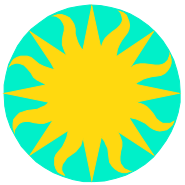


Chandra Calibration Workshop
Cambridge, MA
October 28, 2003

Highlights of Chandra Grating Science

Nancy S. Brickhouse

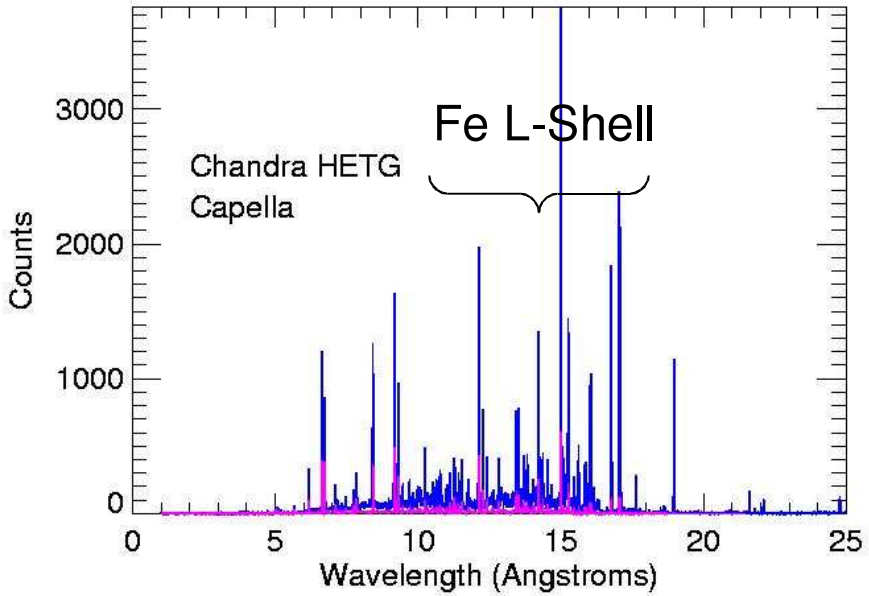
Harvard-Smithsonian Center for Astrophysics

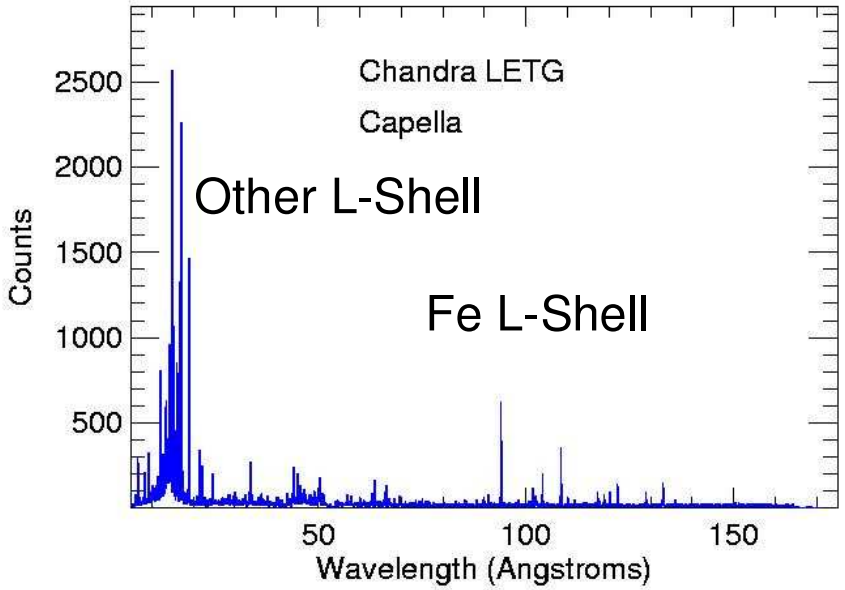
- **Overview: Spectral Diagnostics**
- **Cool Stars: Pressure, Abundances, Location**
- **Hot Star Atmospheres**
- **Cataclysmic Variables: Accretion**
- **Winds and Relativistic Iron Lines in X-ray Binaries**
- **Active Galactic Nuclei: Outflows**
- **Absorption by the Warm-Hot Intergalactic Medium (WHIM)**
- **Conclusions**

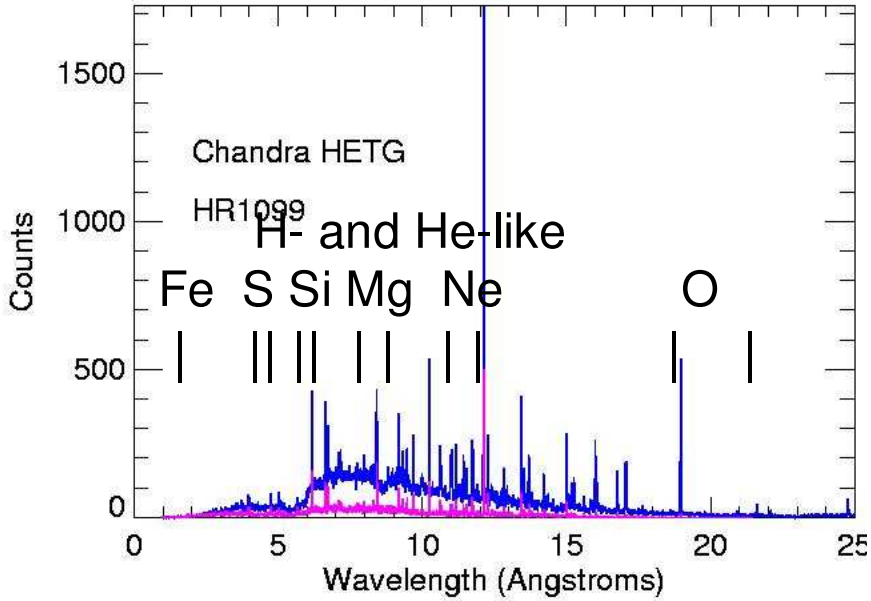
Overview: Spectral Diagnostics

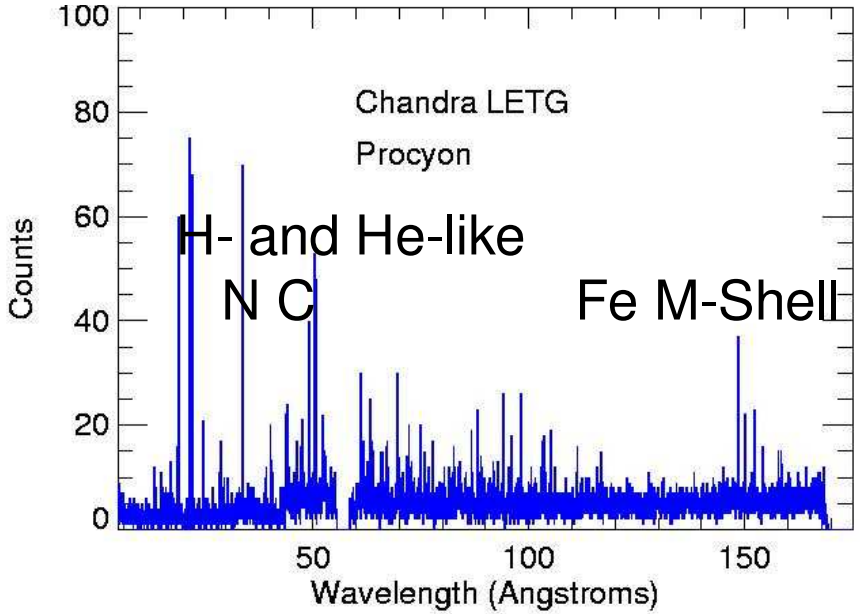
- **Quantifying the Physical Conditions from the X-Ray Spectrum**
  - **Collisionally Ionized Plasma**
    - **Line Flux Diagnostics**
    - **Thermal Continuum Emission**
  2. **X-ray Photoionized Plasma**
    - **Photoionizing Continuum**
    - **Emission Lines from Ionized Gas**
    - **Absorption by Ionized Gas**
    - **Radiative Recombination Continuum**
    - **Fluorescence Lines**
- **Timing Studies**
  1. **Light Curves from Spectral Lines**
  2. **Doppler Velocities**
  3. **Flaring Events and Other Variability**
- **Line Profile Studies**
  - **Doppler Imaging**
  - **Wind Diagnostics**

The X-ray Spectral Content



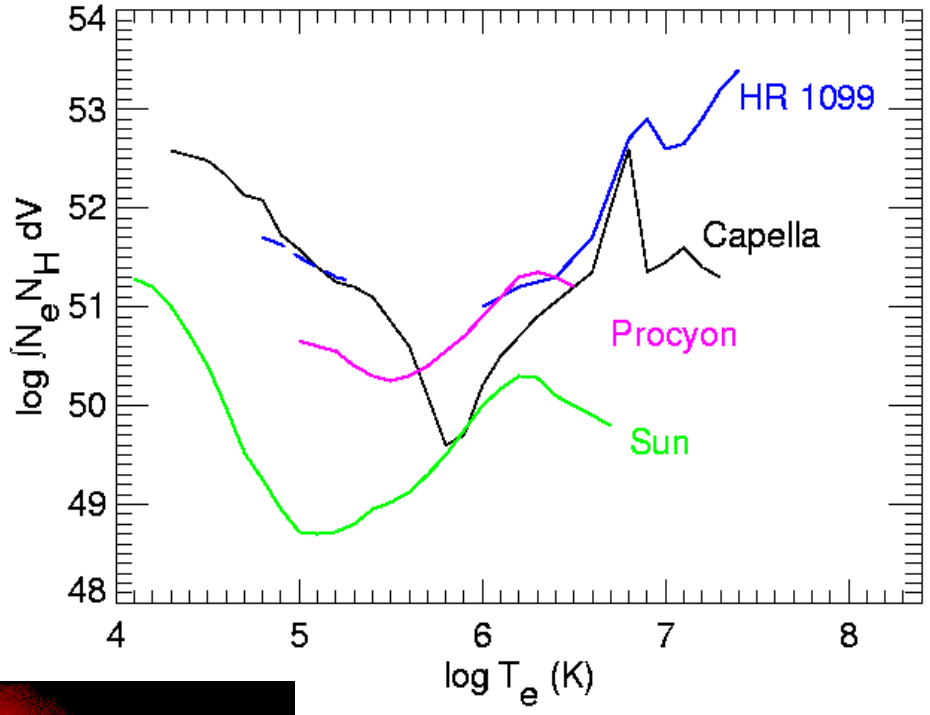


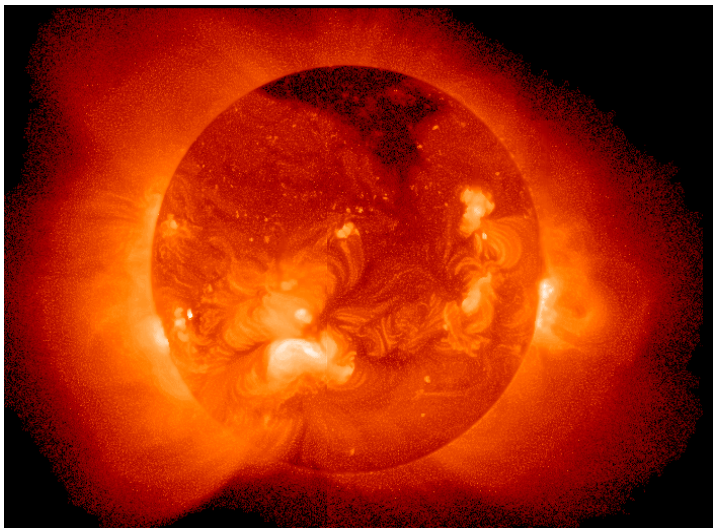




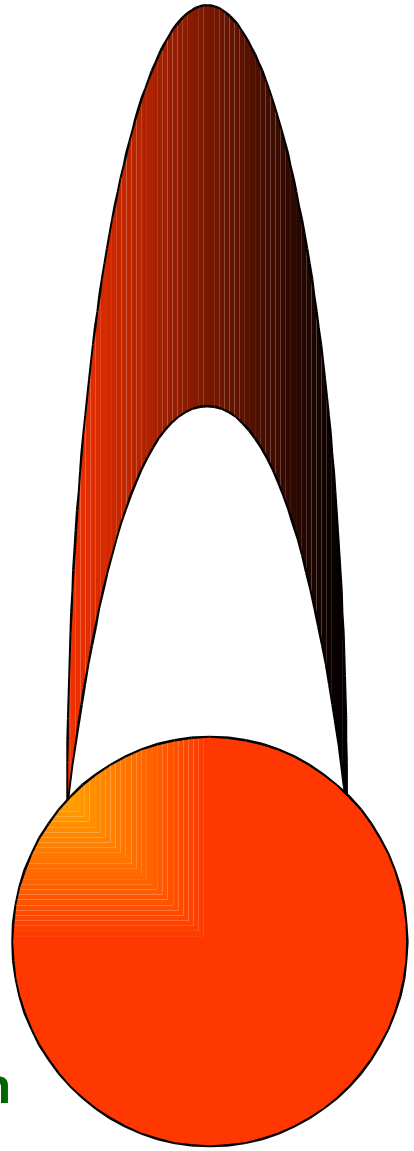
Coronal Loop Models of the Emission Measure Distribution

Brickhouse & Drake 2001





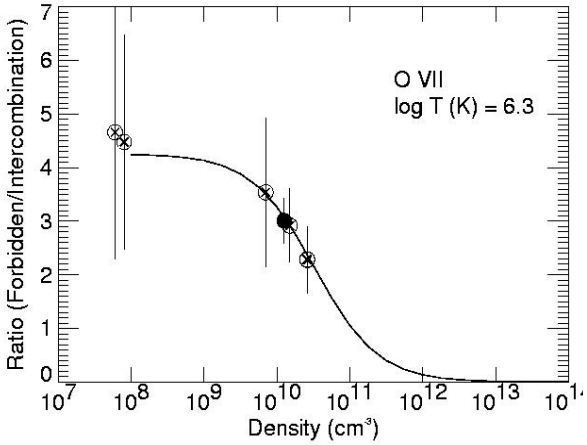
Sun (G2 V)
Extended Emission
Yohkoh Image

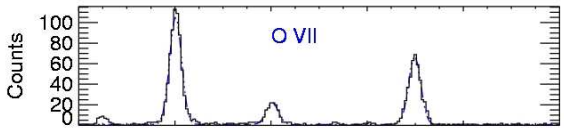


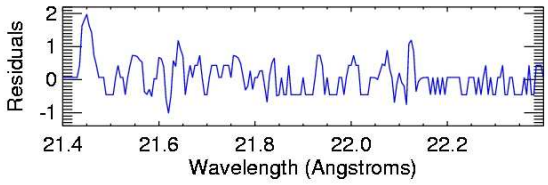
Capella (G8 III + G1 III);
P=108d; G1 has 8 d rotation
Expanding Loops
Schrijver, Lemen, & Mewe 1998

Electron Density Determination

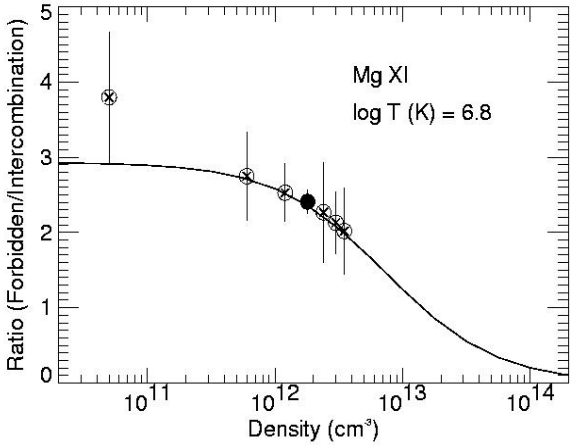
Lower Pressure; L=.02 R_*

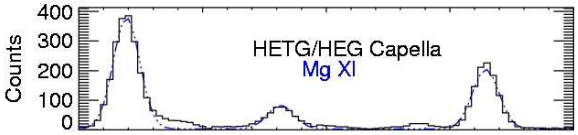


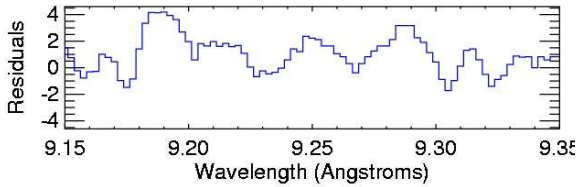


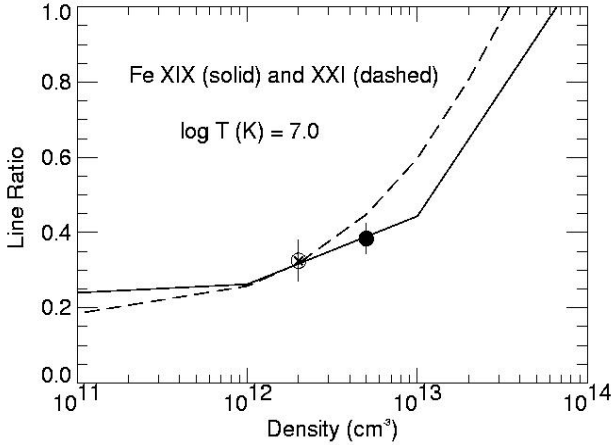


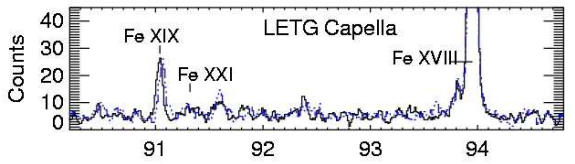
High Pressure; L=.003 R_*

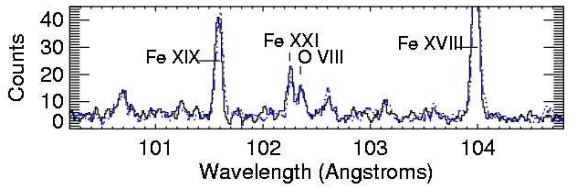










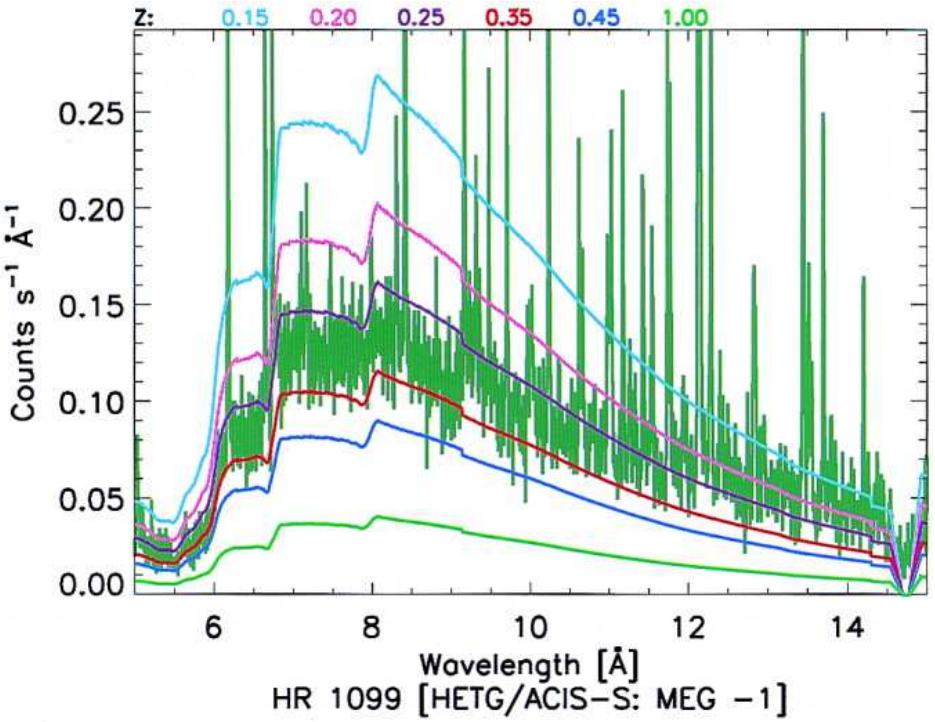


- **Compelling evidence for high density, small emitting region(s)**
- **Multiple pressures in the system**

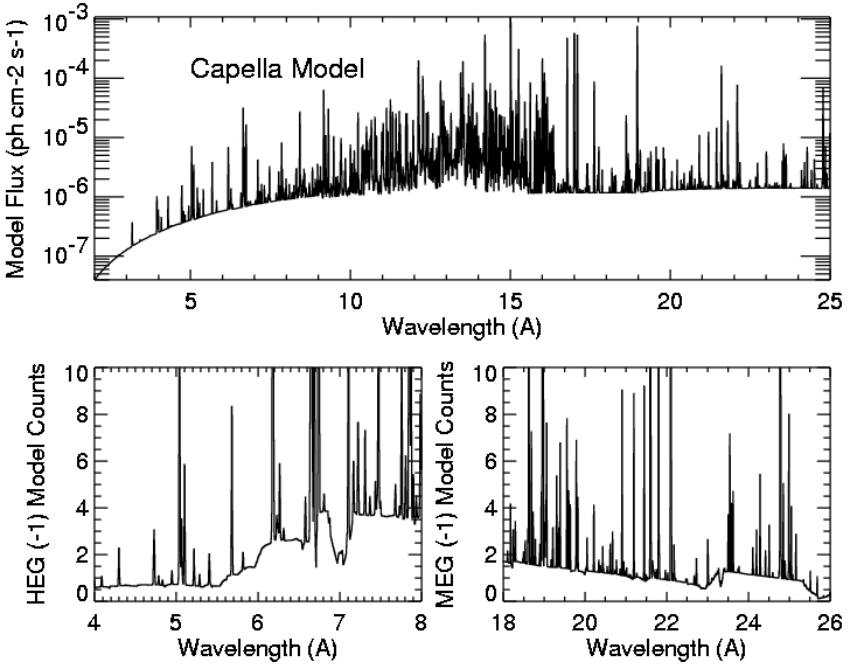
Chandra Gratings

Capella (G8 III + G1 III)
Brickhouse 2001

Abundances: Continuum Modeling and Line-Free Regions

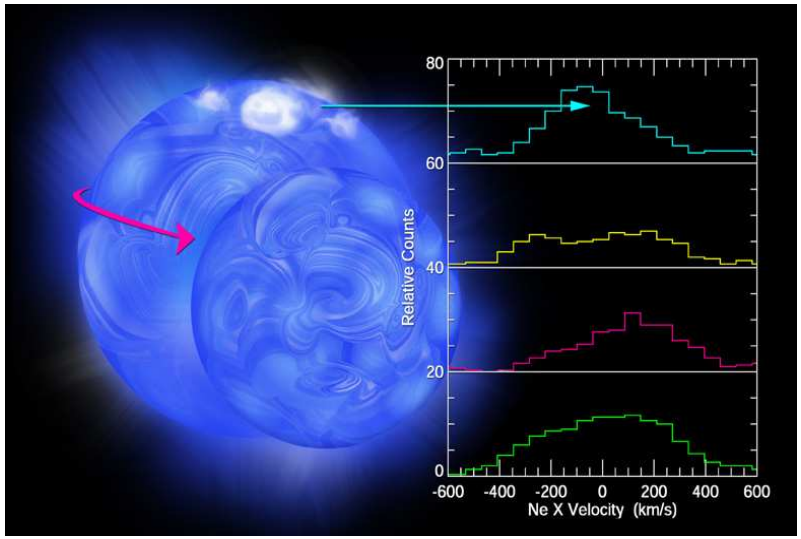


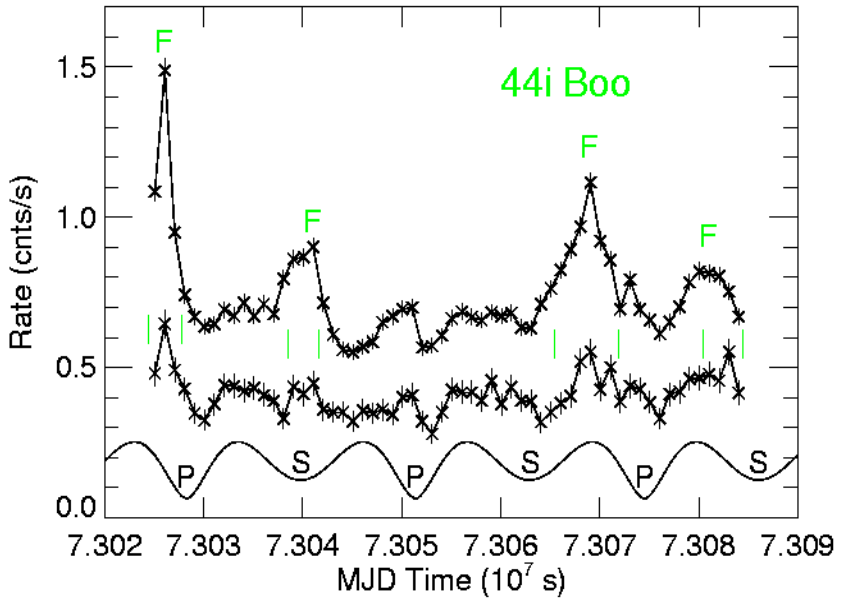
HR 1099
High Ne Abundance
Drake et al. 2001



Capella
Solar Photospheric Abundances
Brickhouse 2001

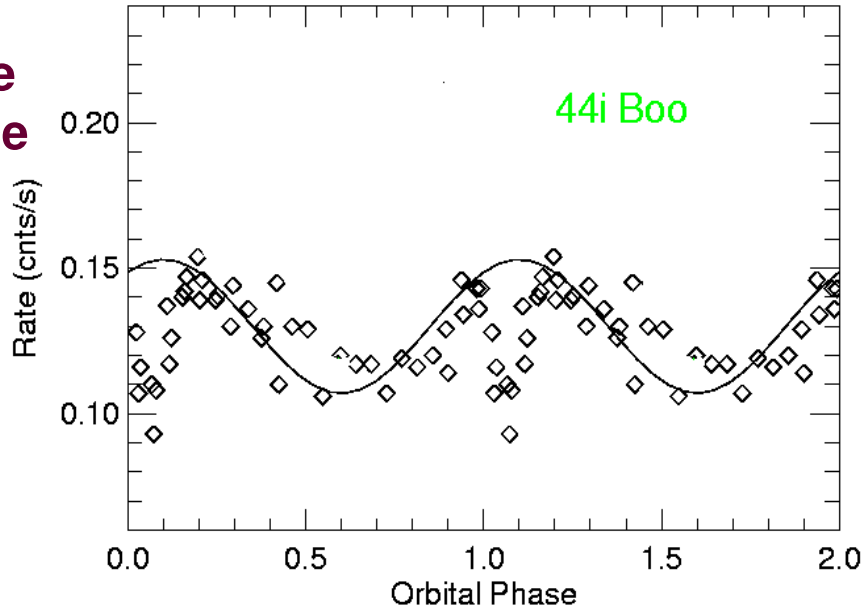
X-Ray Doppler Imaging with Light Curves and Velocity Profiles





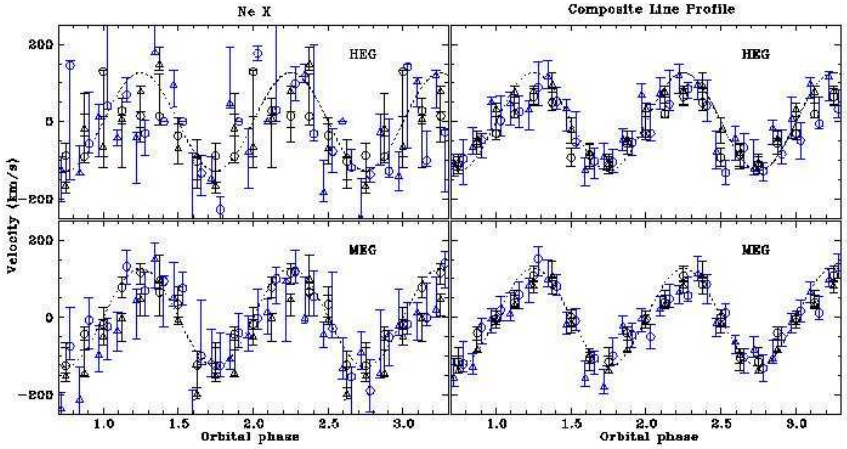
- From light curve analysis:
  - —Near the pole of the primary:
    - ➢A small region on the inner face
    - ➢A larger region on the outer face
  - —Unmodulated emission

- From line centroids:
  - —Dominant velocity follows primary

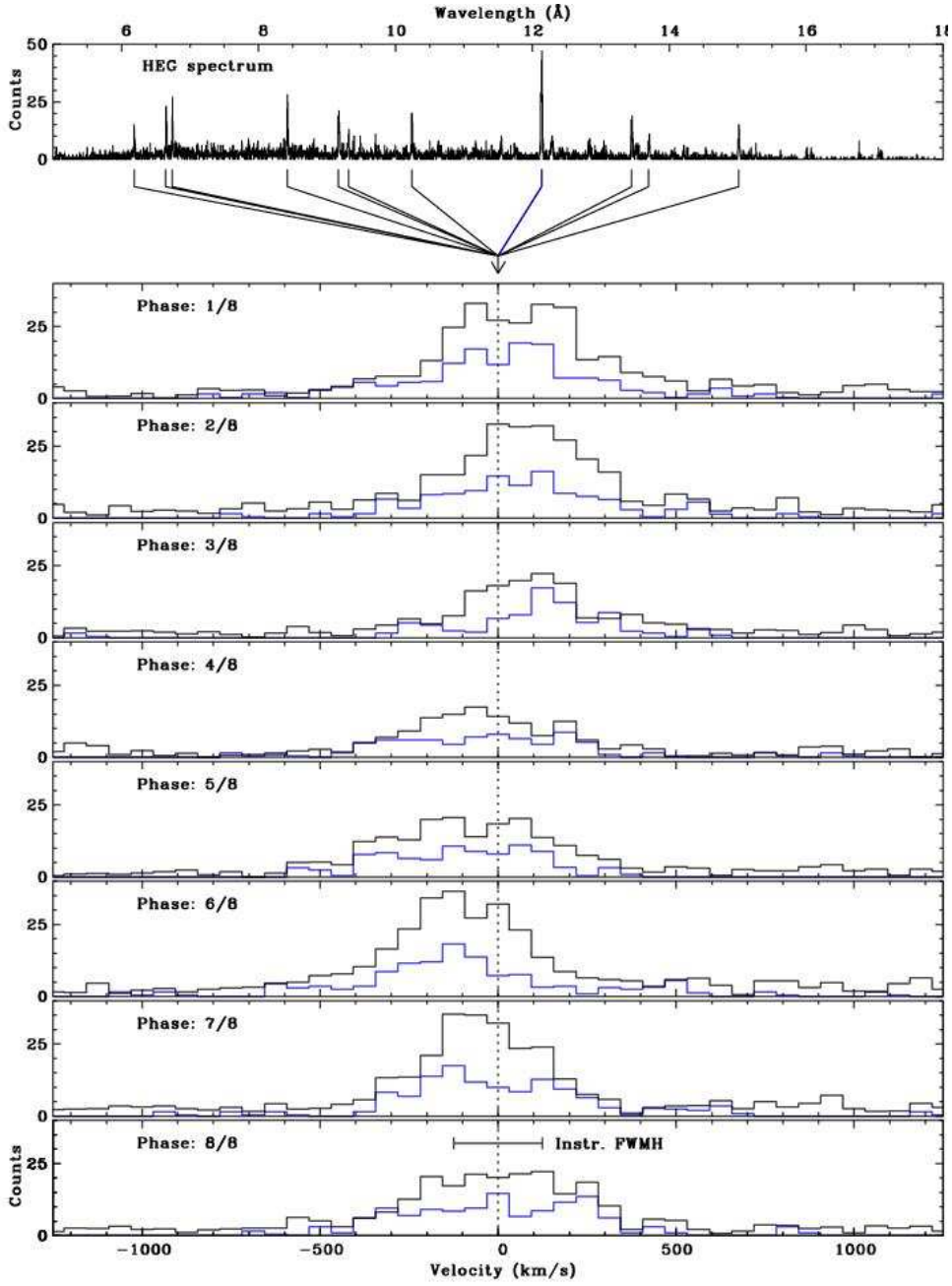


Chandra HETG
44 Boo (2 ~G8 stars); P=0.268 d
Brickhouse, Dupree, & Young 2001

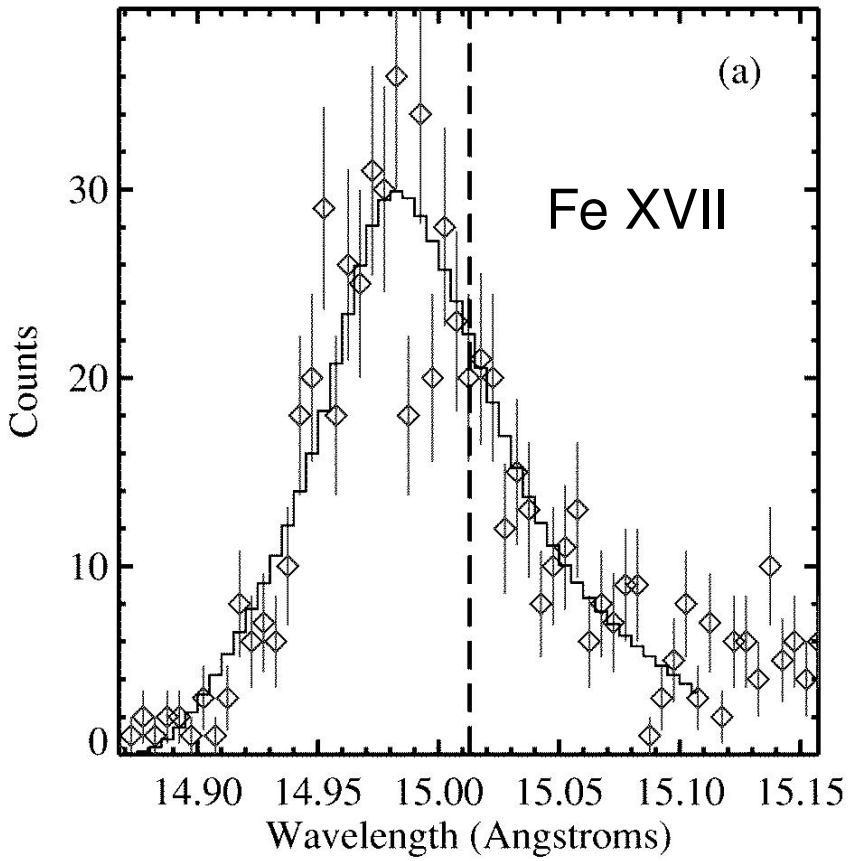
- **A New Technique: Composite line profile to increase S/N**

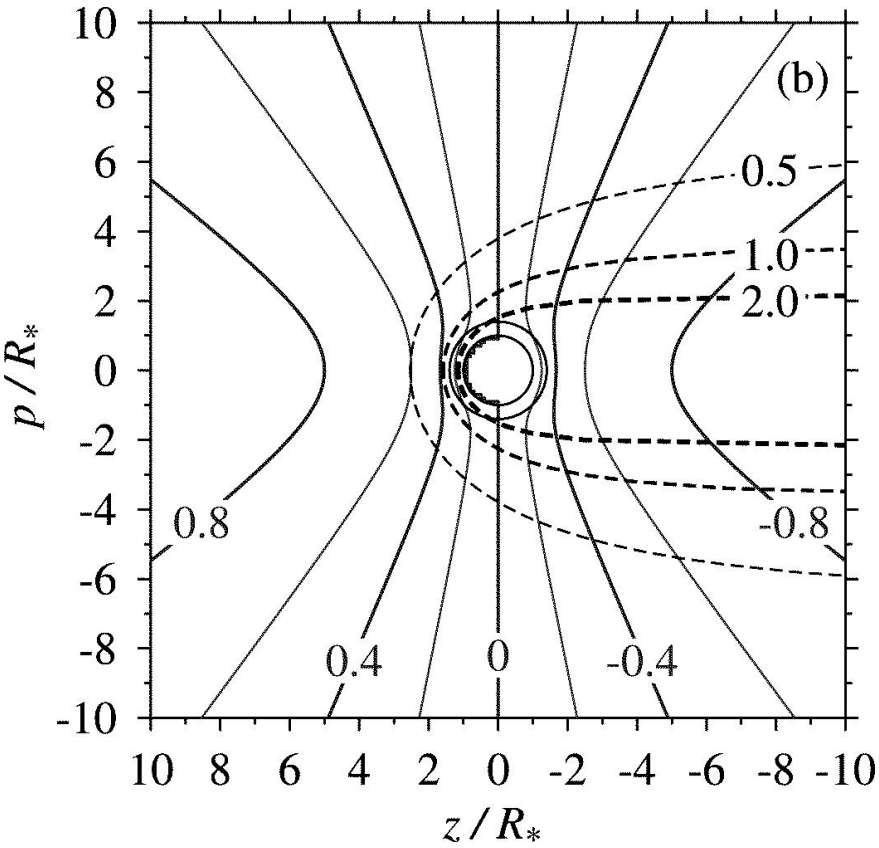


Chandra HETG
44 Boo (2 ~G8 stars); P=0.268 d
Hoogerwerf, Brickhouse, & Dupree 2003



Broad X-Ray Line Profiles of Hot Stars

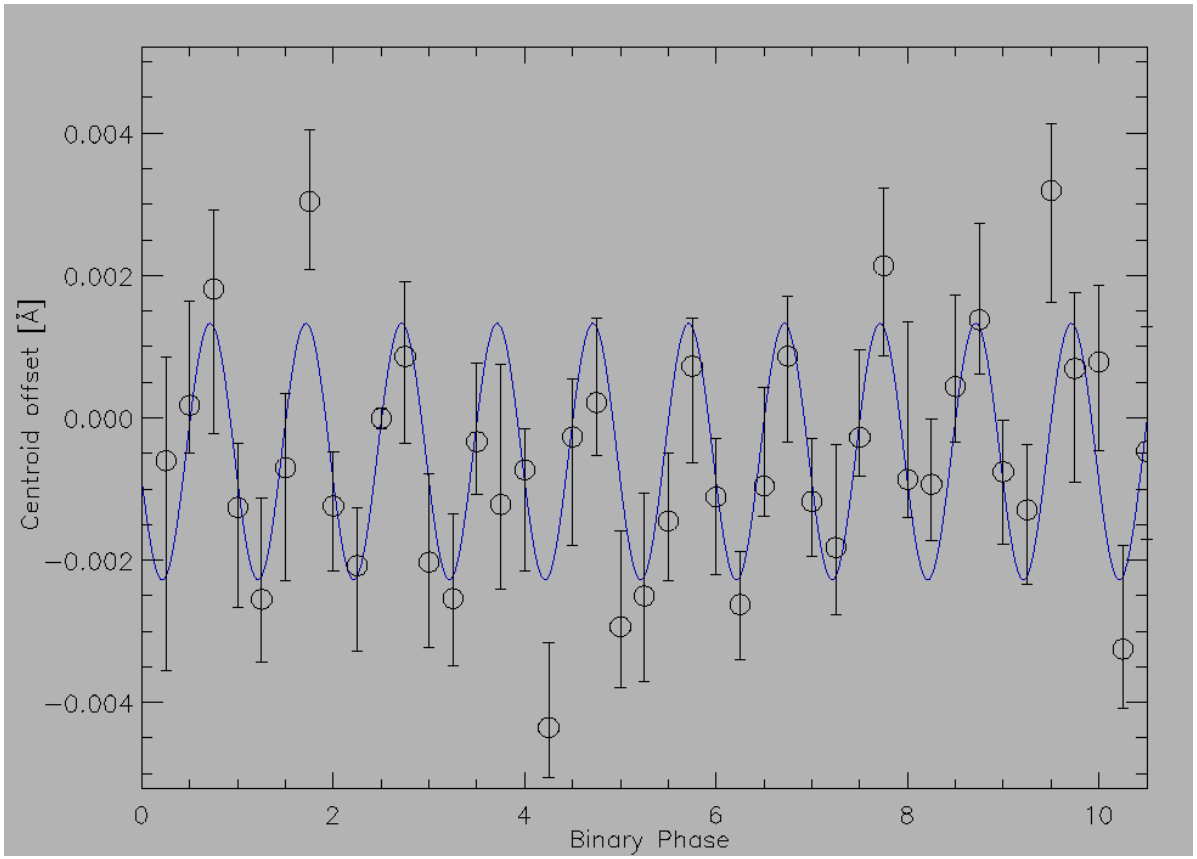




Wind shock model shows wind closer to photosphere than expected.

Chandra HETG
ζ Puppis (O4f)
Kramer, Cohen, & Owocki 2003

Binary Motion in EX Hya with Chandra HETG



EX Hydrae
Magnetic CV
Intermediate Polar
Orbital Period = 98 min
Spin Period = 67 bmin

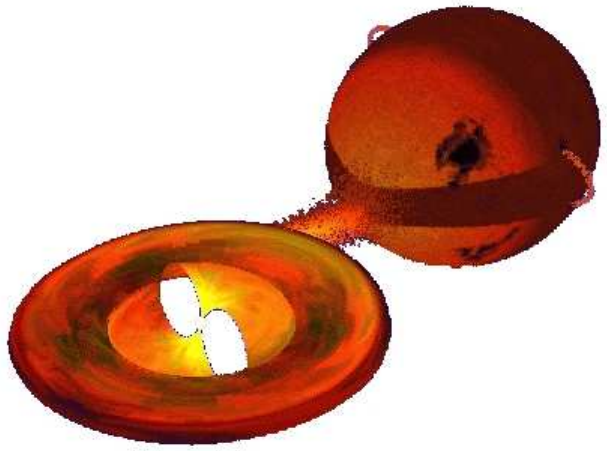
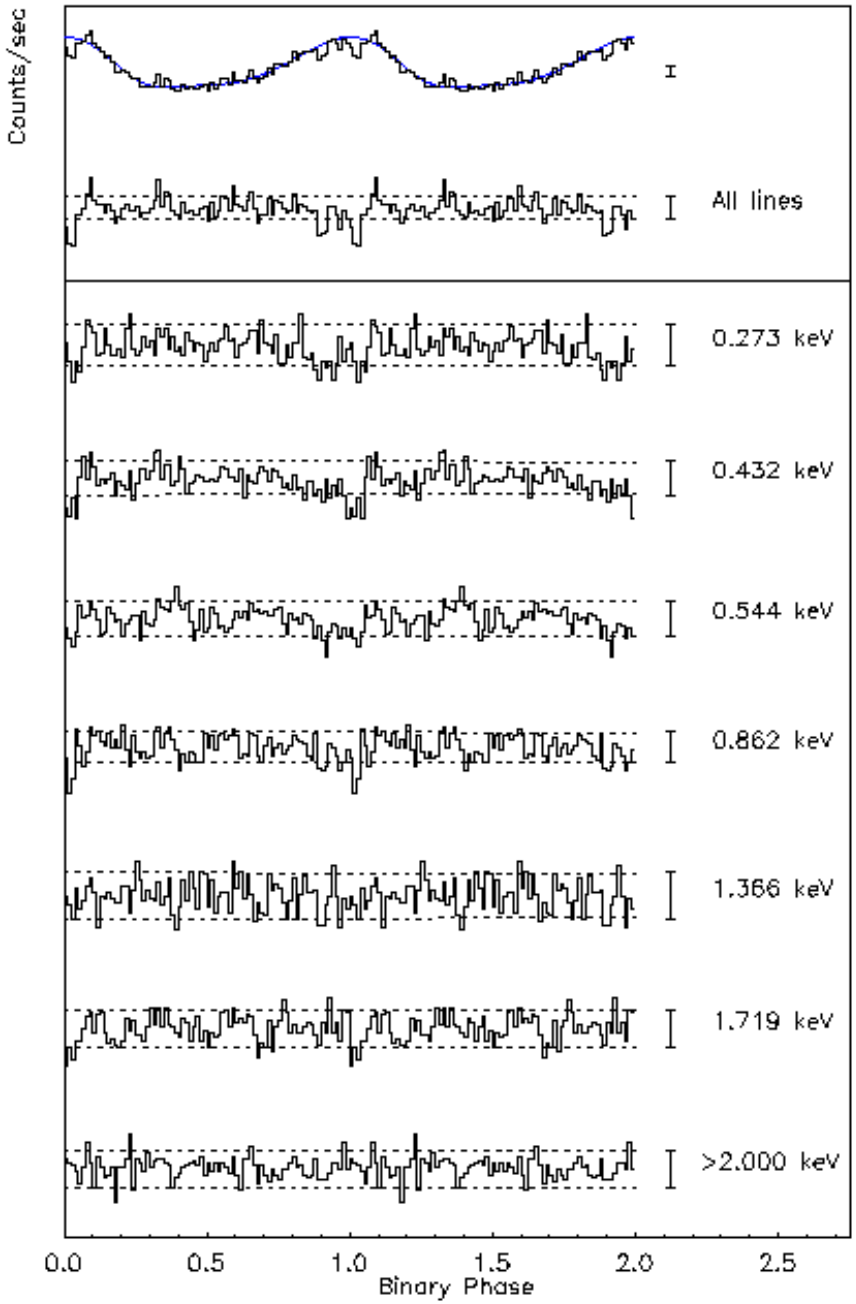


Illustration by Andy Beardmore

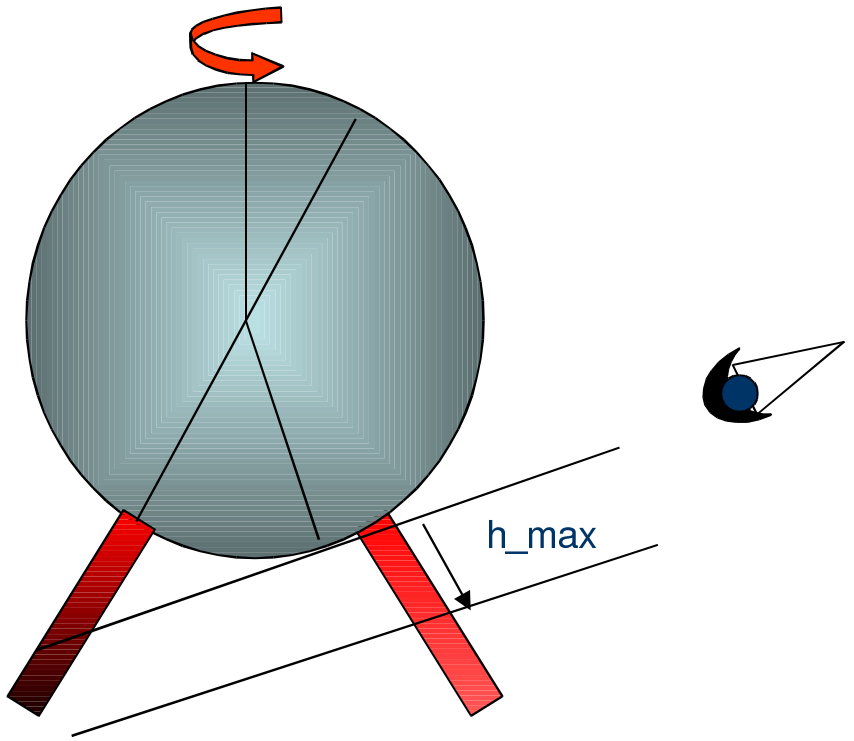
White Dwarf Velocity Measurements

Chandra	54.5 km/s	(Hoogerwerf, Brickhouse, & Mauche 2003, in prep)
Optical	69 ± 9	(Hellier et al. 1987)
UV	59.6 ± 2.6	(Belle et al. 2003)
FUV	85 ± 9	(Mauche 1999)

Measuring the Height of the Accretion Column Shock?

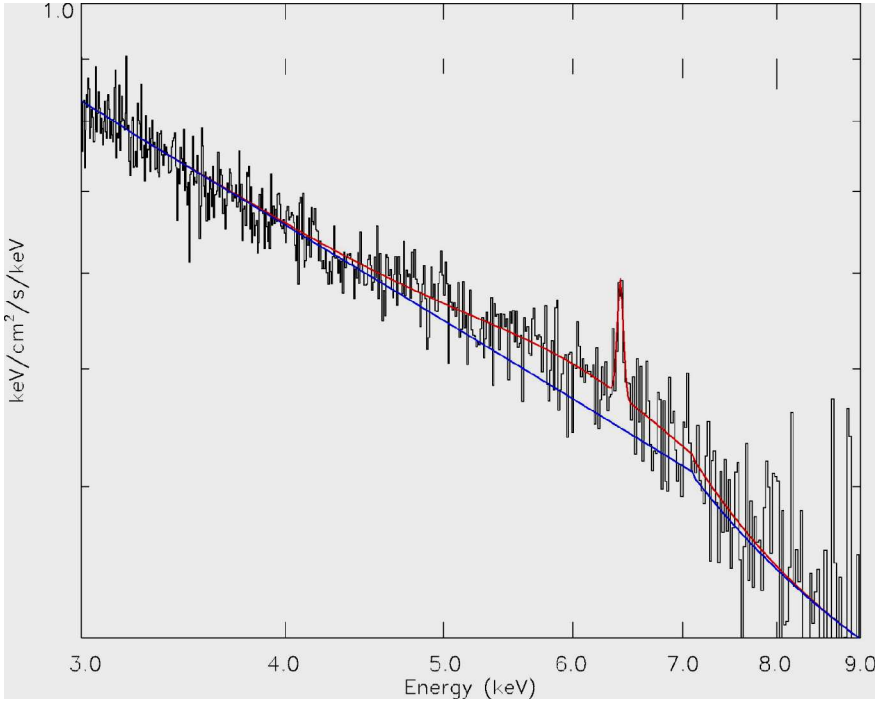


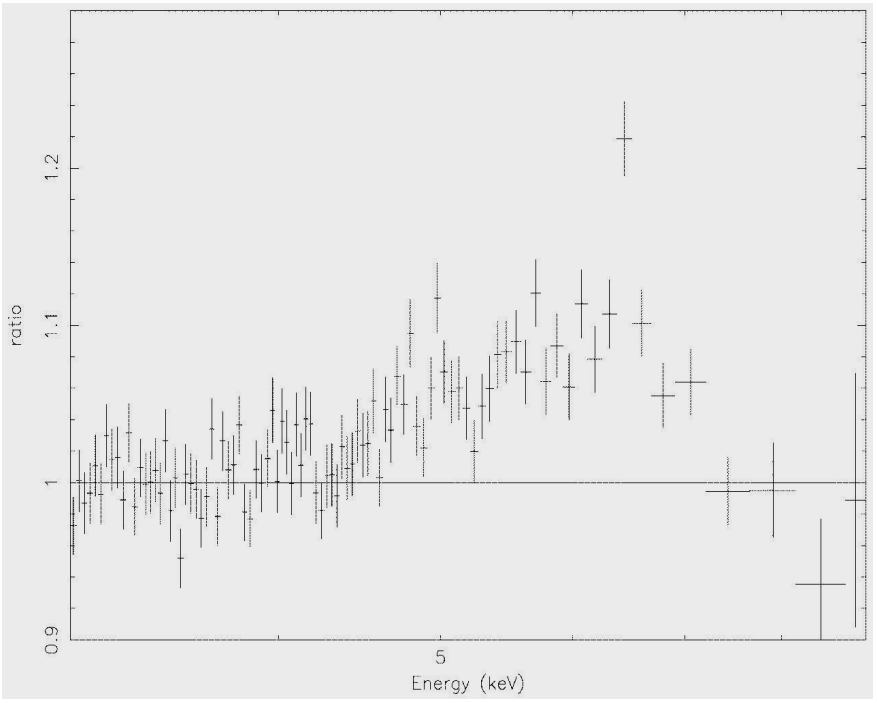
Chandra HETG Fe XVII and Fe XXII indicate 10^{14} cm^{-3} (Mauche et al. 2002). Light curves from lines are different (Hoogerwerf, Brickhouse & Mauche 2003).



Model from ASCA (Allan, Hellier, & Beardmore 1998)

Fe Kα Emission from a Black Hole



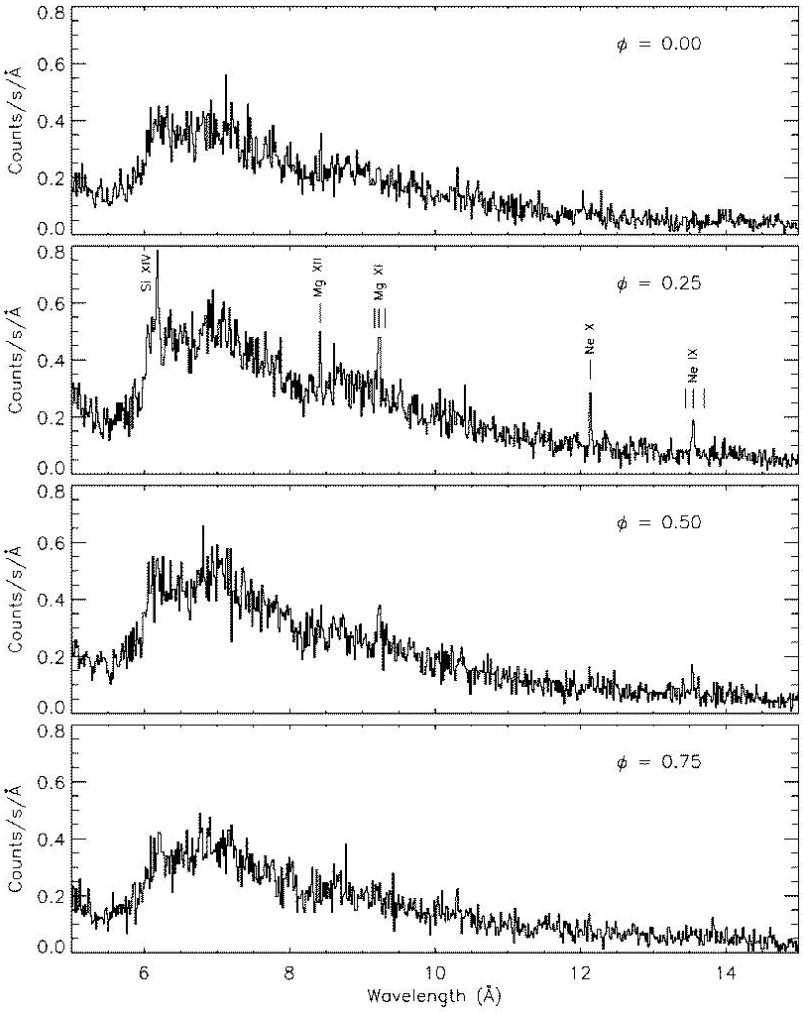


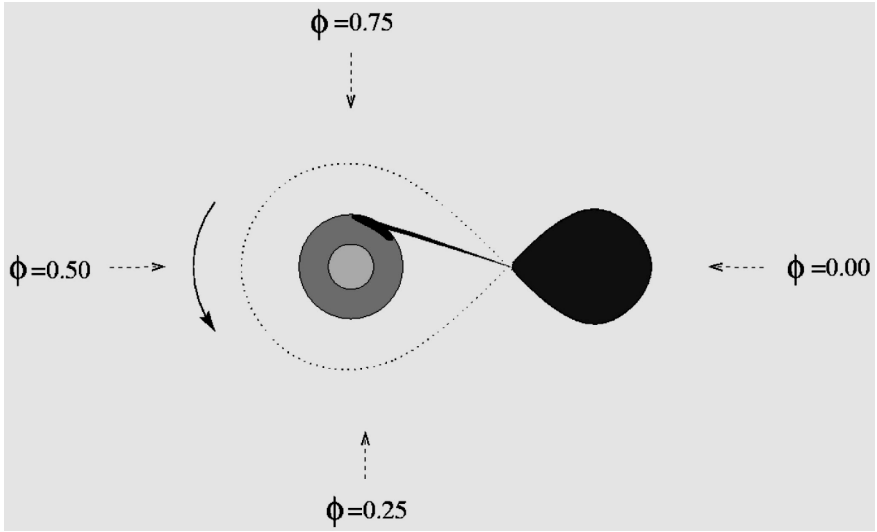
Chandra HETG
Cyg X-1 (HMXB)
Miller et al. 2002

Fe Kα reminiscent of broad iron lines in AGN. Continuum is a multicolor disk plus blackbody.

See also Schulz et al. 2002 for softer spectrum, showing absorption lines and edges.

Accretion Disk Corona in an LMXB

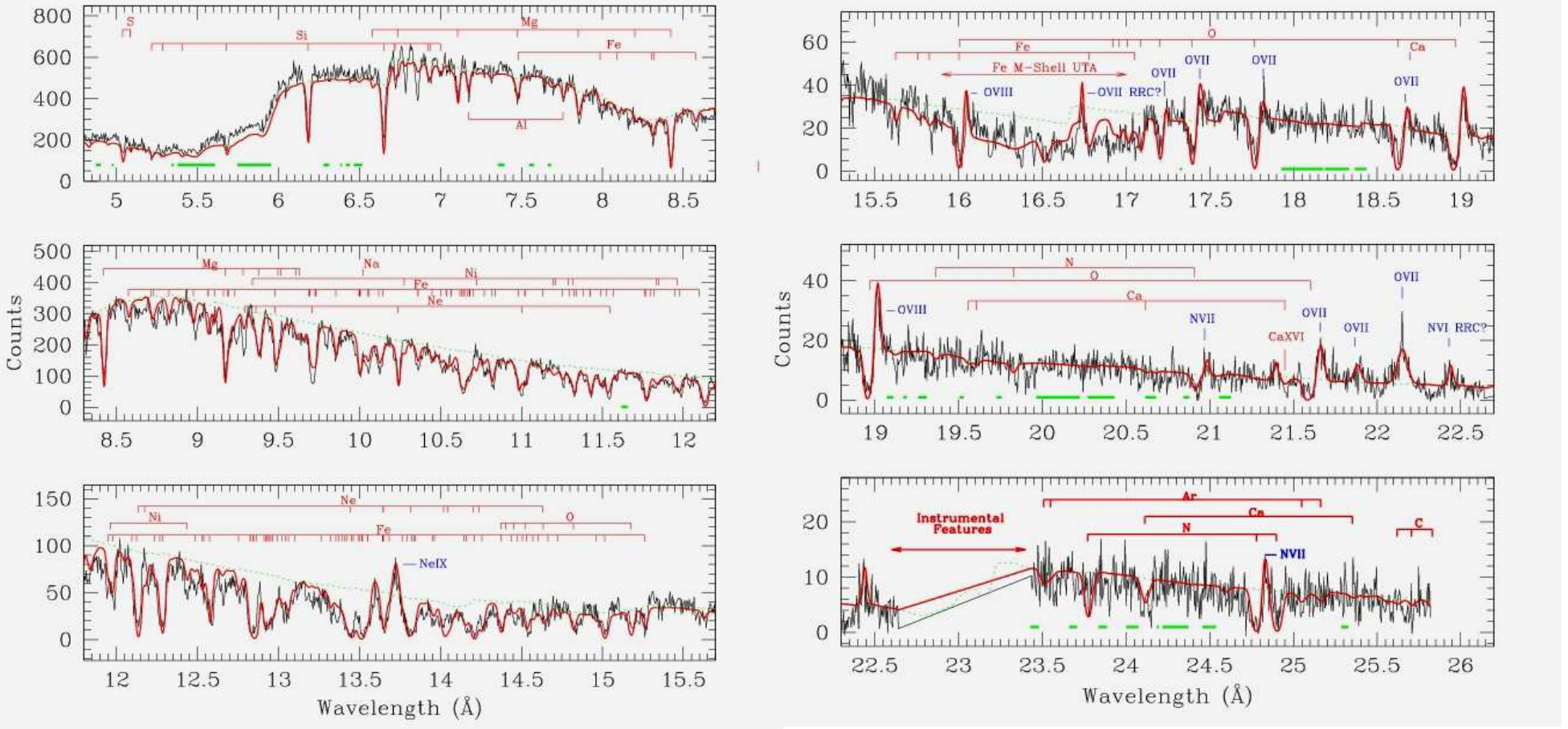




Recombination lines from X-ray illuminated bulge where accretion stream impacts disk. Fluorescent Fe Kα from extended disk corona or accretion stream.

Chandra HETG
4U 1822-37 (LMXB)
Cottam et al. 2001

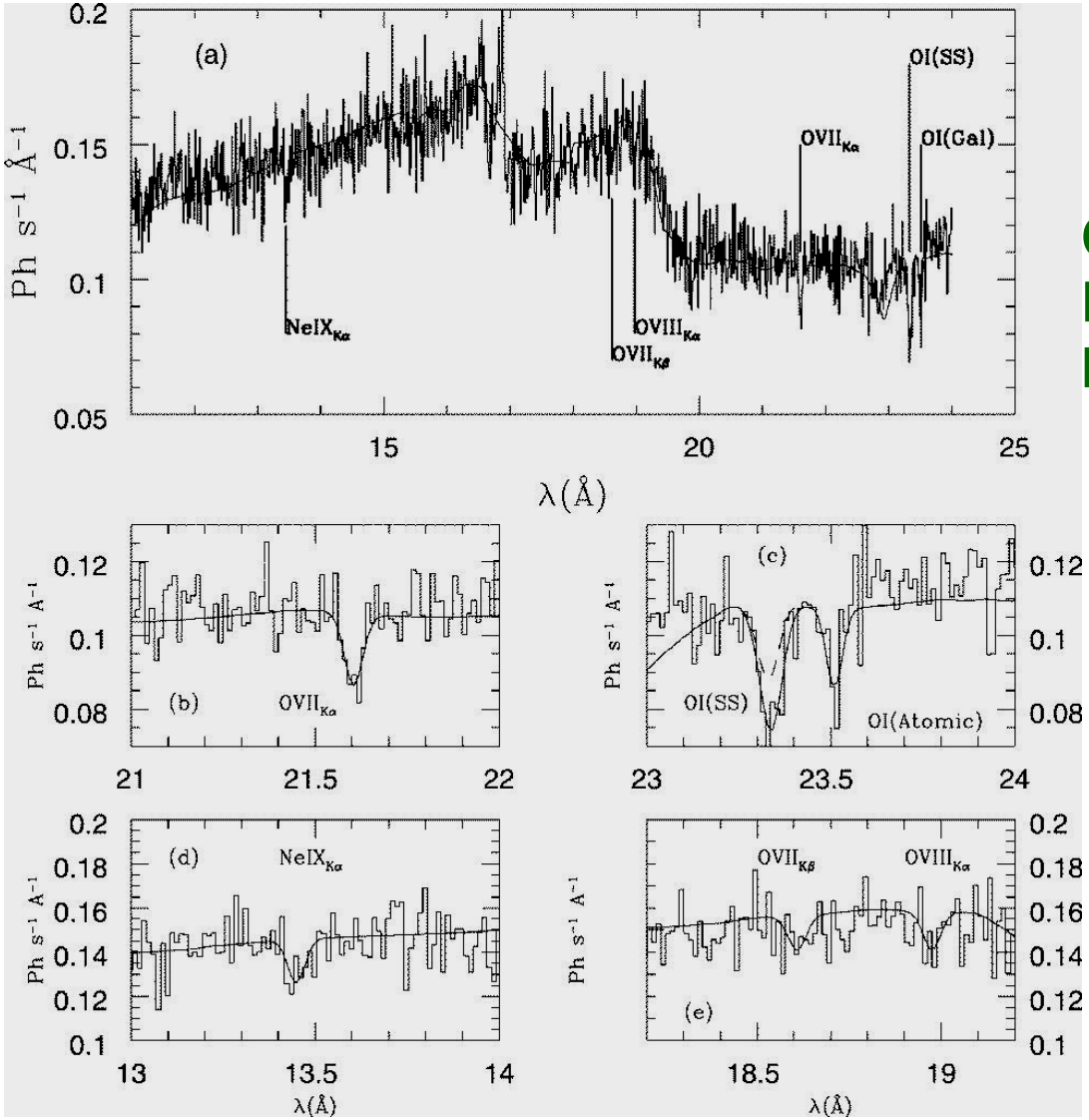
Absorption by Photoionized Gas in NGC 3783



Model fit with 2 kinematically identical ionization components, outflowing velocities of 750 km/s, turbulent velocities of 300 km/s, suggesting they are in pressure balance.

Chandra HETG Krongold et al. 2003

Resonant Absorption Toward PKS 2155-304



Chandra LETG
PKS 2155-304 (blazar)
Nicastro et al. 2002

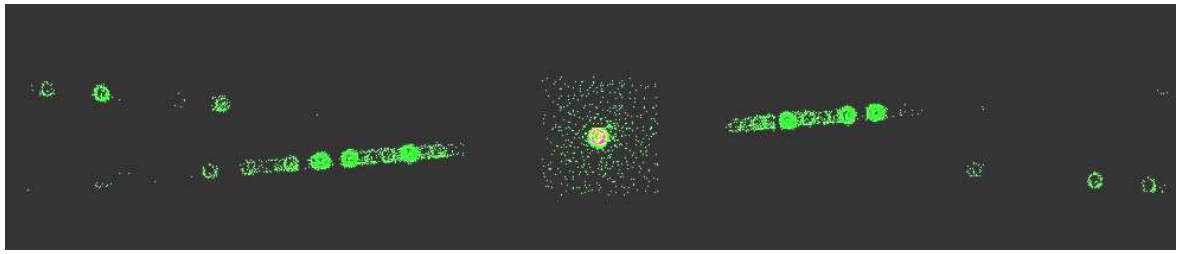
X-ray Forest of O VII, Ne IX, (5 σ) at same redshift as FUSE O VI lines, argues for low density IGM.

Conclusions

- Stellar coronae not just extrapolated Suns
- Hot star wind shock models
- High density accretion shock cooling in magnetic CVs
- Accretion and winds in X-ray binaries
- AGN “warm absorbers”: 2-component outflow in pressure balance
- Detection of the WHIM

8. Challenges:

- Enough Photons
- Beyond Point Sources
- Sophisticated Source/Spectral Models



HETG Spectrum
Flanagan et al. 2003
SNR E0102-72:
An ionizing shock