From *Chandra* to *Lynx* Workshop
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Stellar Coronal Studies at High Spectral Resolution with *Lynx*

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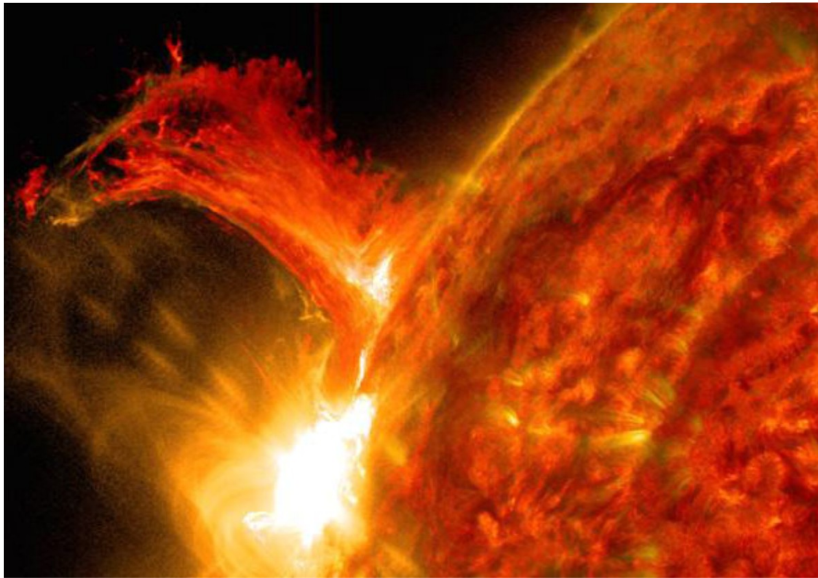
Outline

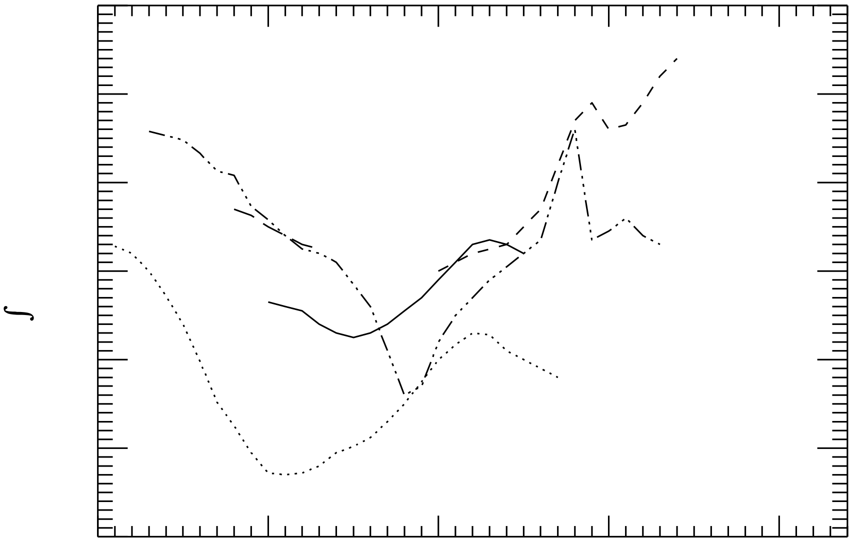
- **Introduction**
- **Selective *Chandra* results and the case for higher spectral resolution and area**
  - **EMD and N_e: Capella**
  - **Polar emission: 44 Boo**
  - **Non-dipole fields: AB Dor**
  - **Accretion: TW Hya**
- **A word on the future of stellar studies**
- **Conclusions**

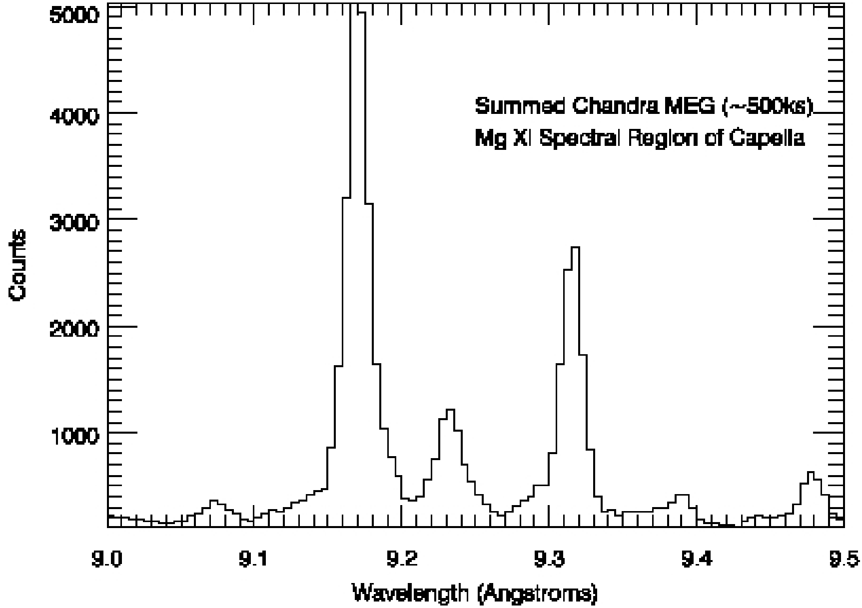
Introduction: Issues in Stellar Coronae

- Magnetic field generation via dynamo
  - Does the activity/rotation relation hold for low mass stars?
- ➢ Coronal heating and radiation
- ➢ Evolution of magnetic activity
  - Angular momentum loss in accreting stars
  - Accretion shocks
- Flares and coronal mass ejections (CMEs)
- Stellar wind drivers



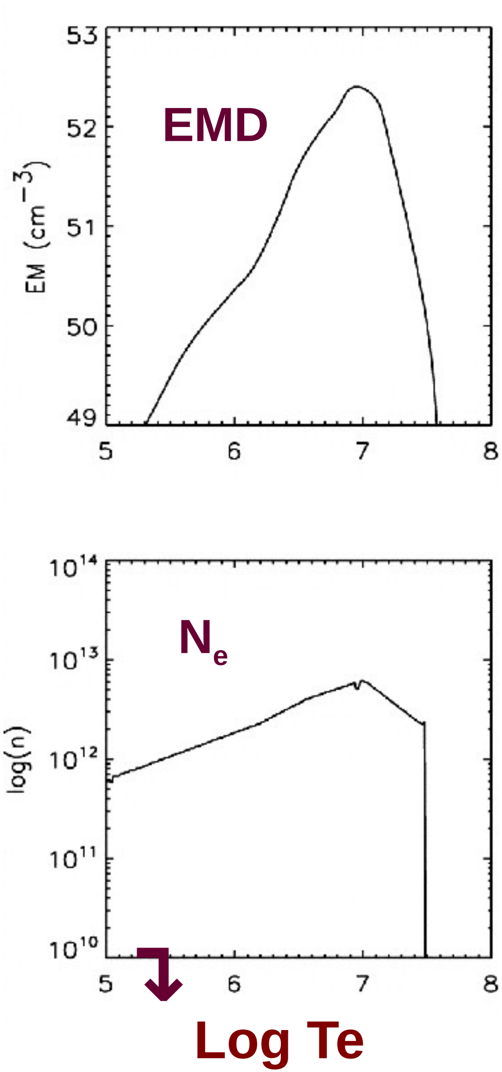
EMD and N_e: Capella





- **EMD sharply peaked**
- **High N_e at peak EMD T_e**
  - **$N_e = 1.8 \times 10^{12}$ cm^{-3} (Mg XI)**
- **N_e below EMD peak T_e**
  - **$N_e < 2.0 \times 10^{10}$ cm^{-3} (Ne IX, Ness+ 2003)**

Modeling Stellar Coronal Structure and Heating

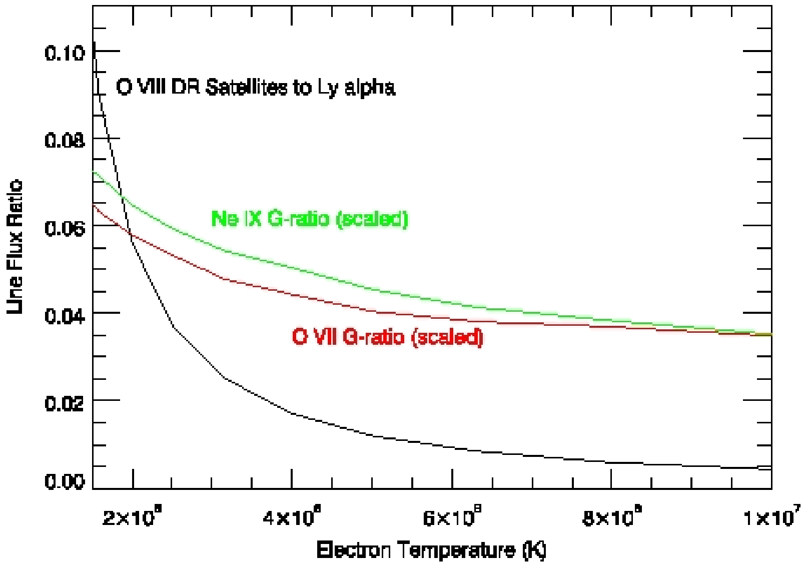


- **Classical loop models can produce EMD shape but not high N_e (Testa+2005)**

- **Solar-type nanoflare heating models (Cargill & Klimchuk 2006):**
  - **EMD Model ok**
  - **N_e at peak ok**
  - **Solar dynamo not applicable**

- **BUT N_e at lower T_e is low (Ness+2003), lower than the models by a couple orders of magnitude**

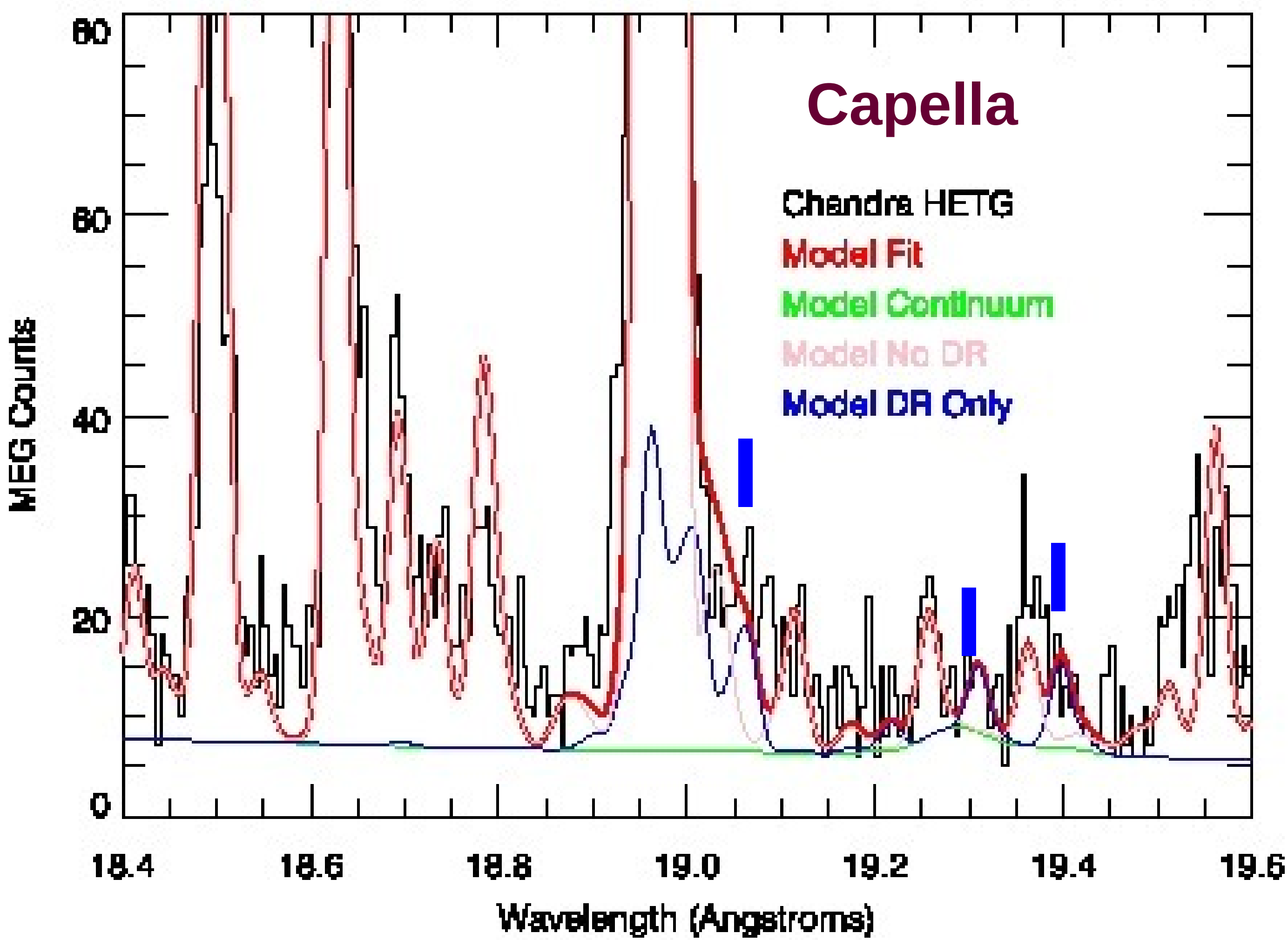
Testing Nanoflare vs Alfvén Wave Heating Models



Compare DR satellites to He-like diagnostics

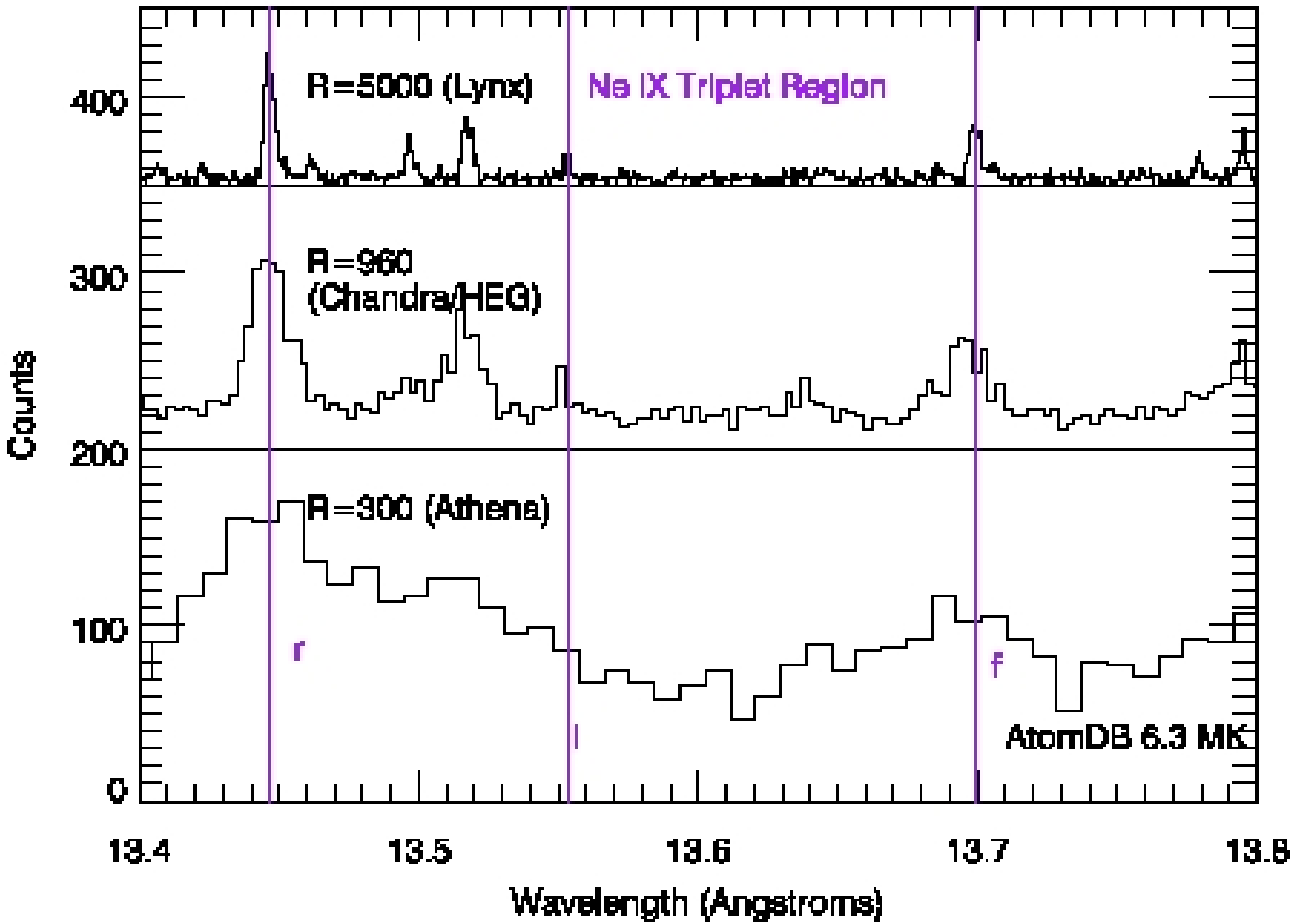
- Nanoflare models should show non-equilibrium ionization (NEI) effects
- Alfvén waves produce steady heating from below corona, so collisional ionization equilibrium (CIE) (Asgari-Targhi & van Ballegooijen 2011)
- Highly sensitive T_e diagnostic needed to distinguish NEI from CIE

High Resolution and Area Needed

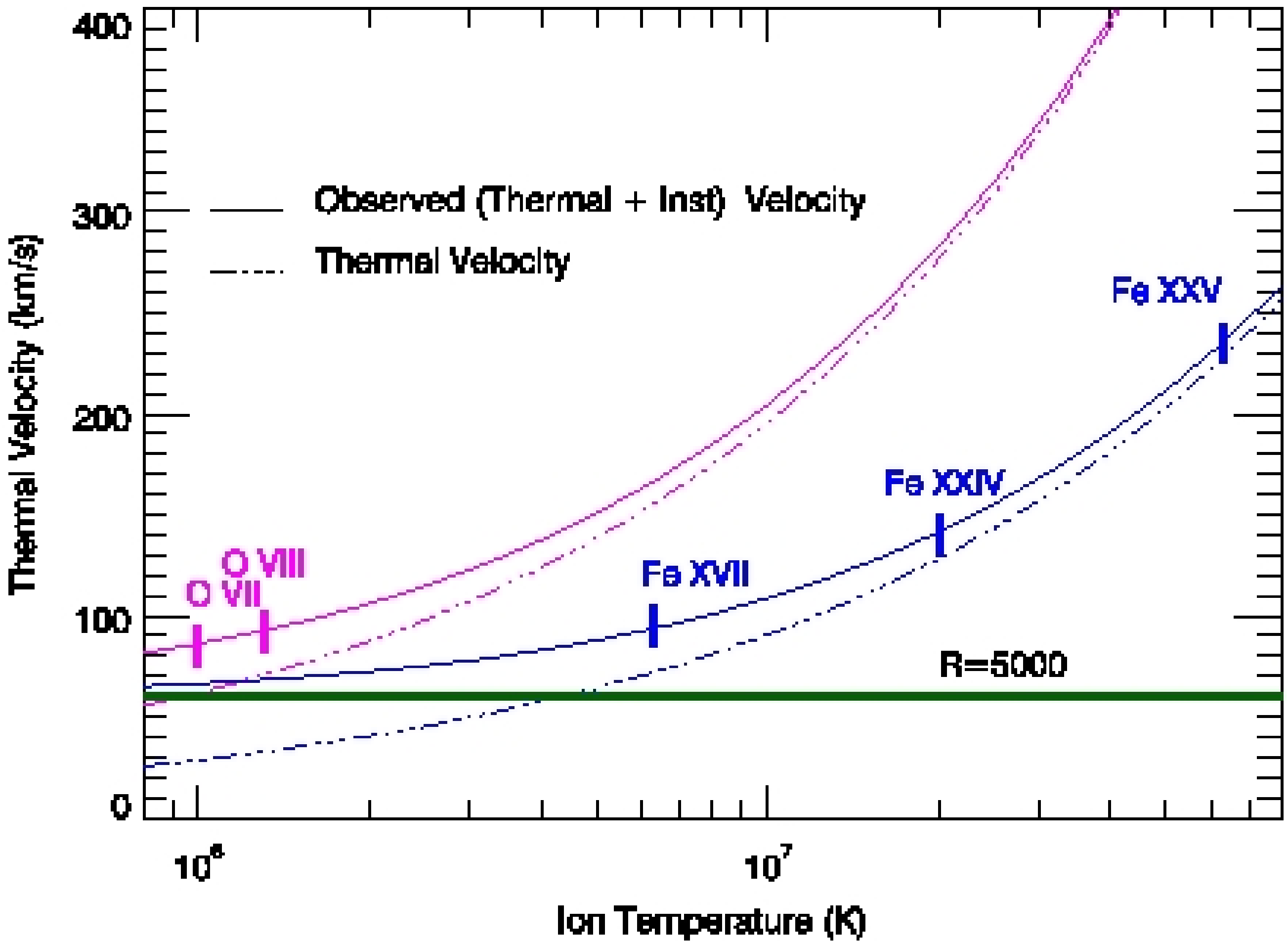


Brickhouse+ in progress

Lynx High Resolution Grating for Diagnostics

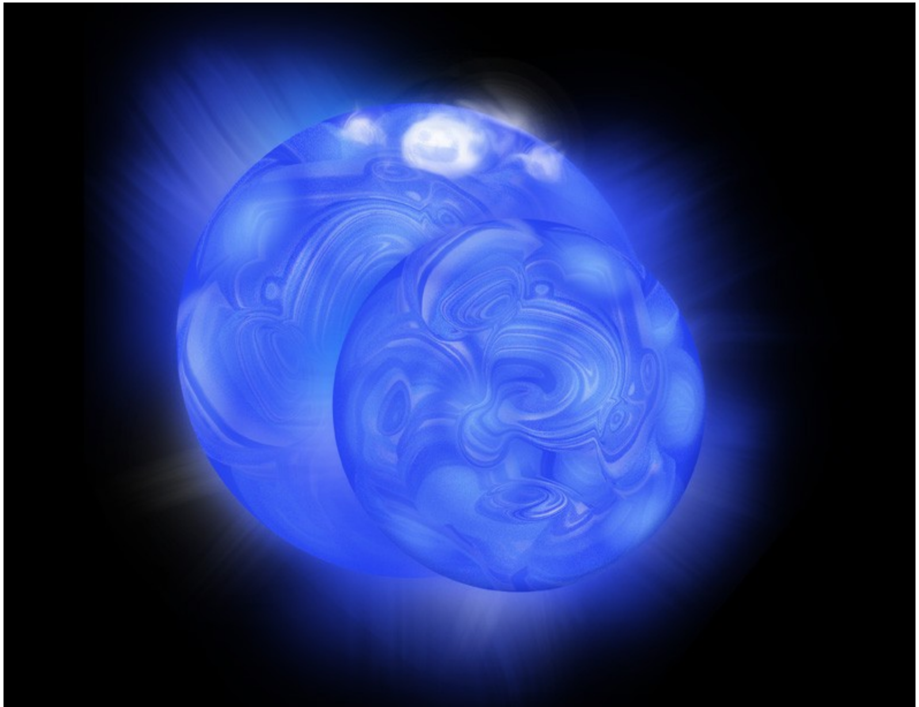


Thermal Velocity Measurements at R=5000

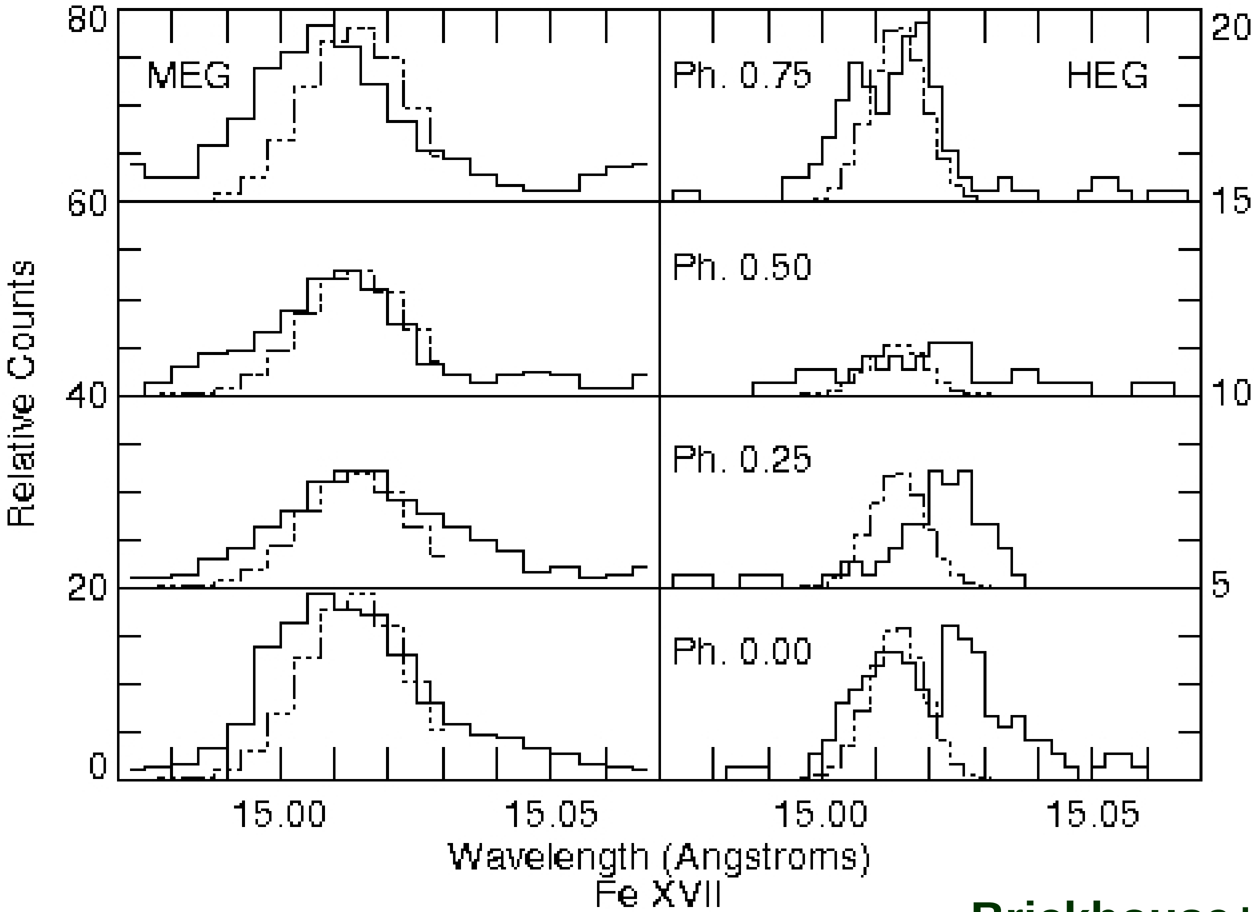


Polar Emission: 44 Boo

- Eclipsing contact binary
- 6.4 hr period
- *Chandra* line centroids vary by 180 km/s
- Doppler-broadened lines 550 km/s
- No eclipses in light curve



59 ksec Chandra constrains location of emission



Brickhouse+ 2001

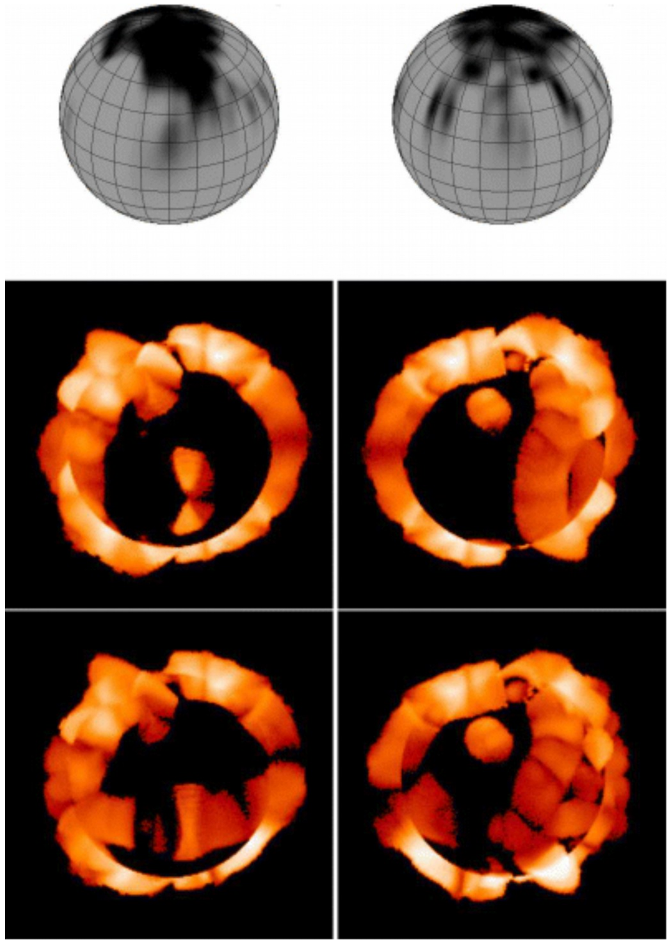
Two North Poles: AB Dor

- **Single ZAMS star**
- **0.51 day period**
- **v sin*i* = 90 km/s**

- ***Chandra* HRC/LETG line shifts constrain emission**

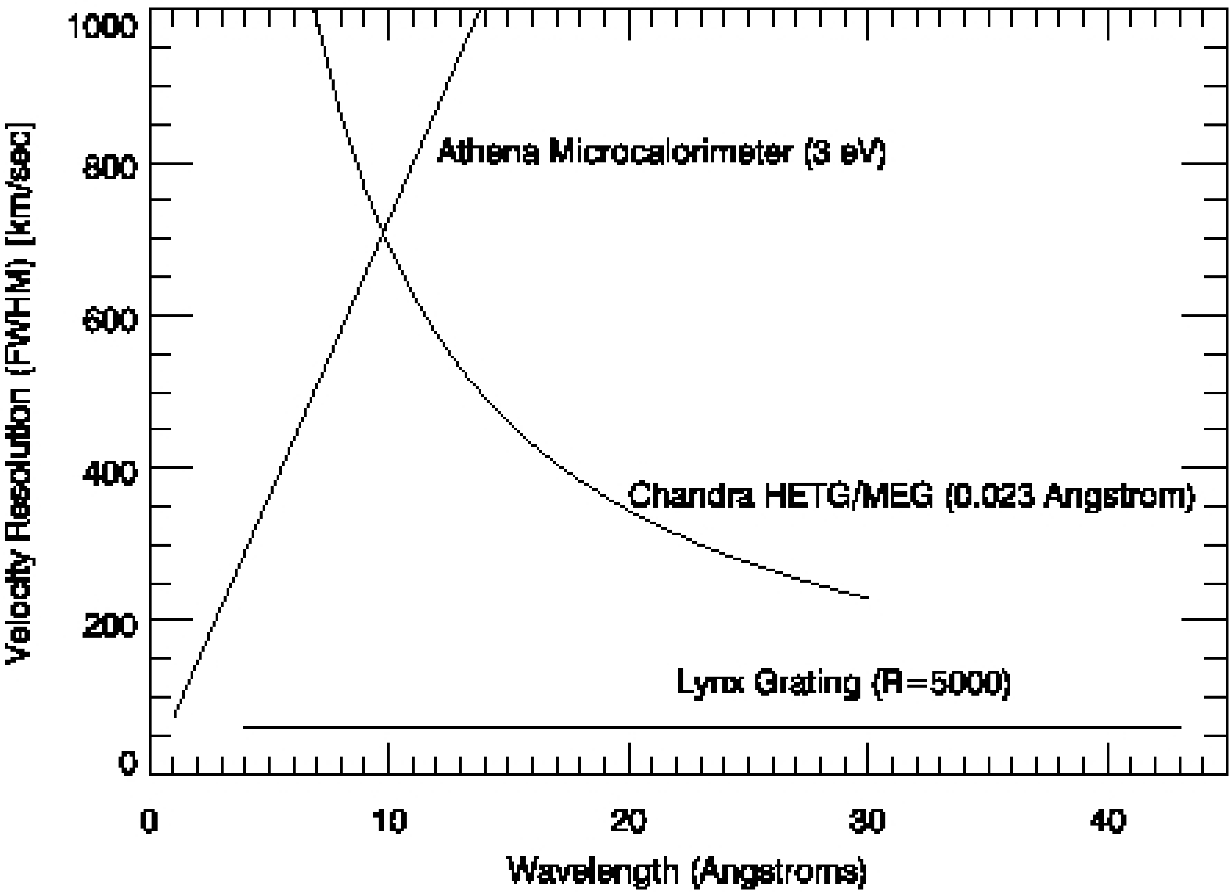
- **Rotational modulation of *Chandra* light curves, in conjunction with Doppler imaging, suggests the poles have the same polarity (Hussain+ 2007)**

- **BUT HETG does not reproduce line shifts, though more sophisticated cross-correlation technique places most of the corona at the pole (Drake+ 2015)**



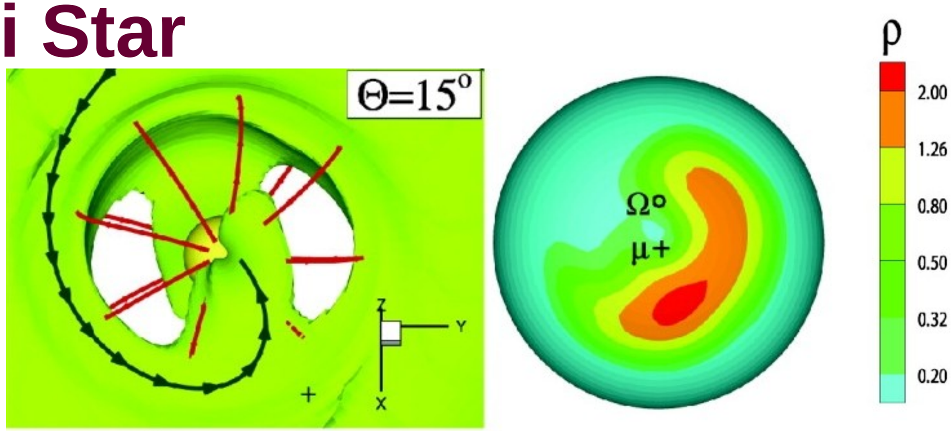
Hussain+ 2007

Lynx Grating Needed for Velocity Studies



Accretion: TW Hydrae

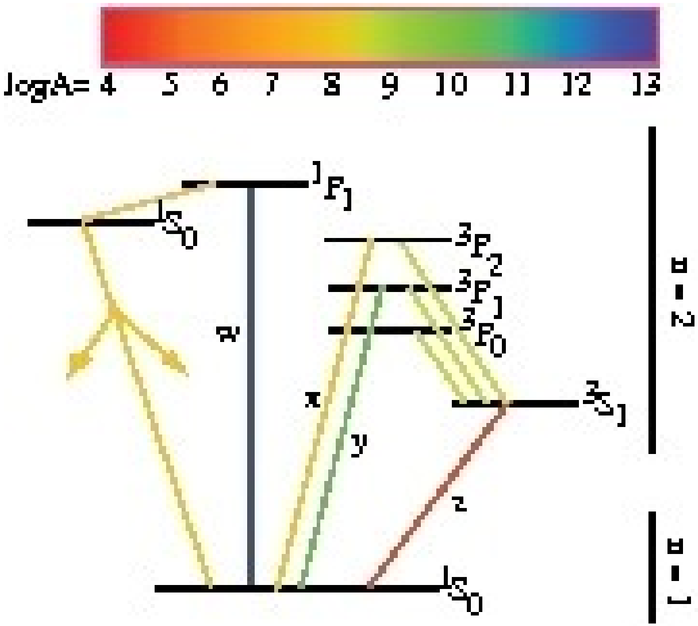
- Classical T Tauri Star
- i=7° (Qi et al. 2004)
- M = 0.8 M_{Sun}
- R = 0.7 R_{Sun}
- Distance 57 pc
- 10 million yr old
- Poised to make planets
- X-ray plasma has high Neon abundance



Romanova et al. 2004

(Kastner+ 2002; Drake+ 2005)

He-like Line Ratio Diagnostics



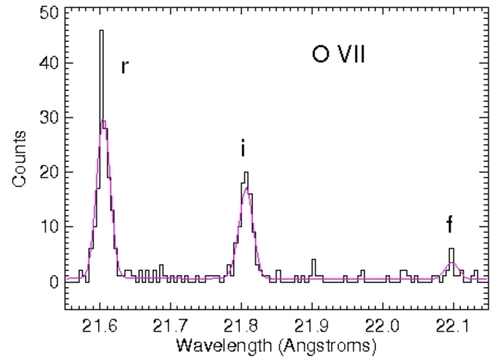
He-like Energy Levels

N_e and Te Diagnostic Ratios

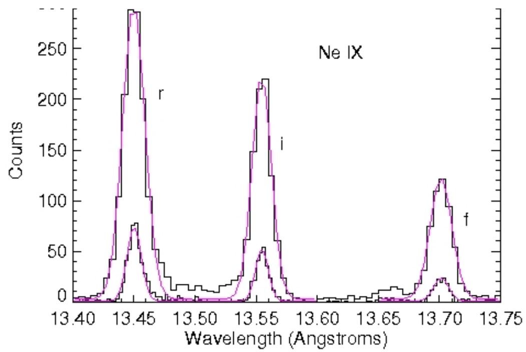
(Smith+ 2009)

***Chandra* HETG ~500 ksec**

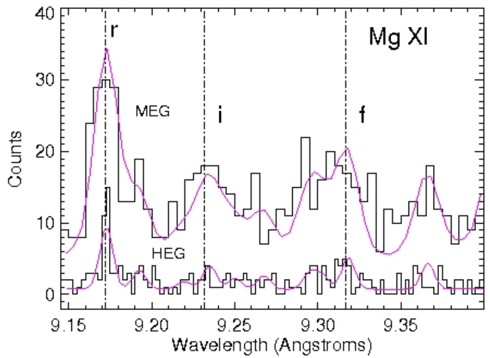
(Brickhouse+ 2010)



O VII

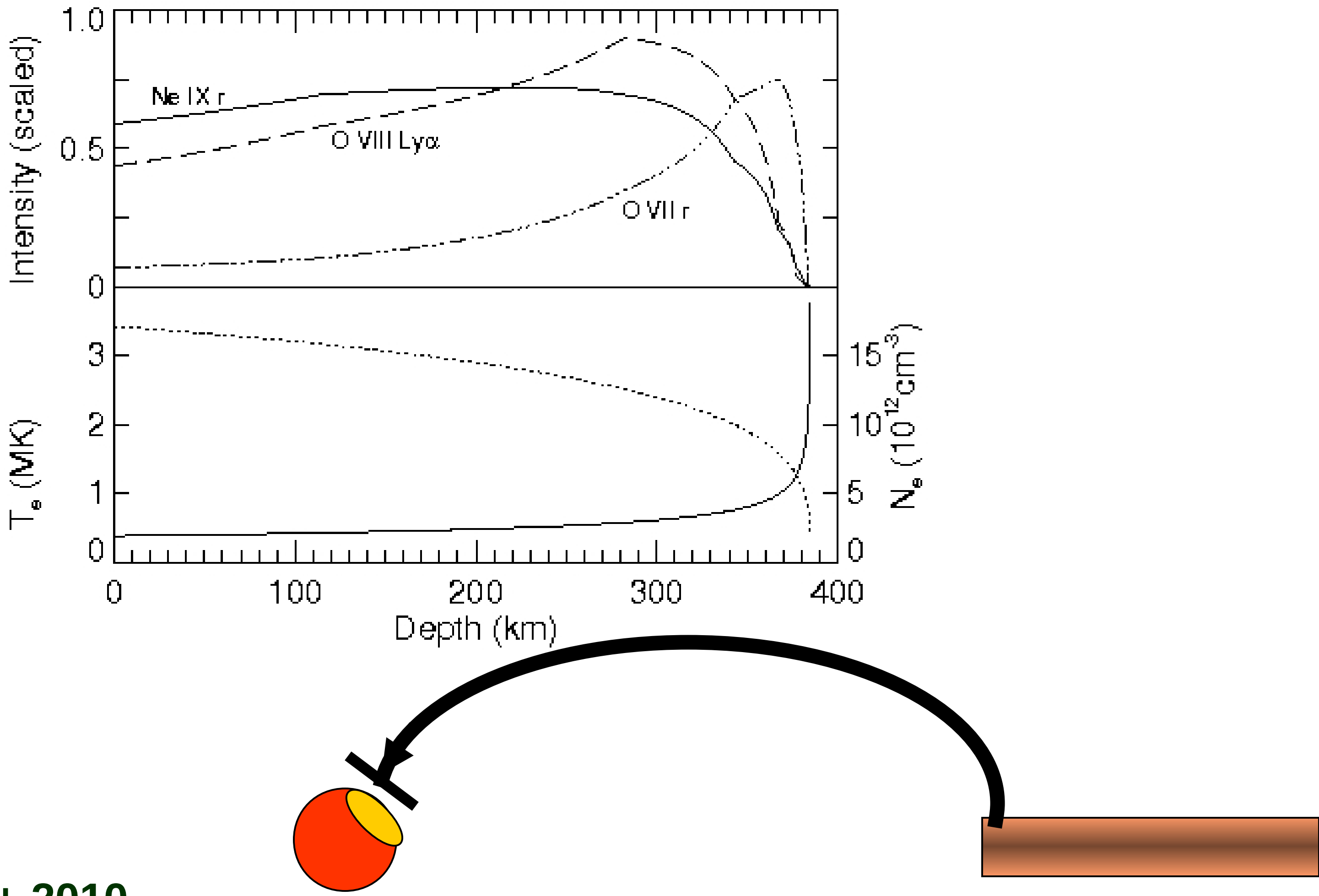


Ne IX



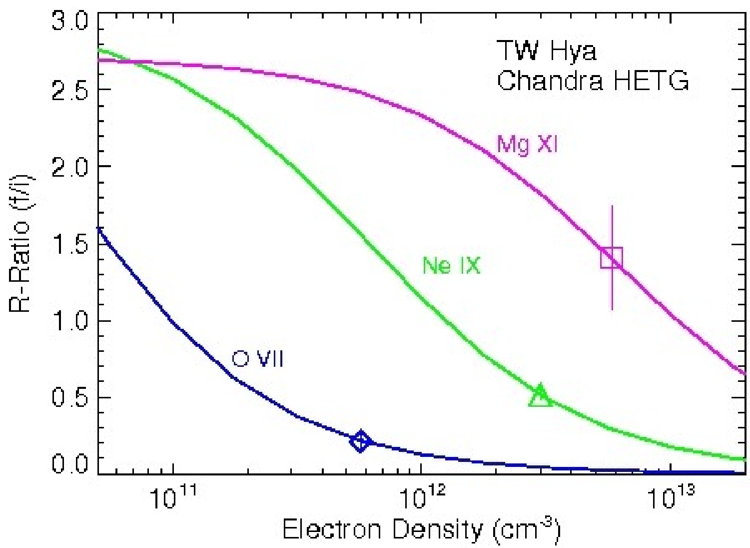
Mg XI

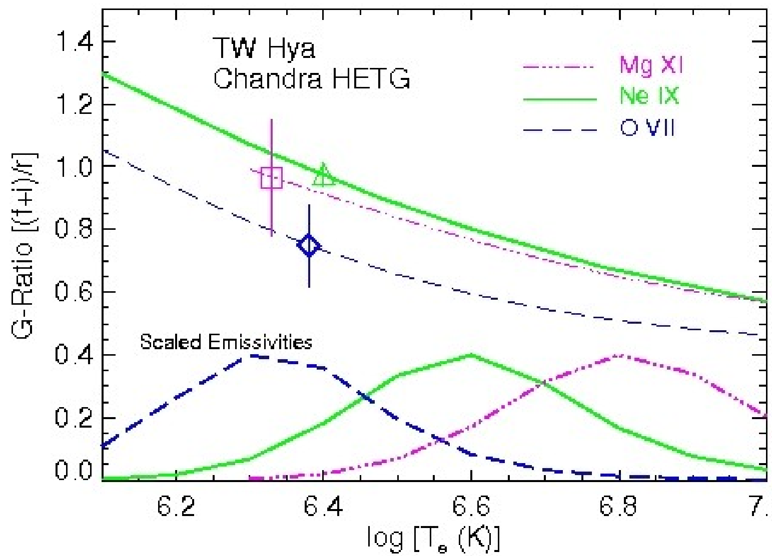
Accretion shock models
→ T_e and N_e for given $\dot{M}_{acc}$



Brickhouse+ 2010

X-Ray Line Ratio Diagnostics for Density and Temperature





N_e = 6 x 10^{12} cm^{-3} Mg XI

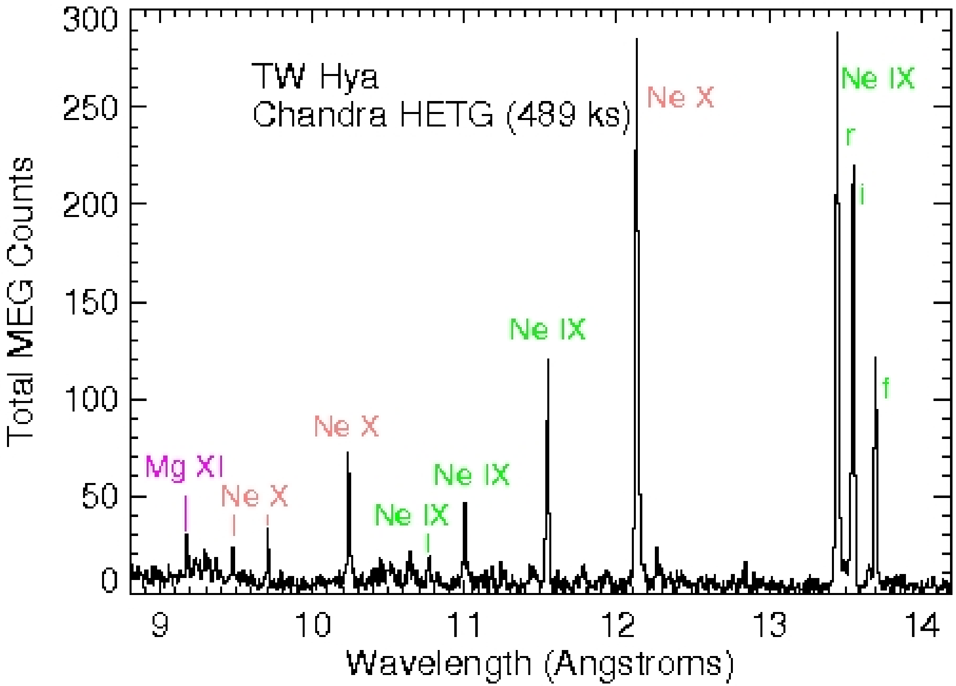
3 x 10^{12} Ne IX

6 x 10^{11} O VII

T_e = 2.50 ± 0.25 MK

This looks like the accretion shock!

Neon Region of HETG Spectrum



Spectrum shows strong H-like Ne X and He-like Ne IX, up to n=7 or 8 in Ne X.

Series lines rule out resonance scattering

O VII: $N_H = 4.1 \times 10^{20}$ cm^{-2}

Ne IX: $N_H = 1.8 \times 10^{21}$ cm^{-2}

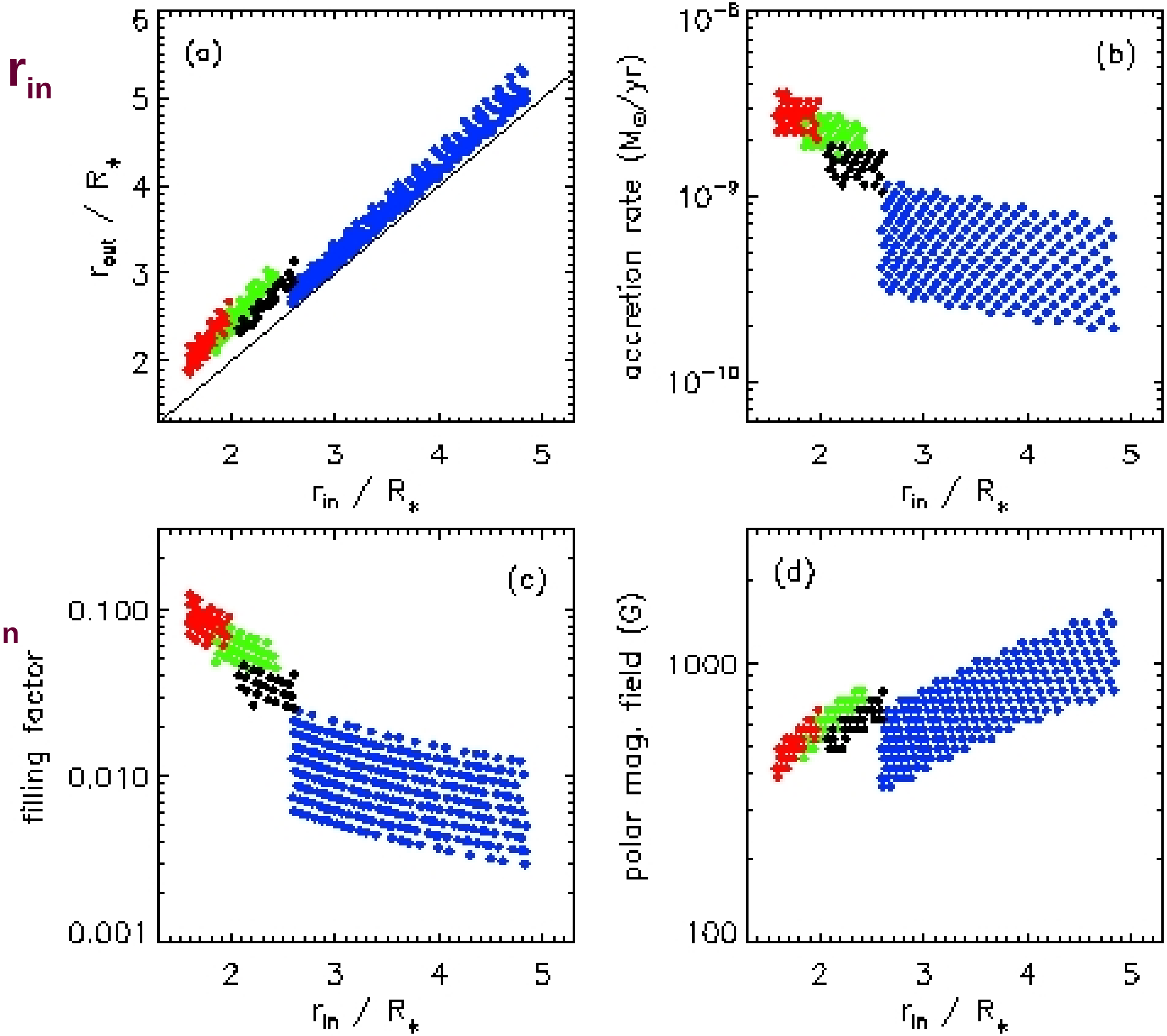
Accretion Diagnostics Vary

r_{out} vs r_{in}

• $\dot{M}_{acc}$ vs r_{in}

f vs r_{in}

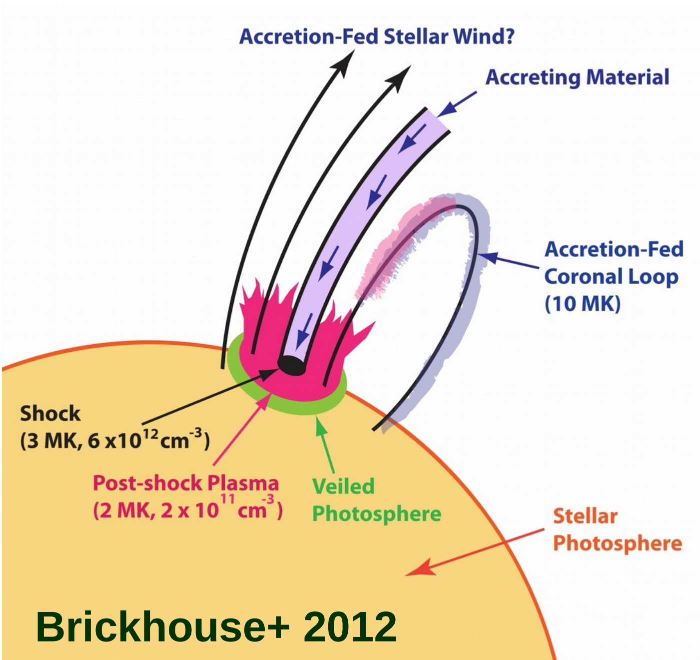
B vs r_{in}



Brickhouse+ 2012

Models from *Chandra* Seem OK

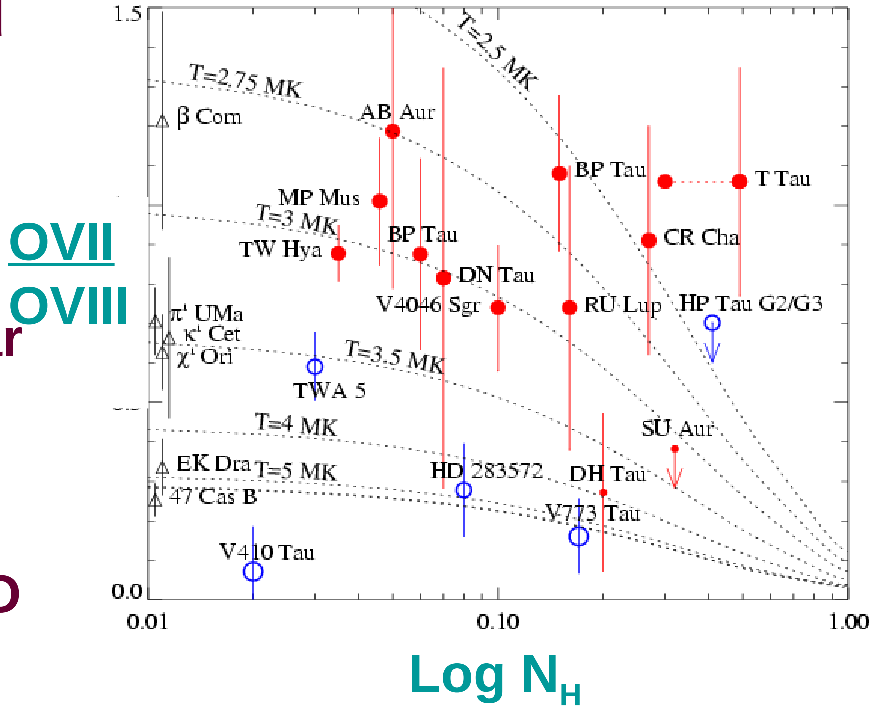
- **Measure T_e, N_e, and N_H from Ne IX**
- **Assume dipole field and**
- **Assume absorption from incoming stream**
- **Model gives reasonable accretion rate range**



Brickhouse+ 2012

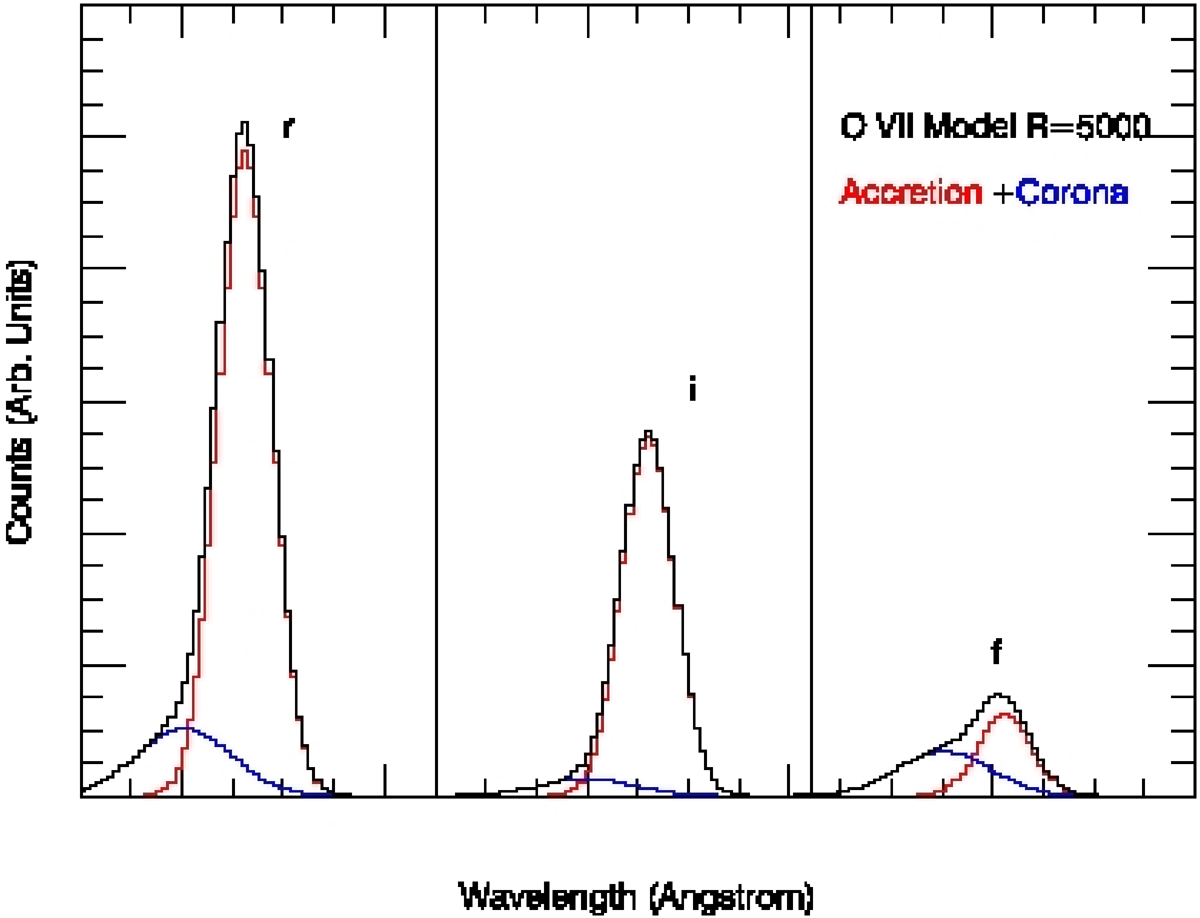
BUT

- **Assumption 1 is wrong. TW Hya has a dominant "octupole" field**
- **Assumption 2 seems ok for TW Hya, but resonance scattering remains a possibility. Also, at higher accretion rates the stellar atmosphere might absorb**
- **In TW Hya, O VII does not fit shock cooling: N_e and N_H from O VII are too low**
- **In other systems Ne IX does not always show high N_e**
- **All systems show excess O VII**



Gudel & Telleschi 2007; Robrade & Schmitt 2007

Lynx Model of Accretion + Corona



Accretion studies on young stars should be a component of a new Lynx pillar on Stellar Life Cycles!

Future Stellar Studies

- **Searching for signs of life**
- **Focused on low mass M dwarfs**
- **Habitable zones are closer to star**
- **Issues include destruction of atmosphere by:**
  - **Stellar flares and concurrent CME's (Linsky today?)**
    - **AD Leo can recover from massive flare/proton flux (Segura+ 2010)**
  - **Stellar UV to X-ray radiation (Linsky today?)**
    - **But UV is promising for catalyzing prebiotic chemistry (Ranjan & Sasselov 2016)**
  - **Stellar winds (Garaffo+ 2017; Wargelin & Drake 2002)**
    - **But planet's B field may channel particles only to polar regions (Driscoll+ 2013)**

Conclusions

- ***Chandra*** **shows active star coronae are more dense and "isothermal" than the Sun and emission occurs near poles.**

- ***Chandra*** **and XMM-Newton grating spectroscopy only available for a few dozen (active) stars.**

- **The soft X-ray spectrum (< 1 keV) provides unique diagnostics for accretion studies.**

- **A *Lynx* grating (R > 5000) and high Area broadens the types of stars we can study, introduces new diagnostics, and opens up the velocity window.**

➢ **Accretion should be a major component of a 3rd *Lynx* pillar: Stellar Life Cycles**