High Energy Astrophysics
X-RAY SPECTROSCOPY AND ATOMIC DATA

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Collaborators

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  The *XMM-Newton* / RGS Consortium:
  Teams from SRON, MSSL, PSI

  LLNL, EBIT team:
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  Hui Chen (and Goddard calorimeter team)

Outline

- Introduction:
  - **The Soft X-Ray Band**
  - ***Chandra* and *XMM-Newton***
- Collisional Plasmas
  - **Cool Stars - Stellar Coronae**
  - **Hot Stars – Shocks in Stellar Winds**
  - Supernova Remnants
  - Elliptical Galaxies
  - **Galaxy Clusters – Big blobs of gas;Cooling Flows?**
  - **Atomic Data Needs**
    - **Needs, Fe-L**
    - **Laboratory Measurements and Status**
- Photoionized Plasmas
  - **Active Galactic Nuclei**
    - **Absorption**
    - Emission
  - X-Ray Binaries
  - **Atomic Data Status and Supporting Lab. Measurements**
- Conclusions

Introduction

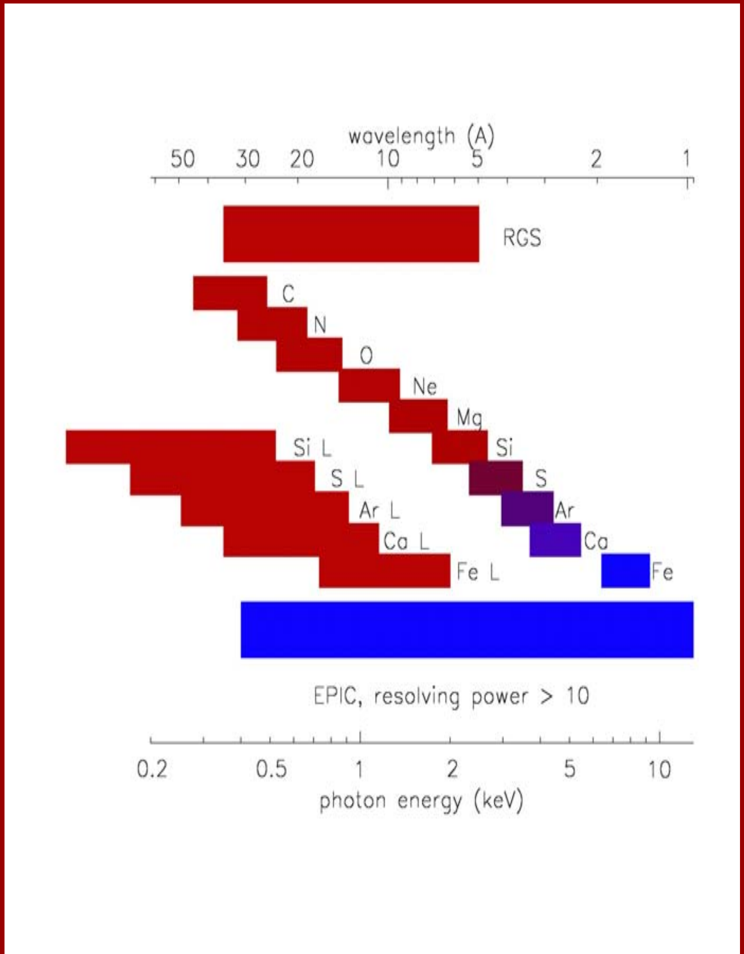
- X-Ray Astronomy was born in 1962 with the discovery of Scorpius X-1.
- Over the years x-ray observatories have revealed a diverse collection of x-ray sources ranging from nearby stars to distant galaxies.
- However, it wasn’t until the recent launches (1999) of *Chandra* and *XMM-Newton* that x-ray line-resolved spectra have become available.
- With this recent achievement, the x-ray branch of astronomy now joins other wavebands in using spectroscopy to perform quantitative investigations of cosmic objects.

Features of the X-Ray Band: Highly Ionized Atoms

- The conventional (soft) x-ray band (1 to 100 Å or ~ 0.2 – 10 keV) comprises emission lines from many K-shell and L-shell ions pertaining to many elements (C – Ni).

- The x-ray band is uniquely compact, having several ions appear from each element and many lines being present from each ion.

- The wealth of lines and ions allows for elaborate plasma diagnostics such as temperatures, densities, ionization state, and elemental abundances.



A New Era in X-Ray Astrophysics: *Chandra* and *XMM-Newton*

- The *Chandra* Observatory (NASA):
  Launched July 23, 1999
  1 telescope
  2 CCD cameras
  2 transmission grating spectrometers (spectroscopy mode is alternative to imaging)

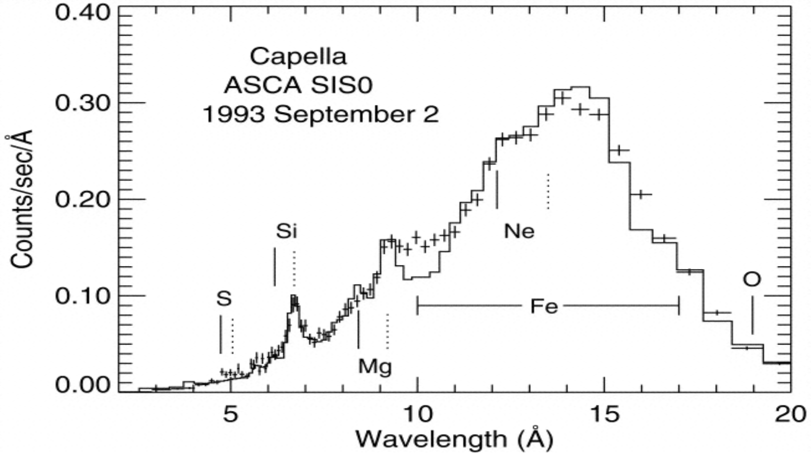
- *XMM-Newton* (ESA):
  Launched December 10, 1999
  3 telescopes
  2 reflection grating spectrometers
  1 Optical/UV monitor

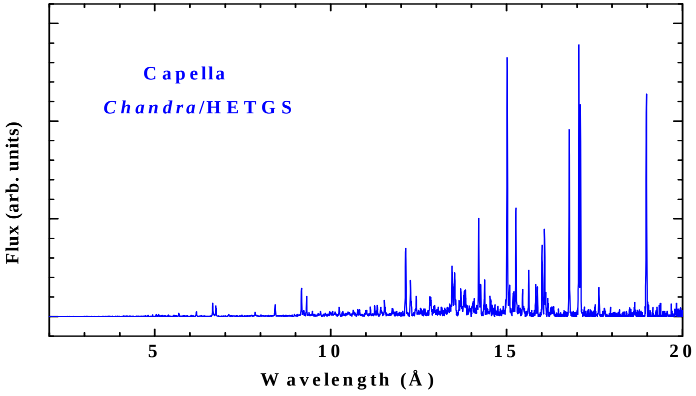
The Difference High Spectral Resolution Makes

- ❖ CCD spectrum of Capella with ASCA

  (Brickhouse, Dupree, Edgar et al. 2000)

- ❖ Grating spectrum of Capella with *Chandra*

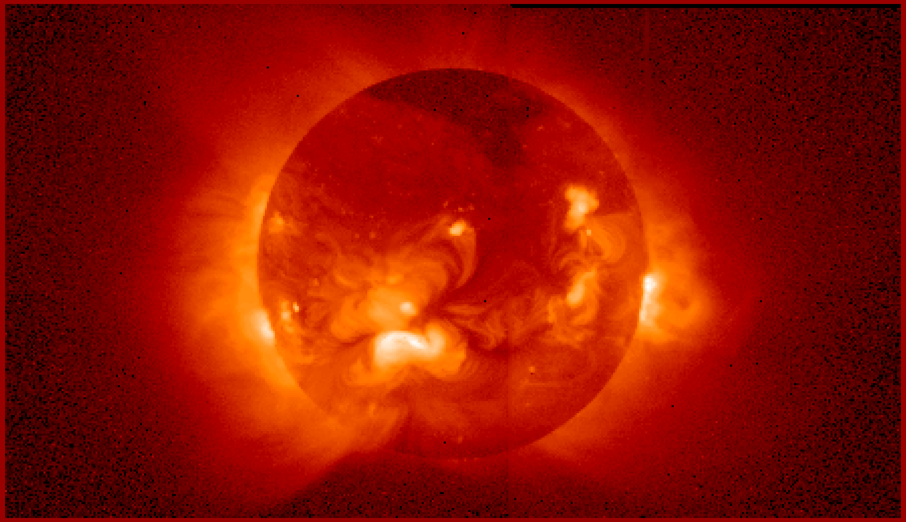




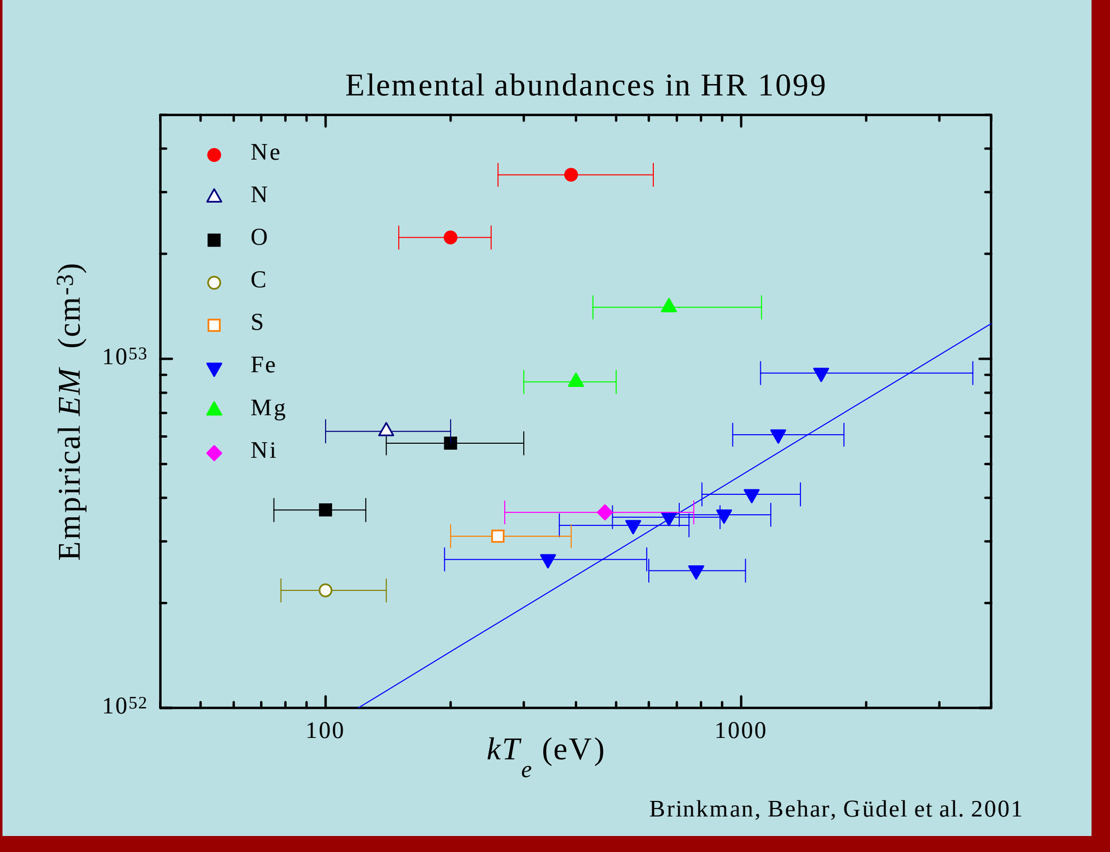
Behar, Cottam, & Kahn 2001

Stellar Coronae:
Hot, Collisional X-Ray Sources

- Physical environment:
  - Magnetic confinement
  - Hot ($kT \sim 0.1 - 3$ keV)
  - Density ($n \sim 10^{10}$ cm^{-3})
  - Optically thin
- Ionization balance:
  - Standard electron-ion collisional processes: CI, RR, as well as EA and DR
- Line emission:
  - Collisional excitation



Stellar Coronae (cont.): Emission Measure and Abundances

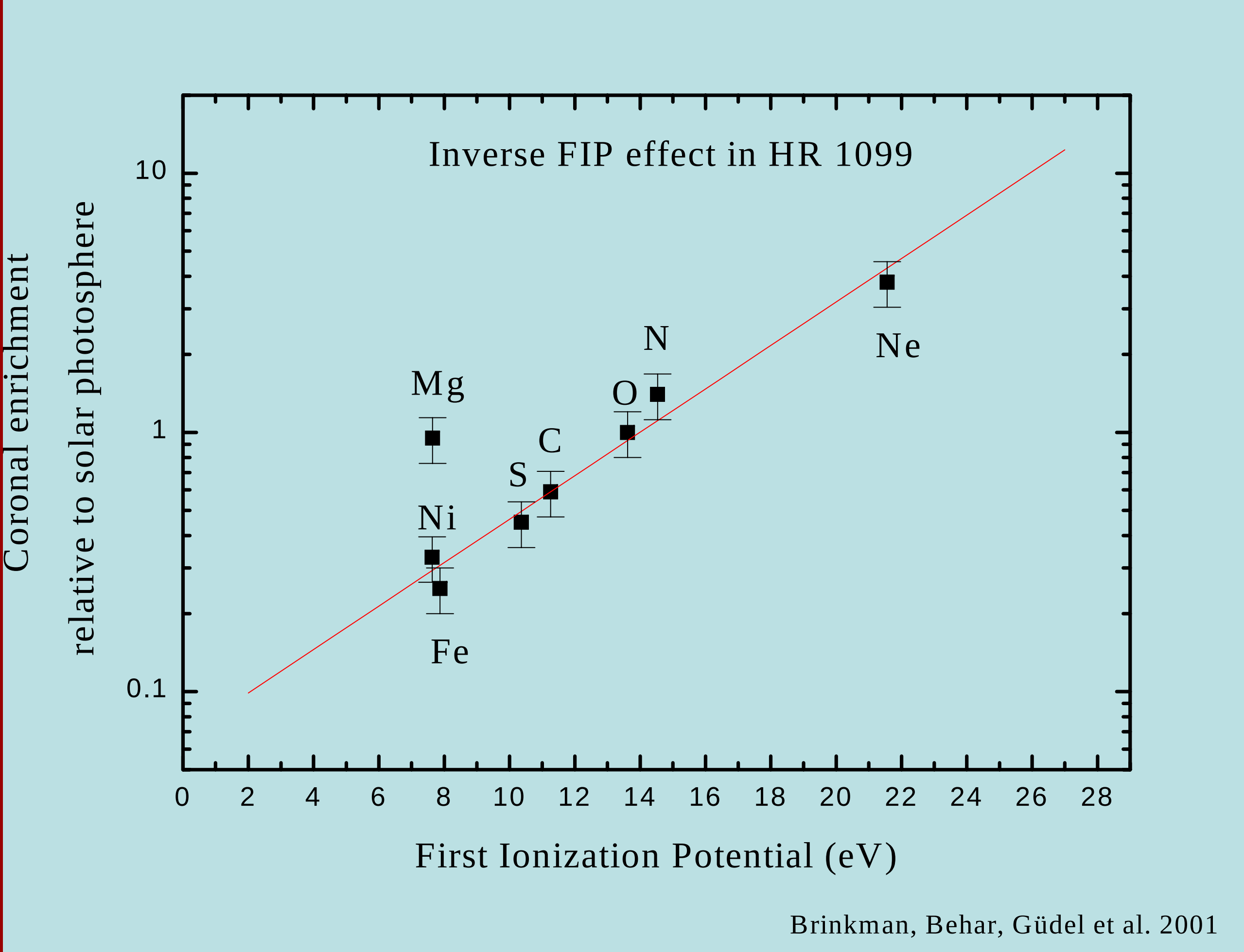


Brinkman, Behar, Güdel et al. 2001

$$n_e n_H V = \frac{4\pi d^2 F_{ji}}{A_{el} P_{ji} f_q(T_e)}$$

F_{ji} – measured
d – known
A_{el} – assumed solar
P_{ji} , f_q – atomic physics

Stellar Coronae (cont.)
Inverse FIP Effect



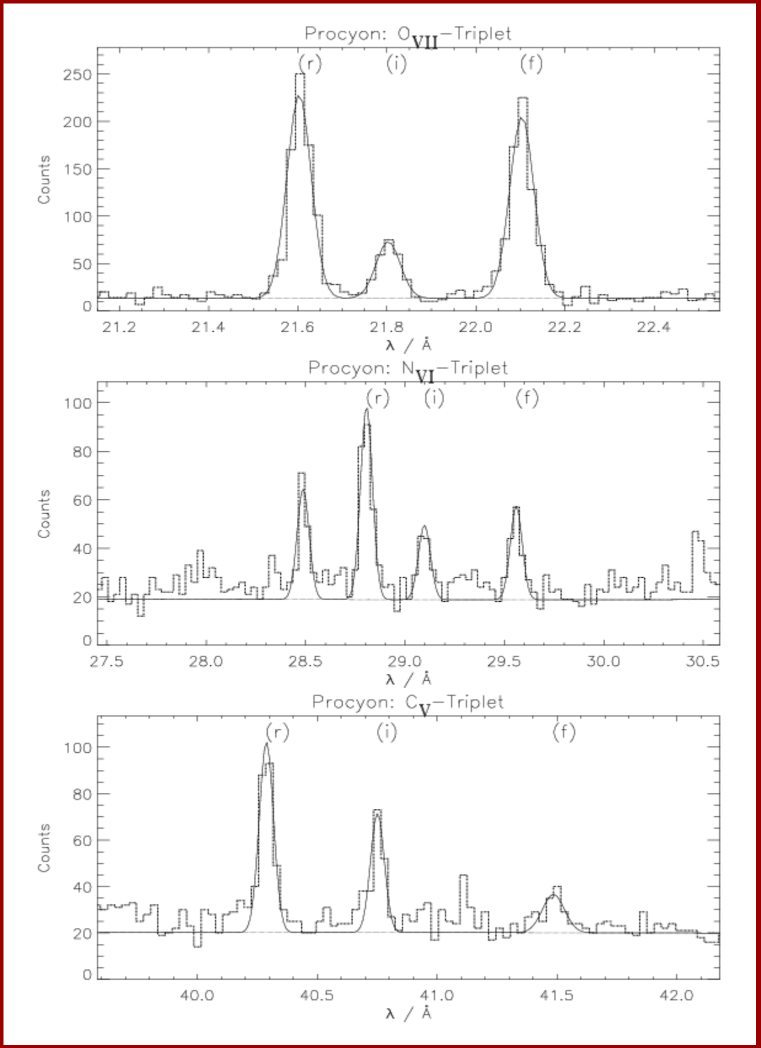
Brinkman, Behar, Güdel et al. 2001

Density Diagnostics

- Collisional depletion of excited levels of forbidden lines.

- Most popular are the He-like triplets (Gabriel & Jordan 1969). The 1s-2s forbidden line is suppressed at high densities.

- Critical density depends on element.



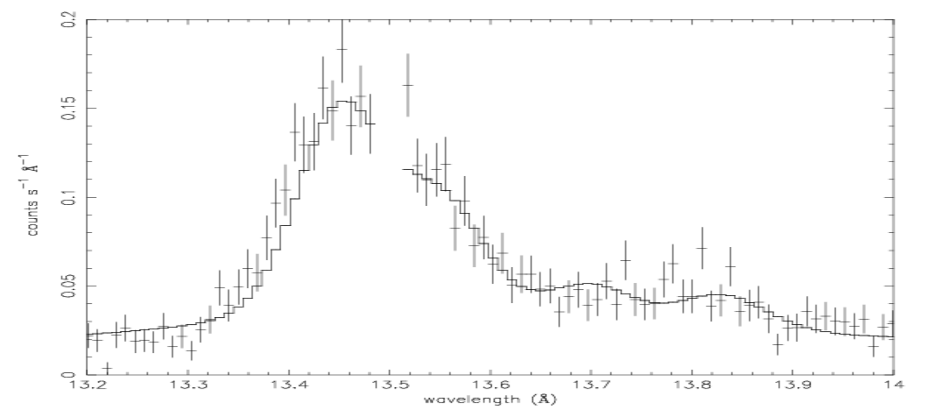
Ness, Mewe, Schmitt et al. 2001

Hot Stars:
UV depletion of excited levels

- UV depletion of excited levels mimics density effects.

- Example: He-like triplets in ζ Pup.

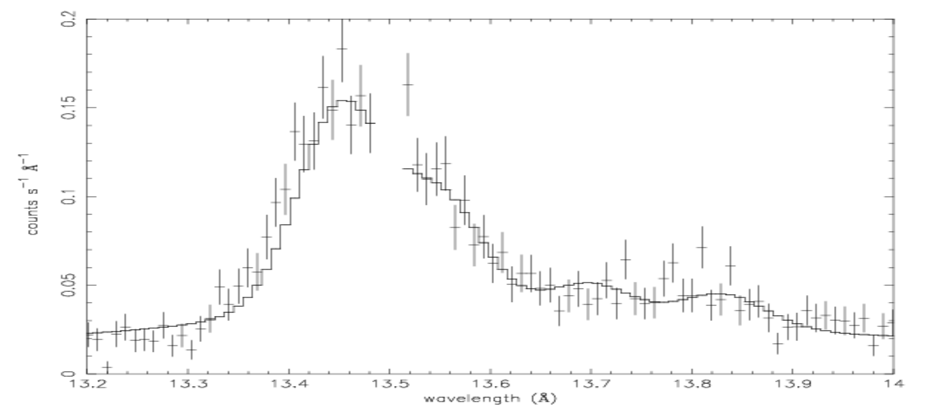
- Provides measurements of distance from photosphere.



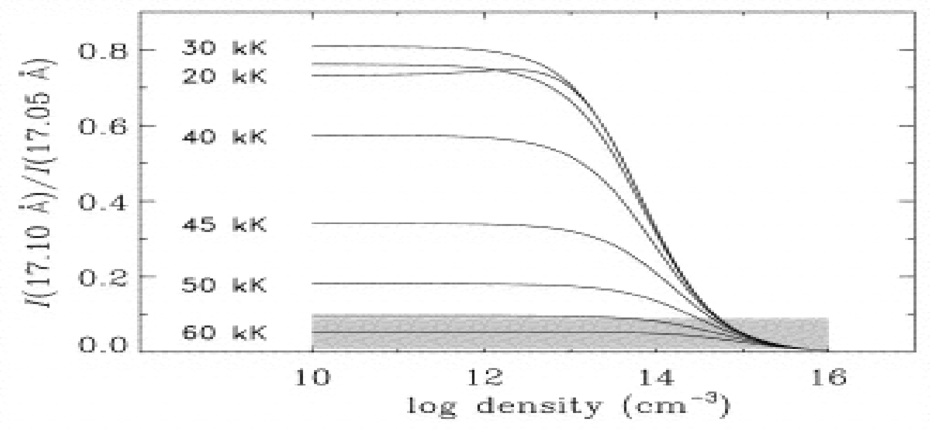
ζ Pup; Kahn, Leutenegger, Cottam, et al. 2001

Hot Stars (cont.)

- UV depletion of excited levels mimics density effects.
- Example: He-like triplets in ζ Pup.
- Provides measurement of distance from photosphere.
- Another example: 2p-3s forbidden line of Fe^{16+} in the magnetic CV (EX Hya).



ζ Pup; Kahn, Leutenegger, Cottam, et al. 2001



Mauche, Liedahl, & Fournier 2001

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- Introduction:
  - **The Soft X-Ray Band**
  - ***Chandra* and *XMM-Newton***
- Collisional Plasmas
  - **Cool Stars - Stellar Coronae**
  - **Hot Stars – Effect of UV field**
  - Supernova Remnants
  - Elliptical Galaxies
  - **Galaxy Clusters – Where Are The Cooling Flows?**
  - **Atomic Data Status and Supporting Lab. Measurements**
- Photoionized Plasmas
  - **Active Galactic Nuclei**
    - **Emission**
    - **Absorption**
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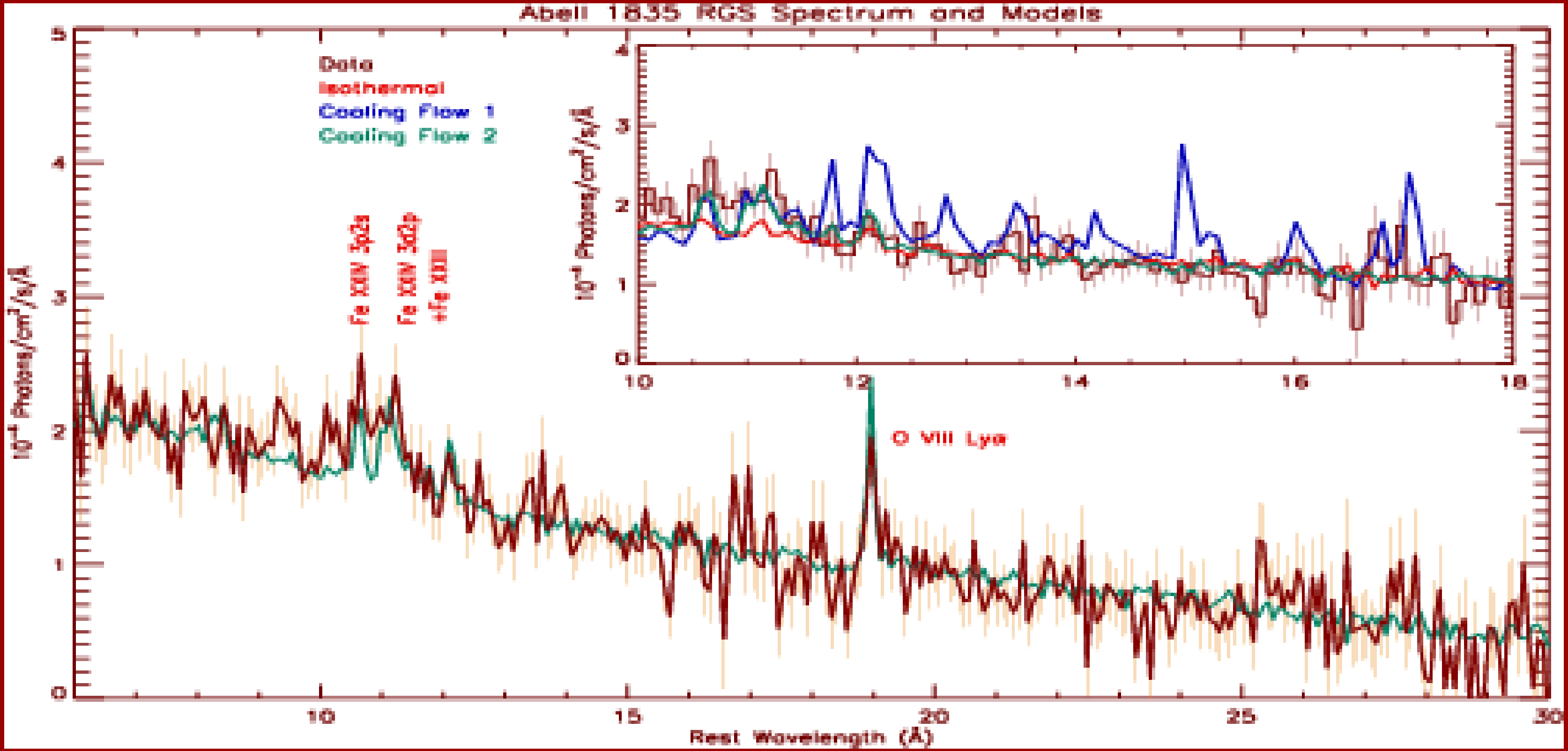
- Conclusion and Discussion on Atomic Data Needs

Galaxy Clusters: What Happened to the Cooling Flows?



Peterson, Paerels, Kaastra et al. 2001

Collisional Plasmas: Atomic Data Needs

- Processes and Data
  - Generally important
    - Wavelengths
    - Collisional emissivities
    - Total ionization and recombination rates
  - More specific
    - Transitions among excited states
    - Ionization and recombination effects on line emission
      - Ionization equilibrium and non-equilibrium
    - Charge exchange

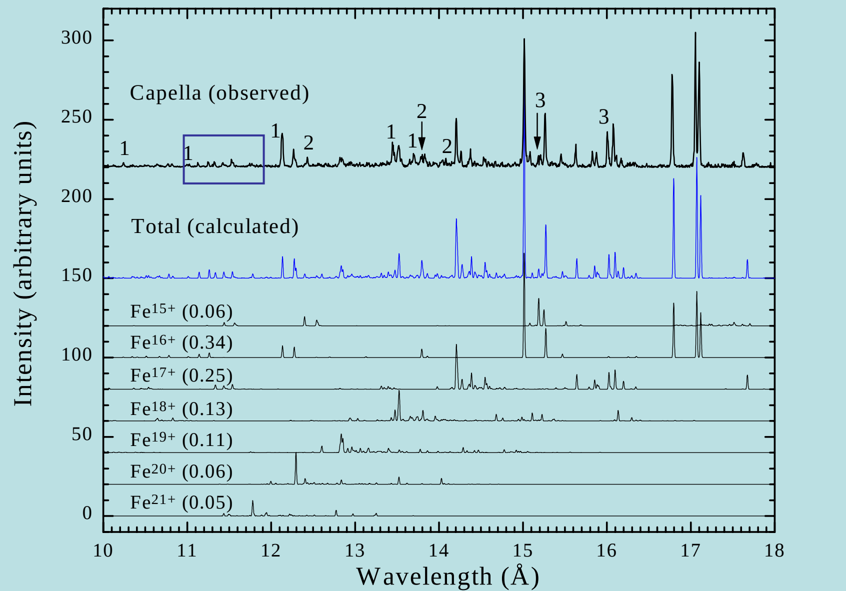
- Ions
  - K-shell of C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni
  - L-shell, particularly Fe, but also Ne, Mg, Si, S, Ar, Ca, and Ni

Fe-L Physics

- 2p-3d and 2p-3s lines of Fe^{16+} - Fe^{23+} dominate the soft x-ray spectrum of many sources.
- Lines of different Fe-L ions are easily discernible with contemporary grating spectrometers, which provides a strong, abundance-independent constraint on the charge-state (T, EM) distribution.
- For years, Fe-L was the nightmare and scapegoat of many x-ray astronomers. Unjustly so!
- The Columbia-LLNL Laboratory Astrophysics program has focused on Fe-L, and along with efficient atomic codes has gone a long way to serve us observers and help us exploit the full potential of Fe-L diagnostics.
- Where possible, it still makes a lot of sense to use single-ion models independent of the ionization balance.

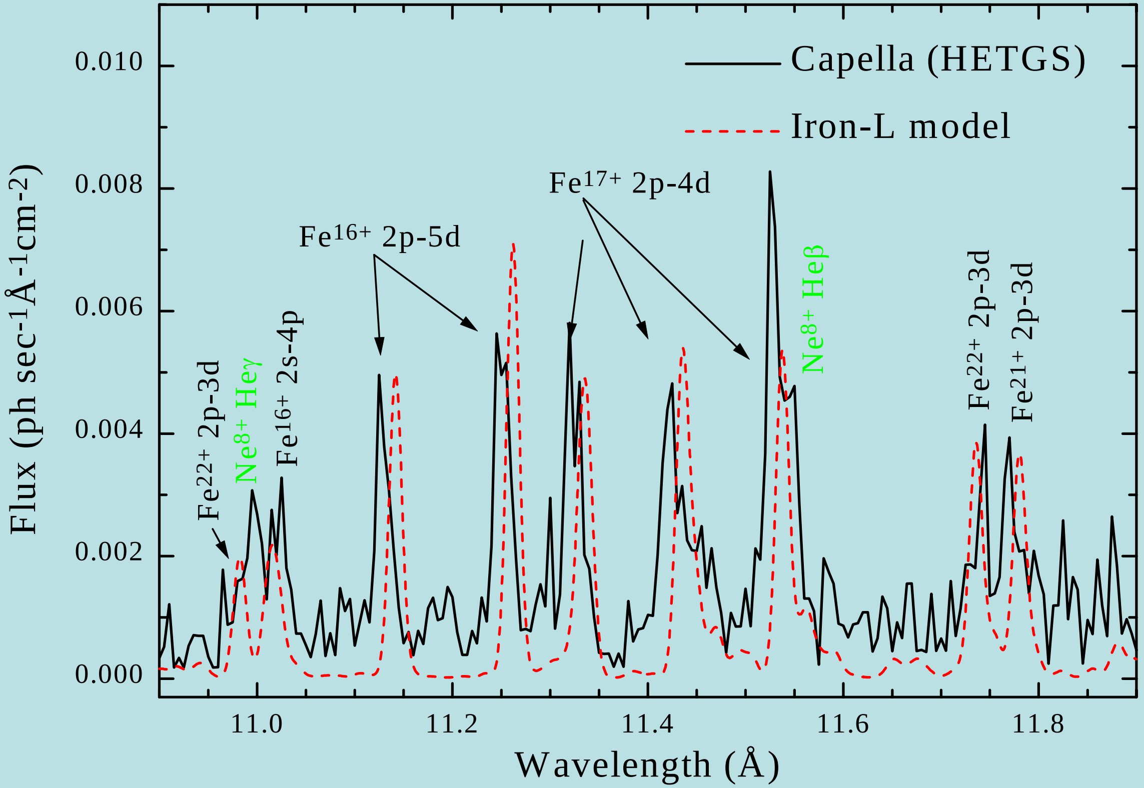
Capella as a Test Case for Fe-L

- ❖ Fe-L dominates.
- ❖ Ab initio DW single-ion calculations (HULLAC) are not so bad.
- ❖ In particular, all lines are identified unambiguously.
- ❖ Most relative line intensities agree to within 20%.
- ❖ Nevertheless, a few outstanding discrepancies remain.



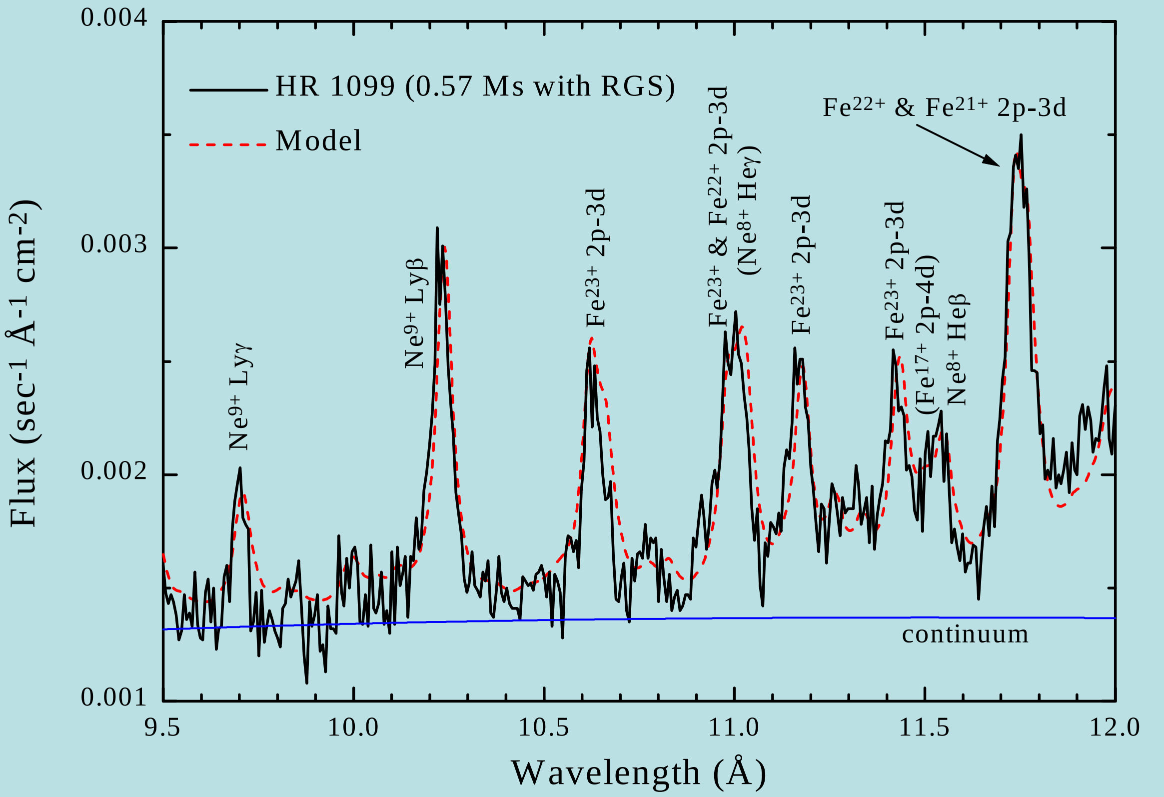
Behar, Cottan, & Kahn 2001

Are Fe-L Data Really that Bad?



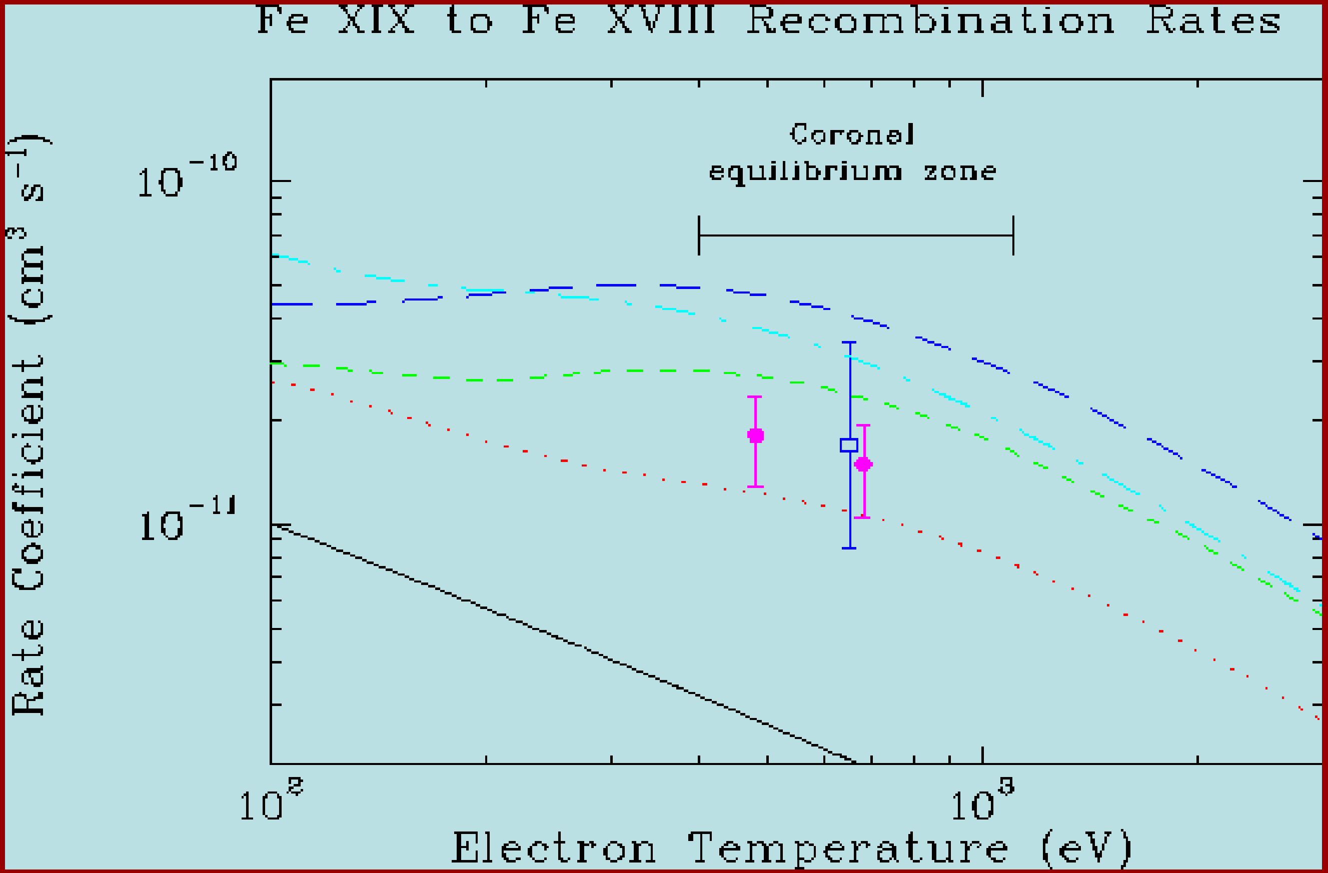
Behar, Cottam, Peterson, et al. 2001

HR 1099 / RGS: Arguably, The Highest Quality X-Ray Spectrum



Behar, Cottam, Peterson, et al. 2001

Dielectronic Recombination (DR): Not Doing As Good



Courtesy of Daniel Savin

Collisional Plasmas:
Fe-L Laboratory Measurements

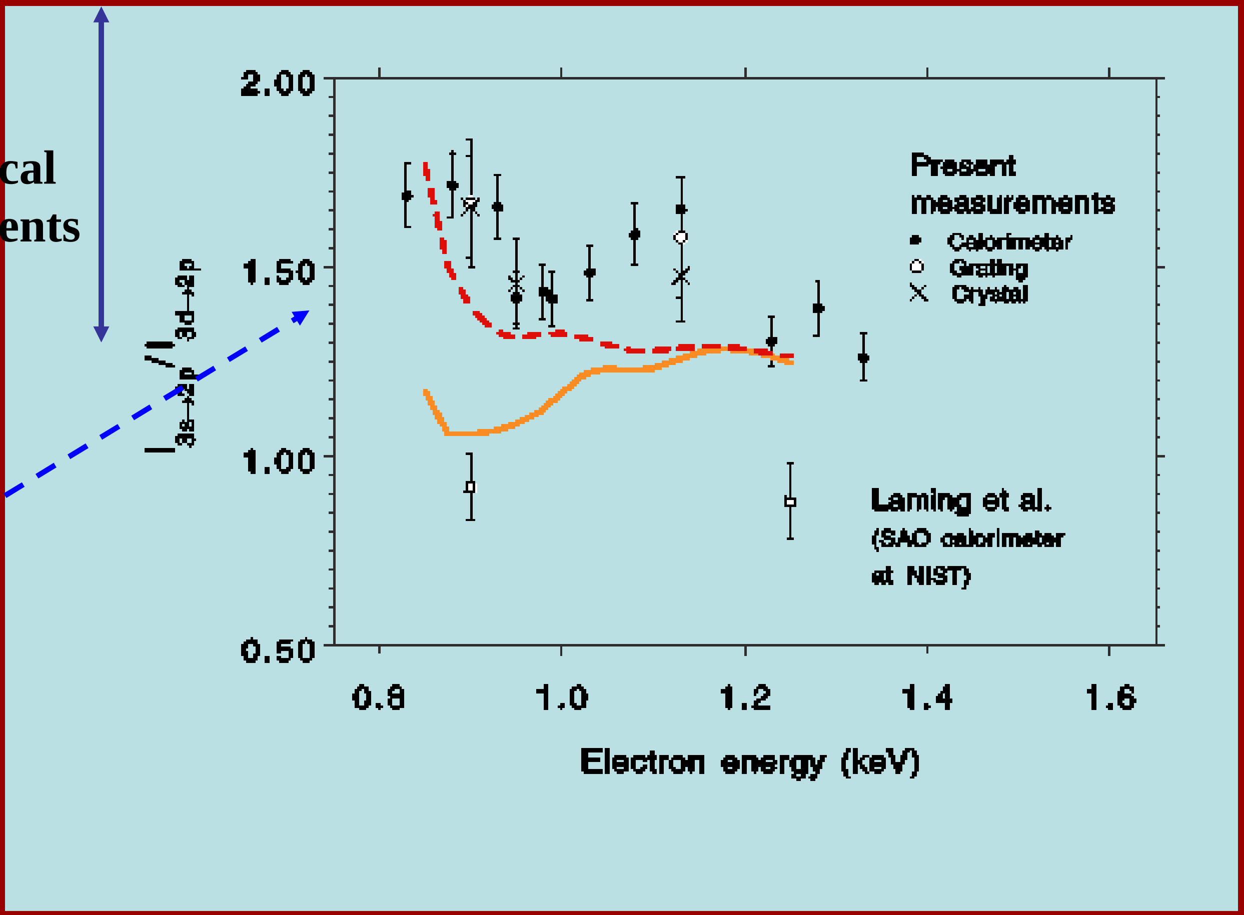
- Wavelengths
  - LLNL EBIT: Brown et al., 1998, 2000
- CE rates / line emissivities
  - LLNL EBIT with crystal spectrometer: Savin et al. 1996, Gu et al. 1999, 2001
  - LLNL EBIT with microcalorimeter: Chen et al. 2002
- Line ratios
  - LLNL EBIT: Brown et al. 1998, 2001
  - NIST EBIT: Laming et al. 2000
  - LLNL EBIT: Beiersdorfer et al. 2002
- Ionization balance
  - TSR: DR rates, Savin et al. 2002
- Other non-Fe-L works:
  - NIST EBIT: Silver et al. 2000, LLNL EBIT: Lepson et al. 2002

The Tale of Fe^{16+}: What's the matter with the 2p-3s lines?

Low-T_e
with RE
(D&B)

Various
astrophysical
measurements

High-T_e with DR
~ 40% effect
(Doron & Behar)



Beiersdorfer, Brown, Gu et al. 2002

Collisional Plasmas: Atomic Data Status

Expected Confidence Levels (Ball Park) and Experimental Benchmarking

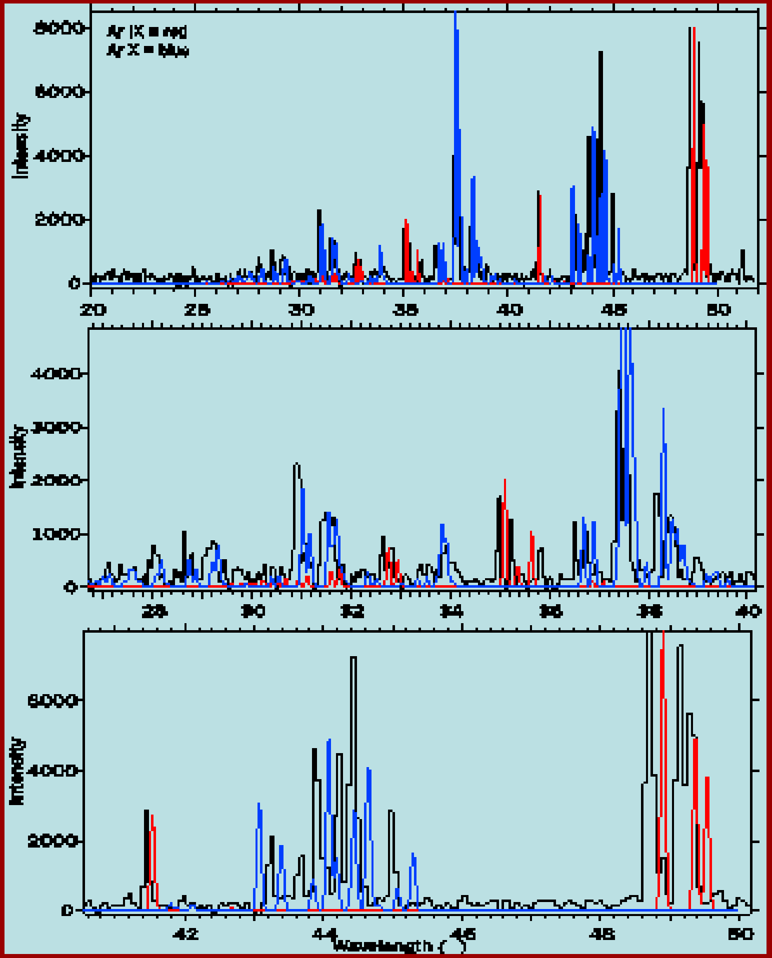
Shell Data	K	K (Fe)	L	L (Fe)
Wavelengths	0.01%	0.01%	0.5%	0.03%
Emissivities	10%	10%	50%	10-20%
Tot. Ionization	20%	20%	30%	30%
Tot. Recomb.	20%	20%	100%	20%
Transitions excited levels	50%	50%	50%	30%

Ongoing and Future Work:
Life After Fe-L

- **Ar IX & X,**

  Lepson et al.:

  EBIT LLNL measurements vs. HULLAC calculations



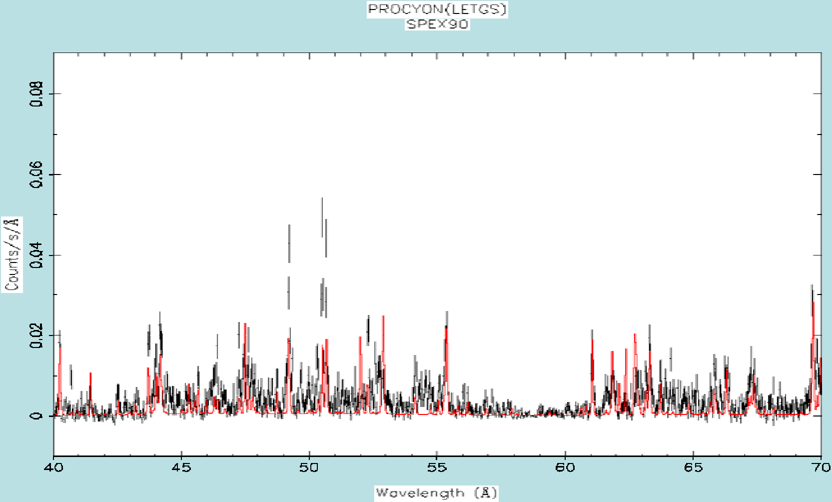
L-shells of Other Elements (contd.)

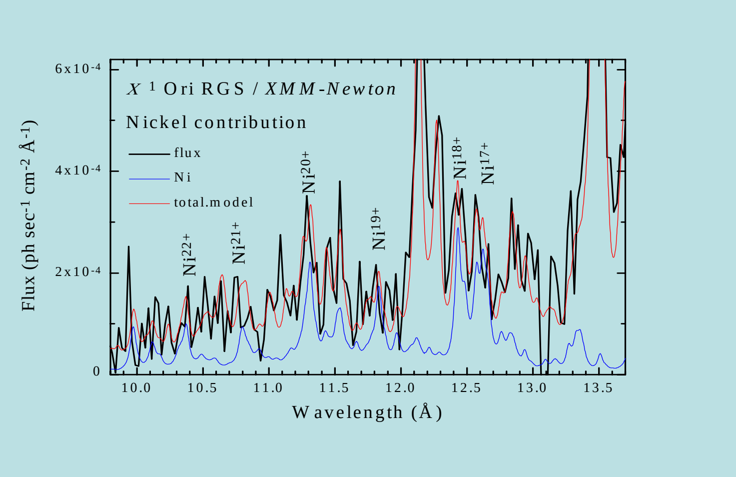
- Procyon (LETGS)

  Raassen, Mewe, Audard, et al. 2002

  Si, S – L are partially missing in the MEKAL database.

- X^1 Ori (RGS): Significant Ni-L contribution.





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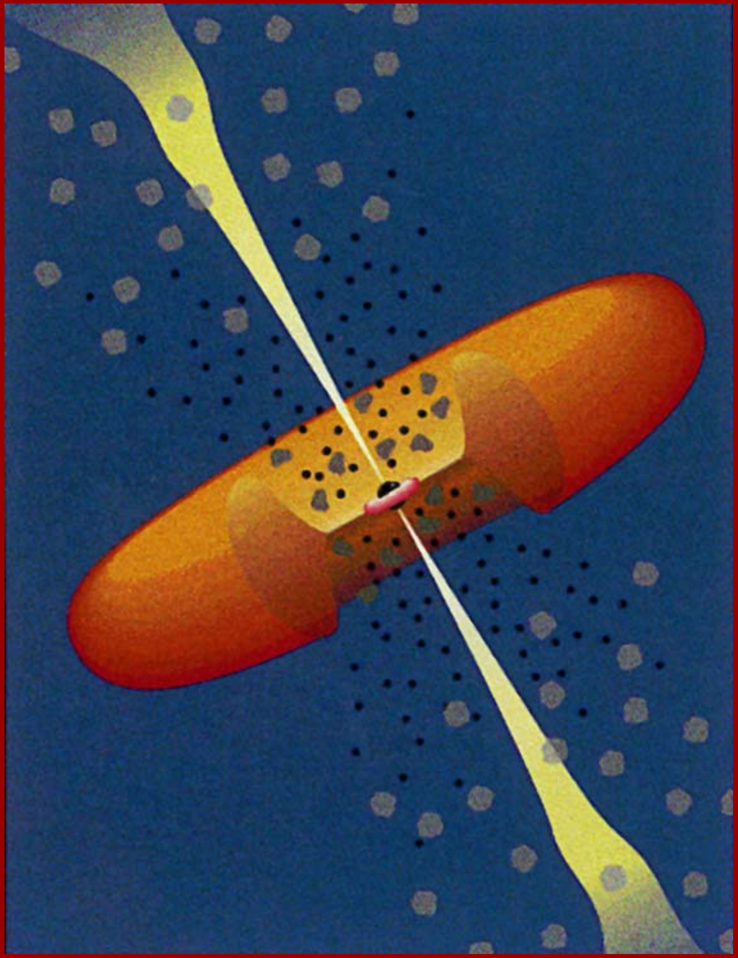
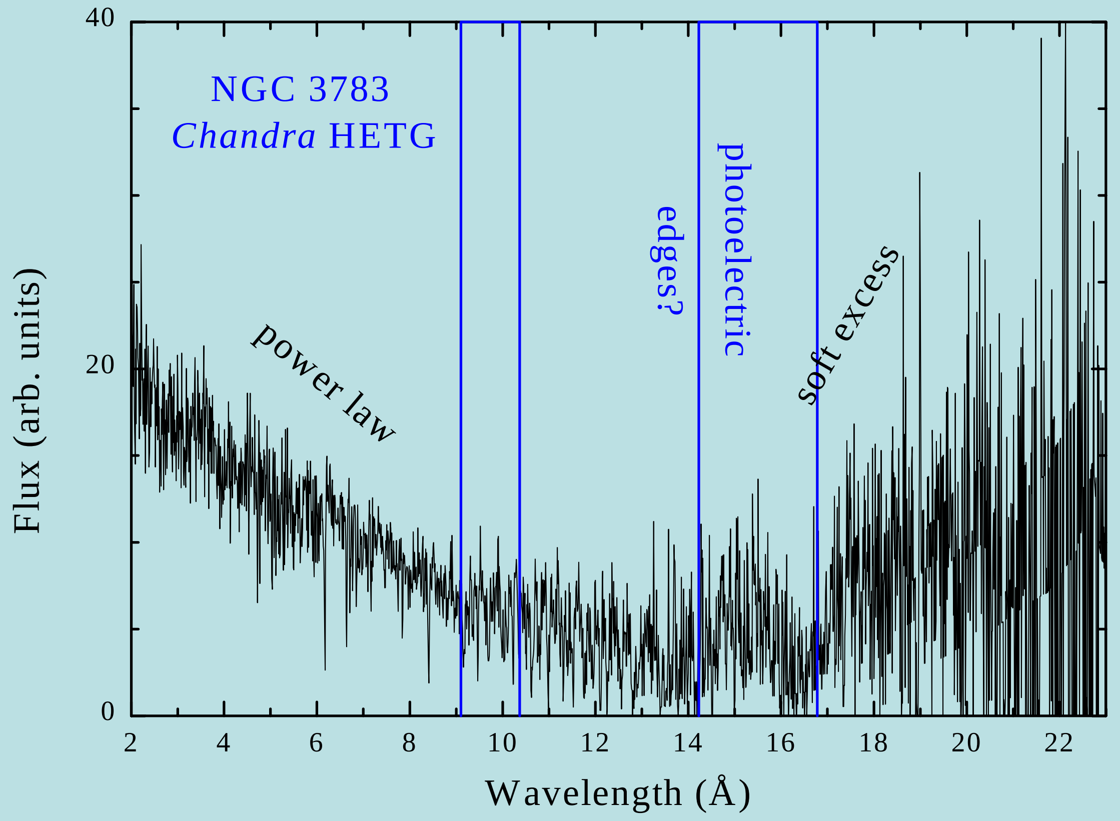
Photoionized Plasma

- Typically, created near accretion sources (X-ray binaries, AGN).
- Only external source of energy is radiation.
- Consequently, low temperatures compared to collisional plasma.
- X-ray emission mechanisms: radiative recombination (ensuing cascades), *photoexcitation*.
- Ionization balance governed by photoionization and $\Delta n = 0$ DR.
- Ionization state determined by ionization parameter (ξ).
- Hard to produce in the laboratory (remarkable exception: Z pinch featuring emission/absorption).

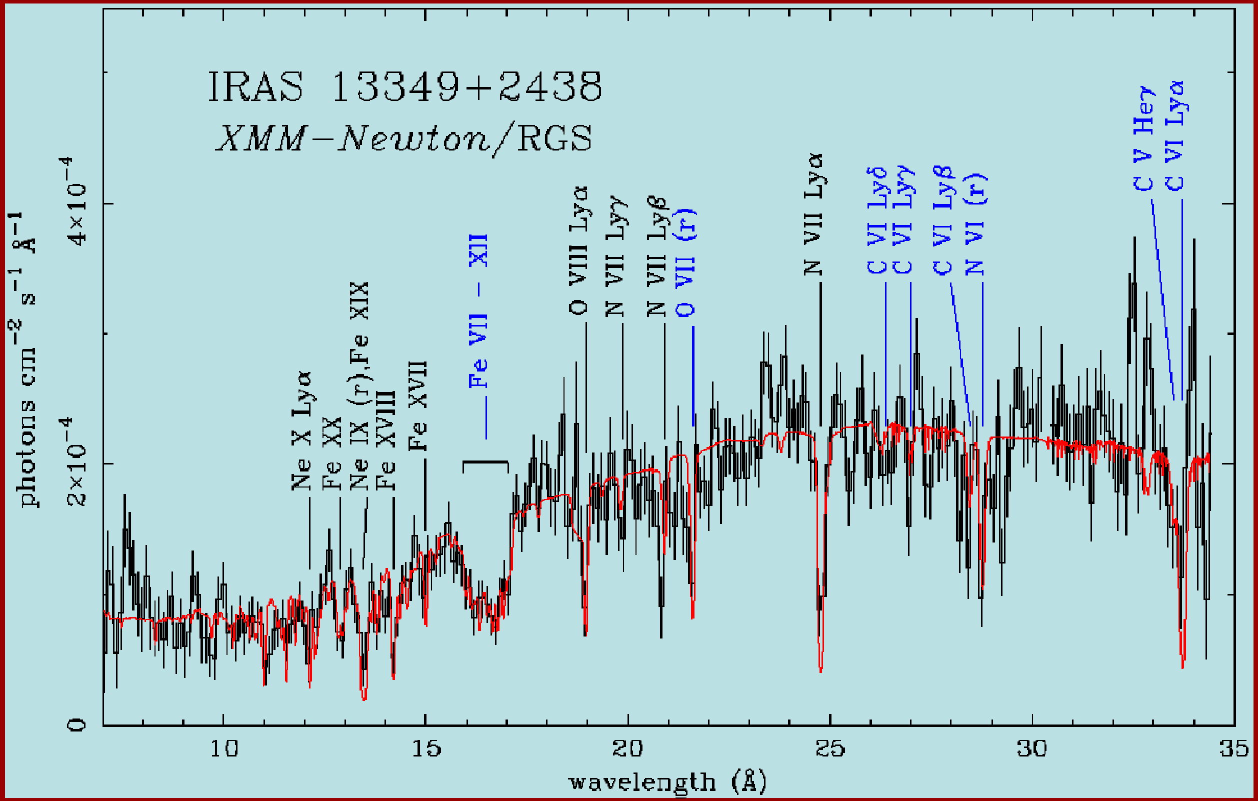


The Type-I AGN Scenario: Absorption



Kaspi, Brandt, Netzer, et al. 2001

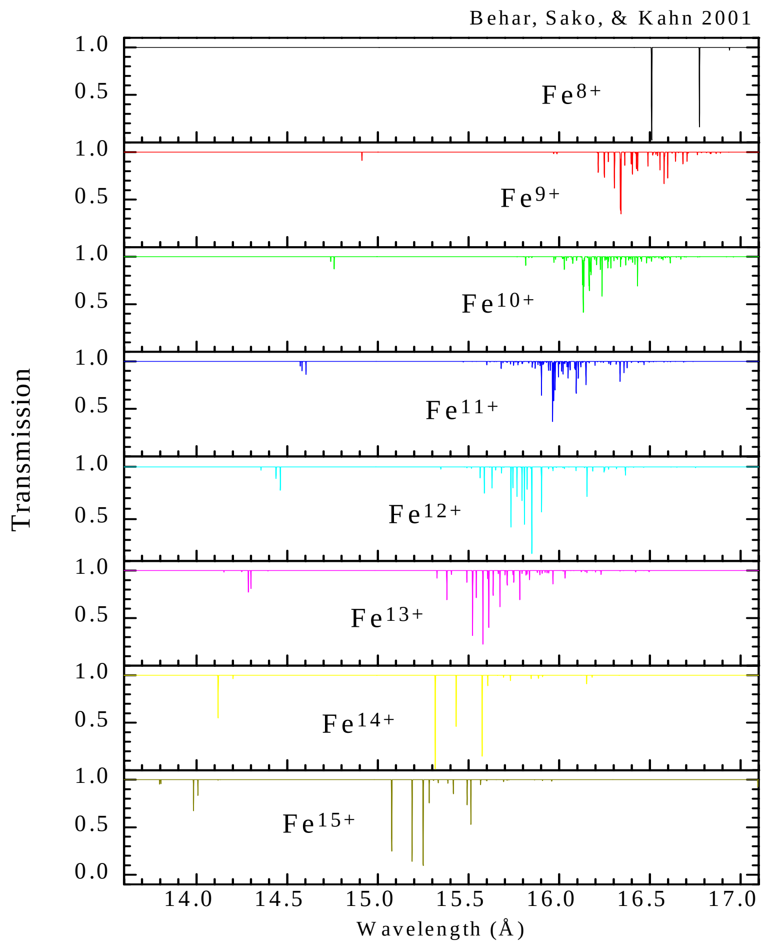
The Type-I AGN (contd.): Wide Range of Charge States



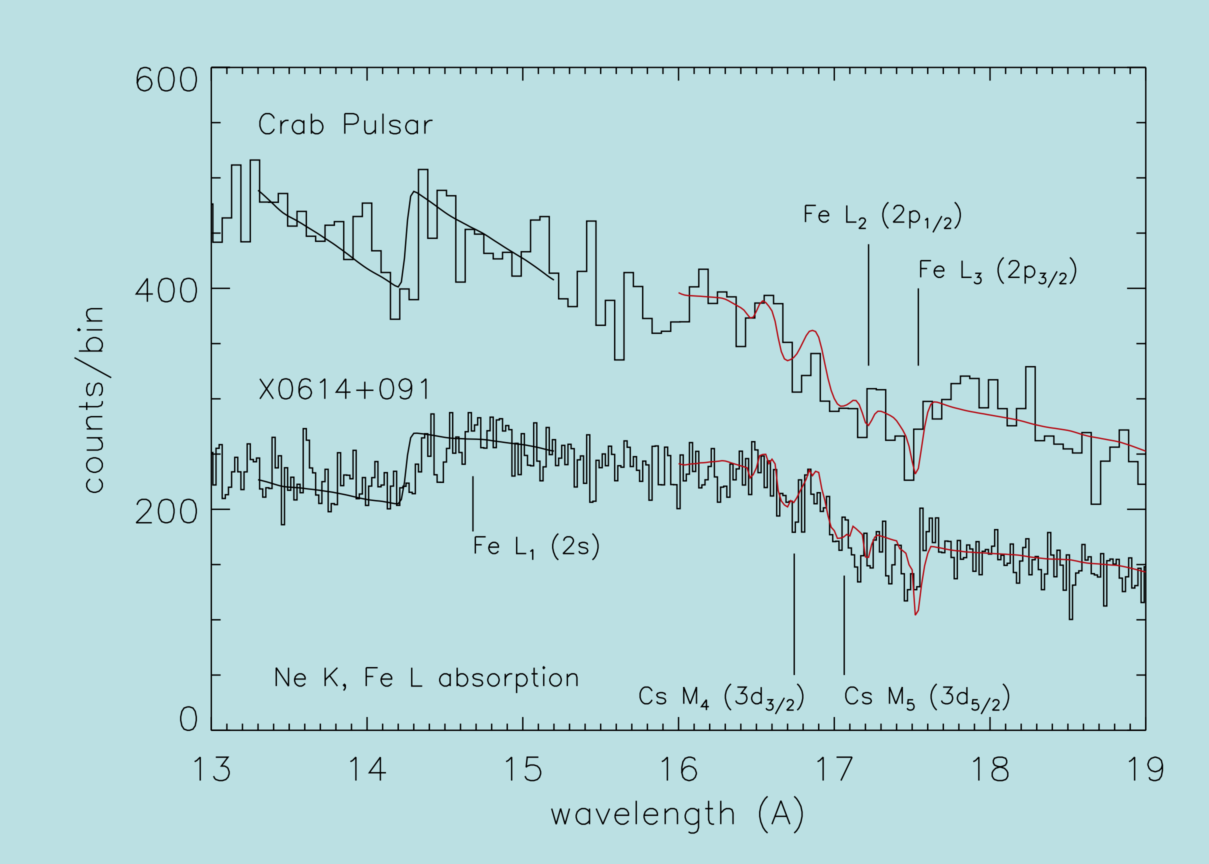
Sako, Kahn, Behar, et al. 2001

The Fe 2p-3d Unresolved Transition Array (UTA)

- Absorption by 2p-3d transitions in Fe-M ions creates a UTA between ~ 15 -17 Å.
- Has been observed in several AGN.
- Incidentally, similar feature has been observed in a very dissimilar laser plasma (Chenais-Popovic, Merdji, Misalla, et al. 2000).
- Wide range of charge states is very useful for diagnostics, especially for ξ.
- Astrophysical origin not totally clear (torus?).
- Data have been calculated and incorporated in x-ray codes.



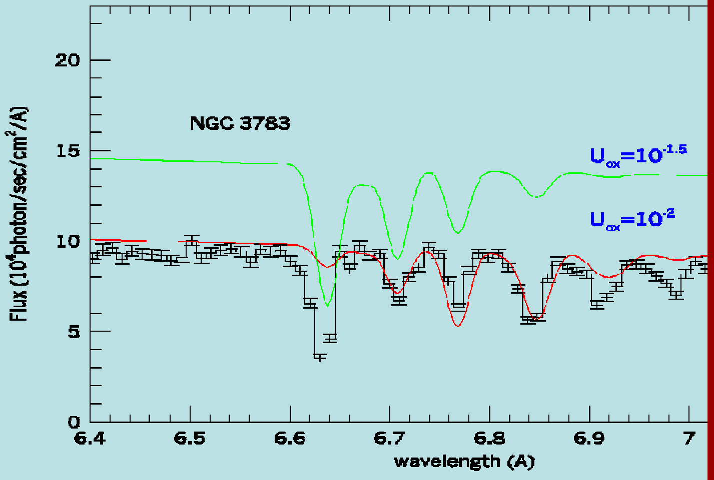
Chemistry of the ISM Using X-Ray Inner-Shell Absorption



X0614+091: Paerels, Brinkman, van der Meer et al. 2001

1s-2p (Kα) Inner-Shell Absorption

- L-shell ions (Li-like to F-like) have vacancies in their 2p sub-shell.
- This makes the 1s-2p resonance absorption lines possible.
- Have been observed in many sources and for many elements.
- Very useful in probing the ionization state(s) of the absorbing plasma.



Behar & Netzer 2002

1s-2p Inner-Shell Line Comparison

Wavelengths (Å) and *f*-values

Code **Ion**	**R-Matrix**	**HULLAC**	**Cowan**	
O^{5+}	22.05 (*f*= 0.384,0.192)	22.01 (0.351,0.174)	22.05	
O^{4+}	22.35	22.33	22.38	
O^{3+}	22.73	22.73	22.77	
Fe^{23+}	1.860 (0.491) 1.864 (0.146)	1.861 (0.469) 1.864 (0.147)	---	

Inner-Shell Line Comparison

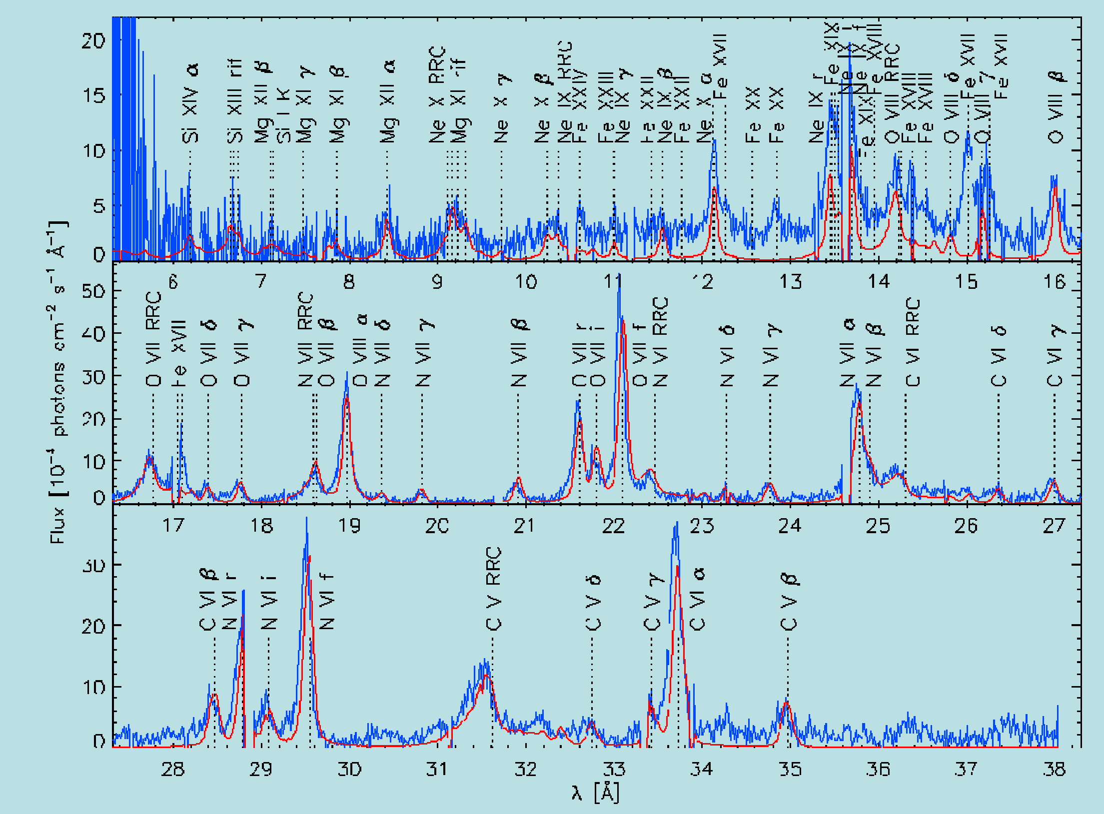
Wavelengths (Å) and *f*-values

Code Ion	R-Matrix	HULLAC	Cowan	NGC 5548*
O^{5+}	22.05 (*f*= 0.384,0.192)	22.01 (0.351,0.174)	22.05	22.01
O^{4+}	22.35	22.33	22.38	22.38
O^{3+}	22.73	22.73	22.77	22.74
Fe^{23+}	1.860 (0.491) 1.864 (0.146)	1.861 (0.469) 1.864 (0.147)	---	---

* Based on velocity of O^{6+} (± 0.01 Å); Courtesy of Jelle Kaastra

Uncertainty of the order of the outflow velocity we want to measure!

The Type-II AGN Scenario: Emission

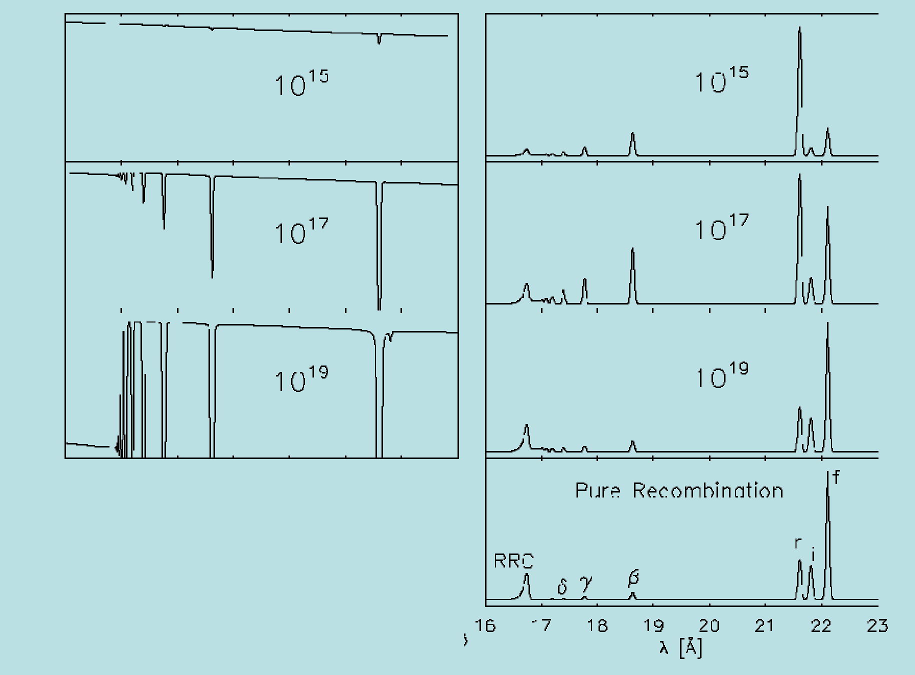


NGC 1068 / RGS

Kinkhabwala, Sako, Behar, et al. 2002

Measuring Column Density Perpendicular to the Line of Sight

- ❖ Line and RRC (re)emission depends strongly on the balance between recombination and photoexcitation (PE), which, in turn, depends directly on the column density (and velocity).
- ❖ When the resonance lines saturate the PE contribution is turned off, while recombination persists.
- ❖ Superficially, the PE effect can be somewhat mimicked by hot collisional gas.
- ❖ This has caused confusion in the x-ray community in the context of the very popular topic of the AGN-Starburst connection.
- ❖ But, the high-*n* lines save the day.

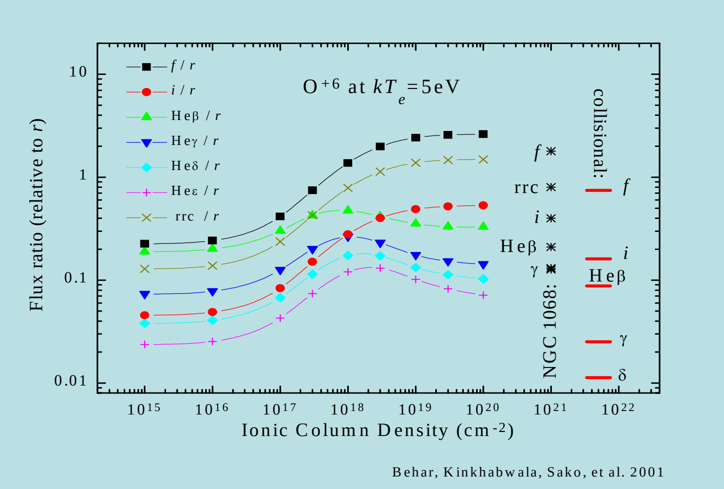


Type I AGN view **Type II AGN view**

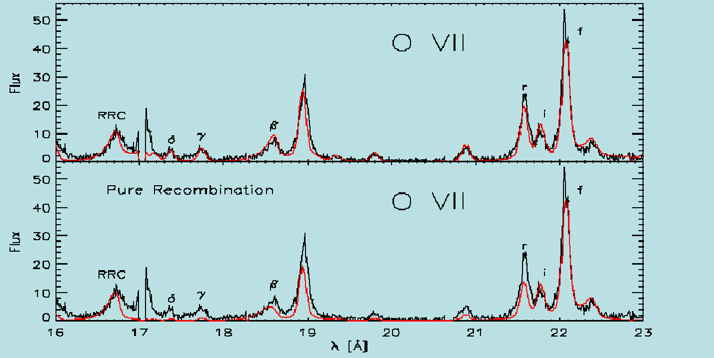
Kinkhabwala, Sako, Behar, et al. 2002

Measuring Column Density (contd.)

- The high-*n* lines provide a clear distinction between AGN and SB.
- The spectra of all type II AGN (e.g. NGC 1068) we’ve looked at so far can be explained by pure photoionization models (i.e., no SB).
- Atomic data seem to be adequate. Still working on Fe-L.



Behar, Kinkhabwala, Sako, et al. 2001



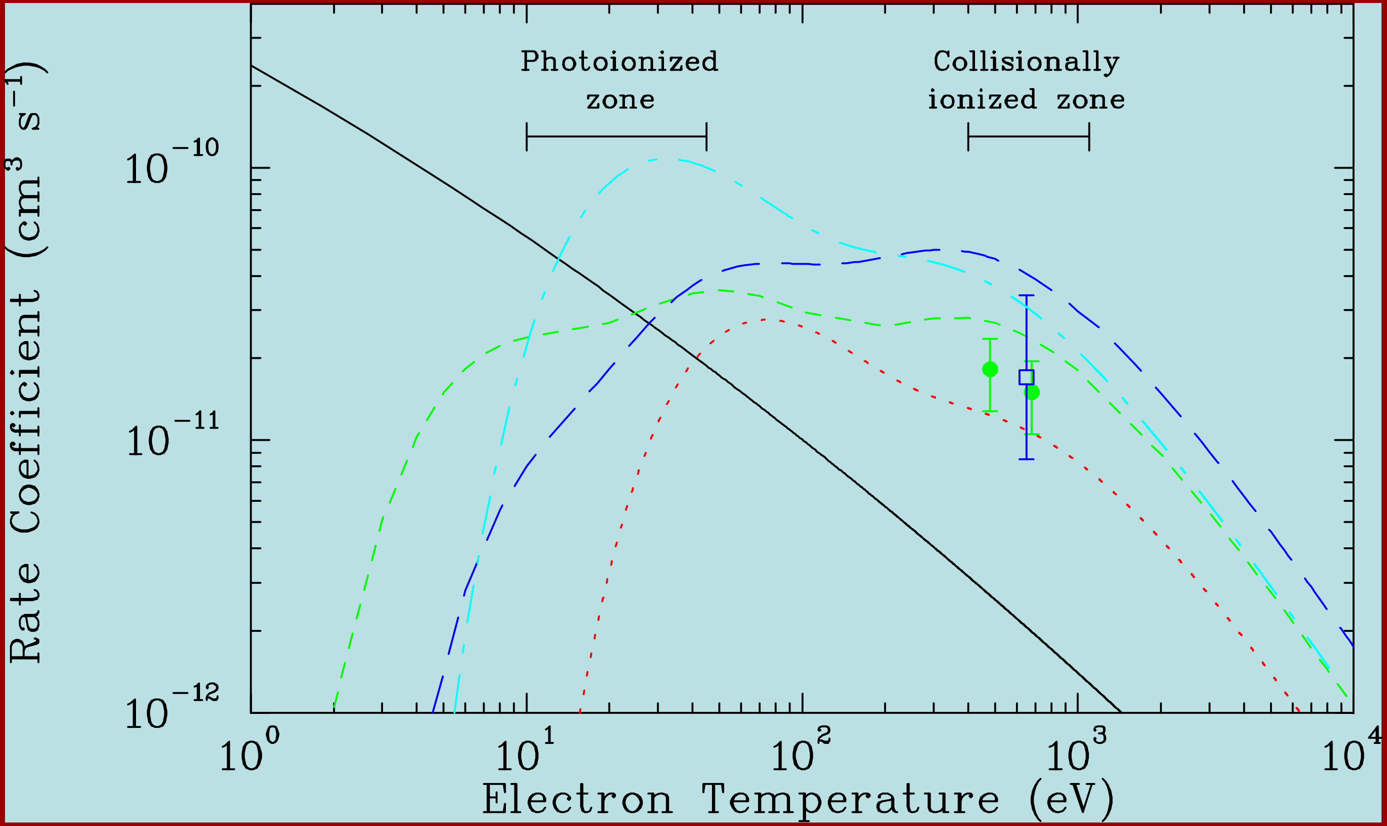
Kinkhabwala, Sako, Behar, et al. 2002

X-Ray Photoionized Plasmas: Atomic Data Needs

- ❖ Processes and Data
  - Generally important
    - ❖ Wavelengths in highly ionized species
    - ❖ Photoionization, recombination, and radiative cascades rates (emissivities)
    - ❖ Photoexcitation (oscillator strengths)**, particularly inner-shell**
    - ❖ **Fluorescence yields** (the above + autoionization rates)
    - ❖ Total ionization and recombination rates
  - More specific
    - ❖ **X-ray impact on dust and molecules**: absorption wavelengths
    - ❖ Transitions among excited states
    - ❖ Charge exchange

- ❖ Ions
  - K-shell of C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe
  - L-shell, particularly Fe, but also Ne, Mg, Si, S, Ar, Ca, and Ni
  - **But also… all the lower charge states through inner-shell transitions**

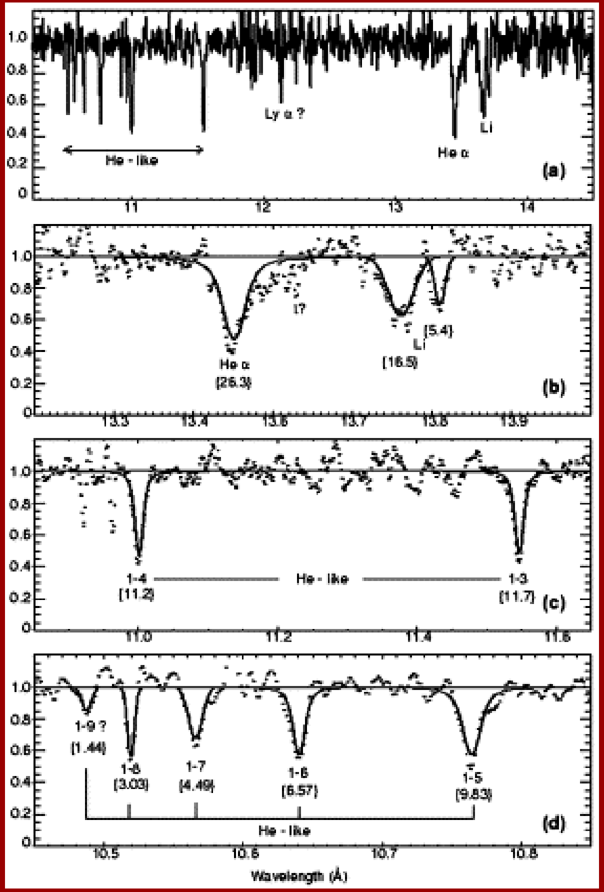
Fe-L DR, Again, Not Doing So Good



Courtesy of Daniel Savin

Laboratory Experiments: Z Pinch (& Laser Plasma)

- ❖ Absorption measurements; wavelengths and oscillator strengths.
- ❖ Particularly needed: Inner-shell lines (see my poster).
- ❖ Ionization balance and emission measurements are also possible (Heeter).
- ❖ High laboratory densities might still hinder direct application.



Bailey, Cohen, Chandler, et al. 2001

Conclusions

- High-resolution spectra are constantly being obtained with the gratings on board *Chandra* and *XMM-Newton.* These require high-quality atomic data.
- For x-ray *collisional plasmas*, much of the available data are of satisfactory quality, allowing for high precision analysis of astrophysical observations.
- For x-ray *photoionized plasmas*, much, but certainly not all of the available data is of satisfactory quality, both for absorption and for emission.
- The remaining outstanding problems need to be identified. Some are being addressed by beam experiments such as EBIT and TSR.
- Fe-L photoionization models remain to be tested.
- A vast amount of data for inner-shell absorption have been calculated, but these are in urgent need of laboratory verification.