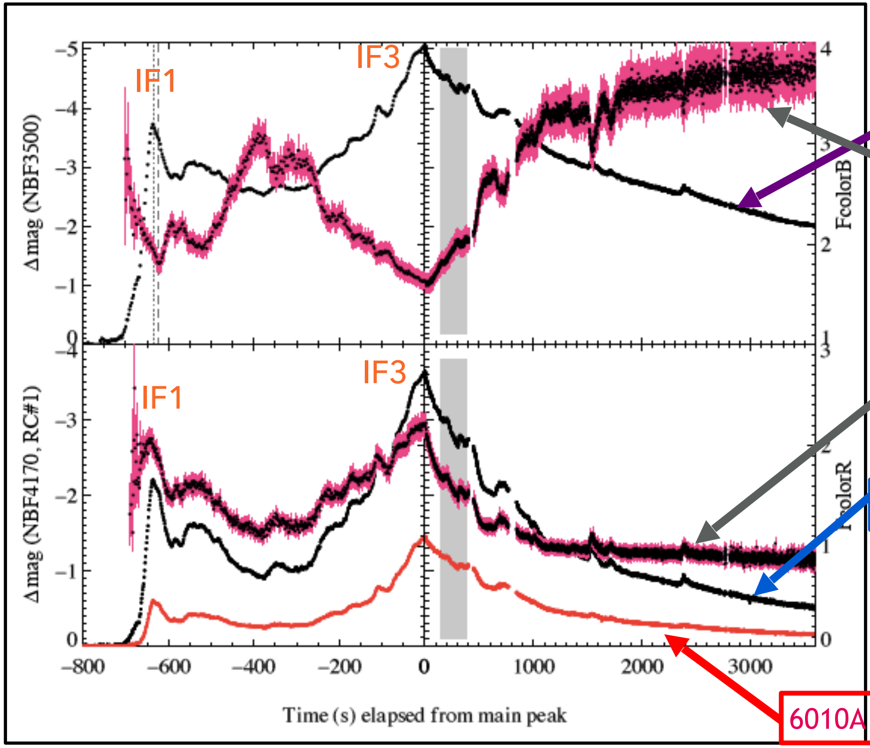
FcolorB – measures Balmer jump ratio

FcolorR – measures color temperature from blue to red

4170A light curve

6010A light curve

BALMER JUMP RATIO TIME EVOLUTION



3500A light curve

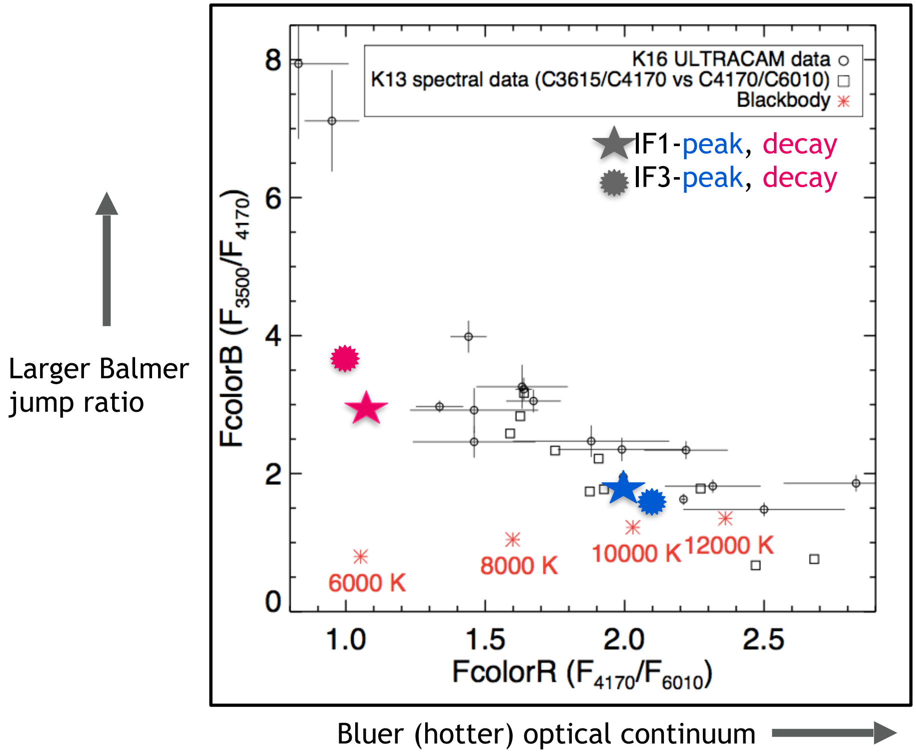
FcolorB – measures Balmer jump ratio

FcolorR – measures color temperature from blue to red

4170A light curve

6010A light curve

BALMER JUMP RATIO TIME EVOLUTION

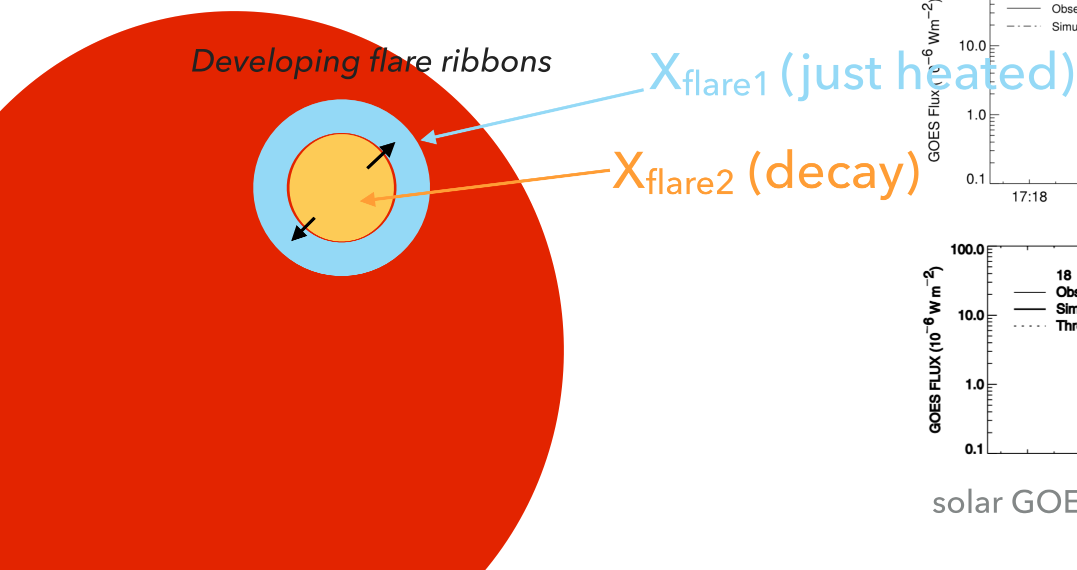


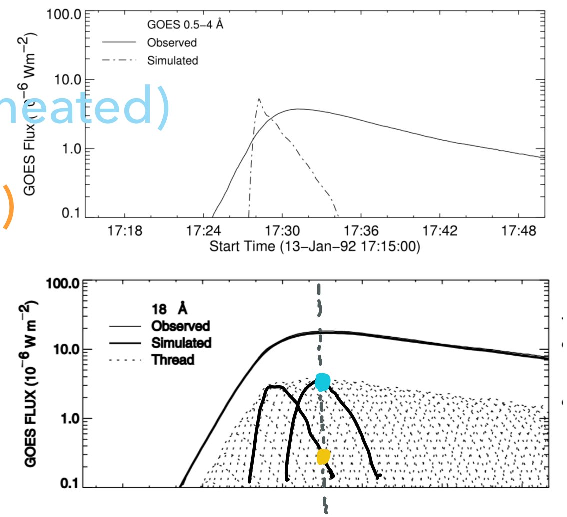
- In decay phase, there is a larger Balmer jump ratio and optical continuum is less blue
- In decay phase, the line flux / continuum flux is larger than at peak

DECAY PHASE SPECTRA OF LARGE FLARES

- At any time during a stellar flare, observed flare flux is from a superposition of rising, peaking, and decaying regions; decay requires continued heating
- Multi-thread modeling (Warren 2006) on Sun-as-a-star light curves (GOES)

$$f_{\lambda,flare,Earth} = [F_{\lambda,flare_1} X_{flare_1} + F_{\lambda,flare_2} X_{flare_2}] \frac{R^2_{star}}{d^2}$$





solar GOES light curves; Warren 2006

SUMMARY

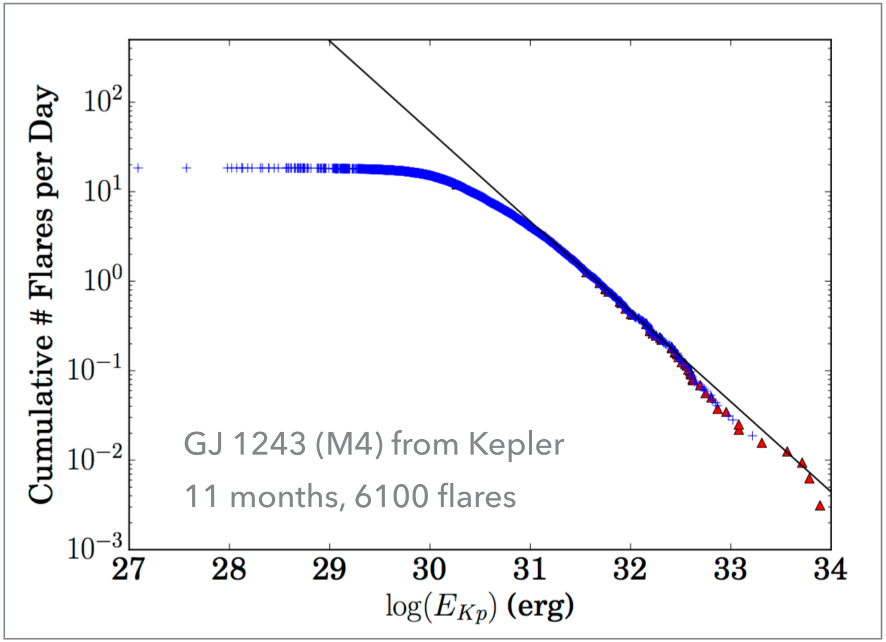
- We study flare energy release in other atmospheric environments; generally observe similar correlations in radio, X-rays, optical.
- Flux ratio values of continuum constrain spectral predictions of RHD models.
- Evidence from observations for large optical depth at 10,000 K, increased charge density in chromosphere, variation in chromospheric conditions from peak to gradual phase.
- Large energy in M dwarf flares: larger flare area, larger flare energy fluxes? Some combination of both?

FLARE STATISTICS (BRIEFLY)

- Flare frequency distributions (FFDs): require long monitoring times

$$N(E)dE \propto E^{-\alpha}dE,$$

- $\alpha > 2$ can account for the quiescent coronal luminosity when extrapolated below the detection limit (Hudson 1991)
- Typically expressed as a cumulative FFD: number of flares / day > E.
  - slope = 1- α
  - typically $\alpha \sim 2$

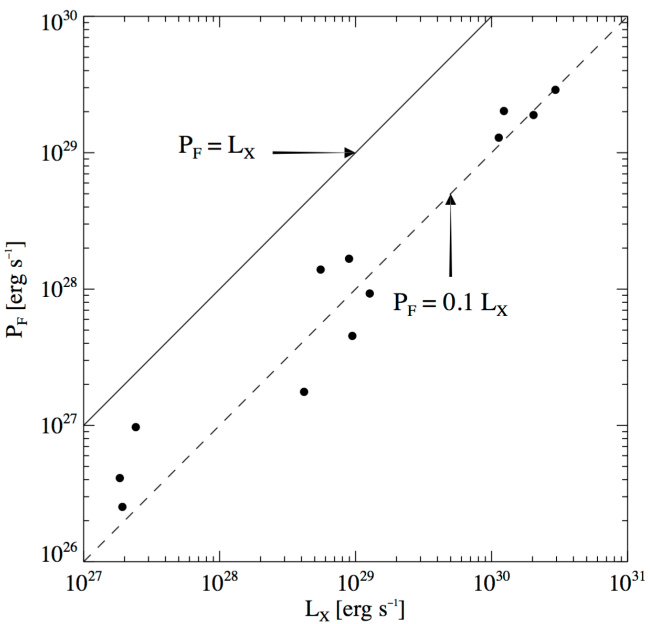


Silverberg et al. 2016, Davenport et al. 2014, Hawley et al. 2014

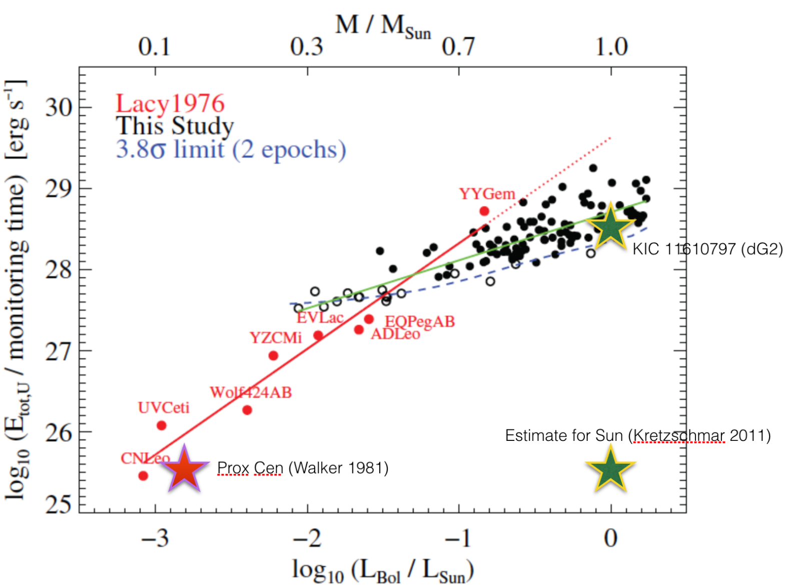
FLARE STATISTICS (BRIEFLY)

- Average flare energy and flare energy release rate is correlated with quiescent luminosity (bolometric and band-specific)…. for saturated-activity stars only?

Total flare energy / total monitoring time



X-rays (XMM-Newton): Audard et al. 2000



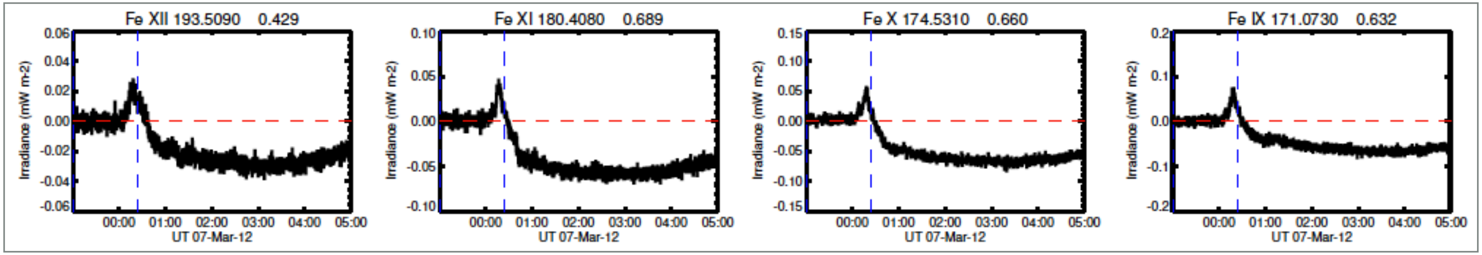
U-band: Lacy et al. 1976, Osten et al. 2012

STELLAR CMES (?)

- 25% of excess non potential magnetic energy released as coronal mass ejection (80% of total event energy); Emslie+2012

- Not all X-class solar flares produce coronal mass ejections (October 2014 X-class flares NOAA 12192; Thalmann+2015)

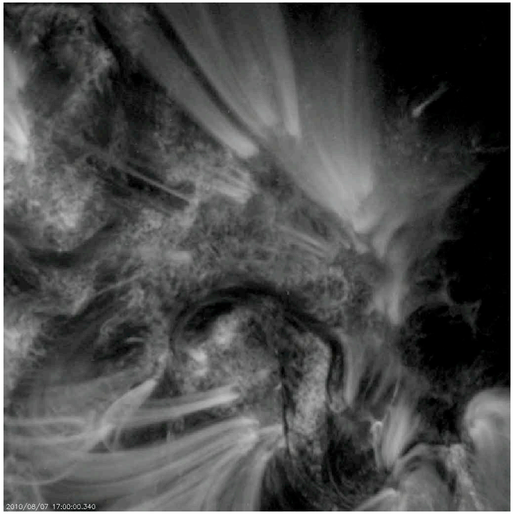
- How to detect CME's from other stars: Ambient coronal (1-2 MK) emission line dimming (Harra+2016), type II radio bursts (Crosley+2016)



Harra et al. 2016

THANKS!

- On behalf of Profs. Longcope, Qiu, Chen, I thank you for the opportunity to teach you about the exciting physics of flares and CMEs!
- Thanks to Profs. Longcope, Qiu, and Chen for all their hard work in pulling this together!
- Thanks to Prof. Cranmer for hosting the video lectures on his website!
- Thanks to Prof. Toomre for the use of the LCD for holding the lectures at CU!



THANKS!

- On behalf of Profs. Longcope, Qiu, Chen, I thank you for the opportunity to teach you about the exciting physics of flares and CMEs!
- Thanks to Profs. Longcope, Qiu, and Chen for all their hard work in pulling this together!
- Thanks to Prof. Cranmer for hosting the video lectures on his website!
- Thanks to Prof. Toomre for the use of the LCD for holding the lectures at CU!