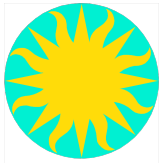

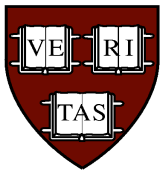

Six Years of Science with
Chandra Symposium
Cambridge, MA
2 Nov 2005

An Episodic Heating Model for Stellar Coronae: Spectral Diagnostics for Non-Equilibrium Ionization

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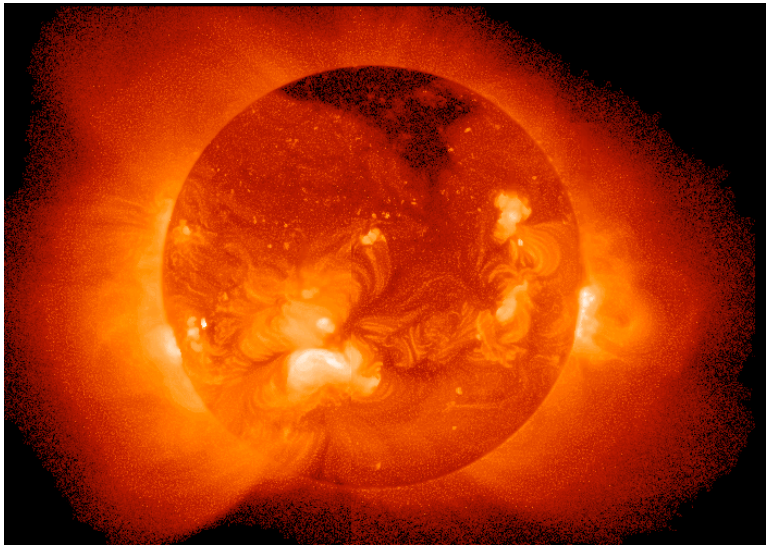
Acknowledgments: Aad van Ballegooijen

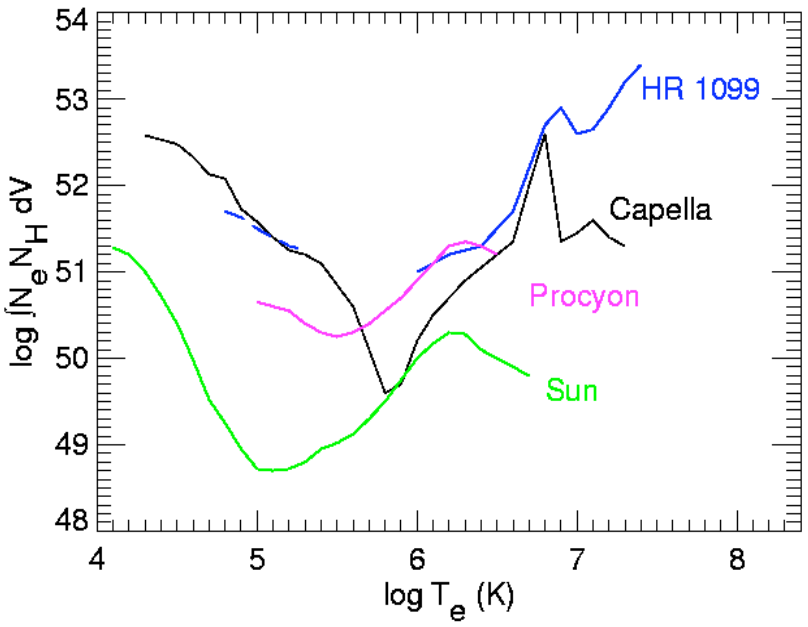
The Structure of Stellar Coronae: Observational Evidence

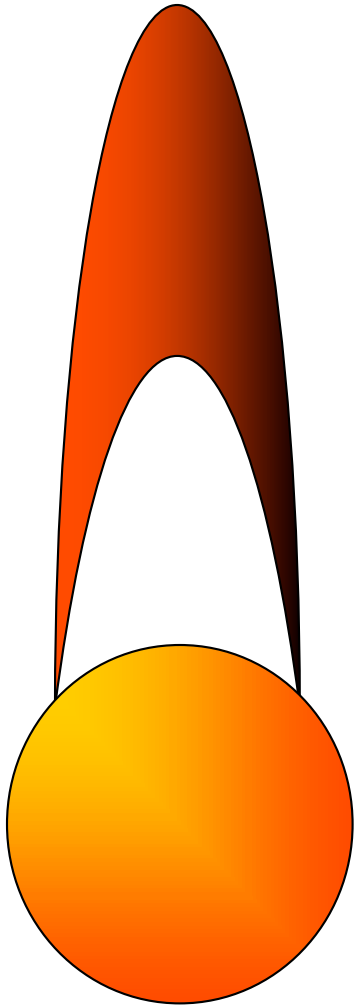
- A diversity of flares in different active stars
- Sharply peaked Emission Measure Distribution
- High N_e (>10^{12} cm^{-3}) at high T_e (10^7 K)
- X-ray/EUV flux ratios anomalously large

Yohkoh Image of the Sun



Coronal Loop Models of the Emission Measure Distribution





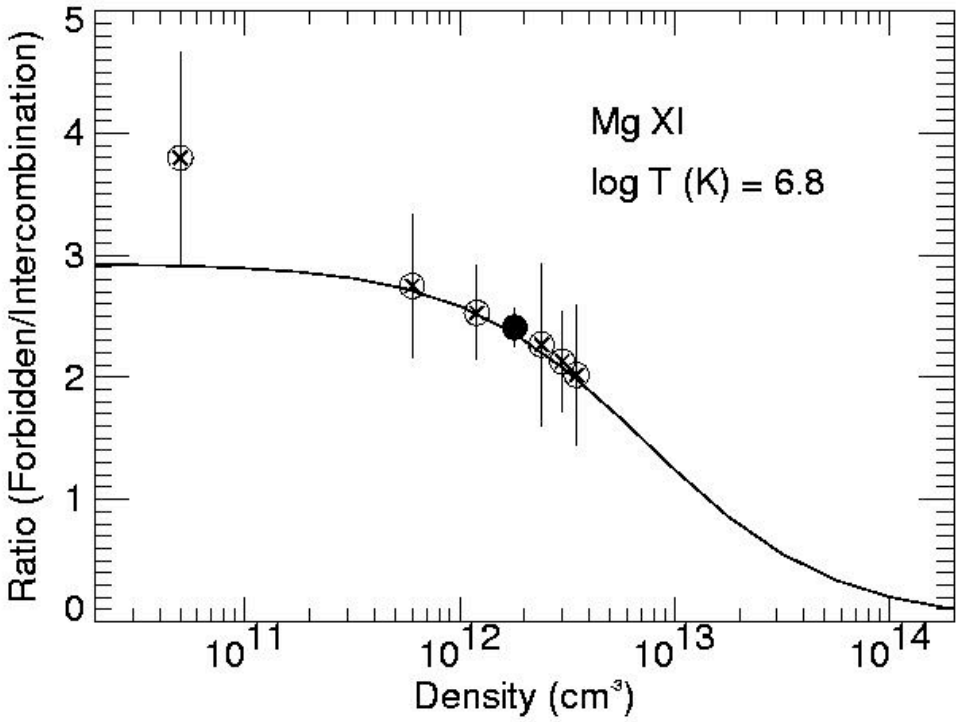
Capella: 2-T_e fits to EXOSAT spectrum required large loops with expanding cross sections.

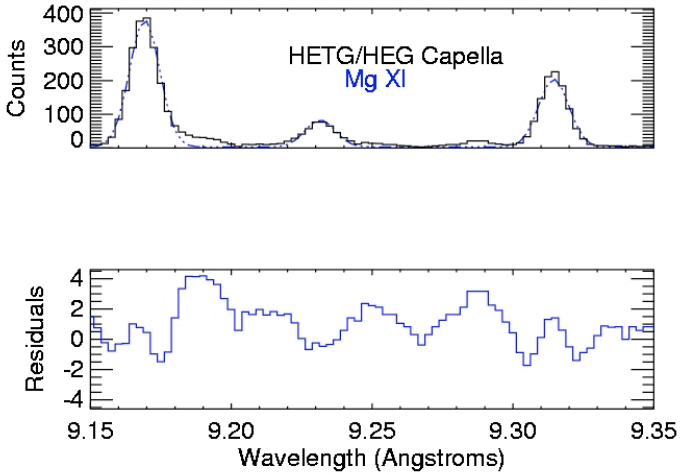
Schrijver, Lemen, & Mewe 1989

EUVE spectra confirmed sharp EMD peak at 6 MK, with extremely steep T_e rise.

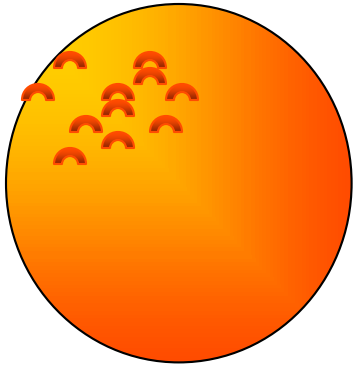
Dupree et al. 1993

Electron Density Determination for Capella





Kotochigova et al. 2005



Fe XIX and Mg XI give strong evidence for high N_e, small loops, L~.003 R_*. Brickhouse 2001

Narrow EMD Peaks and High N_e Inconsistent with Standard Loop Models

- Narrow EMD peaks and high N_e found in many other active systems, though Capella remains an extreme case.
  e.g. Sanz-Forcada et al. 2003, Testa et al. 2004

- Simple hydrostatic loop models with uniform cross section give too broad an EMD.

- Hydrodynamic models can produce the EMD shape, but only for lower N_e (~10^{10} cm^{-3}) at T_{max} (10 MK).
  Testa et al. 2005

- High N_e at high T_e is more reminiscent of large flares on the Sun.

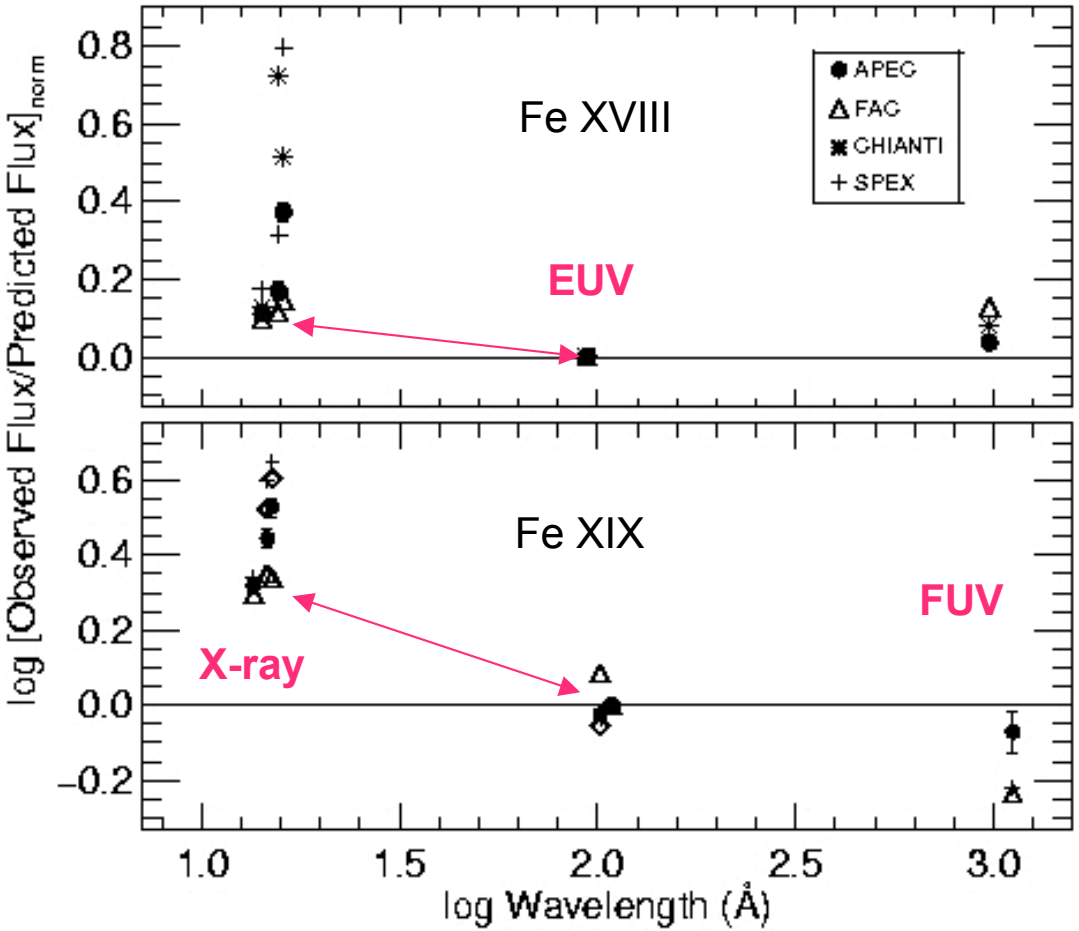
- Note that at lower T_e (2 MK), N_e is also lower (2 x 10^{10} cm^{-3}). It's whether or not these lower pressures are present in the same structures or represent a separate class of structures.

Observed/Predicted Line Ratios

All X-ray/EUV line ratios are larger than predicted (by all codes).

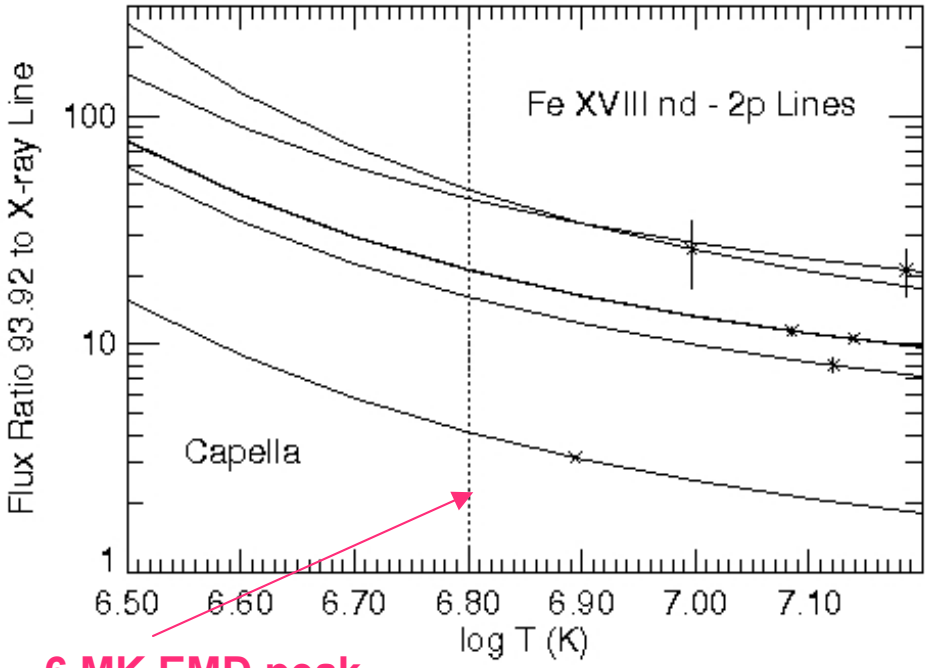
For the strongest lines, the codes agree: discrepancies are 30% for Fe XVIII and a factor of 2 for Fe XIX.

Predictions are based on the EMD with its peak at 6 MK.



Desai et al. (Emission Line Project Collaboration) 2005

T_e-Dependence of Fe XVIII and XIX Line Ratios



6 MK EMD peak

$$\frac{I_{EUV}}{I_{X\text{-}ray}} = \frac{\__{EUV}[T_e]}{\__{X\text{-}ray}[T_e]} \exp(-\_E/kT_e)$$

These simple Te diagnostics are not consistent with the ionization state of the plasma.

This motivates our investigation of time-dependent NEI effects in impulsively heated loops.

Discrepancies are not explained by: atomic rate uncertainties
calibration uncertainties
absorption
time variability

Non-Equilibrium Ionization (NEI)

- EMD models assume collisional ionization equilibrium: Flux ~ $\Lambda(T_e) \int N_e^2 \, dV$.
- In an NEI plasma, the charge state lags the instantaneous temperature T_e.
- $N_e \Lambda t$ determines the charge state.
- For a given N_e and T_e , ionization is very fast compared with recombination.
- Mass conservation (N_e dV = const) implies that a coronal loop, impulsively heated and then cooled by radiation and conduction, will emit primarily during recombination.

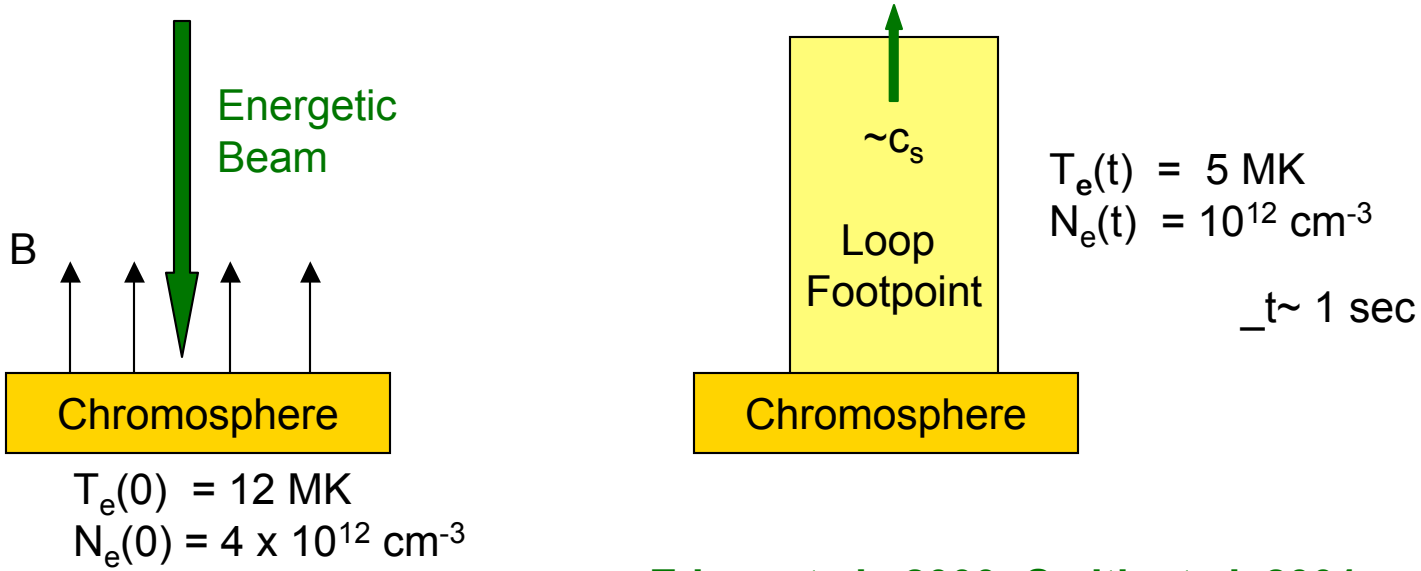
An Episodic Heating Model

We consider episodic heating (nanoflares) with:

- heat input to the chromosphere

- adiabatic expansion with rapid cooling.

We calculate the time-dependent ionization state and obtain the resulting emission w/ APEC.



Edgar et al. 2000; Smith et al. 2001

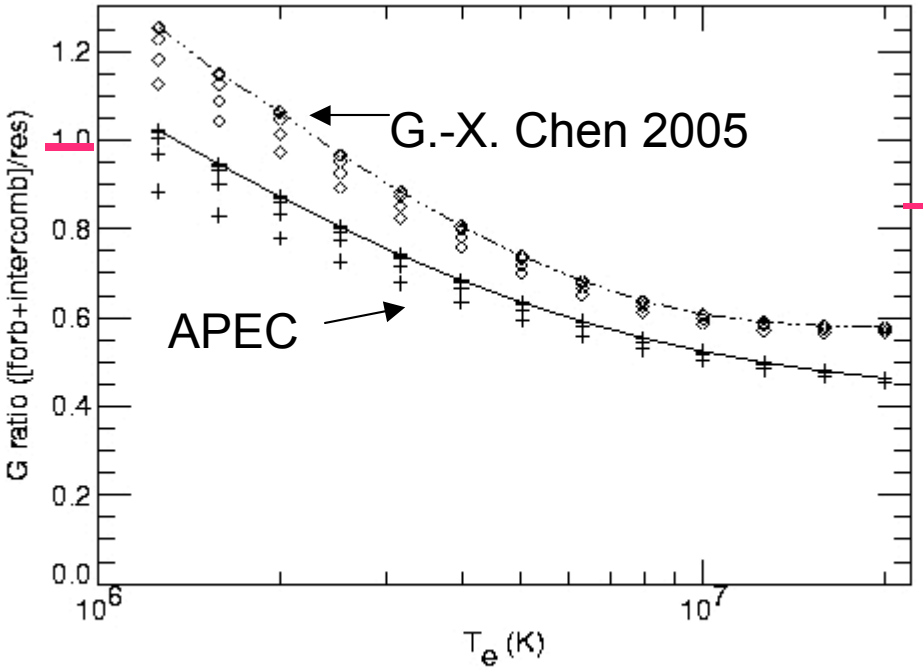
Conclusions

- X-ray/EUV ratios provide new T_e diagnostic.
- Capella observations suggest an ionizing plasma.
- Chromospheric evaporation gives a natural explanation for high N_e at high T_e.
- The ionizing phase is difficult to see. Adiabatic expansion helps, but not enough.
- Heating models require hydrodynamics and NEI.
- Other effects, e.g. non-Maxwellian distributions, might be important for beam heating.

✸ Six years and more of Chandra may shed light on the long-standing coronal heating problem.

See also the poster by Desai et al.

Toward Accurate T_e Diagnostics



Capella

Chen, Kirby, Brickhouse, & Smith 2005