Photoionization

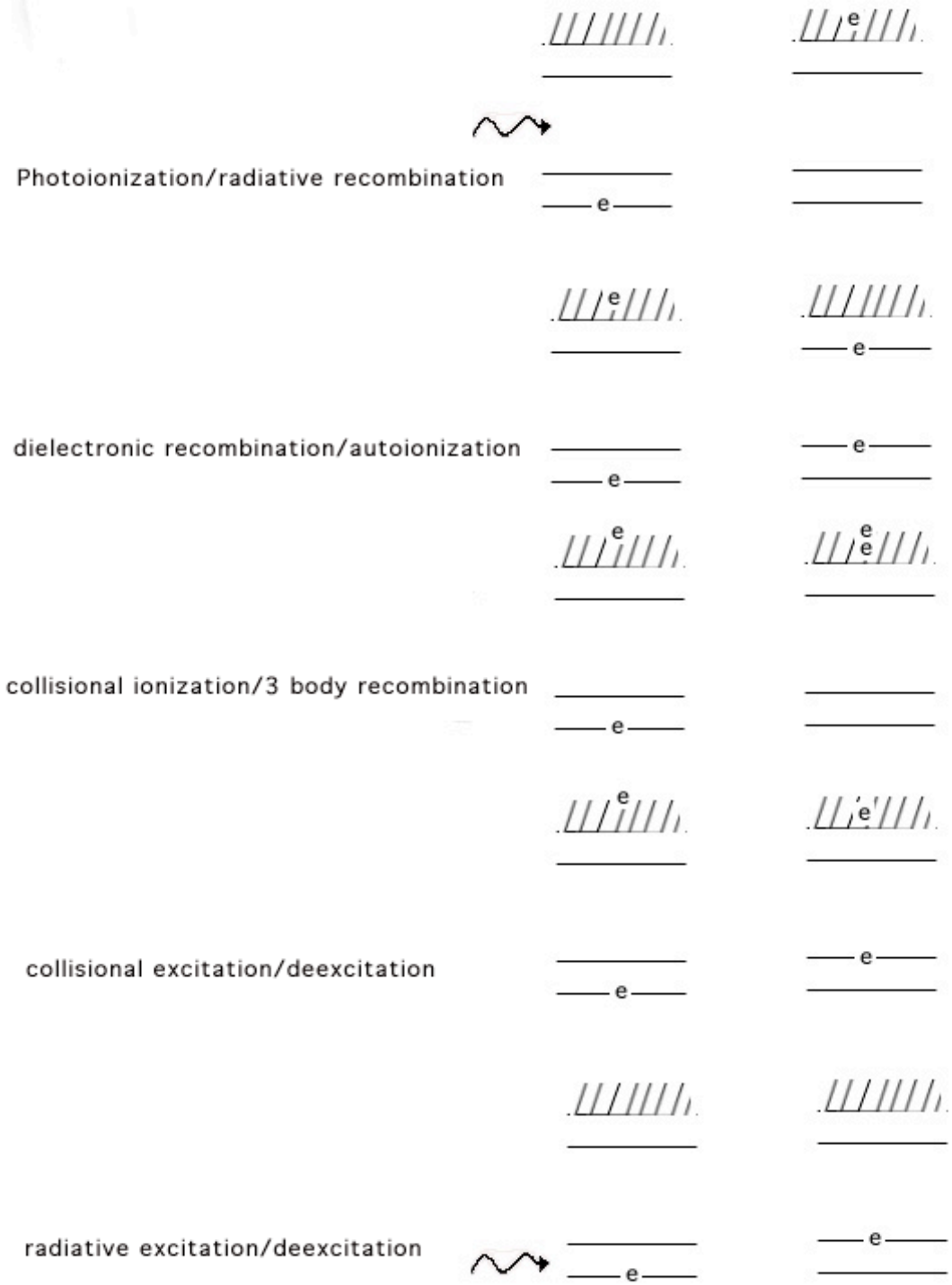
Tim Kallman NASA/GSFC

- *What is photoionization?*
  - Removal of a bound electron by a photon
  - Loosely refers to any situation where external photons are the dominant source of ionization (and heating)
- *Outline:*
  - Review of coronal plasma
  - Effect of photoionization
  - Background, definitions
  - Examples

Coronal ionization

- Assume all processes are in a steady state, so that for each ion species the rate of creation= rate of destruction
- Also assume that electron velocity distribution is Maxwellian, $kT_{ion} \sim kT_{electron}$, so that electron collisions are much more frequent than ion collisions.
- Ion destruction is due to electron impact ionization by thermal electrons
- Ion creation is due to recombination (radiative and dielectronic)
- The fraction of an ion peaks when the electron temperature is $kTe \sim (0.7)I$

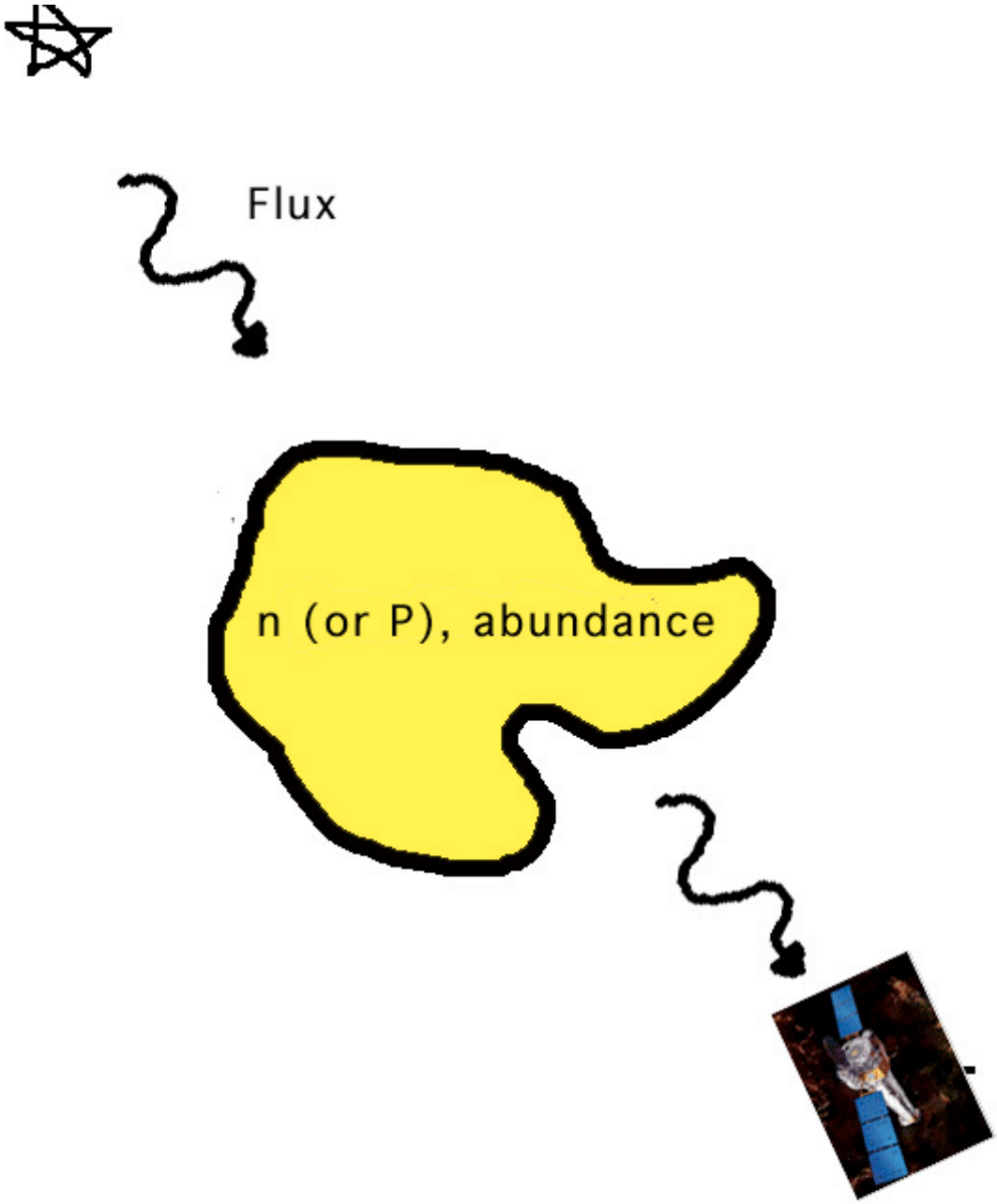

T, n, abundance


Photoionization/radiative recombination
dielectronic recombination/autoionization
collisional ionization/3 body recombination
collisional excitation/deexcitation
radiative excitation/deexcitation
e

Photoionization

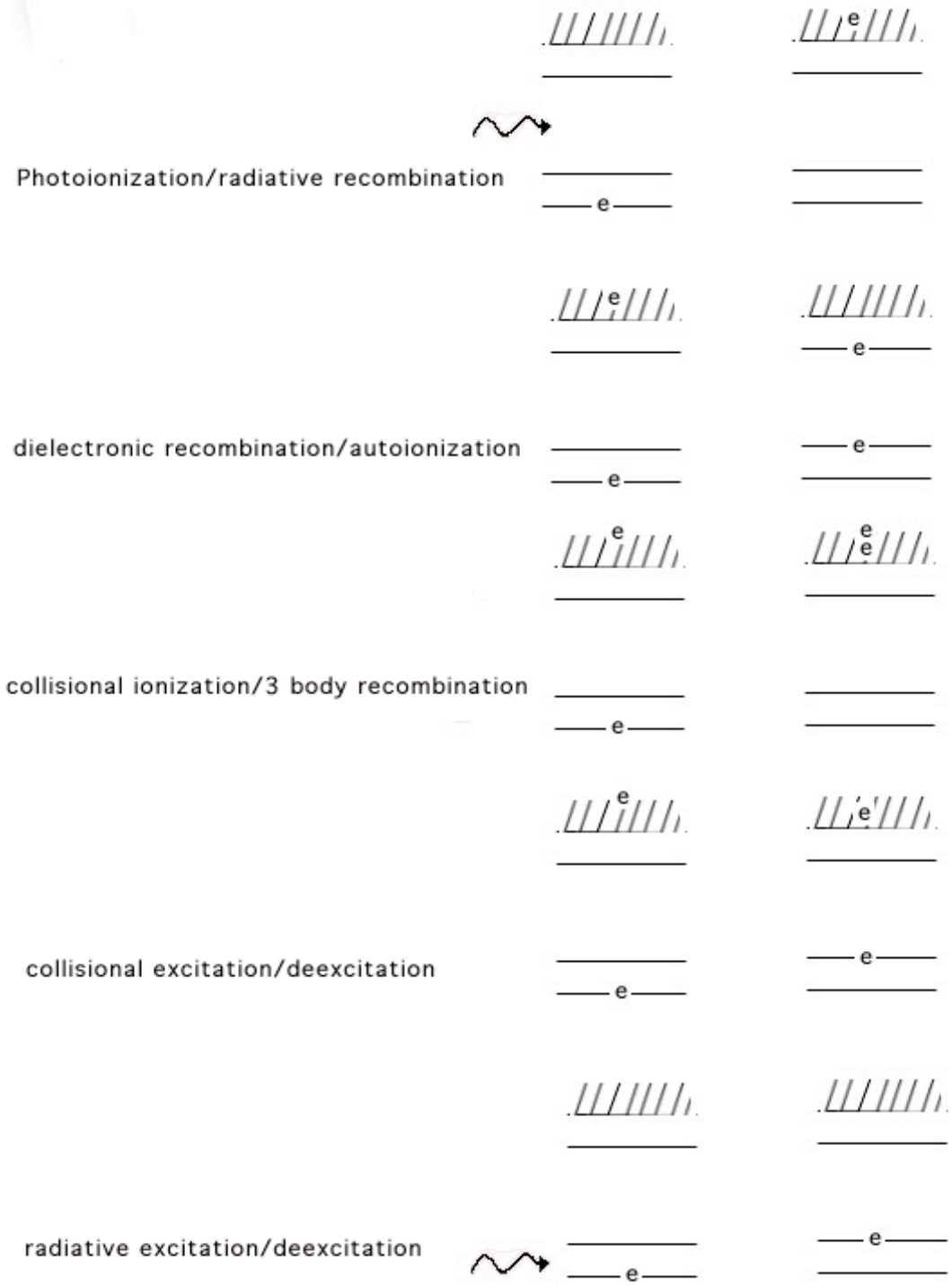
- What happens when an external photon source illuminates the gas?
- The photons ionize the atoms in the gas.
- The photoelectrons created in this way collide with ambient electrons (mostly) and heat the gas
- The gas cools by radiation
- The gas temperature adjusts so that the heating and cooling balance

In a photoionized gas the temperature is not a free parameter
and
The ionization balance is determined by the shape and strength of the radiation field


Flux
n (or P), abundance

Processes

- Photoionization (+heating)
- Recombination (+cooling)
- Dielectronic recombination (+cooling)
- Collisional ionization (cooling)
- Collisional excitation(cooling)
- Compton scattering
- Others (more later)


Photoionization/radiative recombination
dielectronic recombination/autoionization
collisional ionization/3 body recombination
collisional excitation/deexcitation
radiative excitation/deexcitation
e

process/inverse

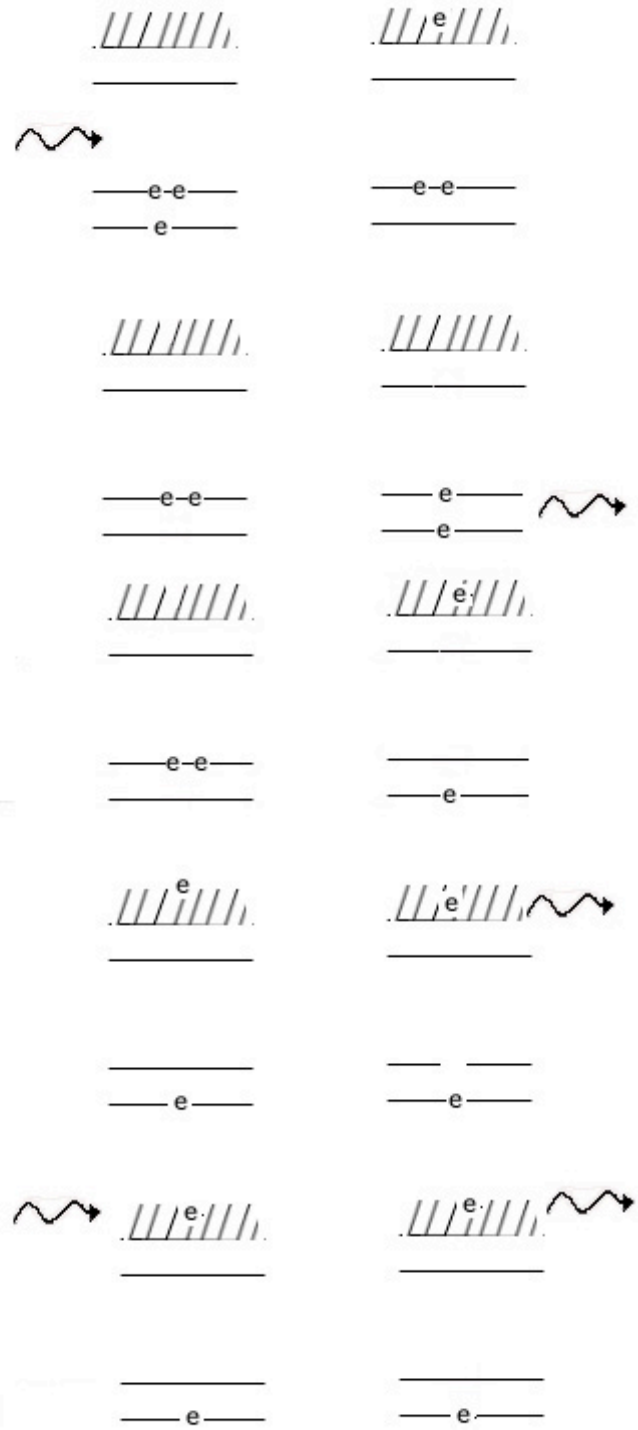
inner shell photoionization

fluorescent decay

Auger decay

bremsstrahlung

Compton scattering



Ionization and Thermal Balance

For each ion:

Ionization = recombination

~photon flux ~electron density

For the gas as a whole

Heating = cooling

~photon flux ~electron density

=> All results depend on the ratio photon flux/gas density or "ionization parameter"

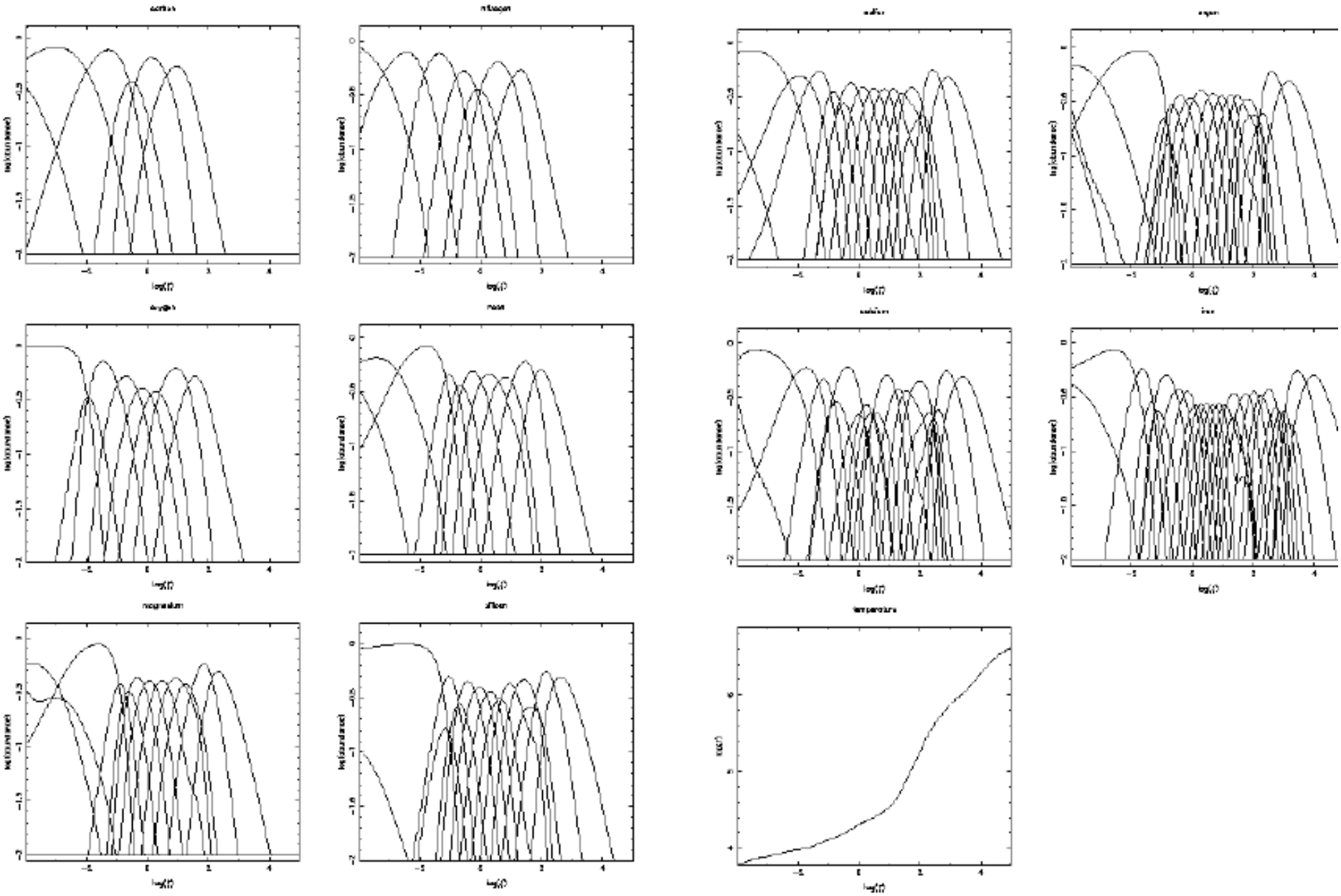
- $\xi \equiv \frac{L}{n_e R^2}$ (Tarter, Tucker and Salpeter 1969)
- $U_1 \equiv \frac{N}{n 4\pi R^2 c}$ (Davidson 1974)
- $\Gamma \equiv \frac{L_\varepsilon|_{13.6eV}}{n 8\pi R^2 c}$ (Kwan and Krolik 1981)
- $\Xi \equiv \frac{L}{4\pi n_e c k T R^2}$ (Krolik, McKee and Tarter 1982)
- $U_x \equiv \frac{N_X}{n 4\pi R^2 c}$ (Netzer 1994)

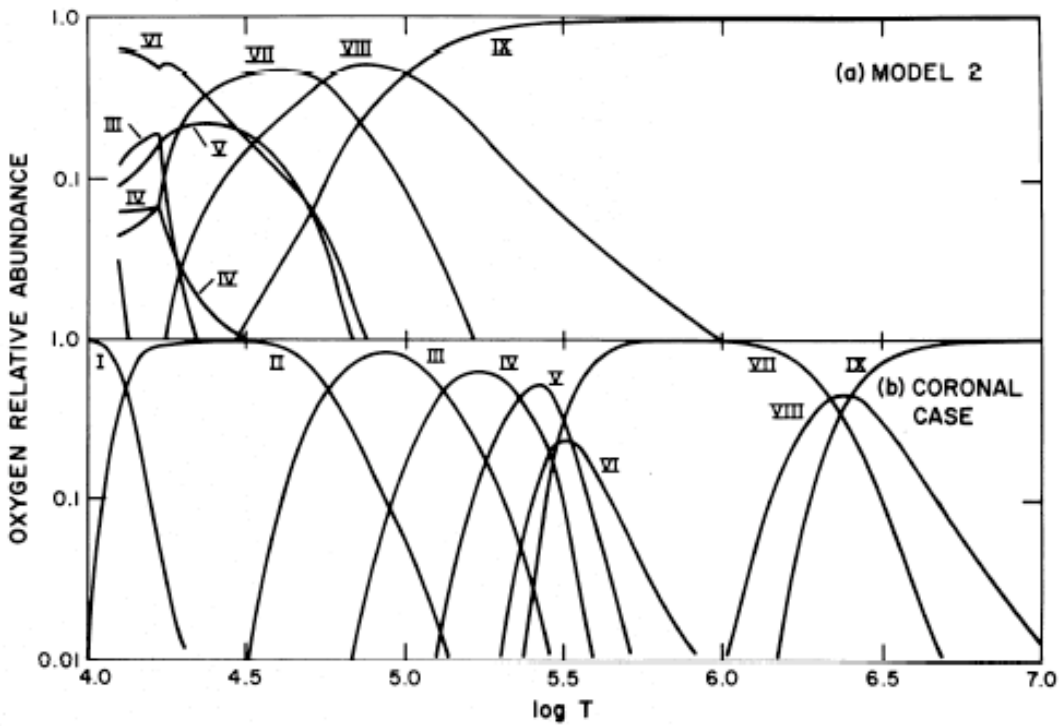
where

$N \equiv \int_{13.6eV}^{\infty} L_\varepsilon \frac{d\varepsilon}{\varepsilon}$

$N_X \equiv \int_{100eV}^{\infty} L_\varepsilon \frac{d\varepsilon}{\varepsilon}$

$L \equiv \int_{13.6eV}^{\infty} L_\varepsilon d\varepsilon$


log(t)
log(counts/sec)
temperature
log(t)


(a) MODEL 2
(b) CORONAL CASE
OXYGEN RELATIVE ABUNDANCE
log T
1.0
0.1
0.01
4.0
4.5
5.0
5.5
6.0
6.5
7.0
I
II
III
IV
V
VI
VII
VIII
IX

Consequences of Photoionization

- Temperature lower for same ionization than coronal, $T \sim 0.1\ Et_h/k$
- Temperature is not a free parameter
- Temperature depends on global shape of spectrum
  - At high ionization parameter, the gas is fully ionized, and the temperature is determined by Compton scattering and inverse $T = \langle E \rangle / 4k$
- Ionization balance is more 'democratic'
- Microphysical processes, such as dielectronic recombination, differ
- Observed spectrum differs

Observed Spectrum: Emission

- In coronal gas, need kTe~ΔE to collisionally excite lines.
- In a photoionized gas there are fewer lines which satisfy this condition.
- Excitation is often by recombination cascade
- Also get recombination continua (RRCs) due to recombination by cold electrons directly to the ground state. The width of these features is directly proportional to temperature
- Due to the democratic ionization balance, it is more likely that diverse ions such as N VII, O VIII, Si XIV can coexist and emit efficiently than it would be in a coronal gas
- Inner shell ionization and fluorescence is also important in gases where the ionization state is low enough to allow ions with filled shells to exist.

process/inverse

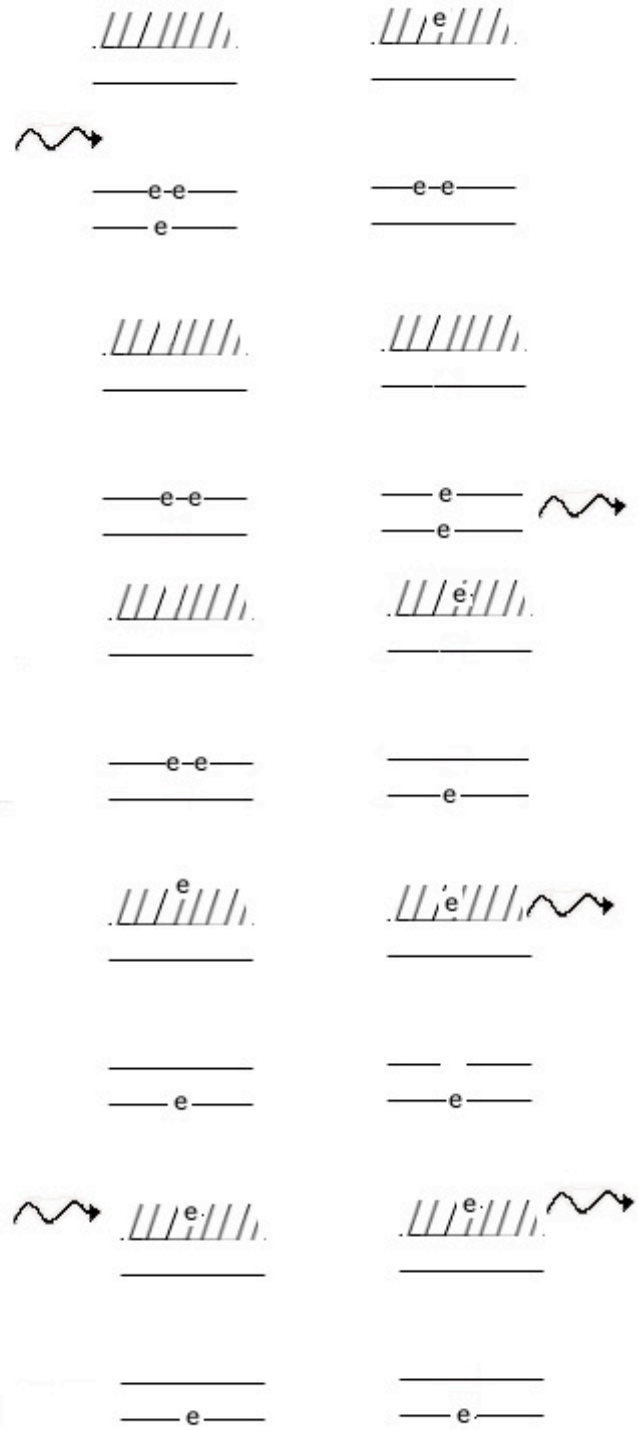
inner shell photoionization

fluorescent decay

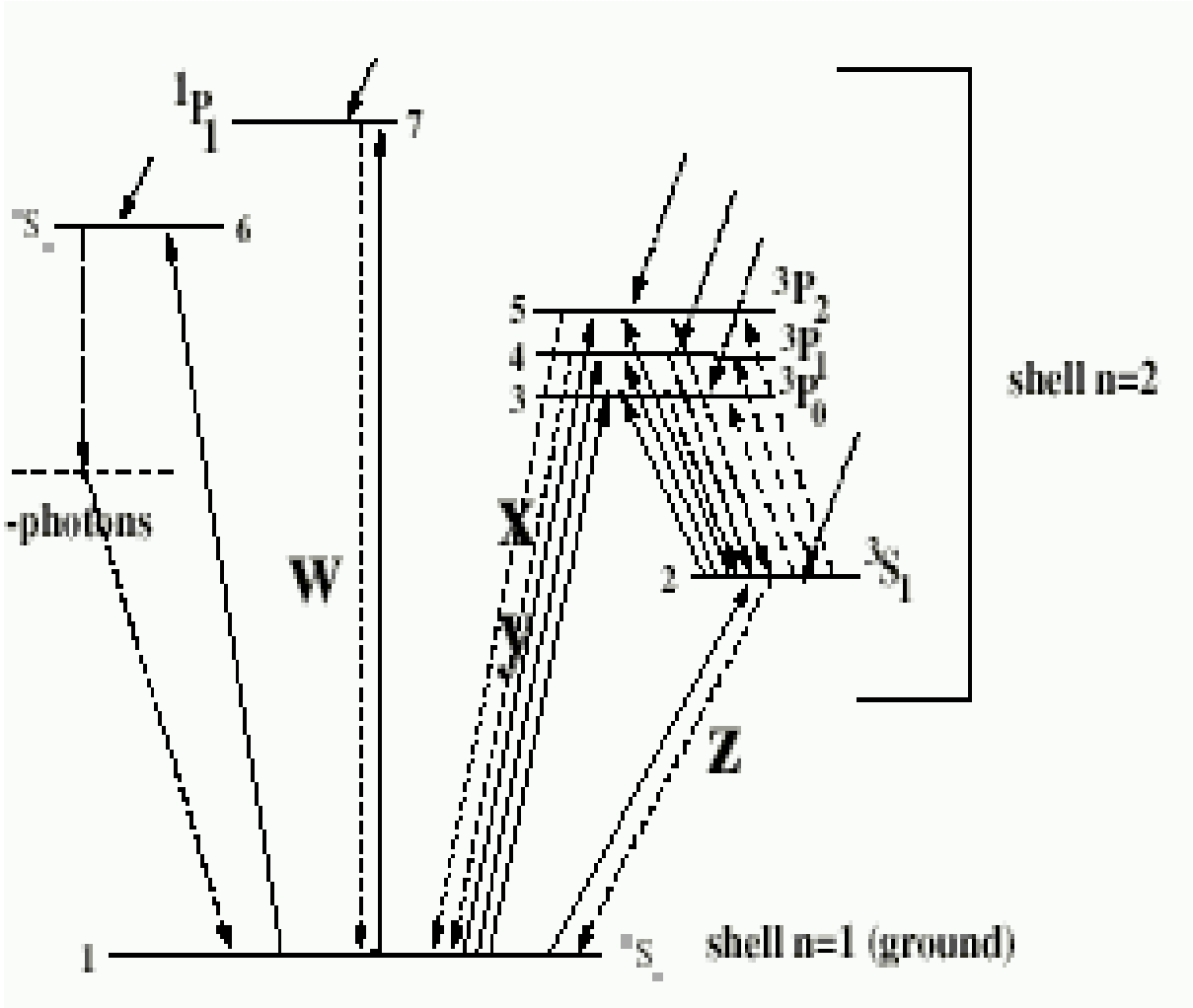
Auger decay

bremsstrahlung

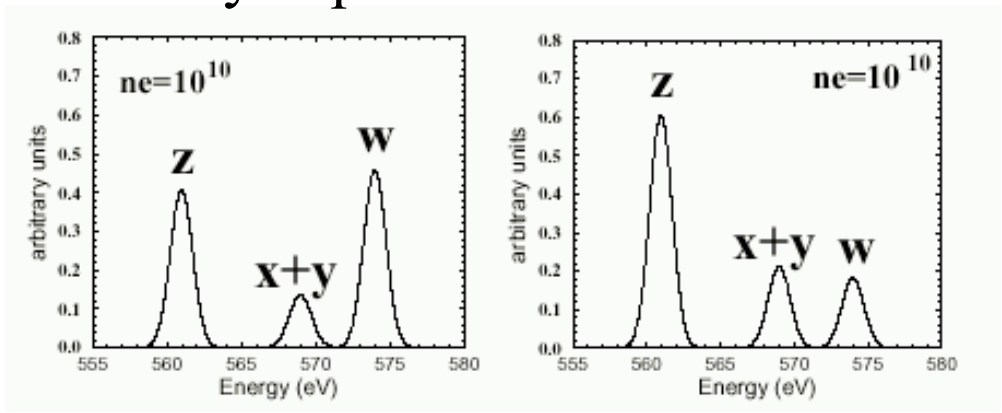
Compton scattering

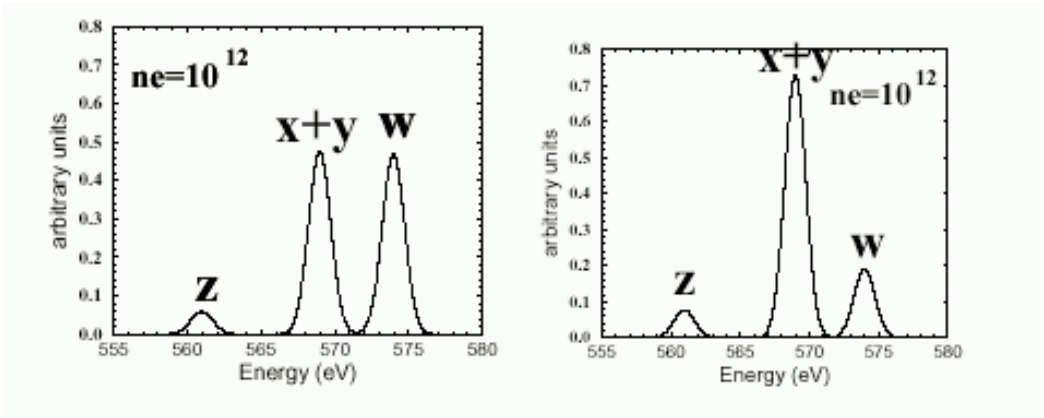


Helium-like ion level diagram



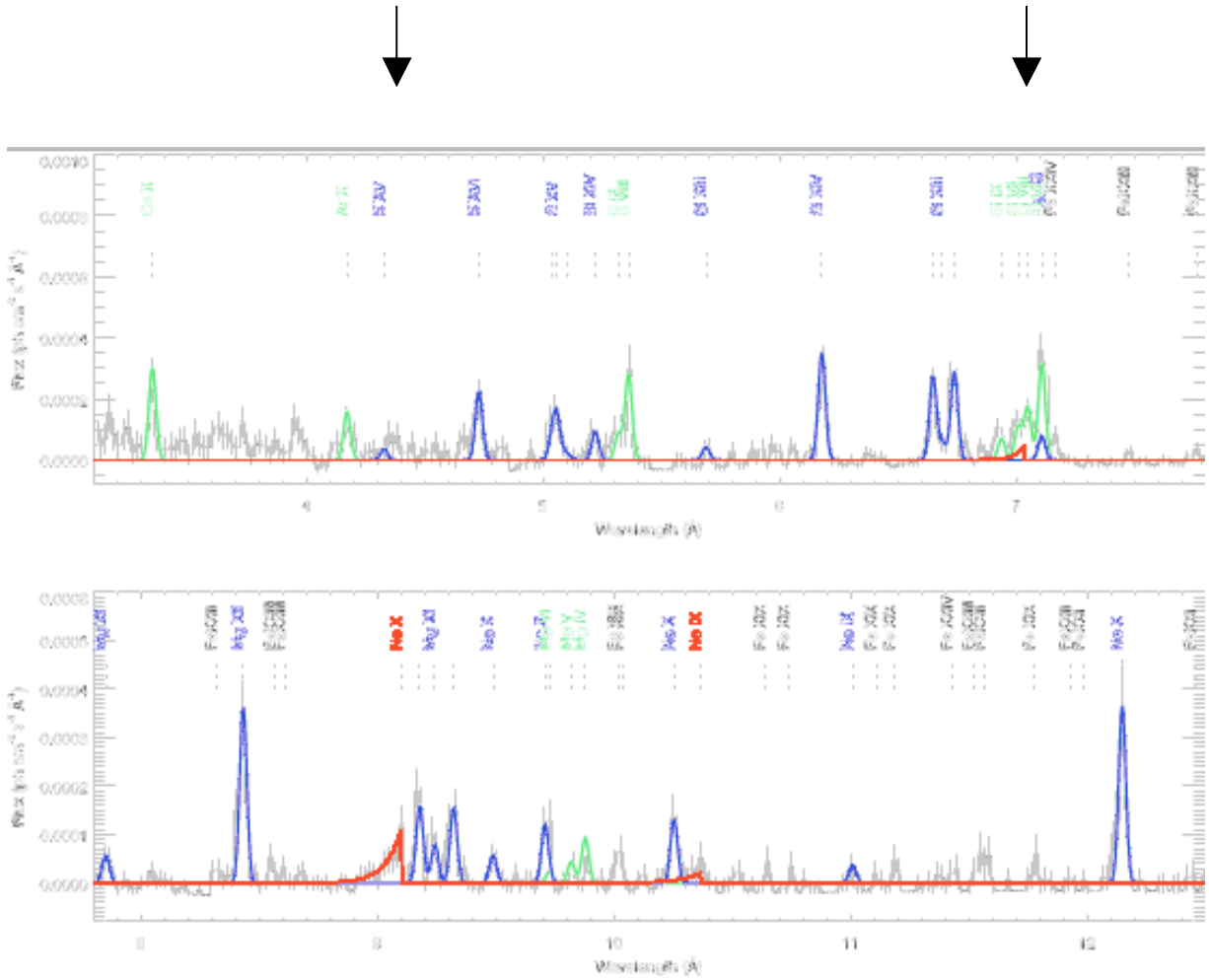
Density dependence of He-like lines



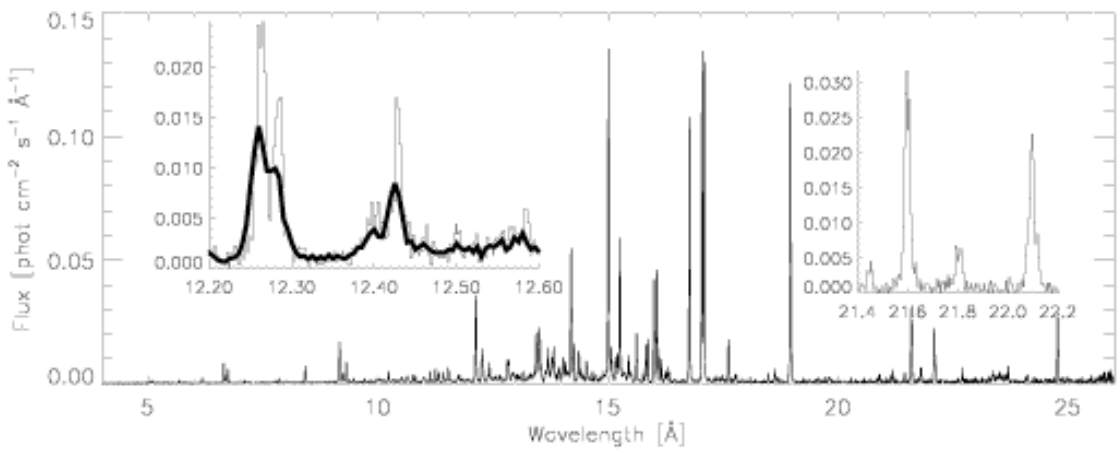


Coronal photoionized

(Porquet and Dubau 1998)



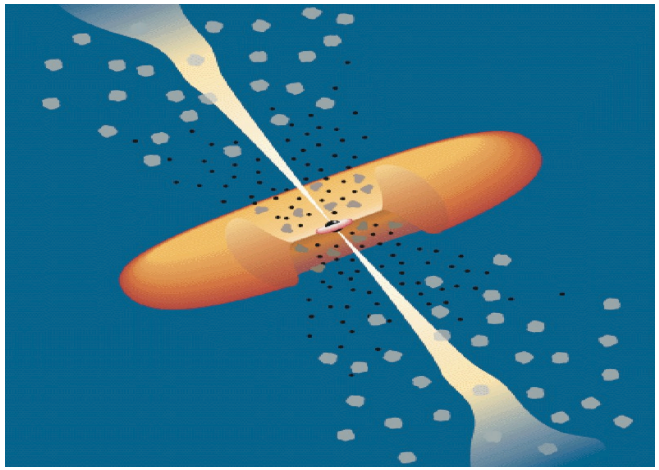
Chandra HETGS spectrum of Vela X-1
(Shulz et al. 2002)

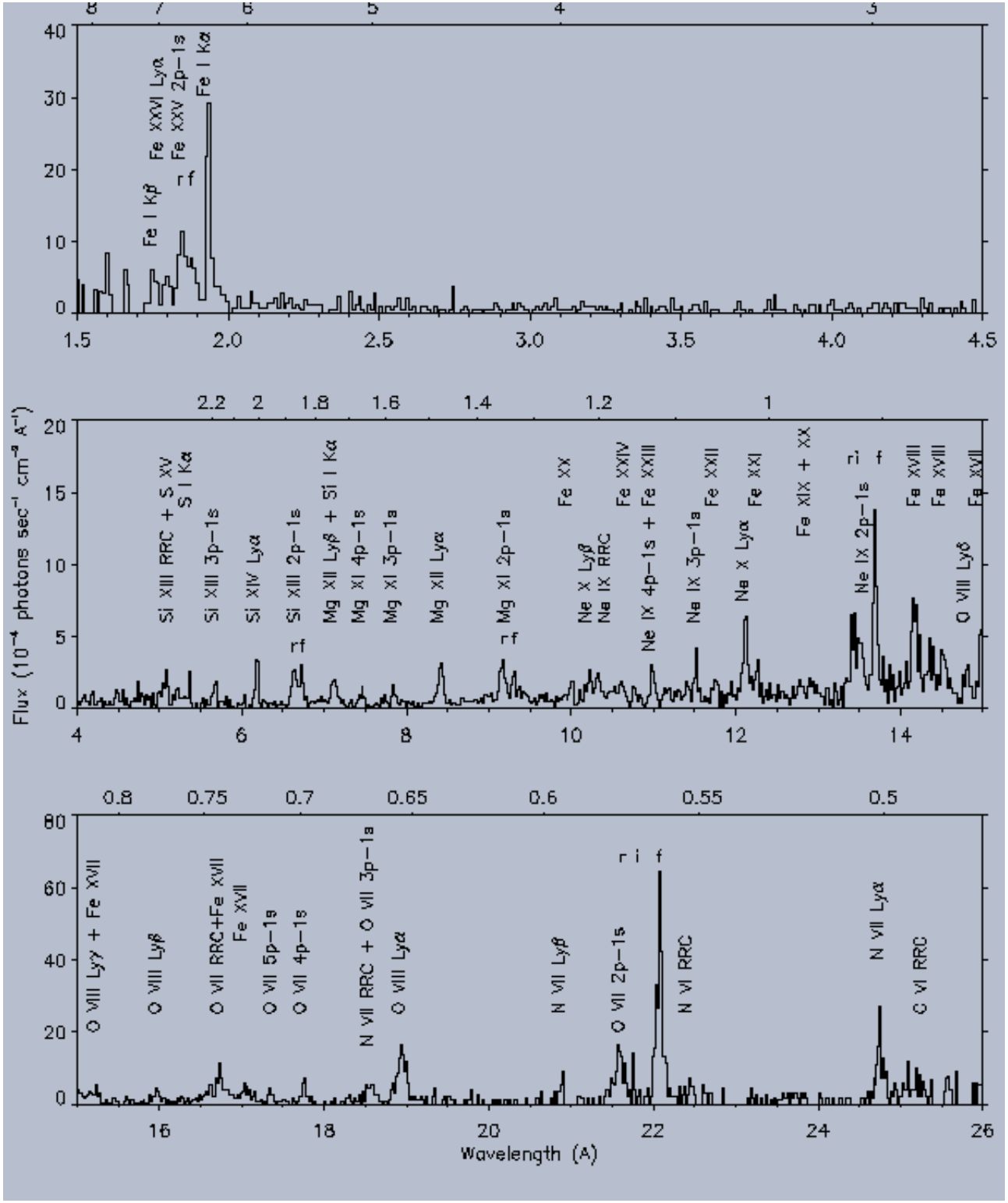


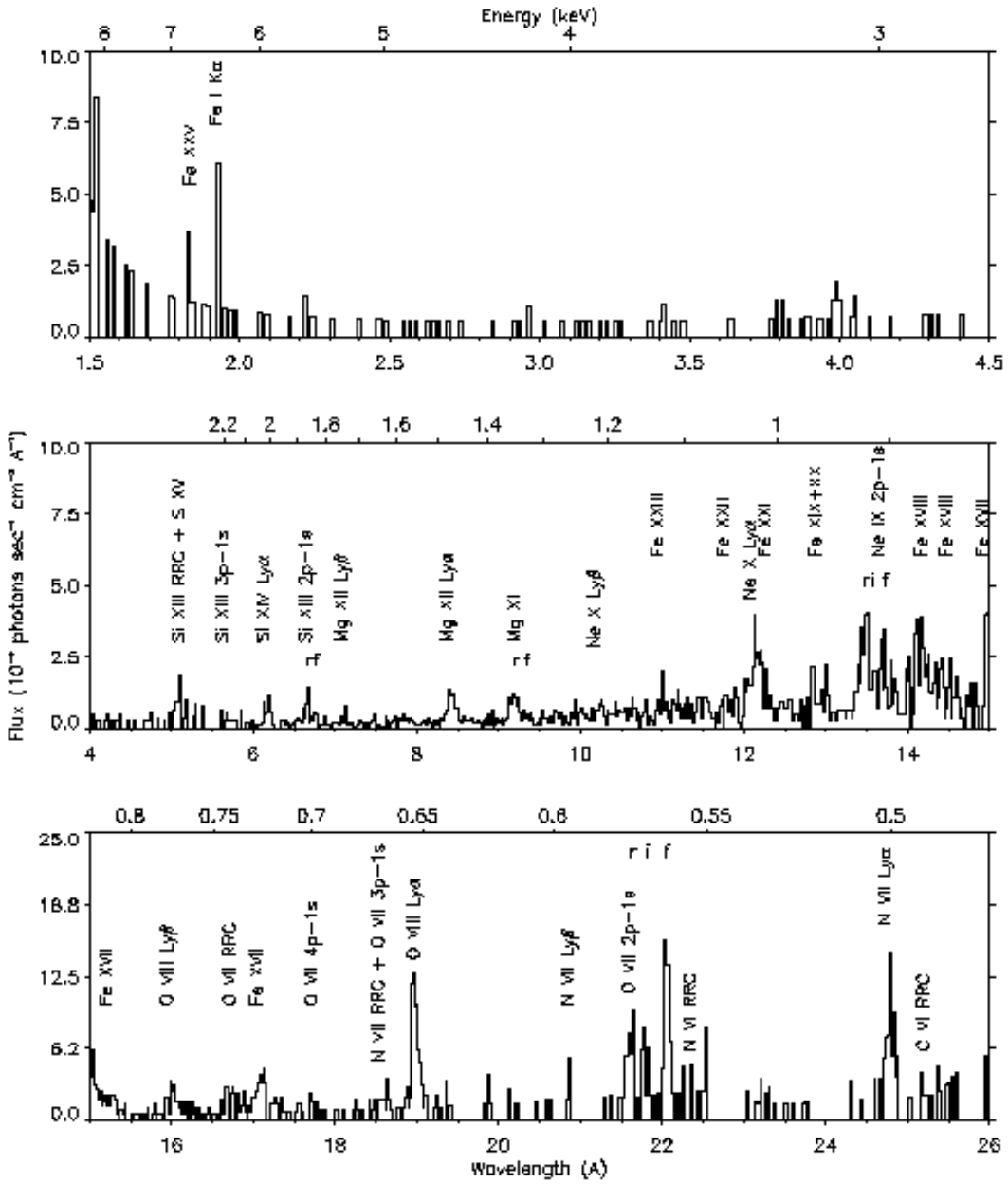
Chandra HETGS spectrum of Capella
(Canizares et al. 2000)

Emission spectrum of NGC 1068

- NGC 1068 is the prototype of Seyfert 2 galaxies, i.e. AGN in which our direct line of sight to the nucleus is blocked by a thick ring of cold material.
- If so, we should see emission from photoionized material in the 'hole' of the doughnut, even though we don't see the nucleus directly
- Chandra HETGS X-ray spectra appear to confirm this prediction



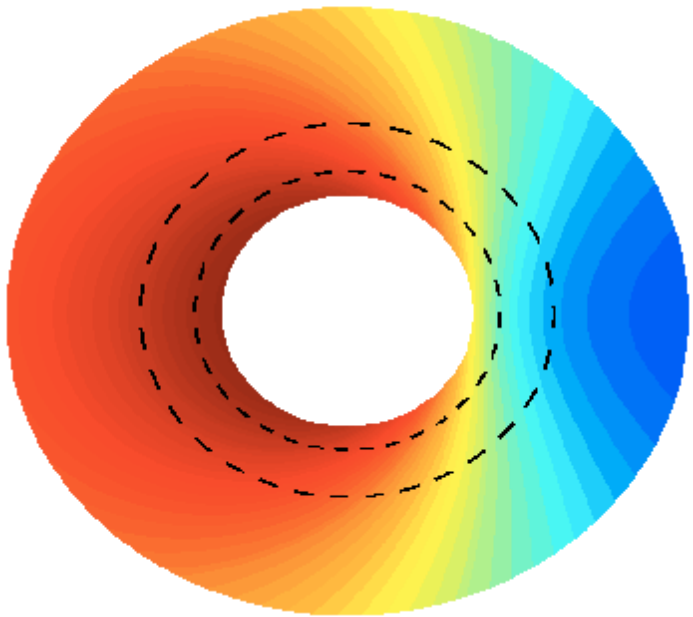

Fe I Kβ
Fe XXVI Lyα
Fe XXV 2p−1s
r f
Fe I Kα
Si XIII RRC + S XV
S I Kα
Si XIII 3p−1s
Si XIV Lyα
Si XIII 2p−1s
Mg XII Lyβ + Si I Kα
Mg XI 4p−1s
Mg XI 3p−1s
Mg XII Lyα
Mg XI 2p−1s
Fe XX
Ne X Lyβ
Ne IX RRC
Fe XXIV
Ne IX 4p−1s + Fe XXIII
Ne IX 3p−1s
Fe XXII
Ne X Lyα
Fe XXI
Fe XIX + XX
Ne IX 2p−1s
Fe XVIII
Fe XVIII
O VIII Lyδ
Fe XVII
O VIII Lyγ + Fe XVII
O VIII Lyβ
O VII RRC+Fe XVII
Fe XVII
O VII 5p−1s
O VII 4p−1s
N VII RRC + O VII 3p−1s
O VIII Lyα
N VII Lyβ
O VII 2p−1s
r i f
N VI RRC
N VII Lyα
C VI RRC
Flux (10⁻⁴ photons sec⁻¹ cm⁻² A⁻¹)
Wavelength (A)

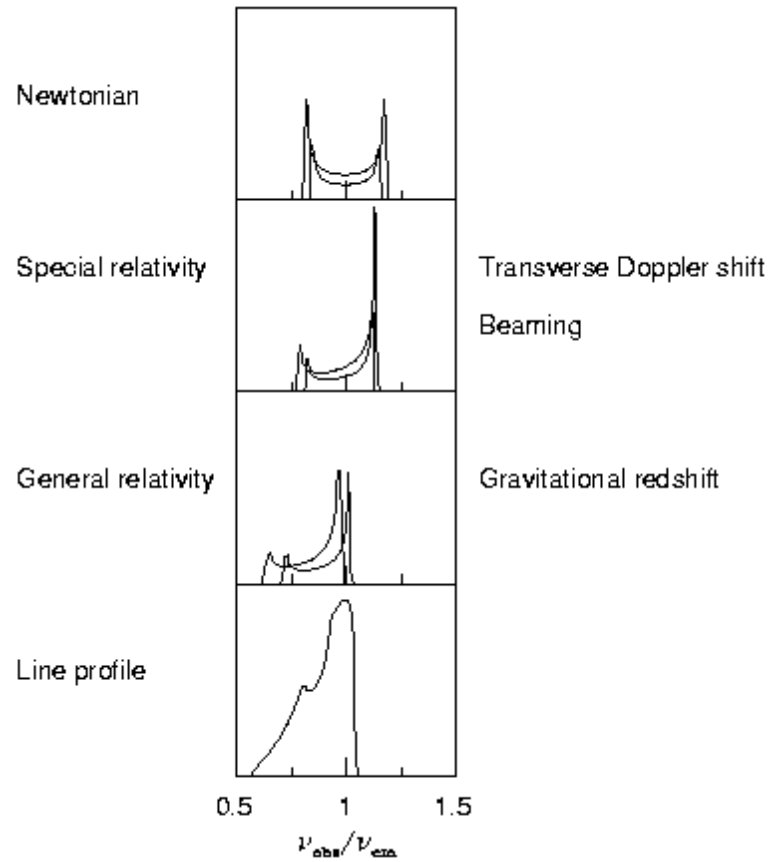

Energy (keV)
Fe XXV
Fe I Kα
Si XIII RRC + S XV
Si XIII 3p−1s
Si XIV Lyα
Si XIII 2p−1s
Mg XII Lyβ
Mg XII Lyα
Mg XI
Ne X Lyβ
Fe XXIII
Fe XXII
Ne X Lyα
Fe XXI
Fe XIX+XX
Ne IX 2p−1s
Fe XVIII
Fe XVII
Flux (10⁻⁴ photons sec⁻¹ cm⁻² A⁻¹)
Fe XVII
O VIII Lyβ
O VII RRC
Fe XVII
O VII 4p−1s
N VII RRC + O VII 3p−1s
O VIII Lyα
N VII Lyβ
O VII 2p−1s
N VI RRC
N VII Lyα
C VI RRC
Wavelength (A)

Iron K Lines

- Widely Emitted by all stages of iron, due to the efficiency of the K shell fluorescence process, and expected to be bright due to the relative abundance of iron.observed from all classes of (photoionized) X-ray sources.
- Are likely to probe the hottest and most highly ionized regions of photoionized gases, due to the high atomic number of iron.
- As discovered by ASCA, this line shows evidence for relativistic broadening in Seyfert galaxies and some black hole candidates.
- The combined effects of special and general relativity broaden and redden the line profile, and the shape depends on the inclination of the accretion disk and on the range of radii where emission occurs.

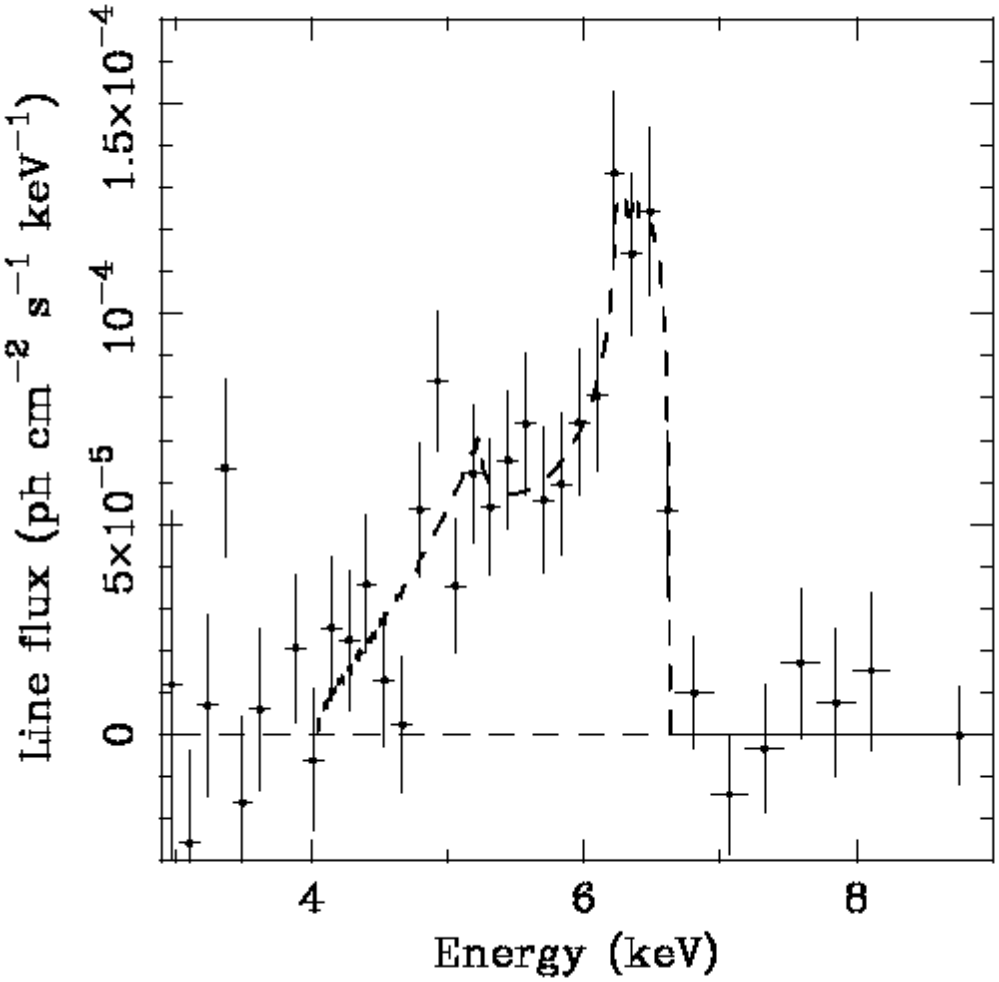
Line Broadening by Black Hole Disk Emission





Fabian et al. 2000

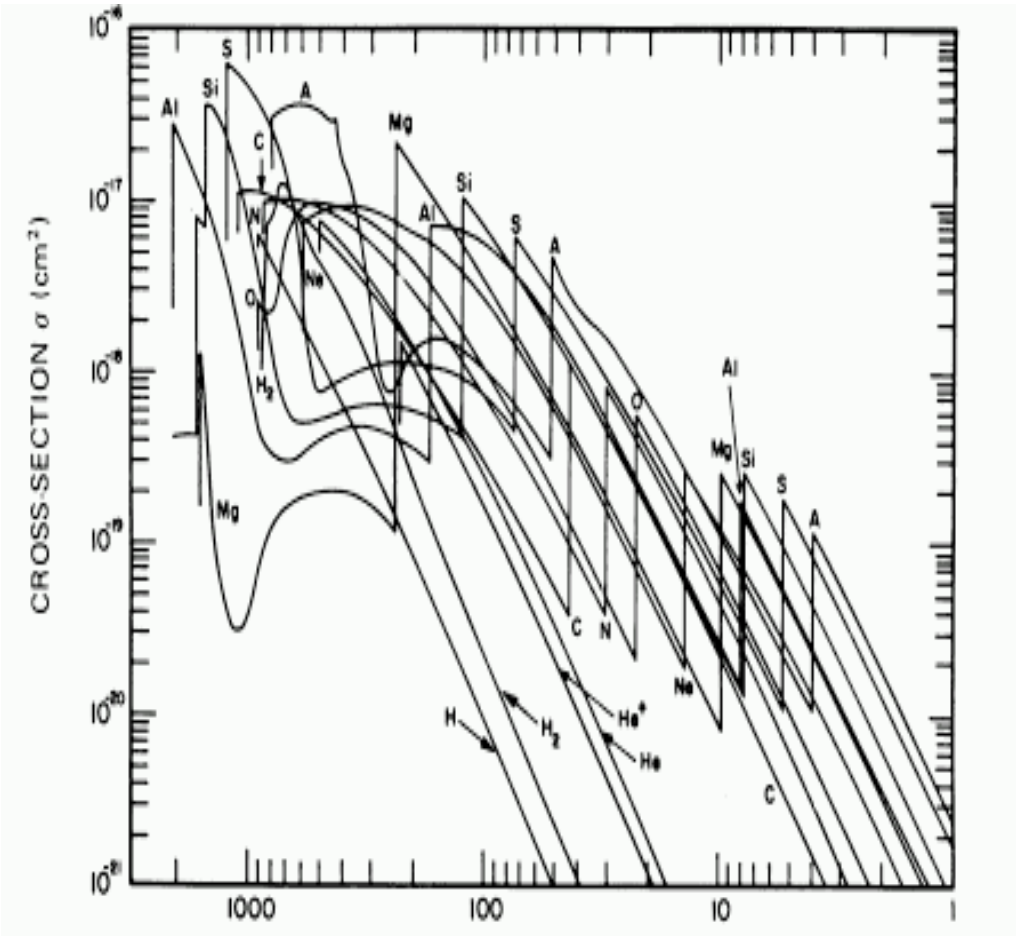
Iron K Line from Seyfert Galaxy MCG-6-30-15



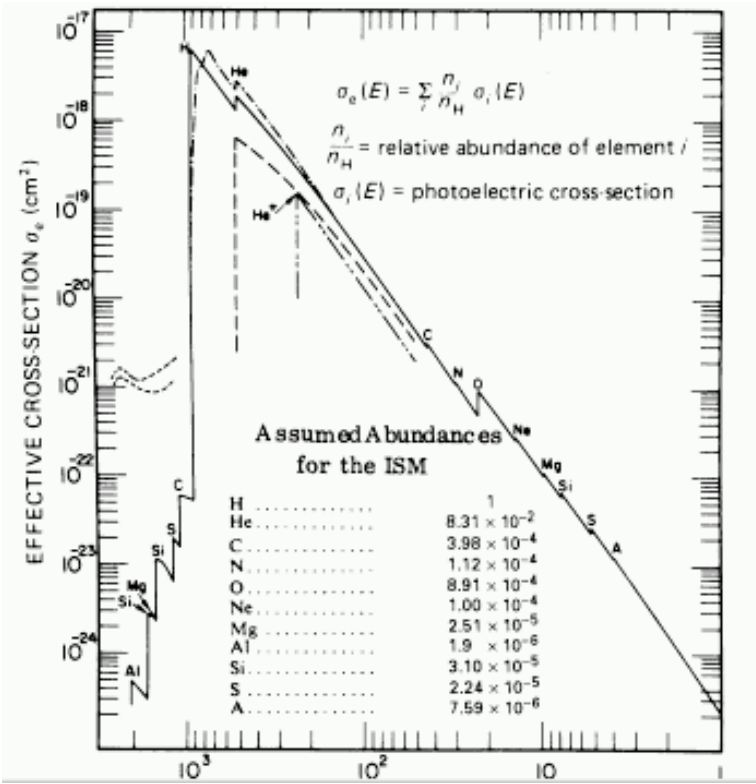
Tanaka et al., 1995

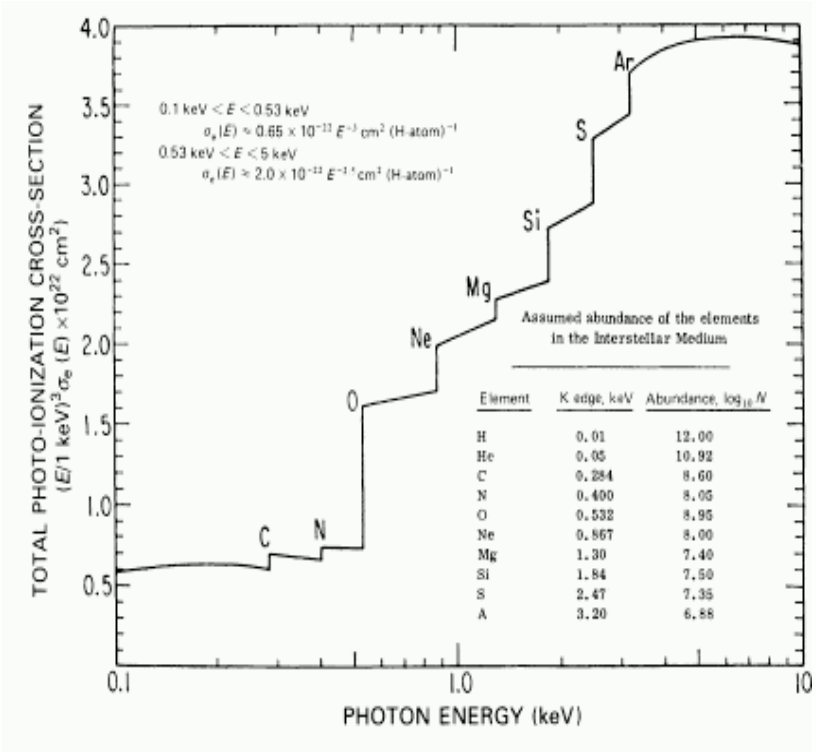
Absorption

- Absorption by interstellar material is in every spectrum, but absorption is uniquely associated with photoionized sources.
- A crude approximation for the photoabsorption cross section of a hydrogenic ion is that the cross section is $\sim Z^{-2}$ at the threshold energy, and that the threshold energy scales $\sim Z^{2}$.
- In addition, the cosmic abundances of the elements decrease approximately $\sim Z^{-4}$ above carbon
- So the net cross section scales as E^{-3}, and large jumps in absorption are not expected at the thresholds.
- Detection of such edges are indicative of abundance anomalies or partial ionization of the gas



Cross section for photoionization for abundant elements vs. wavelength (Zombeck)



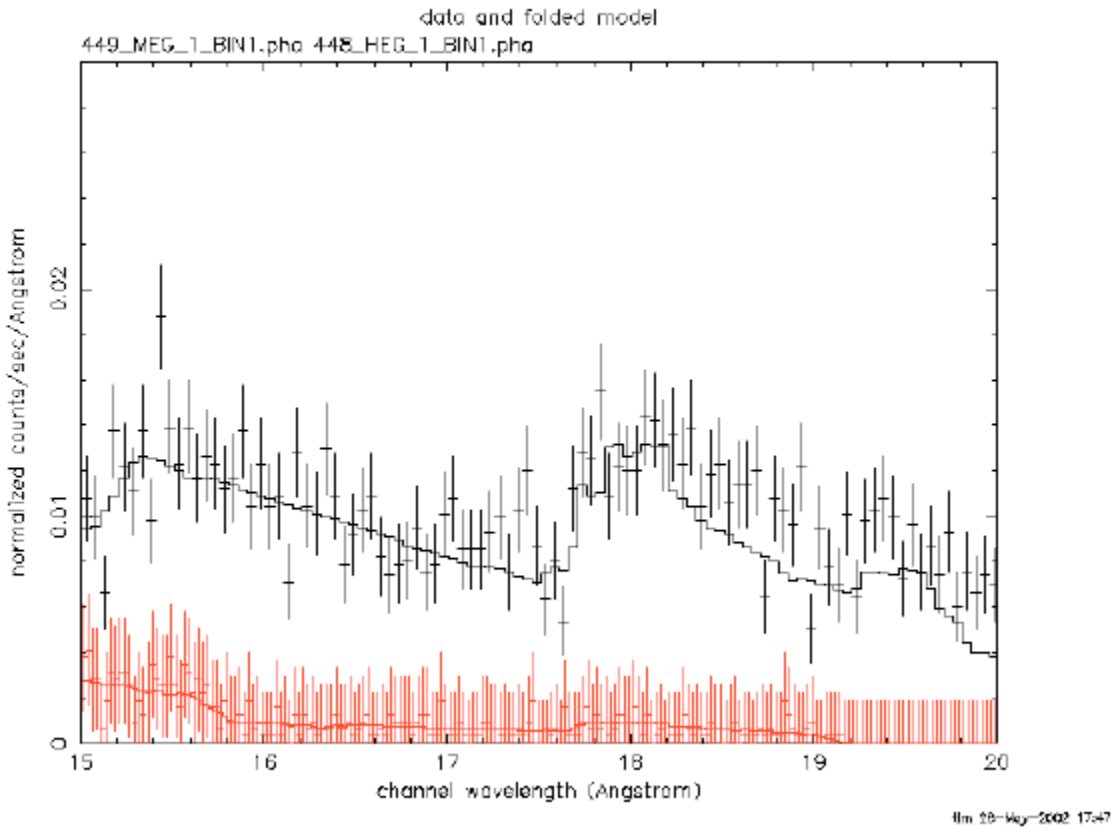


Interstellar absorption (Morrison and McCammon; Zombeck)

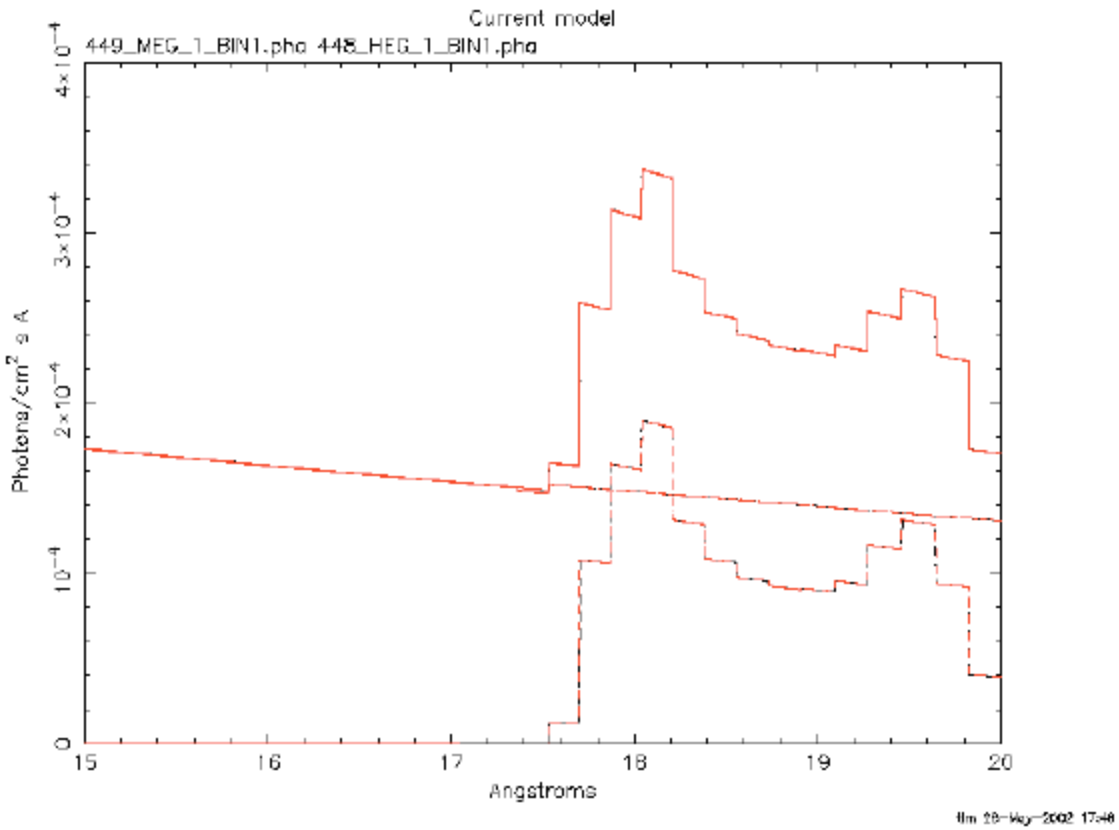
Example 4: Photoabsorption spectrum of the Seyfert 1 galaxy MCG-6-30-15

- MCG-6-30-15 is a relatively bright Seyfert 1 galaxy
- ASCA discovered the first relativistically broadened iron K lines from this source, and it remains one of the most extreme examples of this phenomenon.
- ASCA also discovered features which were interpreted as absorption by O VII and O VIII photoionization 'edges', i.e. Photons absorbed in photoionizing these ions from the ground state.
- The first Chandra spectra failed to find the same features.

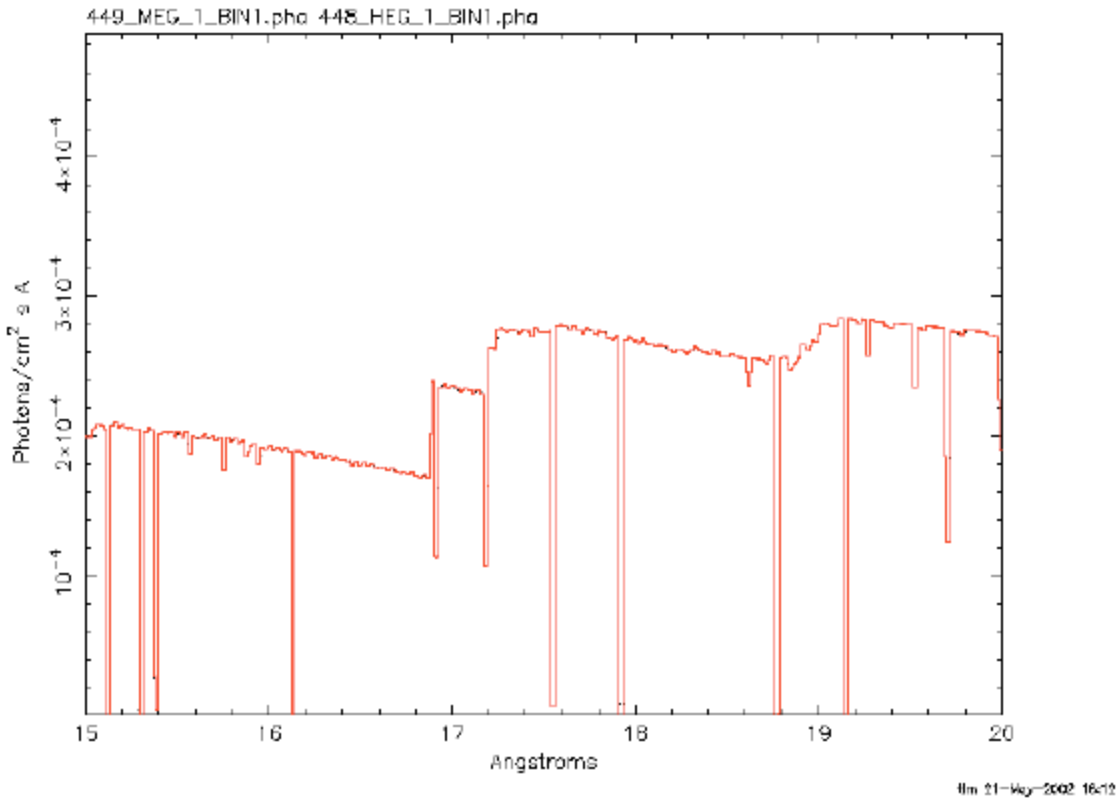
Chandra HETG Spectrum of MCG-6-30-15



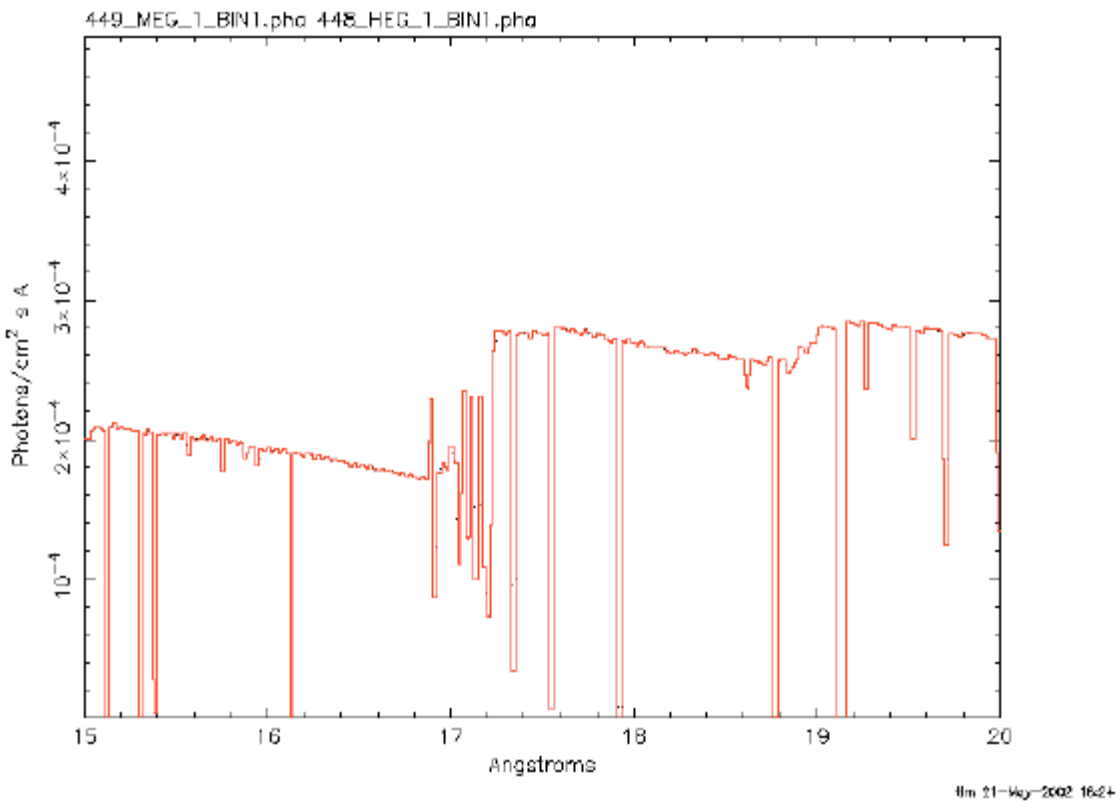
Relativistically broadened O VII Emission



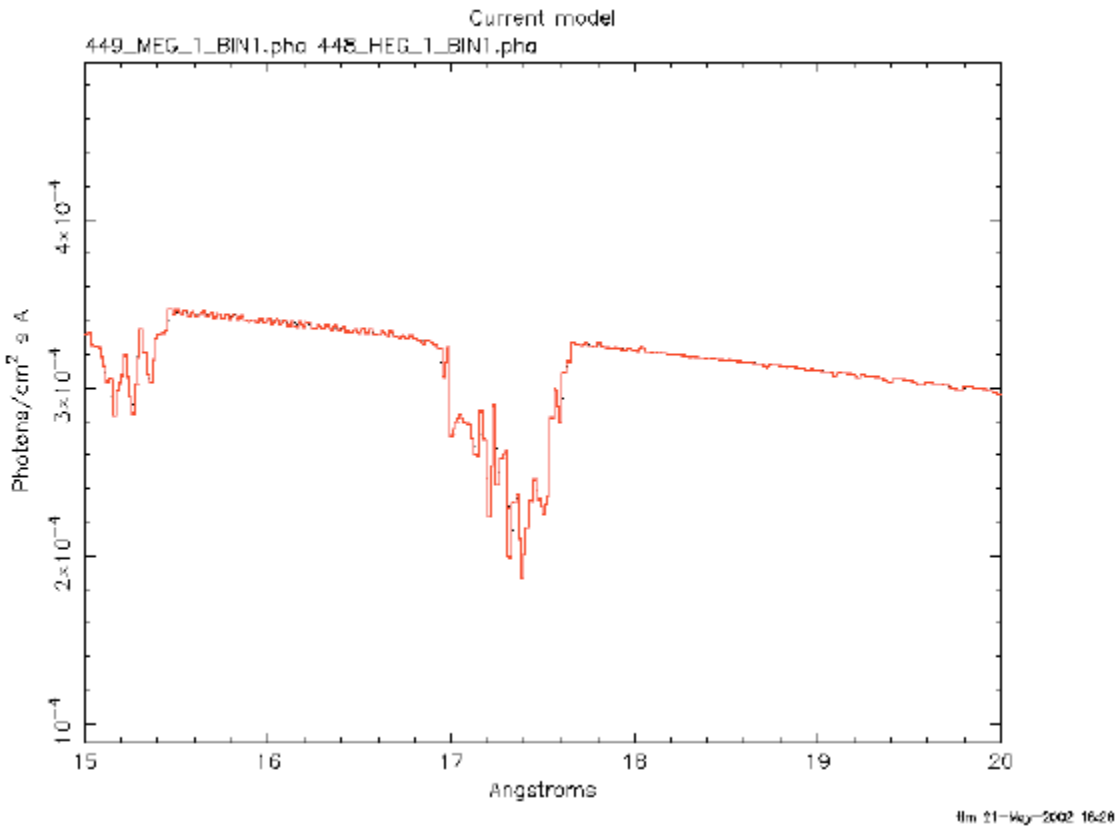
Simple Absorption (O VII, O VIII)l



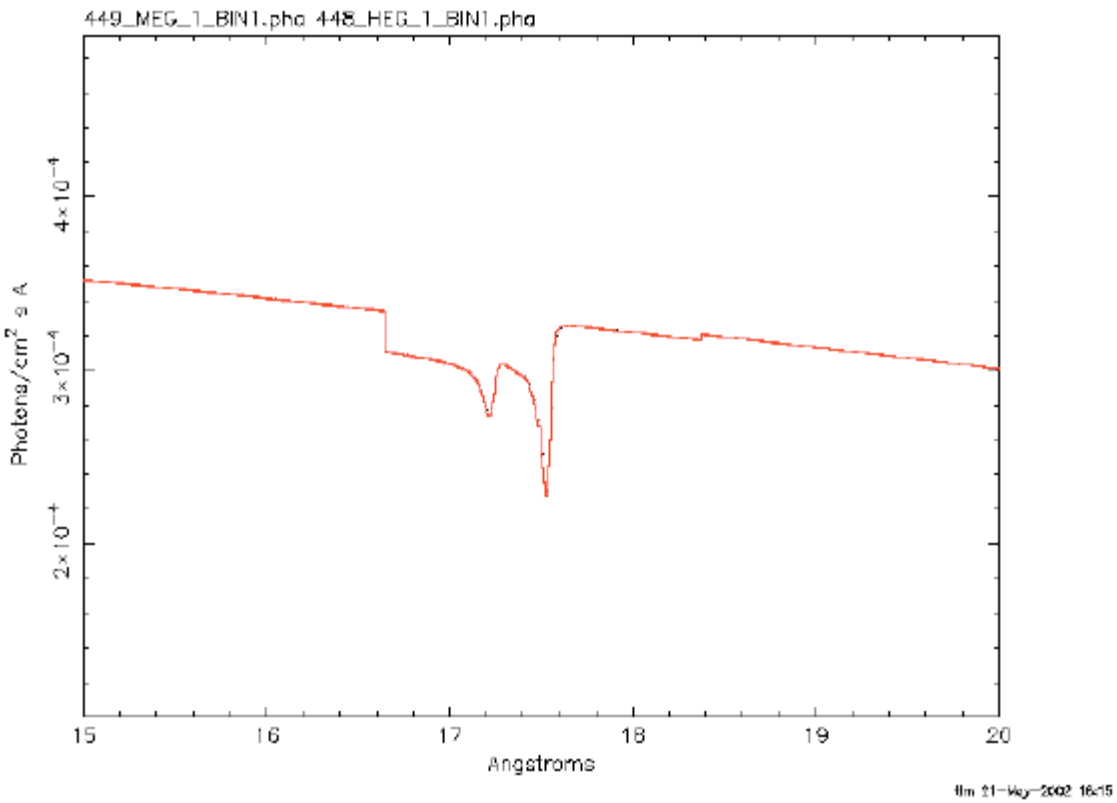
Including O VII 1s-np absorption



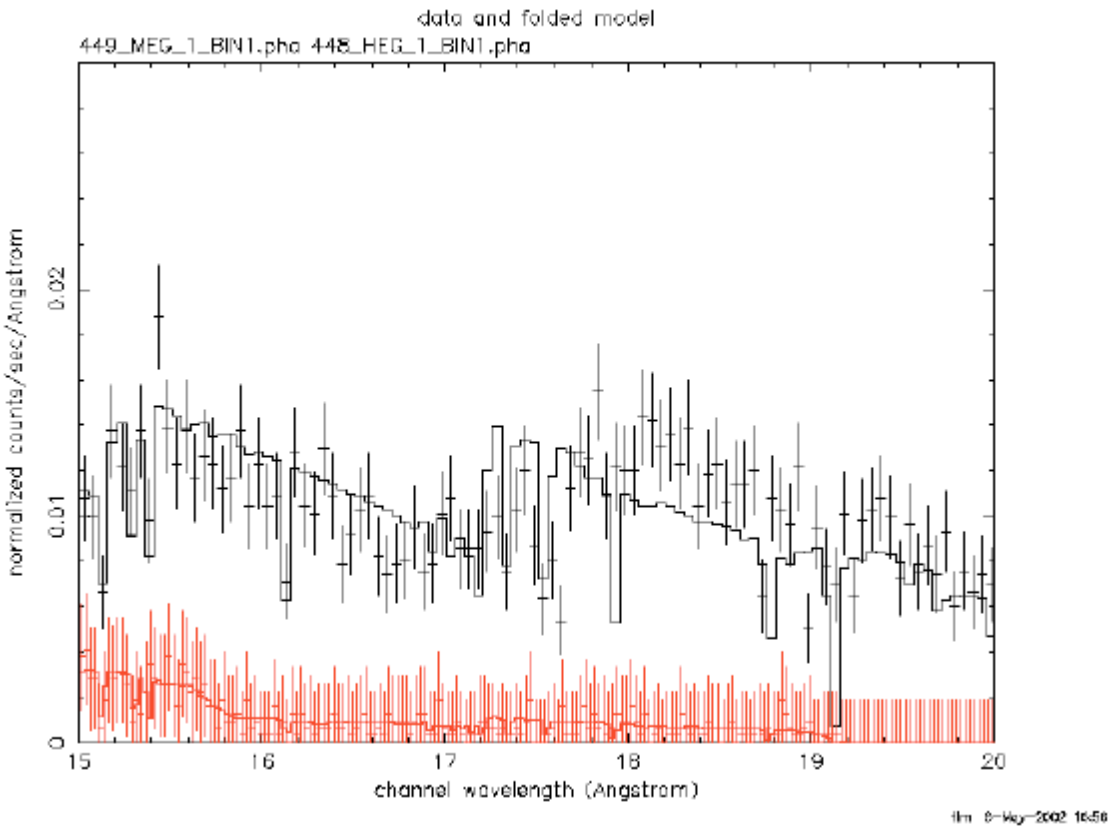
Iron n=2-3 UTAs (Fe II-V)



Fe I L shell photoionization



Best fit: OVII + Fe UTA



Summary: Absorption spectra of MCG-6-30-15

- The spectrum in the 15-20 A (0.6-0.8 keV) band observed with Chandra and XMM gratings contains complex features which do not fit with simple photoelectric absorption
  - The O VII absorption edge is not at the energy expected, 16.8 A (739 eV)
- One possible explanation is relativistically broadened emission in the O VIII Lalpha line (and N VII).
- Combined effects of the 1s-np absorption + n=2-3 transitions of iron + n=2 photoabsorption appear to provide a good fit without requiring an exotic explanation.

Summary

- 'Photoionization' is likely important in a wide range of astrophysical situations, including AGN, galactic binaries (BHT, XRB, CV), and the physics of photoabsorption is in every spectrum.
- Photoionization equilibrium differs from coronal equilibrium in significant ways, i.e. Lower temperature, more democratic ion distribution.
- The spectra emitted by photoionized plasmas contain characteristic features which have use as diagnostics.
- Absorption spectroscopy is (essentially) unique to photoionized sources, and is more important than was thought 5 yrs ago

What's Missing

- Time dependence:
  - time average spectrum may not be the same as the response to the time average ionizing spectrum
  - Gas we see may be transiently ionized due to, eg., gas flow
- Radiative transfer
- Non-thermal gases
- Multi-component

Where to go from here

- Tools
  - Cloudy
  - Xstar
  - Photoion
  - APEC
- Books
  - Osterbrock ‘Astrophysics of Gaseous Nebulae’ (Ferland)
  - Mihalas ‘Stellar Atmospheres’