Recent Observations and Modeling of Flares on dMe Stars

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Solar and Stellar Flares,
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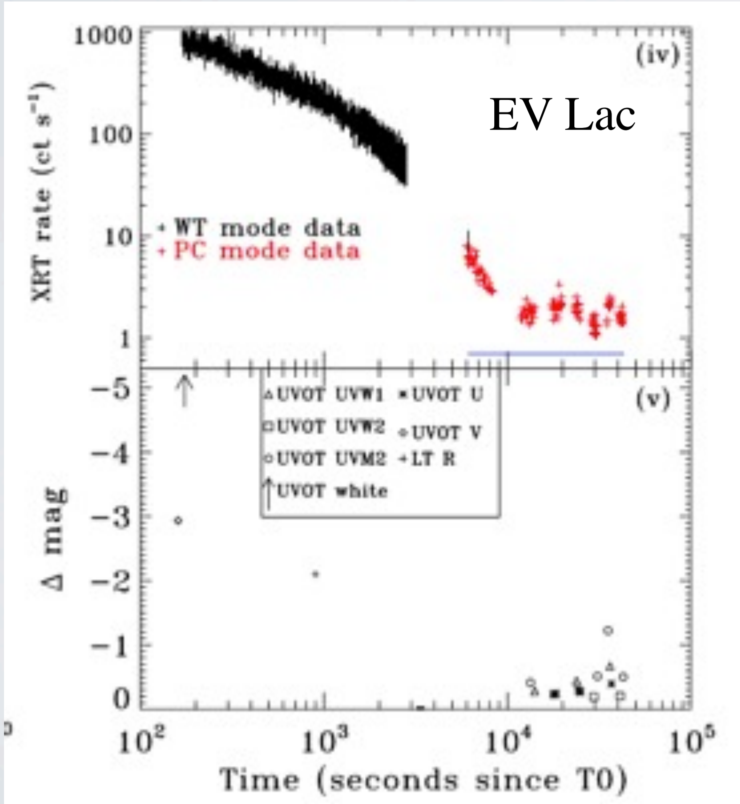
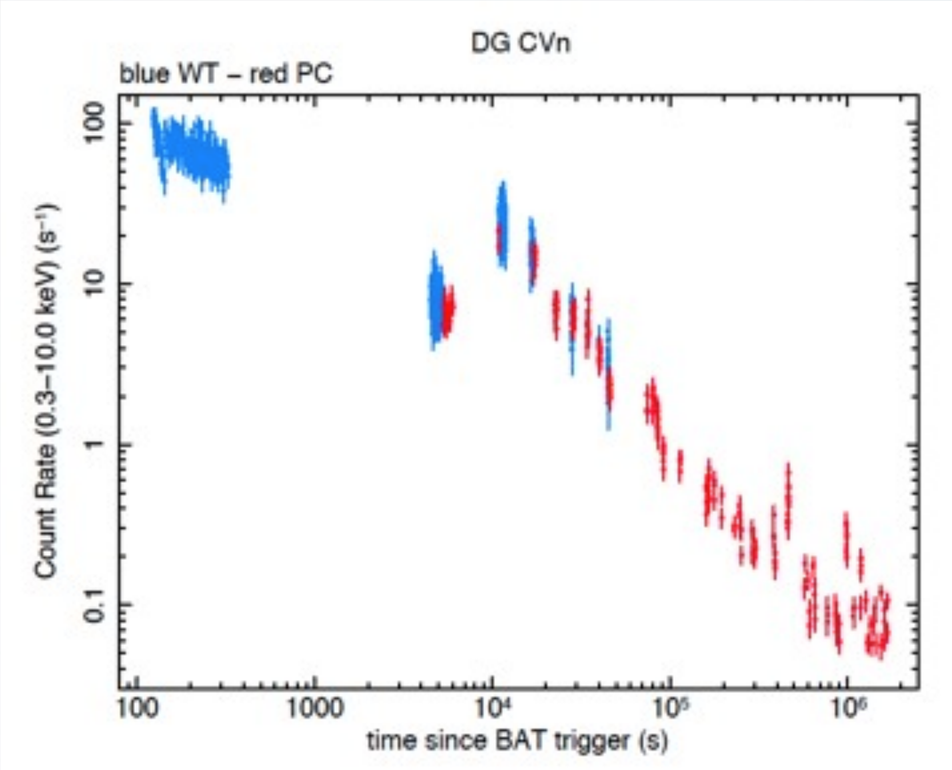
Concept art courtesy G. Bacon (STScI)

Hard X-ray observations of super-bolometric flares

Swift Burst Alert Telescope sometimes triggered by nearby stellar flares



Osten et al. 2010



ATEL #6121; Kowalski, Drake, Osten et al in prep

Outline

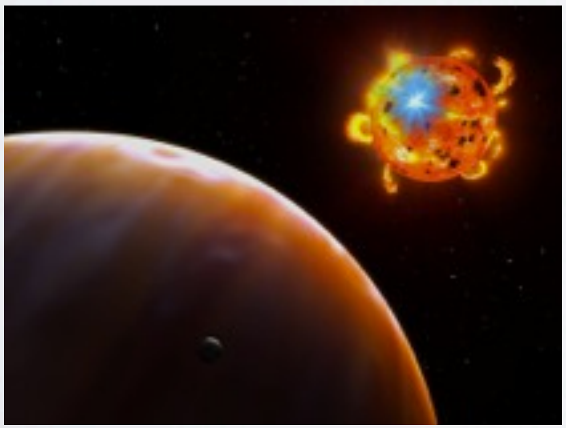
✦ observational constraints from blue/optical spectra around the Balmer jump (3646Å)

✦ new results from radiative-hydrodynamic (RHD) models of flares

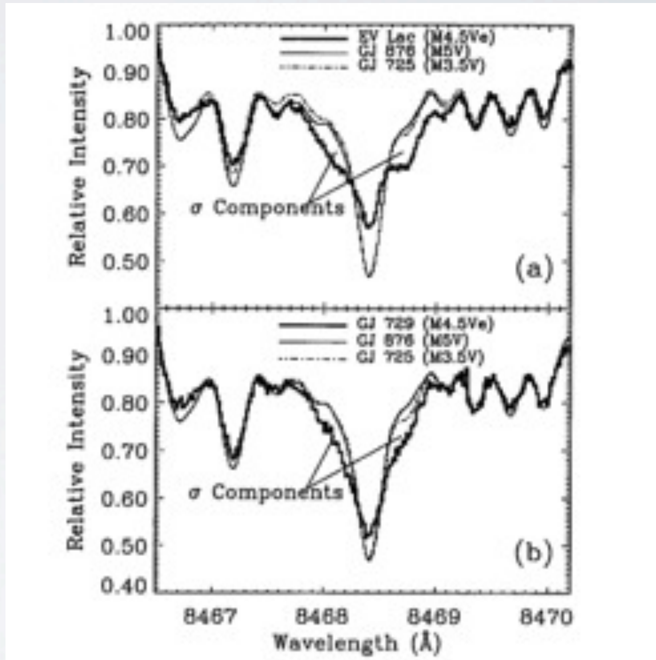
- results from high beam flux simulations
- non-ideal opacities around the Balmer jump

M dwarf (dM) Stars

-- 1/3 R_{Sun} ;1/3 M_{Sun}
-- T_{eff} ~ 2200-3800 K
-- 1/100 L_{Sun}
-- 70% of stars
-- P_{rot} < 3 days
-- dM**e** => H-alpha emission in quiescence ("active")
-- rate of 10^{32} erg flares ~2x / day



-- very strong photospheric magnetic fields: 4 kG, 50% of surface

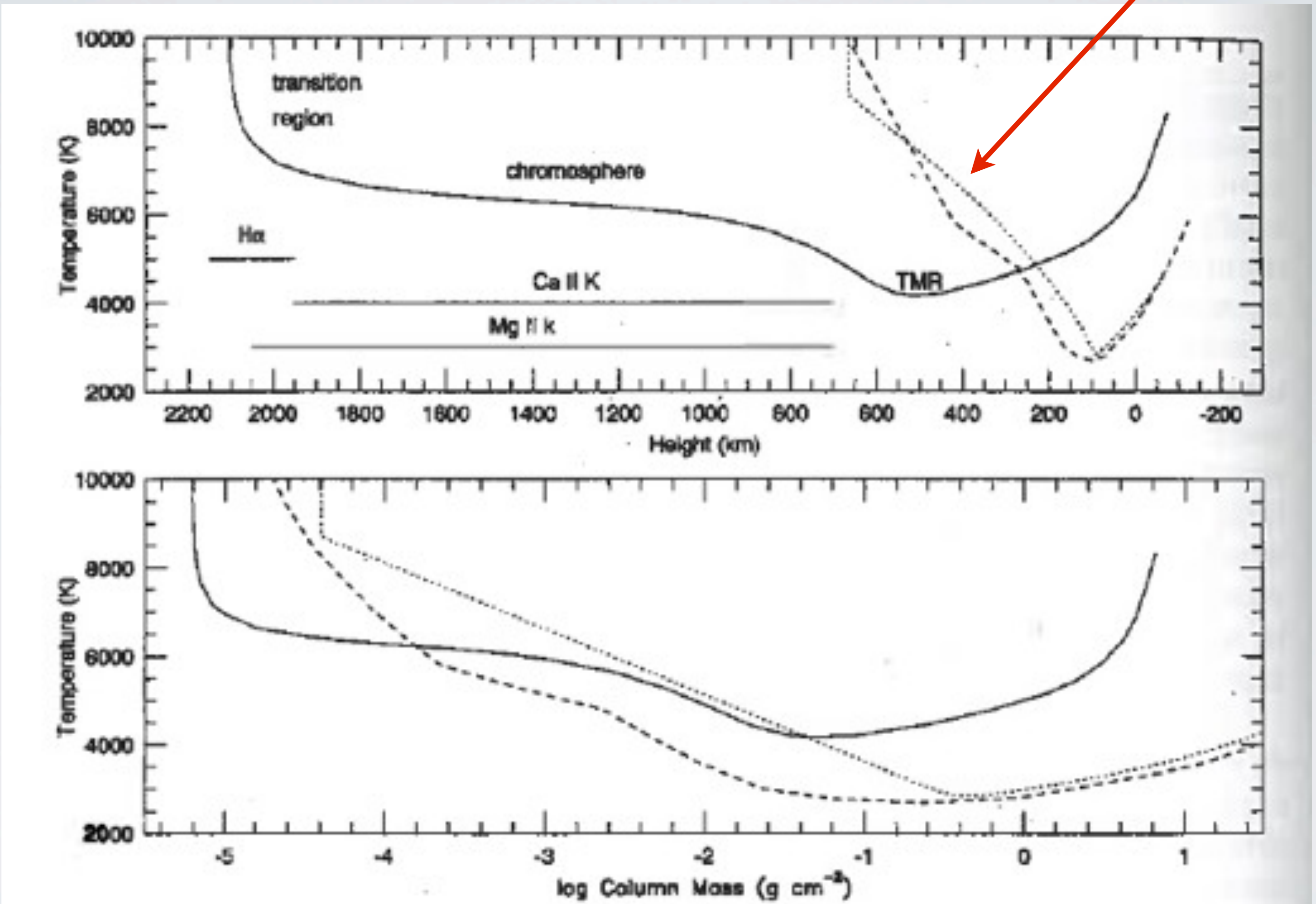


Johns-Krull & Valenti 1996
Saar & Linsky 1985

M Dwarf Atmospheres (semi-empirical models)

gravity = 2 - 3.5 x solar gravity

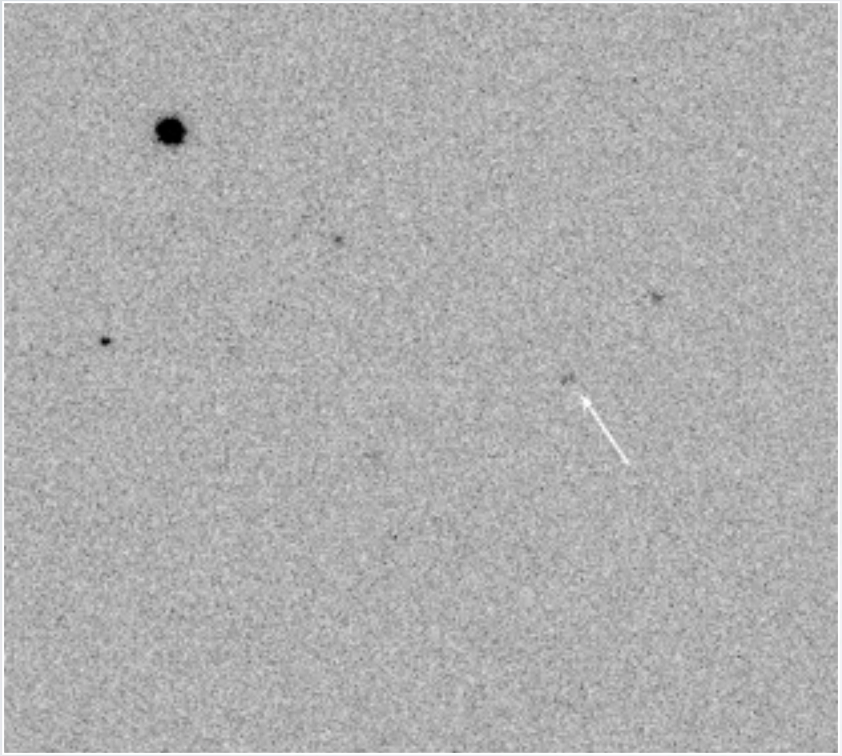
M dwarf



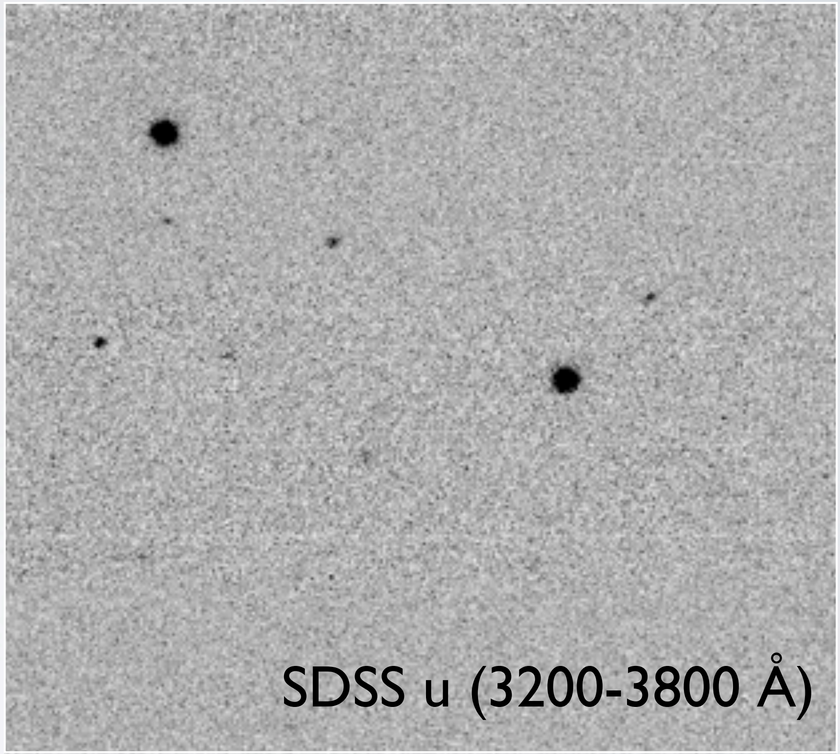
Reid and Hawley (1995)

White-light flares on nearby active M dwarfs (dMe)

Red dwarf flares are very conspicuous in blue light



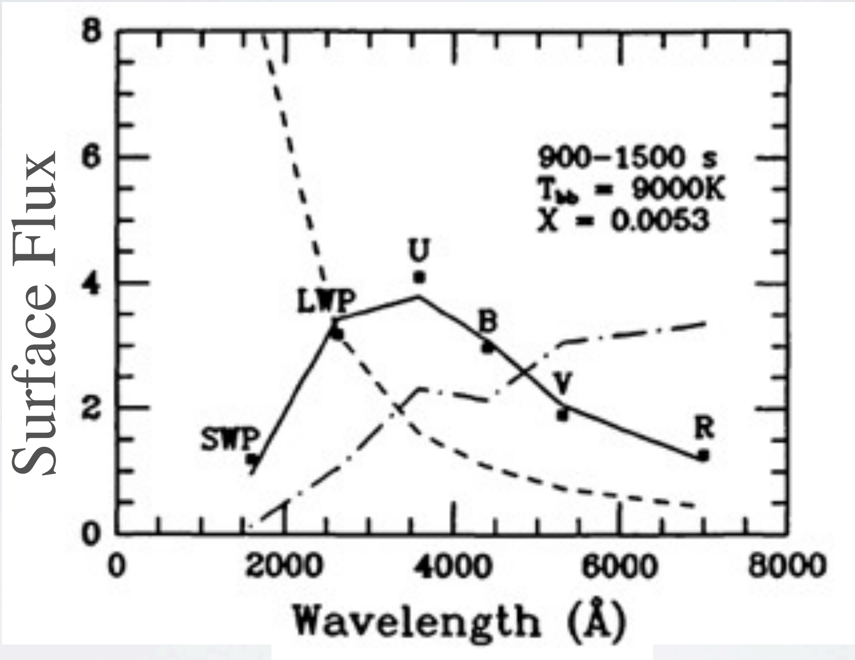
Quiescence



Flaring

Sloan Digital Sky Survey Stripe 82

White-light continuum (from photometry) fits to ~9,000-10,000K blackbody, compact area



Hawley & Fisher (1992), Hawley & Pettersen (1991)

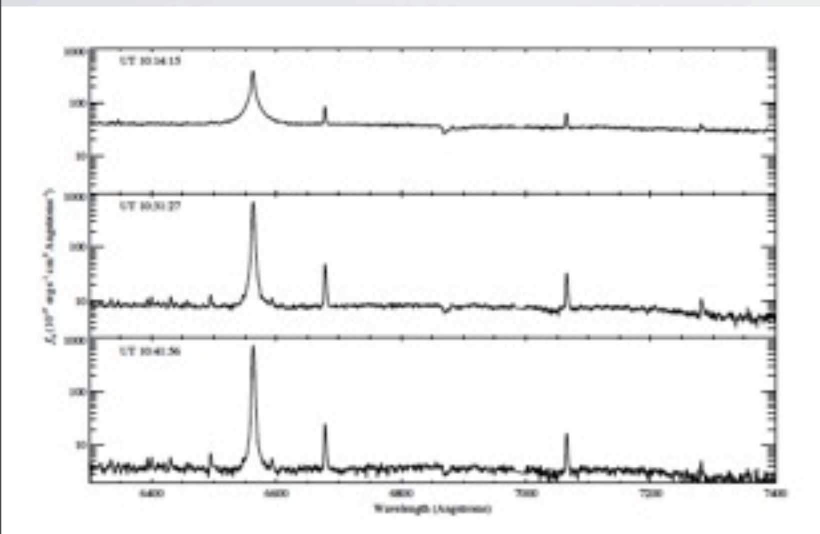
T_{bb}=9000K
900-1500s
X < 1%

- Continuum energy dominates emission line energy (9:1)

Svestka's Legacy on dMe Flares: Stark broadening

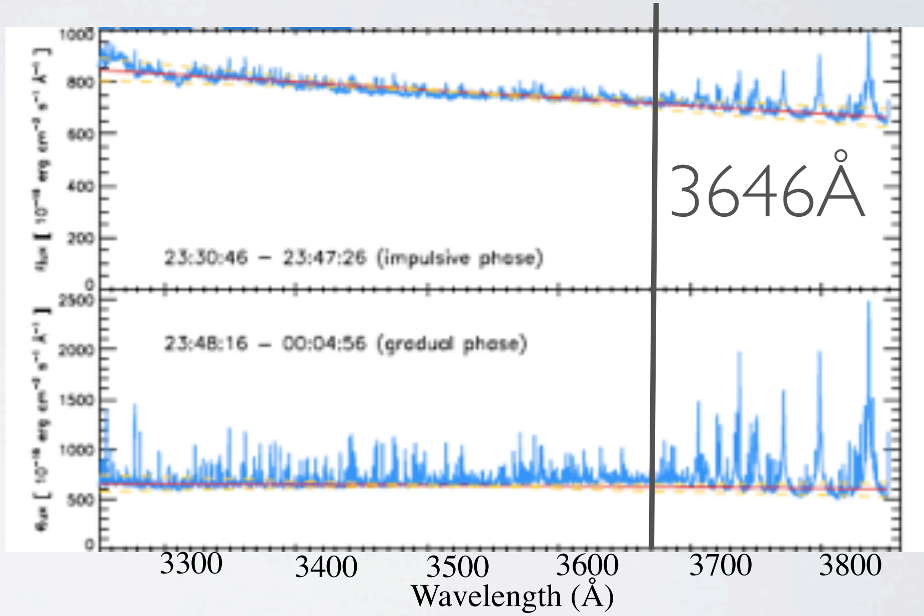
Svestka (1963)

Very broad hydrogen lines (FW of 20Å)



Gizis et al. 2013
(L1 dwarf)

Lack of Balmer discontinuity at 3646Å



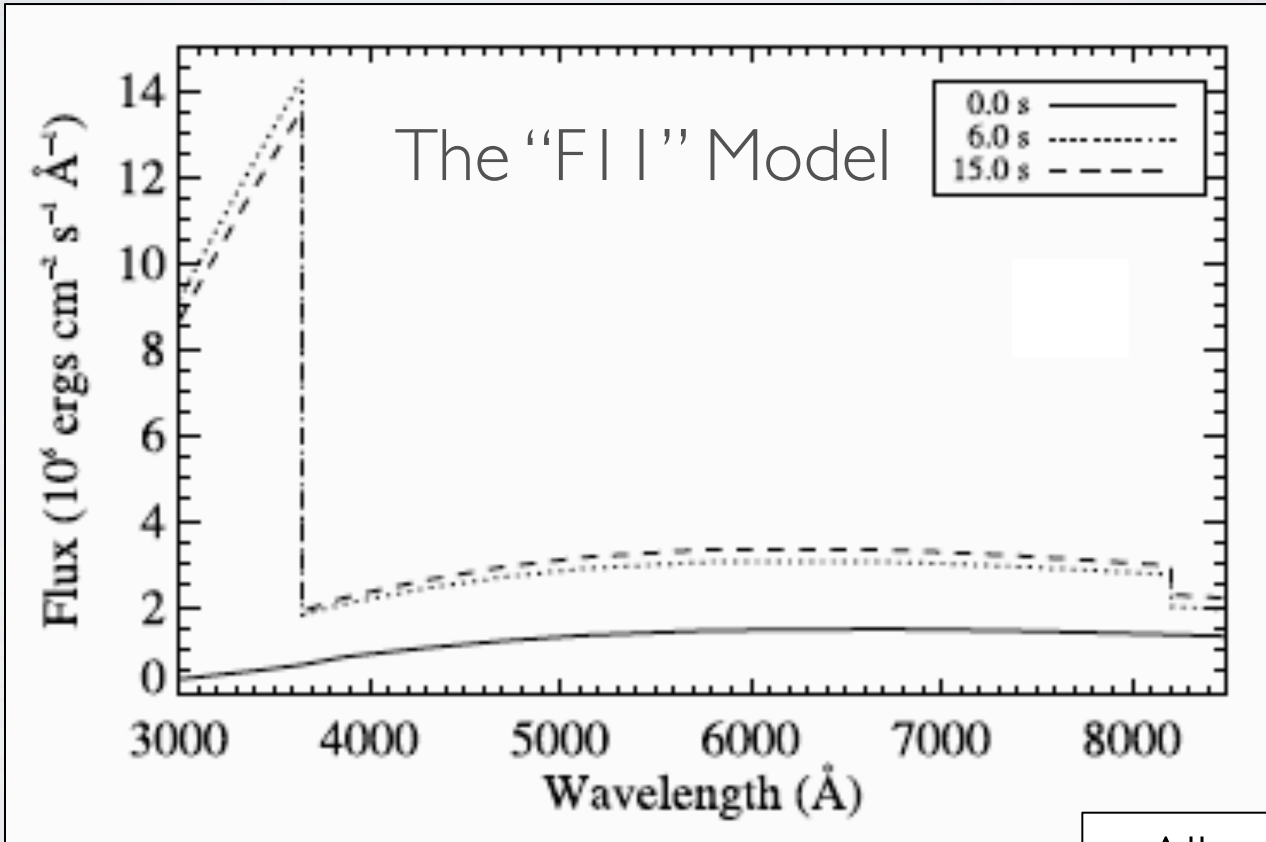
Fuhrmeister et al. 2008

Last observed Balmer line is typically ~H15/16

Stellar Flare Models using RADYN

RADYN: Carlsson & Stein (1994, 1995, 1997)

Model continuum show large Balmer discontinuity

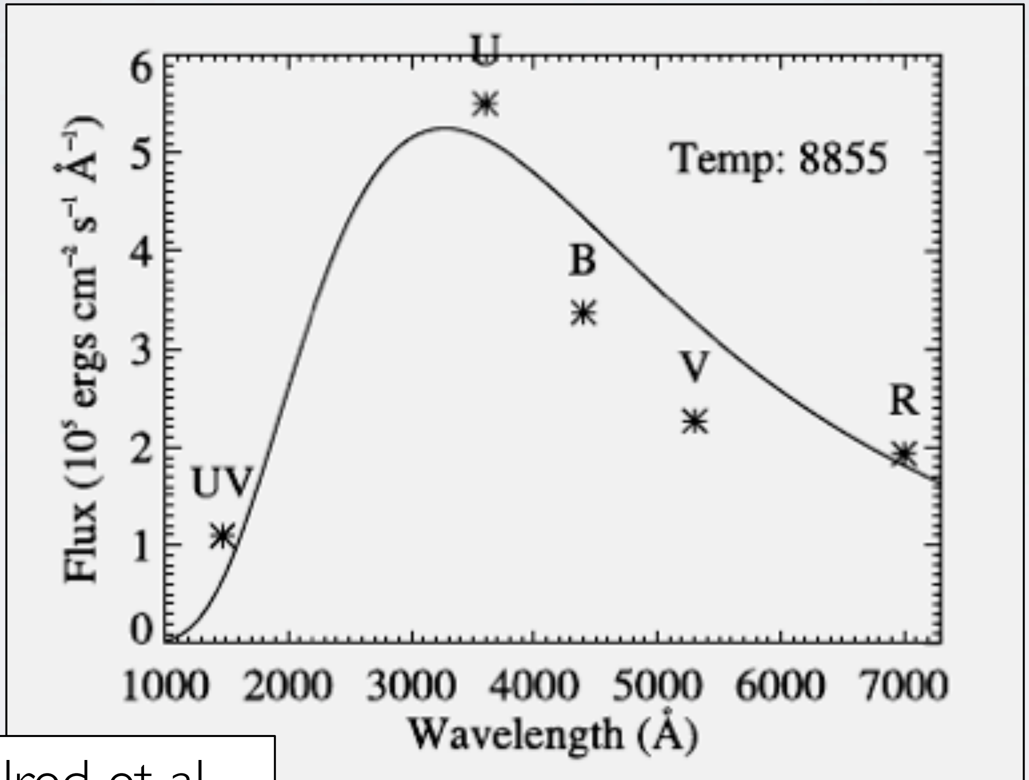


Allred et al. 2006

F11 e- beam (10^{11} ergs s^{-1} cm^{-2})
parameters from Holman et al. (2003)

Model Spectrum Convolved with Broadband Filters

NEED SPECTRA!

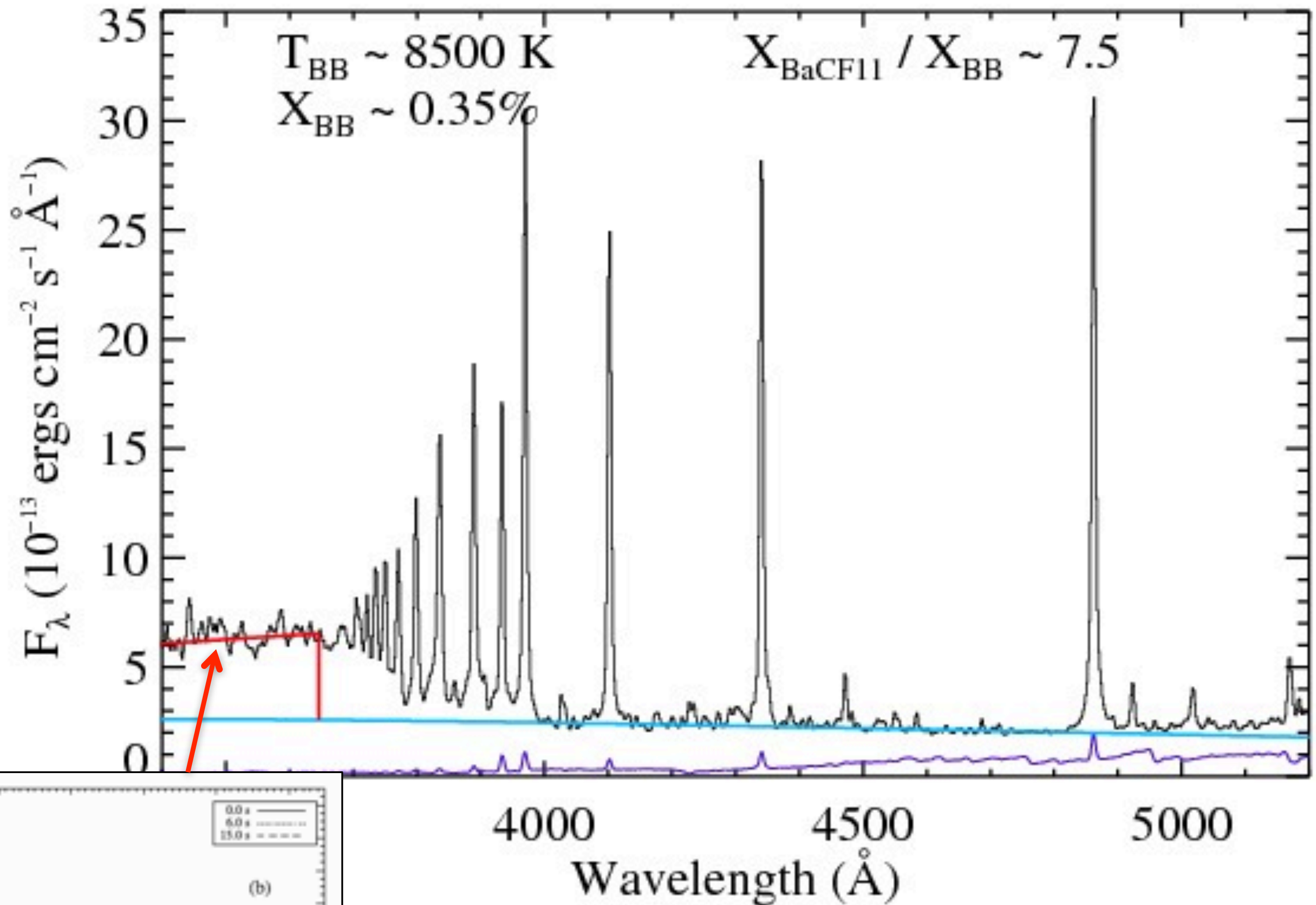


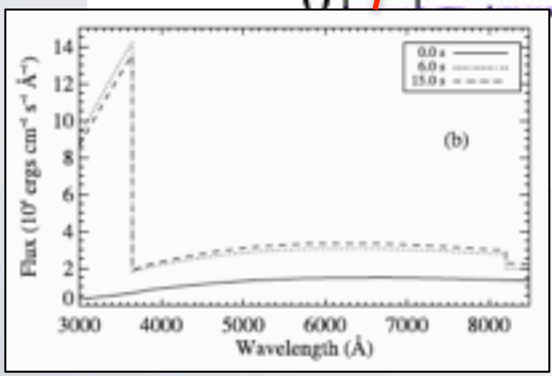
Allred et al. 2006

The Flare Atlas (Kowalski et al. 2013, *ApJ Supplement*)

- R≈300-800 spectra from ARC 3.5-m at APO, 1.8-m at DAO
- Full spectral coverage: 3400-9200Å
- Exposure times: 1-45 seconds
- Simultaneous U, u, or g photometry from NMSU 1-m or ARCSAT 0.5-m at APO
- *20 flares, 3 previously published in Hawley & Pettersen (1991), Schmidt et al. (2012), Kowalski et al. (2010)*
- *AVAILABLE ONLINE THROUGH VIZIER !*

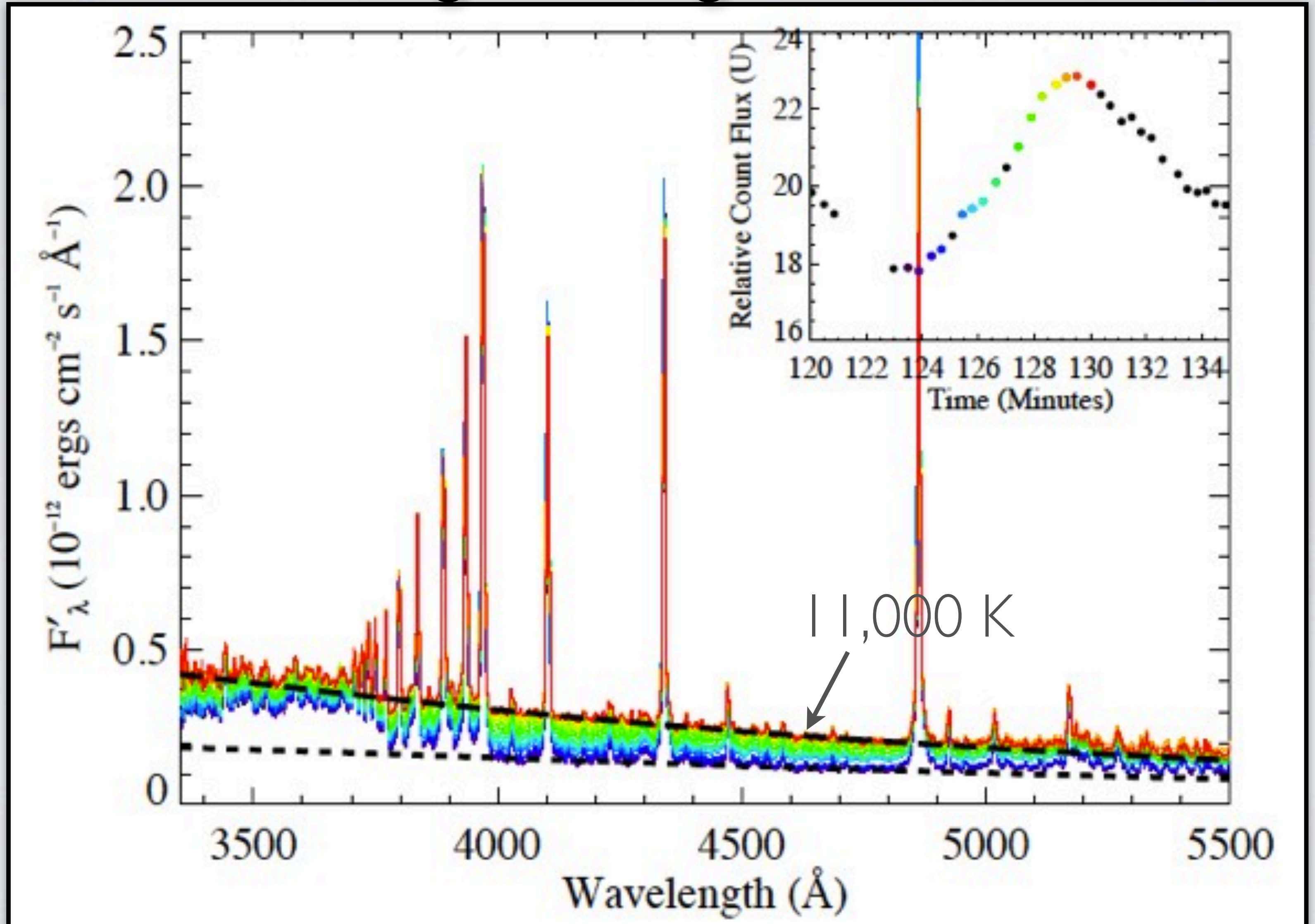
Gradual decay phase shows multiple continua





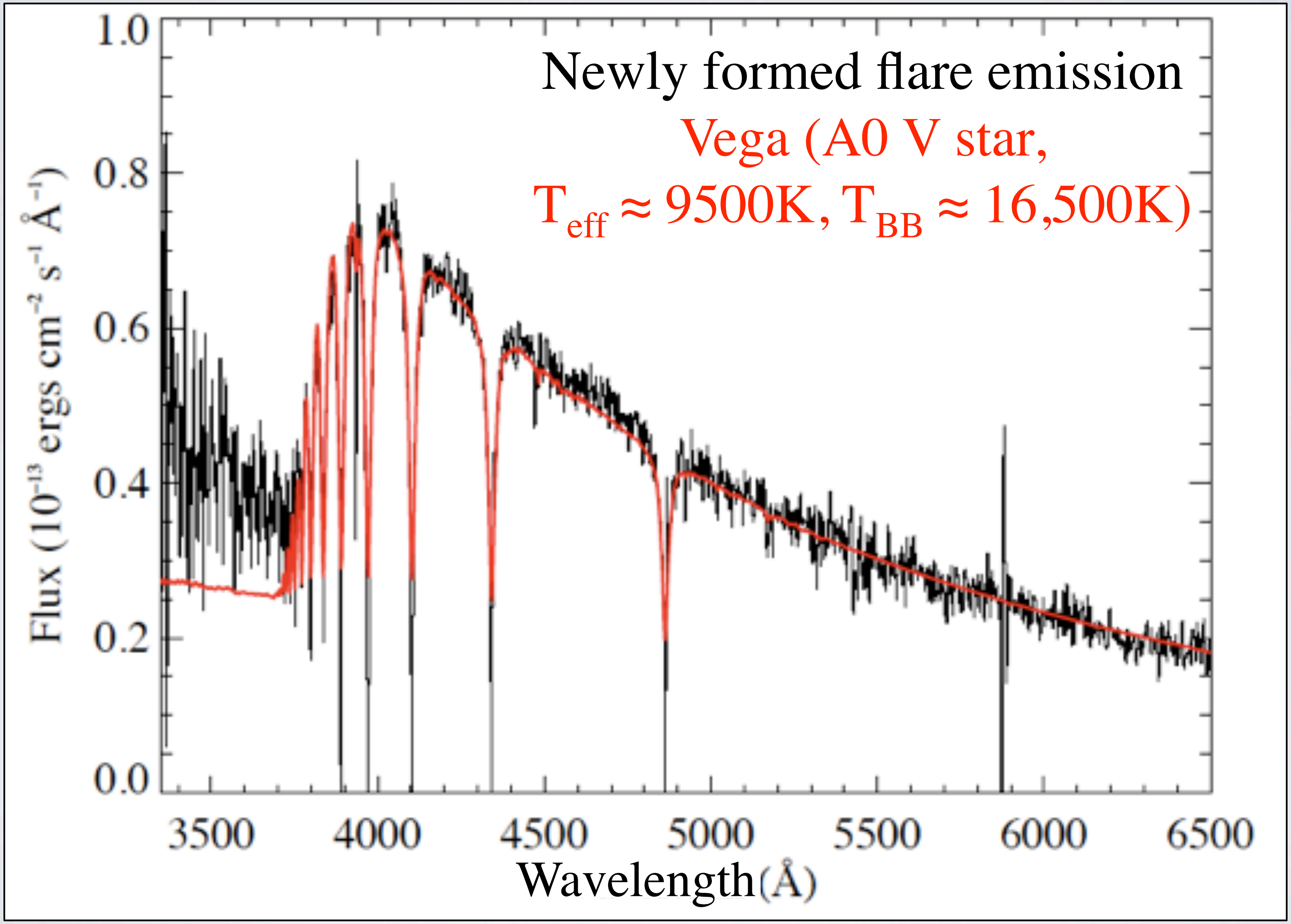
Kowalski et al. 2010, ApJL

Relative amount of each continuum component changes throughout the flare



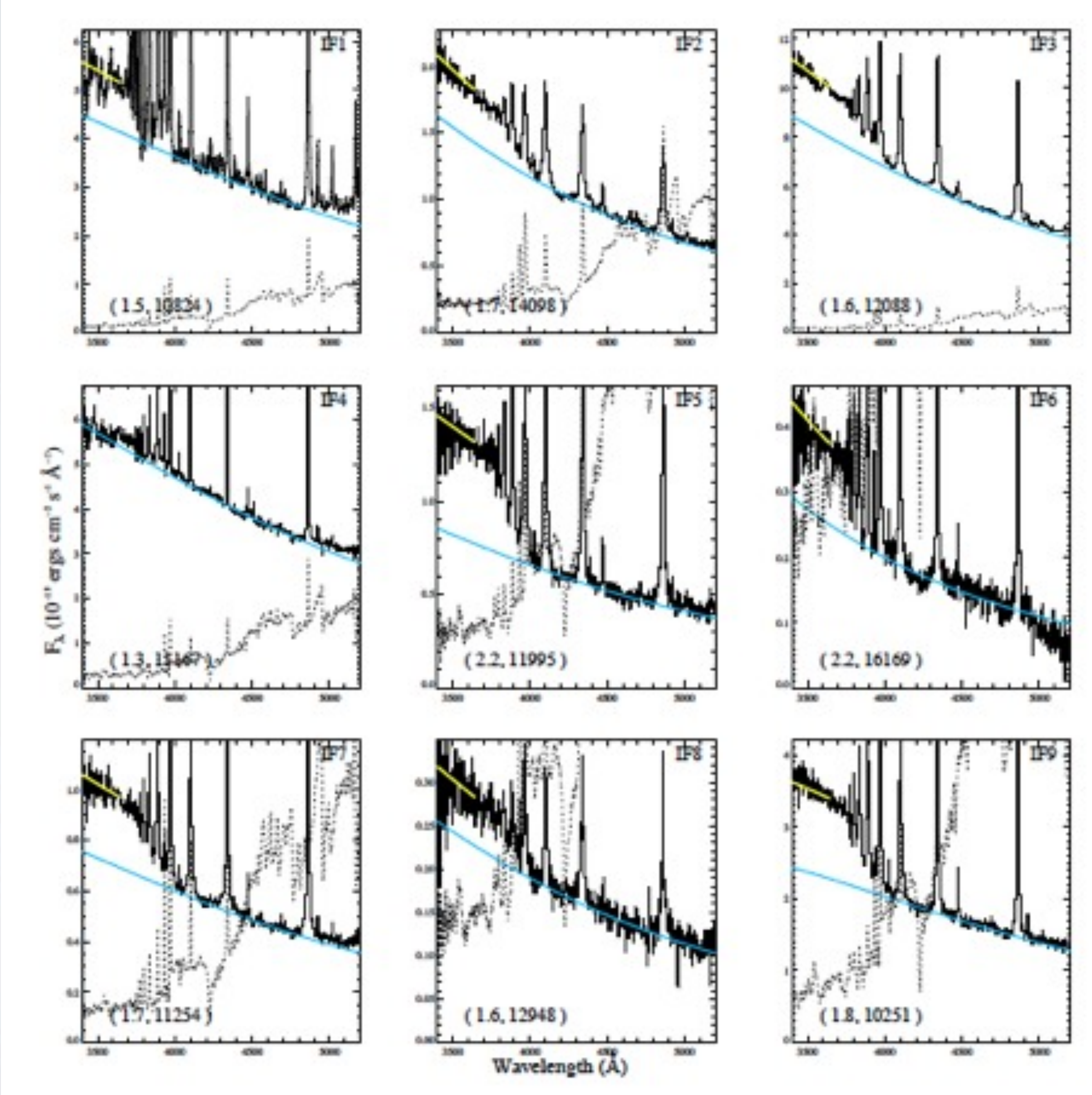
Kowalski et al. 2012

Flare emission is not a perfect blackbody!



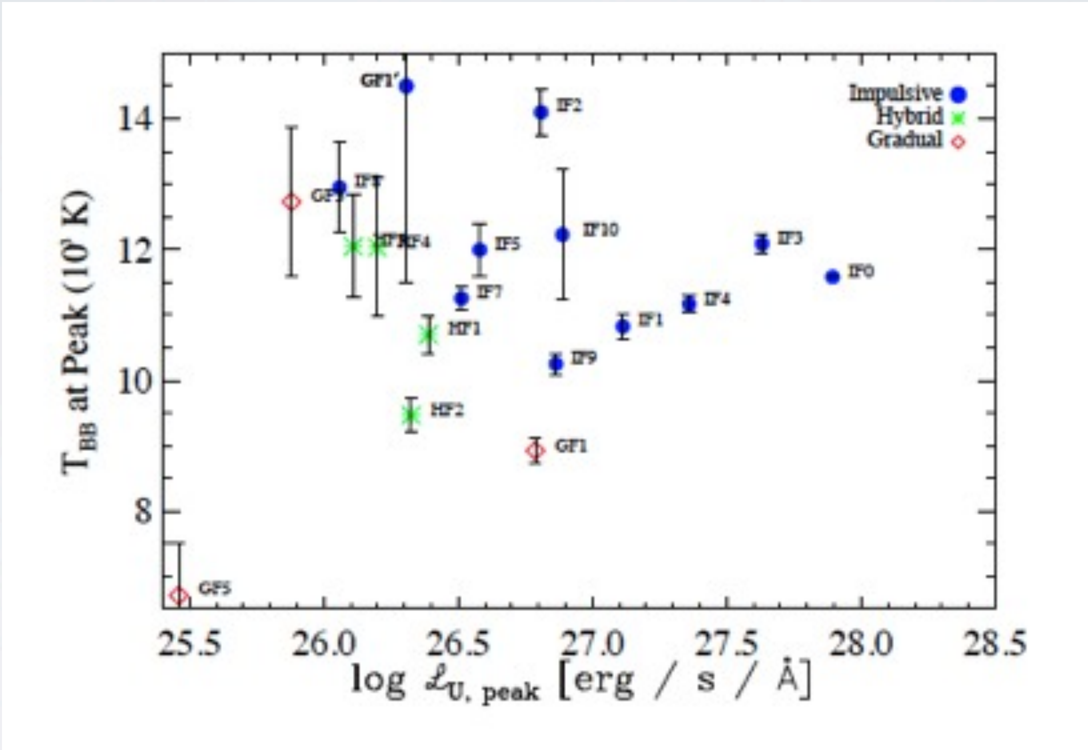
Kowalski et al. 2011, 2013

A Sample of the Flare Atlas
Total (unresolved) flare emission at peak



Color temperature analysis of total flare emission

Peak: T ≈ 10,000 - 12,000 K from **λ**=4000-4800Å

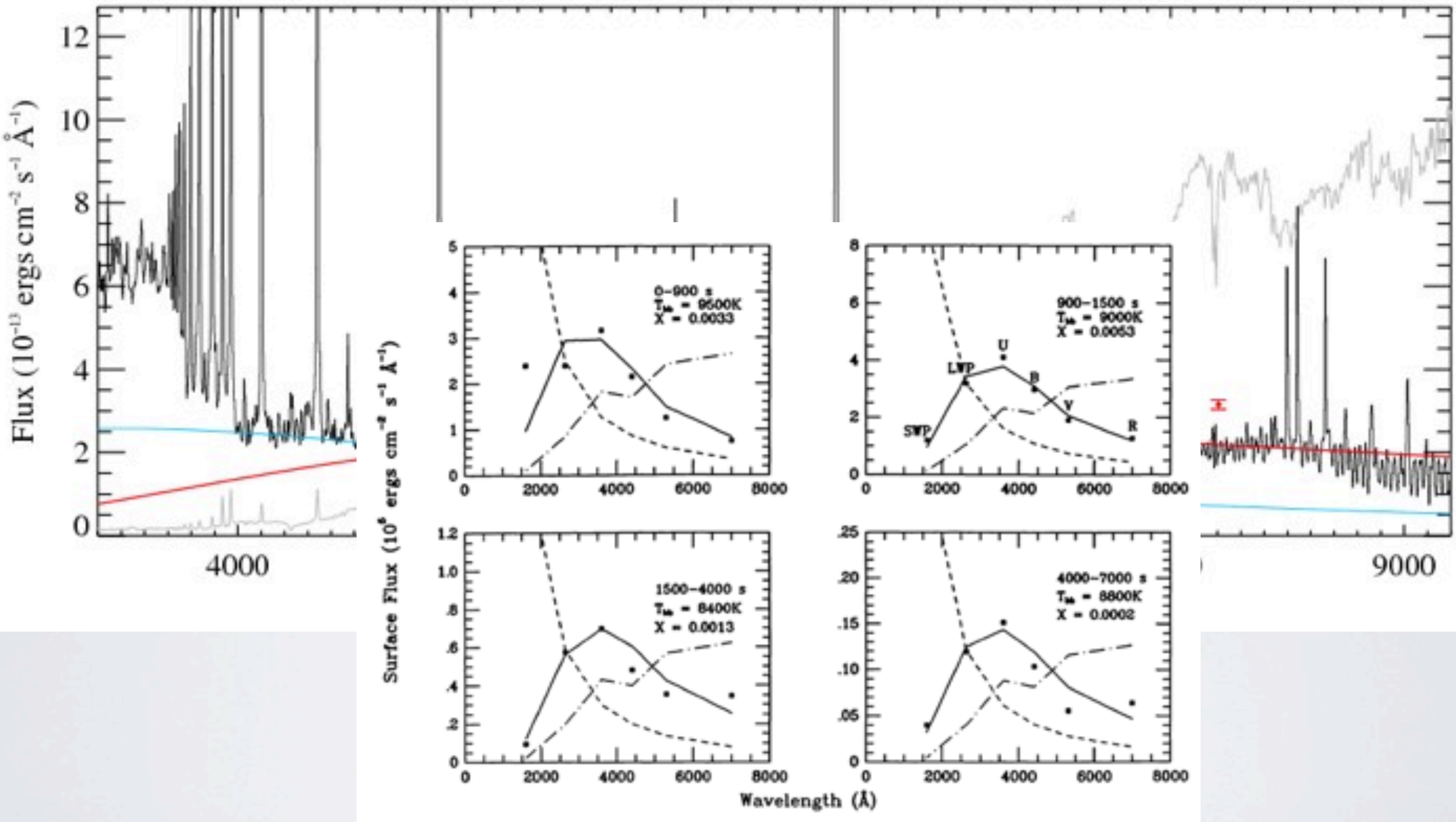


Systematic temperature uncertainty 500-1000 K

Gradual decay phase: T ≈ 8000 K from **λ**=4000-4800Å

Kowalski et al. 2013

Continuum in the red/optical (gradual decay)

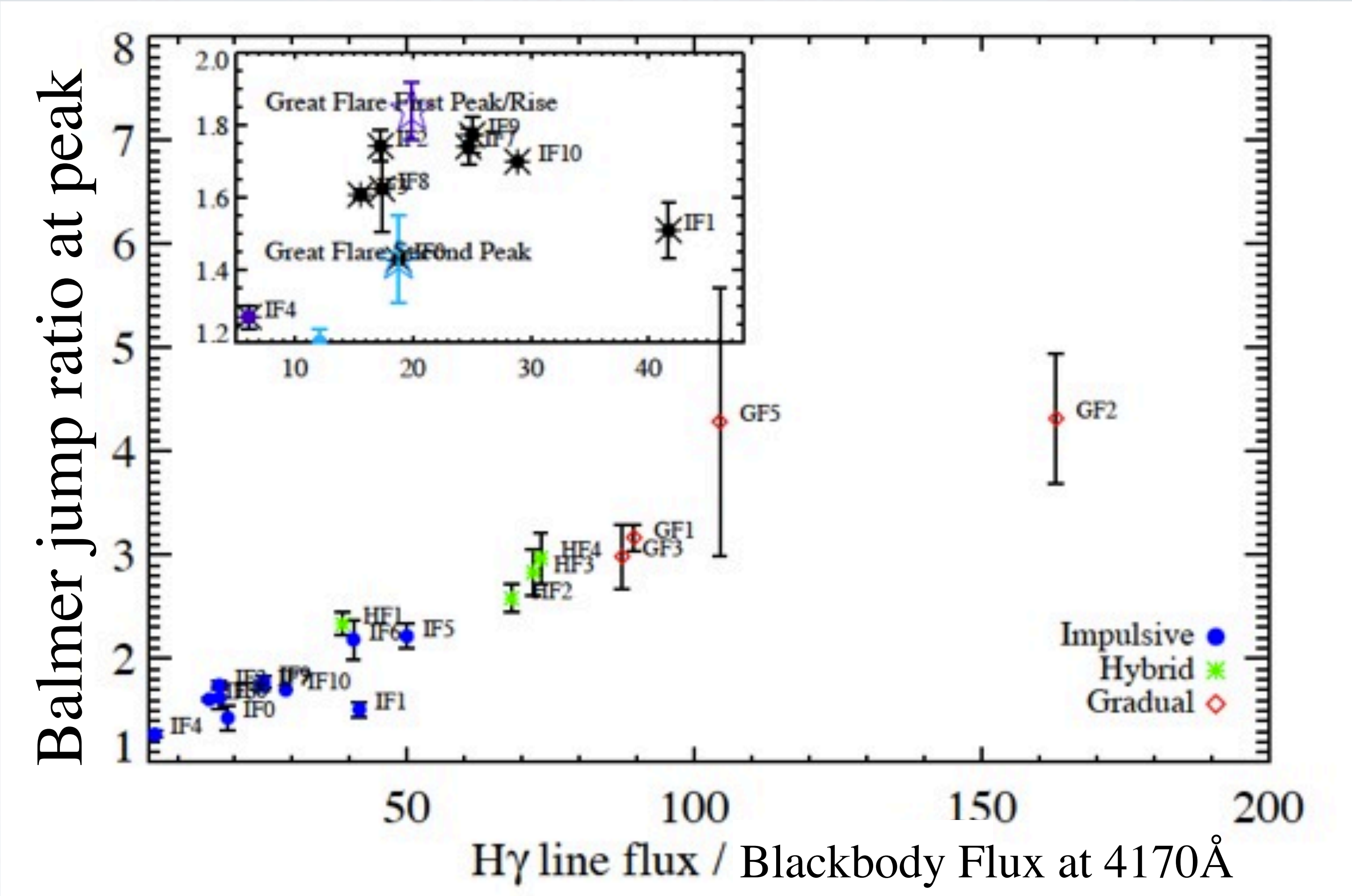


Hawley & Fisher 1992

A Red Conundrum!

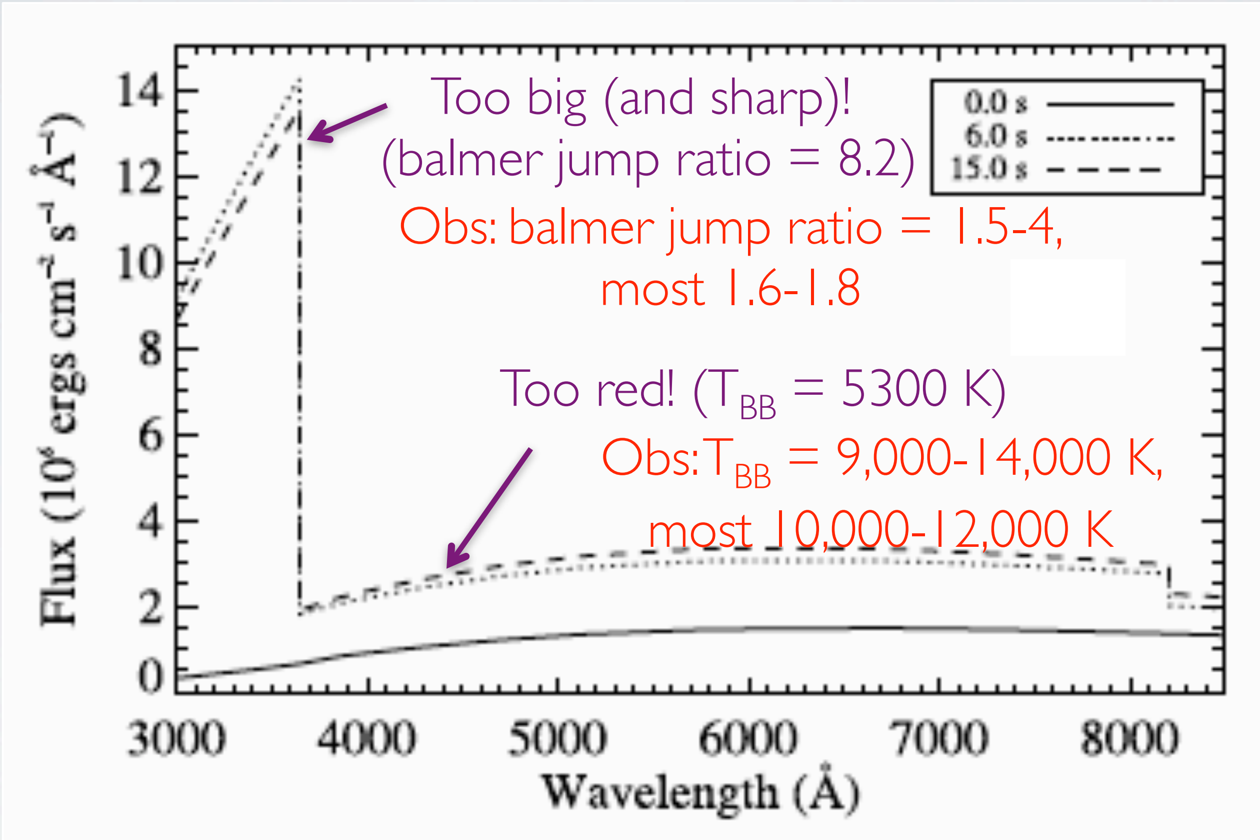
Balmer jump in emission in most flares

Balmer jump ratio at peak: 1.5 - 3.5



Kowalski et al. 2013

Stellar Flare Impulsive Phase Models using RADYN



Allred et al. 2006

F11 e- beam (10^{11} ergs s^{-1} cm^{-2})
"Solar-type" – parameters from RHESSI

Radiative Hydrodynamic Modeling with the RADYN code

with Mats Carlsson (University of Oslo), Joel Allred (GSFC)

RADYN: Carlsson & Stein (1994, 1995, 1997, 2002)

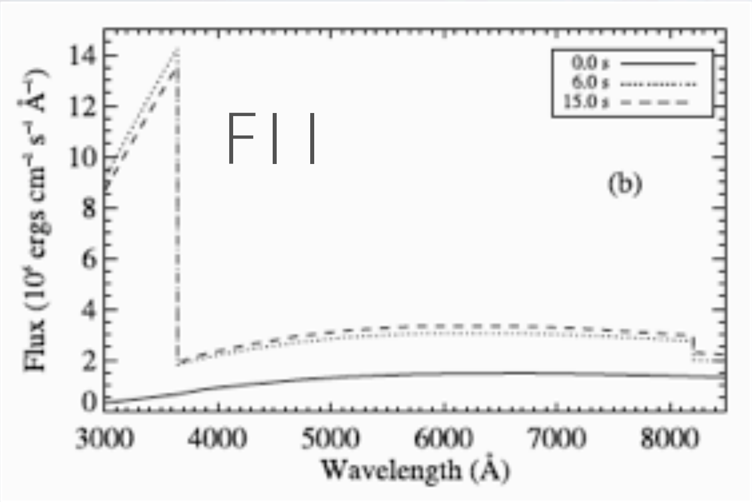
RADYN Flare code: Hawley & Fisher 1994, Abbett & Hawley 1999, Allred et al. 2005, Allred et al. 2014 in prep

- 1D adaptive grid to resolve shocks
- Detailed radiative transfer for H, He, and Ca
- "Catch-all" optically thin radiative losses
- X-ray backwarming from corona
- Non-thermal electron beam energy deposition
  -- analytic formulae from Emslie (1978)
  -- Fokker-Planck solution
  (McTiernan & Petrosian 1990, Allred et al. 2014)
  -- nonthermal ionization and excitation rates of H and He
- A relaxed M dwarf starting atmosphere (Teff = 3600 K)

The RADYN M Dwarf Flare Model Grid

Using high electron beam fluxes: the F13 model aka "the sledgehammer approach"!

Kowalski et al. 2014 in prep



×100 =

?

F9-F12
(F11 = 10^{11} ergs s^{-1} cm^{-2})
"Solar-type" – parameters from RHESSI

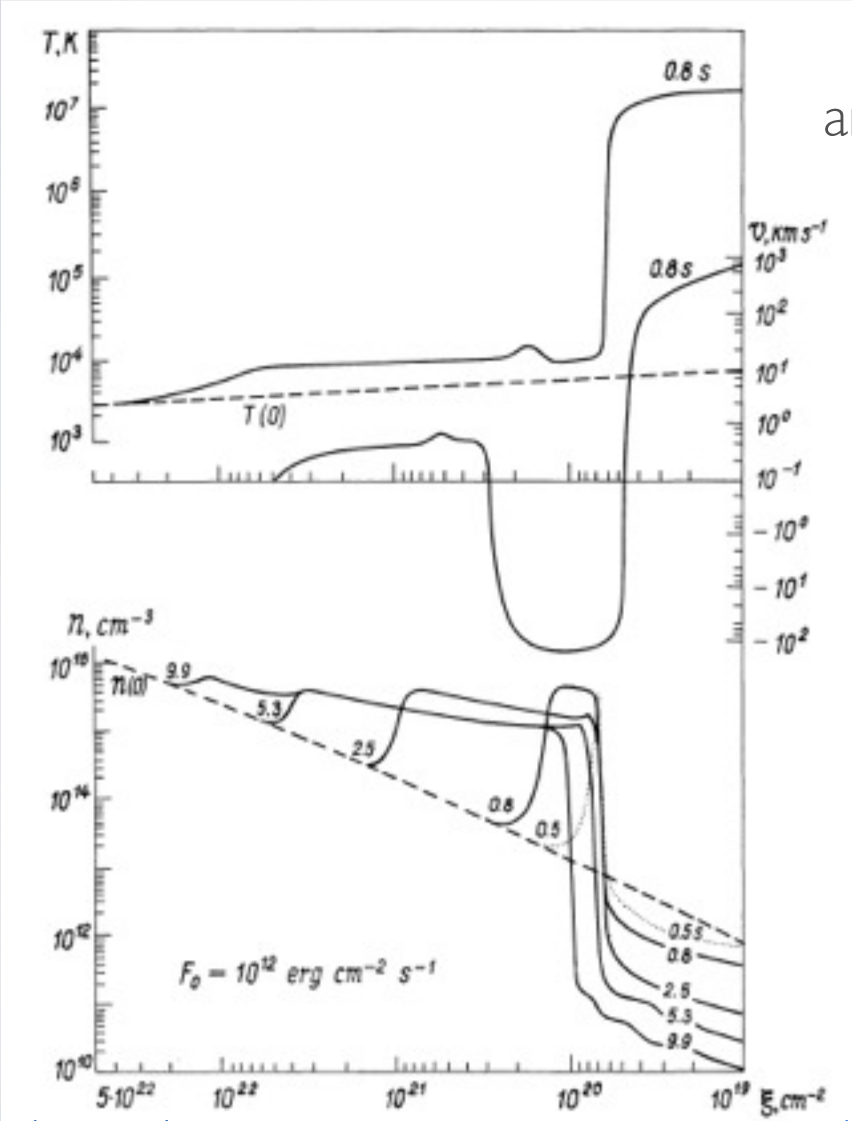
F13 e- beam
(10^{13} ergs s^{-1} cm^{-2})

The F13 Stellar Flare Model Atmosphere

At just over 2 seconds....

1.) a 10 MK temperature "bubble" has formed at the region of maximum initial beam energy deposition (upper chromosphere)
2.) shocks formed in the atmosphere when He III forms
3.) thermal pressure from lower shock generates a 50 km/s heated (12,000 K) compression wave with high density ($\sim 5 \times 10^{15}$ cm^{-3})
4.) optical depth at optical/NUV λ increases > 1 in the compression
5.) the "flare photosphere" is now ~250 km higher than the quiescent photosphere
6.) These atmospheric conditions are very similar to the F12 gasdynamic simulation of a dMe flare from Livshits et al. (1981), and the "chromospheric condensation" phenomenon of Fisher et al. (1985, 1989)

Gas-dynamic models predicted 100 km/s "chromospheric condensations" that are optically thick in the optical continuum!



photosphere

outer atmosphere

Livshits et al. 1981

Why get so complicated?

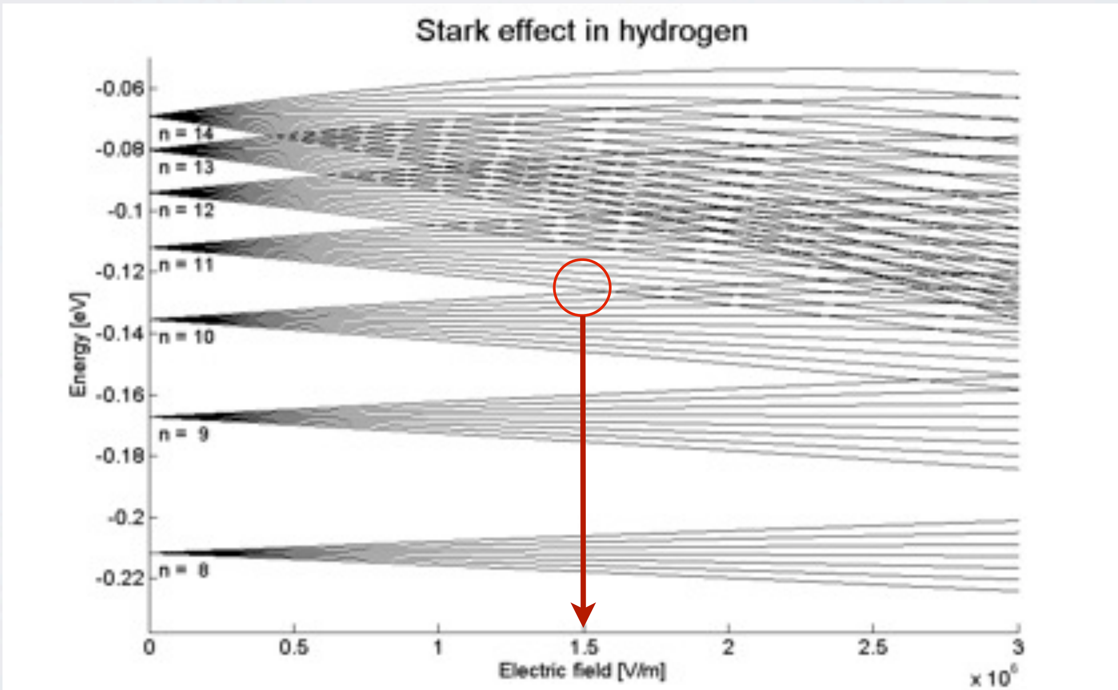
1. Better understanding of the electron beam (from RHESSI)
2. Must account for ionization of Helium
3. Need a (detailed) model spectrum to understand Balmer jump
4. Need to understand *range* of observations

Non-ideal opacities at the Balmer Jump

Hummer & Mihalas 1988, Dappen et al. 1987

Widely used and developed by the hot star community, e.g., Hubeny, Hummer, & Lanz 1994, Tremblay et al. 2009

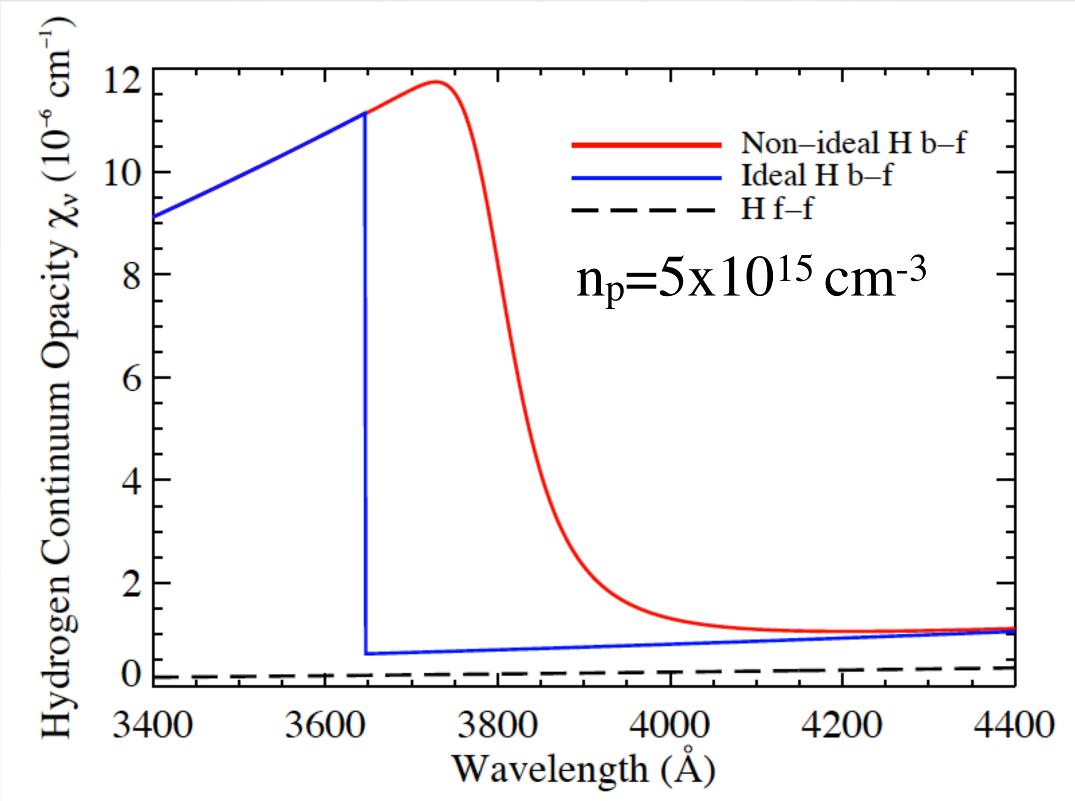
Level crossings (of n and n+1) lead to enhanced ionization rates



critical field strength for n = 10

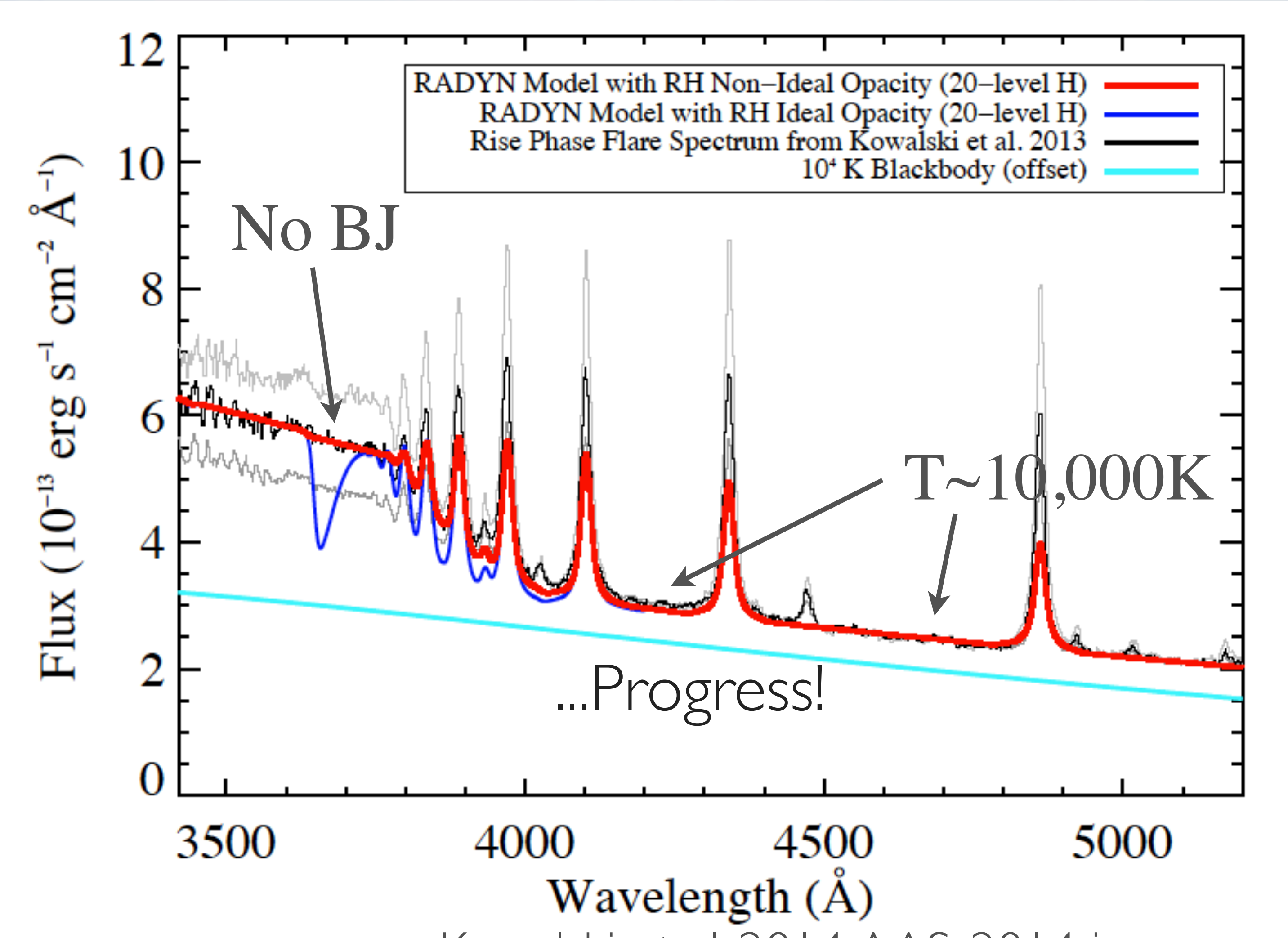
Modify continuum and line opacities to account for pressure ionization from the Stark effect

Dappen et al. 1987, Hubeny et al. 1994



Take a snapshot from *RADYN* simulation, put into static *RH* code with n=20 hydrogen and modified opacities (Uitenbroek 2001)

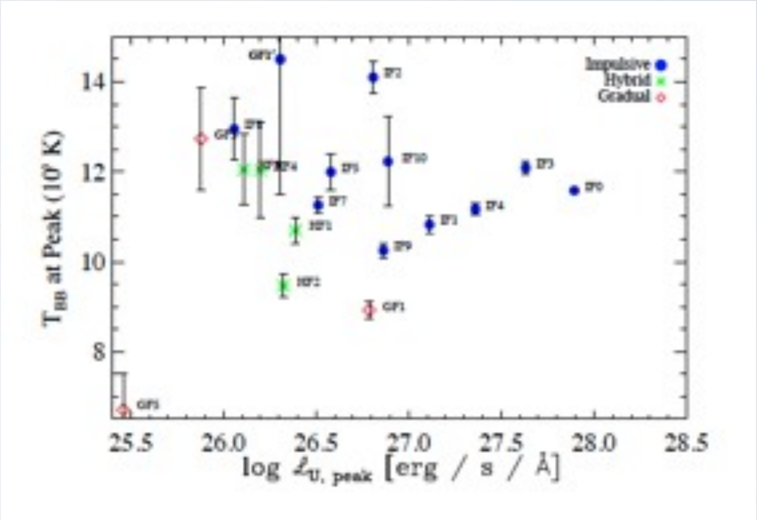
Our first flare model to produce 10,000 K blackbody-like spectrum self-consistently (with no Balmer discontinuity)



Kowalski et al. 2014 AAS, 2014 in prep

The origin of 10,000 K blackbody-like spectrum

A heated compression wave (aka "chromospheric condensation") with enough density / large opacities



✷ hot blackbody spectrum =

hydrogen recombination radiation from larger height range for more optically thin wavelengths:

e.g., $\Delta z \sim 0.5$ km at 4300 Å

$\Delta z \sim 0.1$ km at 6690 Å

Summary

- Optical and NUV continuum emission in flares show a range of properties

  - *but*, show signatures of hydrogen continuum opacities in all cases
  - *in other words*, dMe flare kernel is NOT a perfect blackbody emitter

- Very dense heated compression wave can generate impulsive phase continuum properties well! (with Balmer jump in "emission")

- Hydrogen opacities modified by Stark ionization important for understanding spectra, while giving new constraint on proton density

- Lots of work to do with modeling: emission line evolution, gradual phase of the continuum emission, return current effects

- Superflares on M dwarfs are promising for searching for a hard X-ray signature

Image credit:HST, NASA, ESA, W. Clarkson (Indiana University and UCLA), and K. Sahu (STScI)