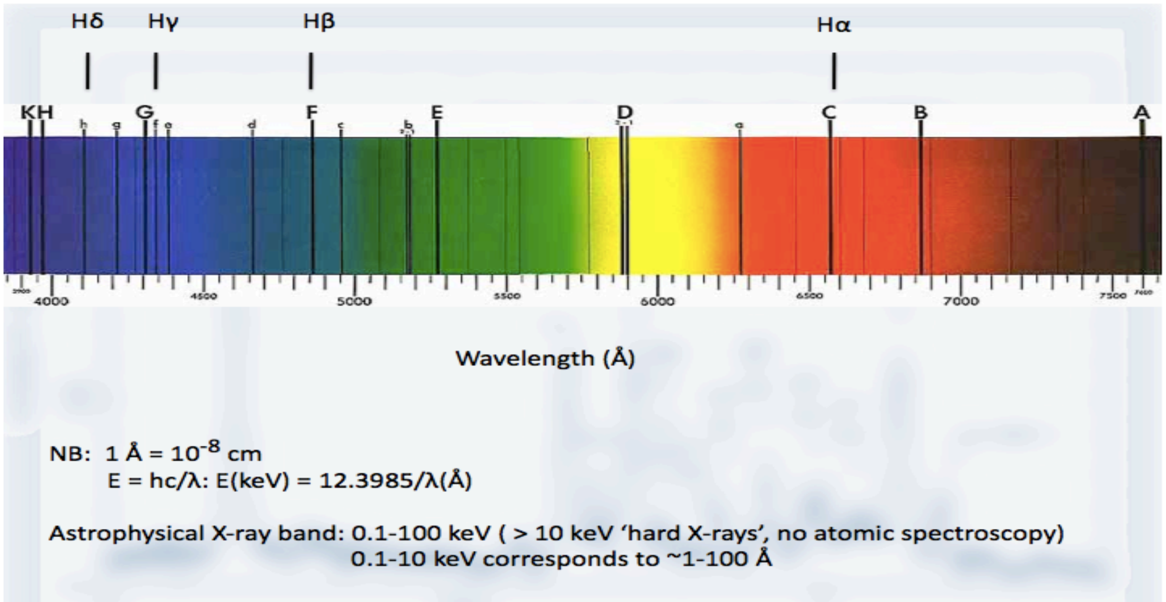
High Energy Spectroscopy
How does one get information about celestial objects



Goal of lecture

- What does 'line' emission and absorption tell us about the physics of the source
  - plasma diagnostics
- what sort of measurements are necessary to obtain this information
- what do we need to know about 'atomic' physics to interpret the information

Goal of Lecture:Physics of Emission from Gas

- Lines have enormous range of energies/wavelengths
  - molecular and fine structure lines in IR/radio band
  - atomic lines in the IR, optical, UV and **x-ray**
- Ionized gas also emits a continuum via thermal bremmstrahlung - shape of which is a measure of temperature, **intensity goes as density squared**
- Observed line energies give velocity information: redshift, velocity field
- Relative strength of lines determines ionization temperature, abundance of given element (corrected for ionization balance (go to board)).

- see **Thermal radiation processes** J.S. Kaastra, F.B.S. Paerels, F. Durret, S. Schindler, P. Richter

Space Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008 astro-ph/0801.1011 for the background physics

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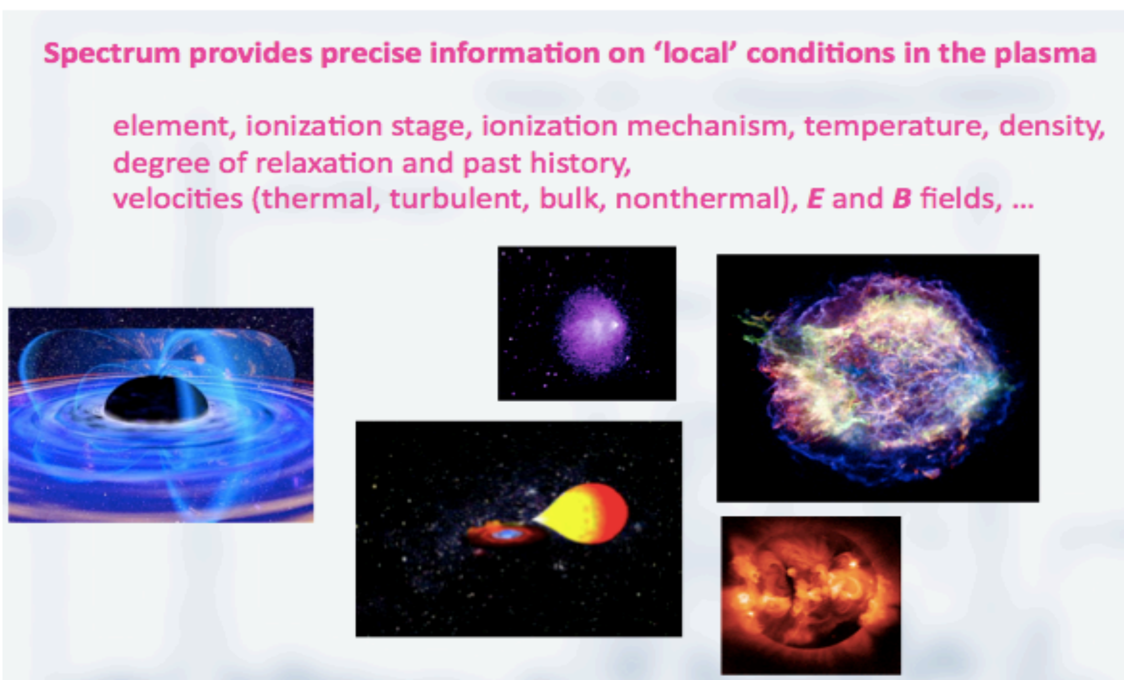


There are 4 sources of information in astrophysics- image, spectrum, time series and polarization. All of these are derived from observations- This can be combined- imaging spectroscopy, or time resolved spectroscopy etc

3 energy (wavelength ranges)

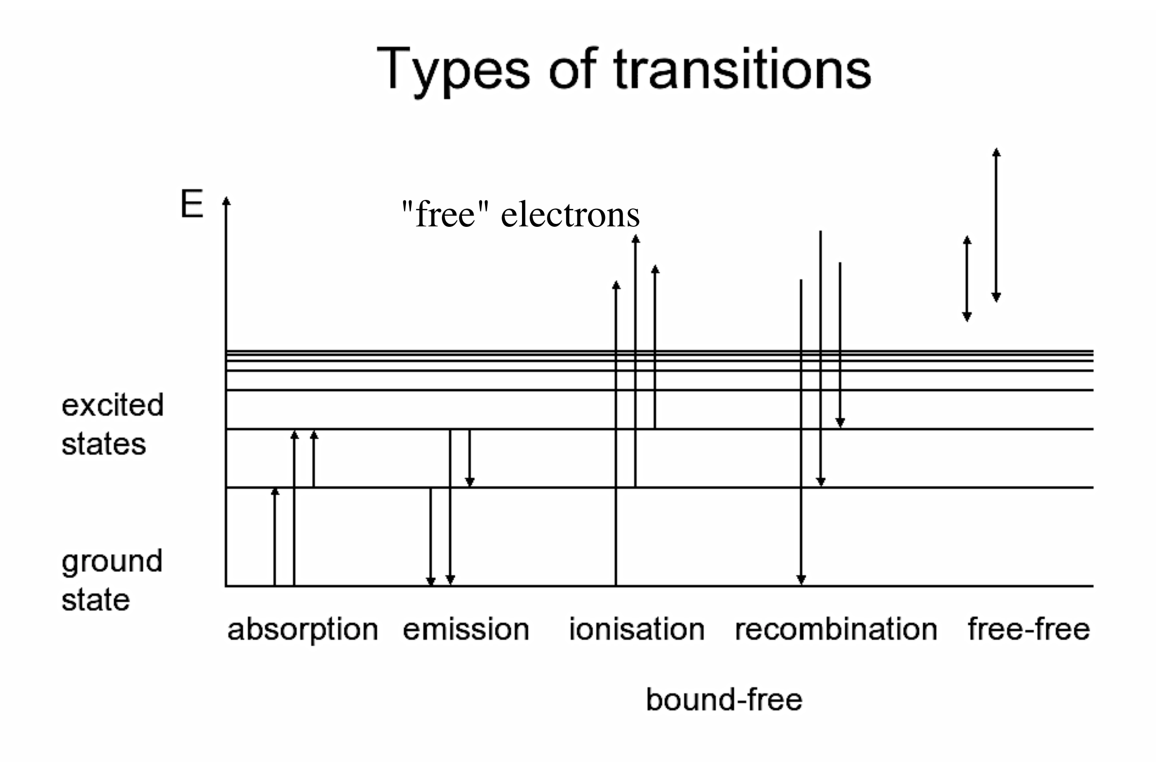
In all energy ranges have continuum process

The other main source of information is emission and absorption 'lines'

- At 1 Å < λ <50μ 'atomic processes' dominate
  - In x-ray band most transitions from He or H-like ions (1-2 electrons). Also have features from Si,S Fe L shells (3-10 electrons).
    - fluorescence* lines from all shells
- At λ >50μ molecular processes (e.g. features due to CO etc)
- At E>10 keV nuclear processes dominate- e.g. radioactive decay, β capture etc

Notice mixed units (!)

* fluorescence-when an orbital electron of a molecule or atom relaxes back to its ground state, emitting a photon, after being excited to a higher quantum state



- http://www.astro.uu.se/~ulrike/Spectroscopy/PPT/Arten_von_Uebergaengen.GIF

Radiative Processes

- Bound–bound processes: These are the processes by which an electron makes a transition from one bound level to another bound level in an atom (or ion).
  - Such transitions can be made either by collisions with electrons (collisional excitation and de-excitation) or by interactions with photons (photon excitation, spontaneous and stimulated decay).

- Bound–free processes: These processes involve the removal of an electron from a bound orbit,
  - when an atom (or ion) collides with an electron (collisional ionization) or
  - when it absorbs a photon (photoionization).

  The reverse process is recombination, by which a free electron recombines with an ion.

Radiative Processes

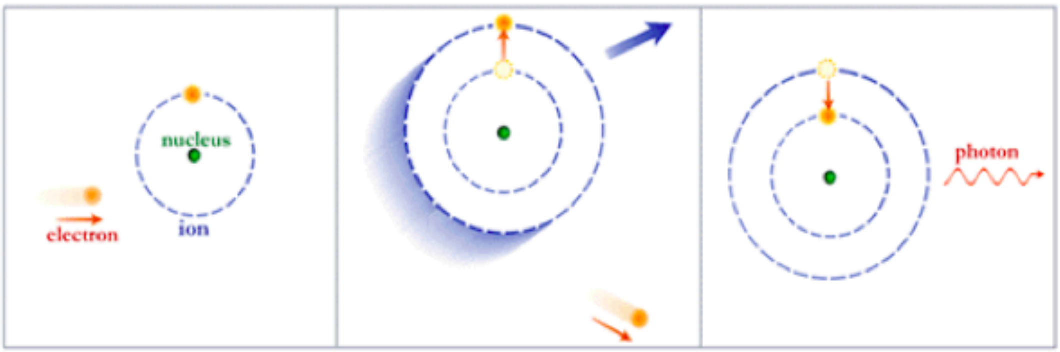
- Free–free processes: These processes involve electrons only in unbound (free) states.
  - a free electron is accelerated or decelerated, it emits photons through **bremsstrahlung.**
  - A free electron can also absorb a photon through free–free absorption.

LINE EMISSION

- Excitation of atoms by:
  - Thermal collisions
  - Radiative excitation
- Then radiative de-excitation

the most common mechanism of line emission is from collisionally excited radiative decay

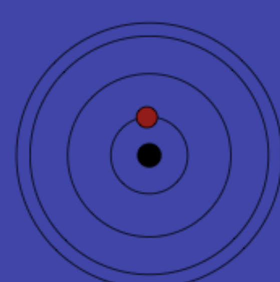
Radiative transition rate (aka "Einstein A value") is the expected number of spontaneous transitions per second/atom from one level to another $A_{ij}=1/t_{radiative}$



Specific Emission

Electron in bound orbitals around an atomic nucleus of nuclear charge Z can produce radiation at specific frequencies or energies, since electrons can only orbit the atomic nucleus in a well-defined set of allowed orbits.

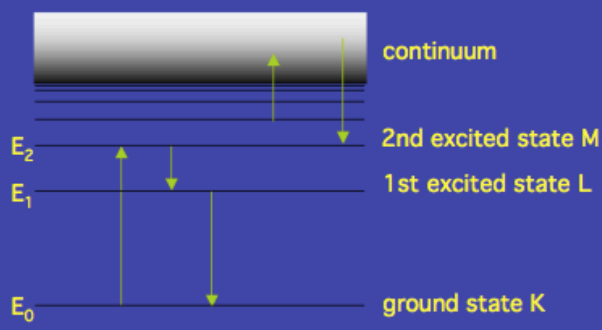
Each orbit is associated with an electron energy, so are sometimes called energy levels. An electron has to gain energy to move from an inner to an outer energy level. An electron loses energy when moving from an outer to an inner energy level.



Each element has its own unique set of energy levels:

For the 3rd time

Electronic Processes



$E_0<E_1<E_2$ (it takes energy to move the electron away from the positively charged nucleus)

Atomic Energy Level Diagram (Schematic)

Excitation: an electron absorbs radiation of energy $E=E_N-E_M$ and jumps from energy level M to level N (M<N)

De-excitation: an electron jumps from level N to level M (M<N) and emits a quantum of radiation (a photon) of energy $E=E_N-E_M$

Ionization: an electron jumps from level N to the continuum (E_∞) after absorbing a photon of energy $E > E_N$. The energy required to ionize an atom from its ground state is called the Ionization Potential.

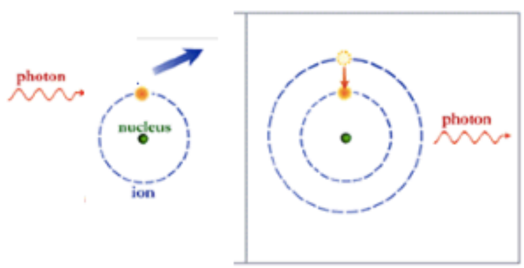
Recombination: A free electron is captured by an atom into some energy level N.

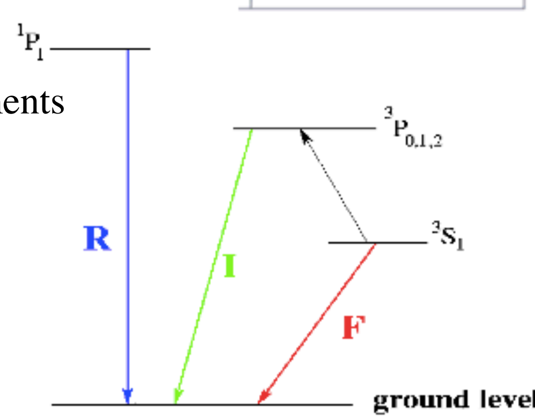
TYPES OF LINE EMISSION

- Fluorescence:
  - Needs L-shell electrons
  - Photoionization, then either:
  - 2p->1s radiative transition
  - *or* Auger ionization
  - **Fluorescence yield** measures ratio

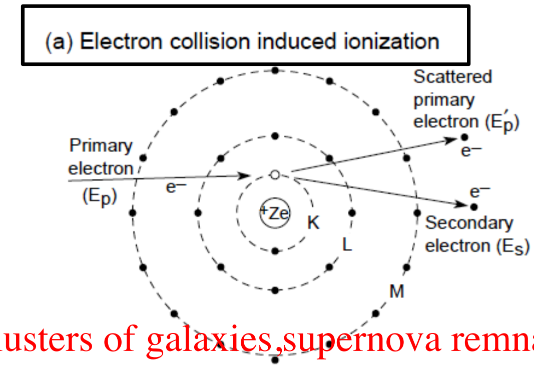
Yield~Z^4 important for high Z elements

- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination

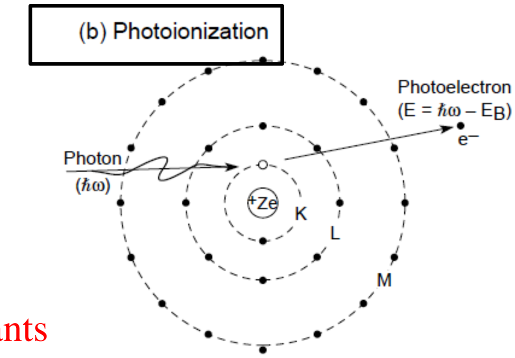




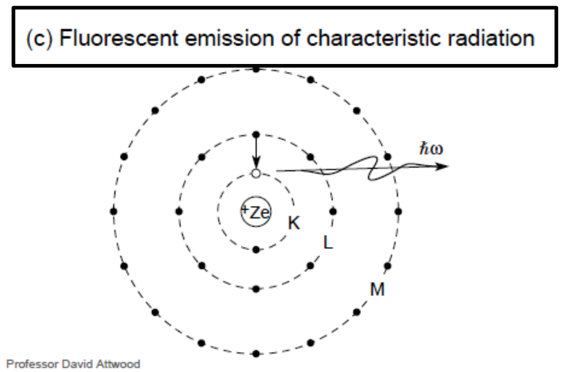
From R. Smith



Clusters of galaxies,supernova remnants



AGN

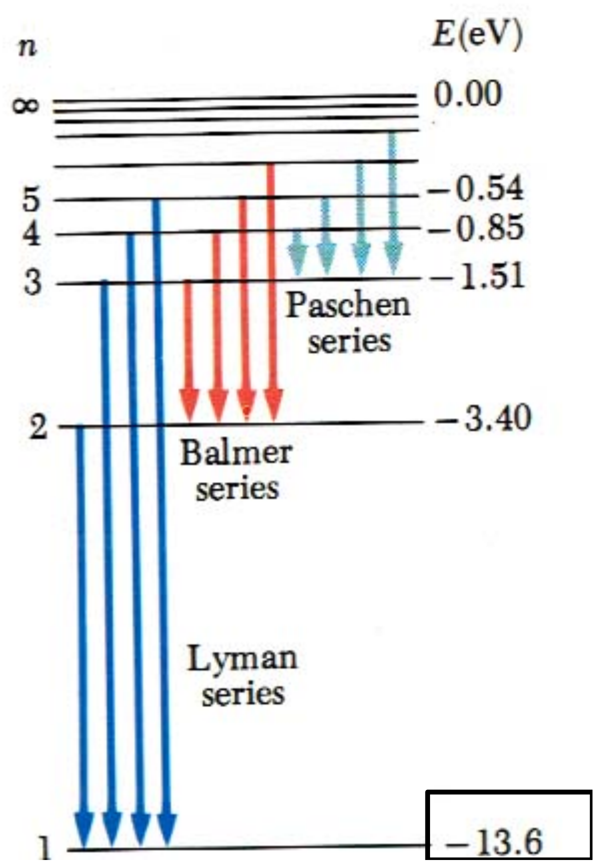


AGN and x-ray binaries

3 ways to produce a Photon via 'atomic' process (an incomplete set)

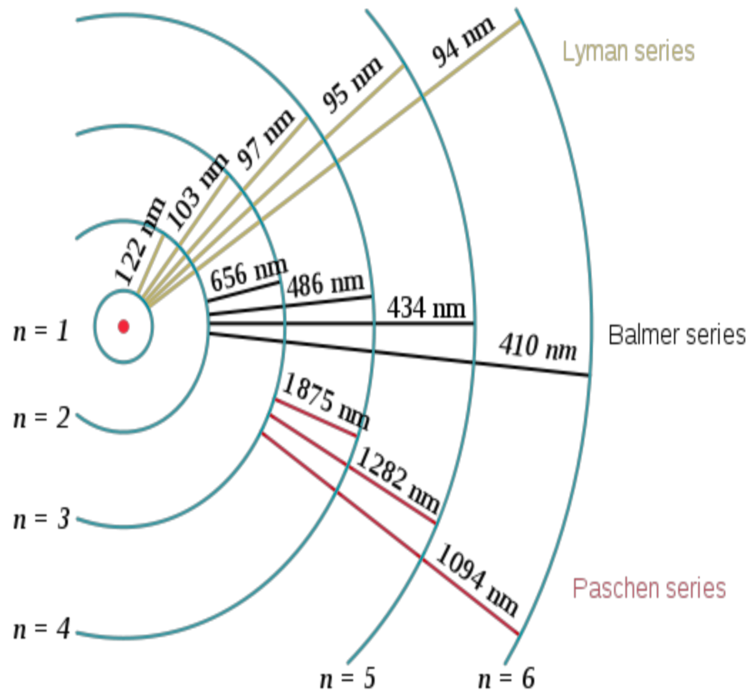
Atomic Lines

- The energy levels and transitions for **hydrogen**
  - **e.g Lyman is n → 1**
  - Balmer is **n → 2**
- Each element and ionization set has a similar (but more complex) set of lines
- The probability of emitting a given line depends on the temperature and density of the gas

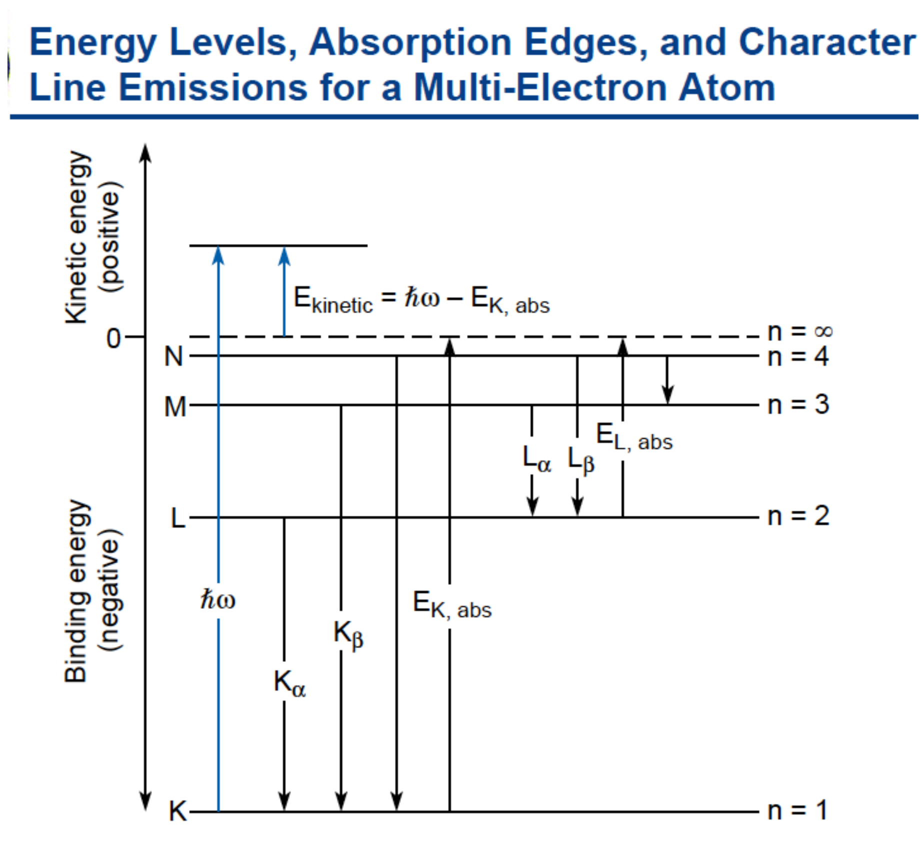


Hydrogen Line Wavelengths

- Lyman lines are in the UV
- Balmer lines in the optical
- Paschen in the IR
- Moseley law
  $E_{line} \sim (Z-1)^2 \times 13.6 eV$

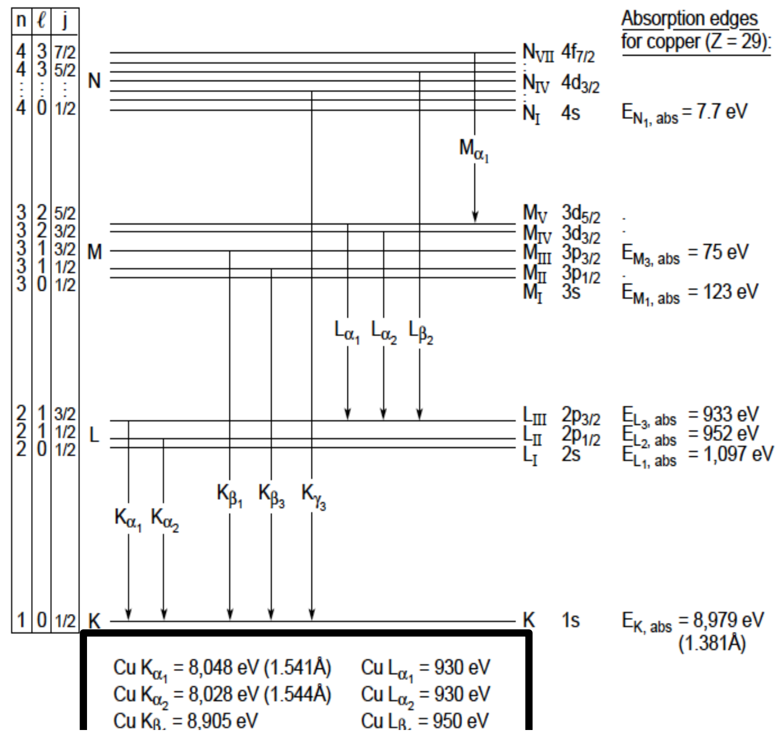


Generic Atom



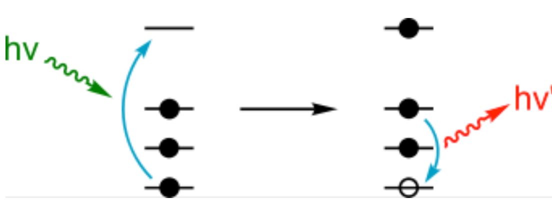
Copper Atom

Energy Levels, Quantum Numbers, and Allowed Transitions for the Copper Atom

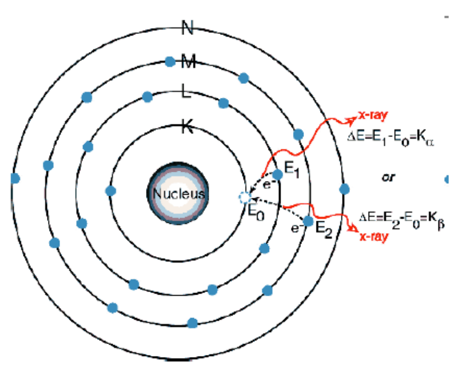


Fluorescence

- Following removal of an inner electron by an energetic photon by radiation source, an electron from an outer shell drops into its place. -
- *This process can produce x-ray line radiation even from totally unionized (cold) atoms*
- L-→K transition Kα,
- M-→K Kβ, M→L Lα etc



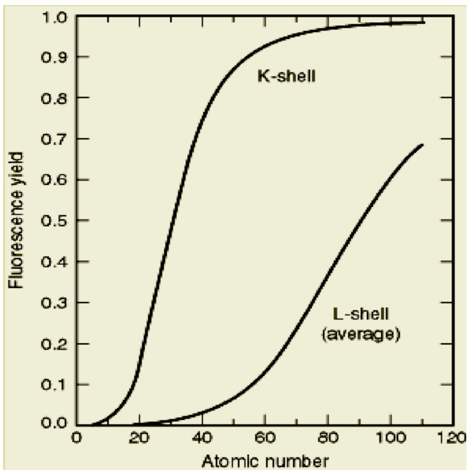
- X-ray fluorescence

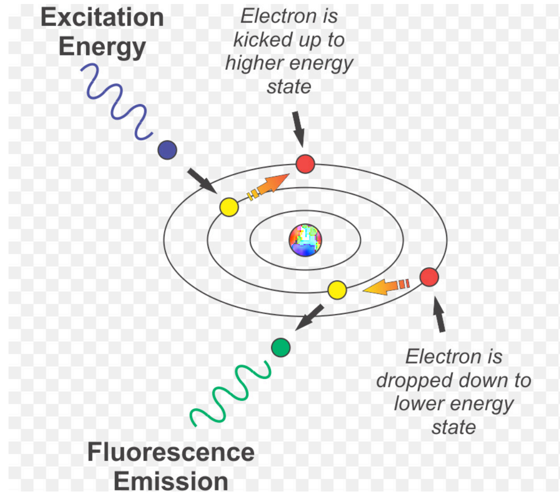


  – discrete lines!

Fluorescence

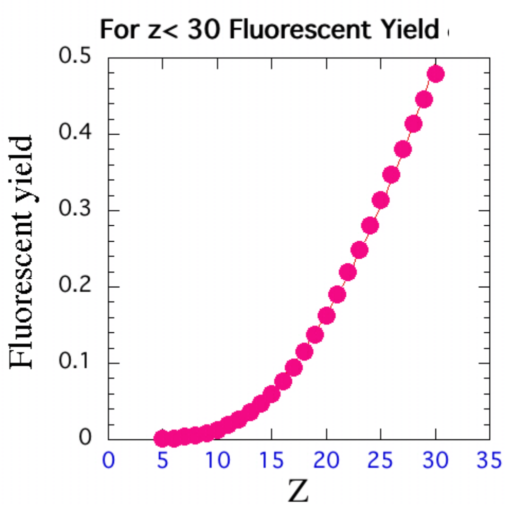
- Fluorescence yield is proportional to Z^4 and abundance so **Fe is the strongest fluorescence line in x-ray spectra**

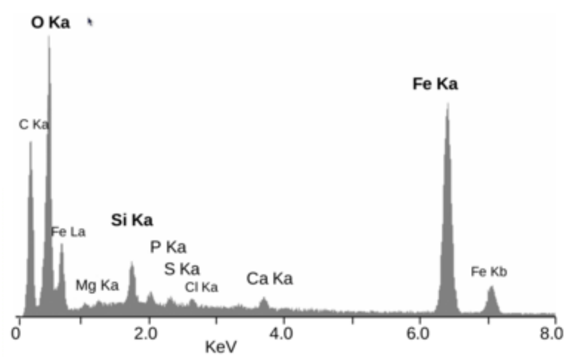




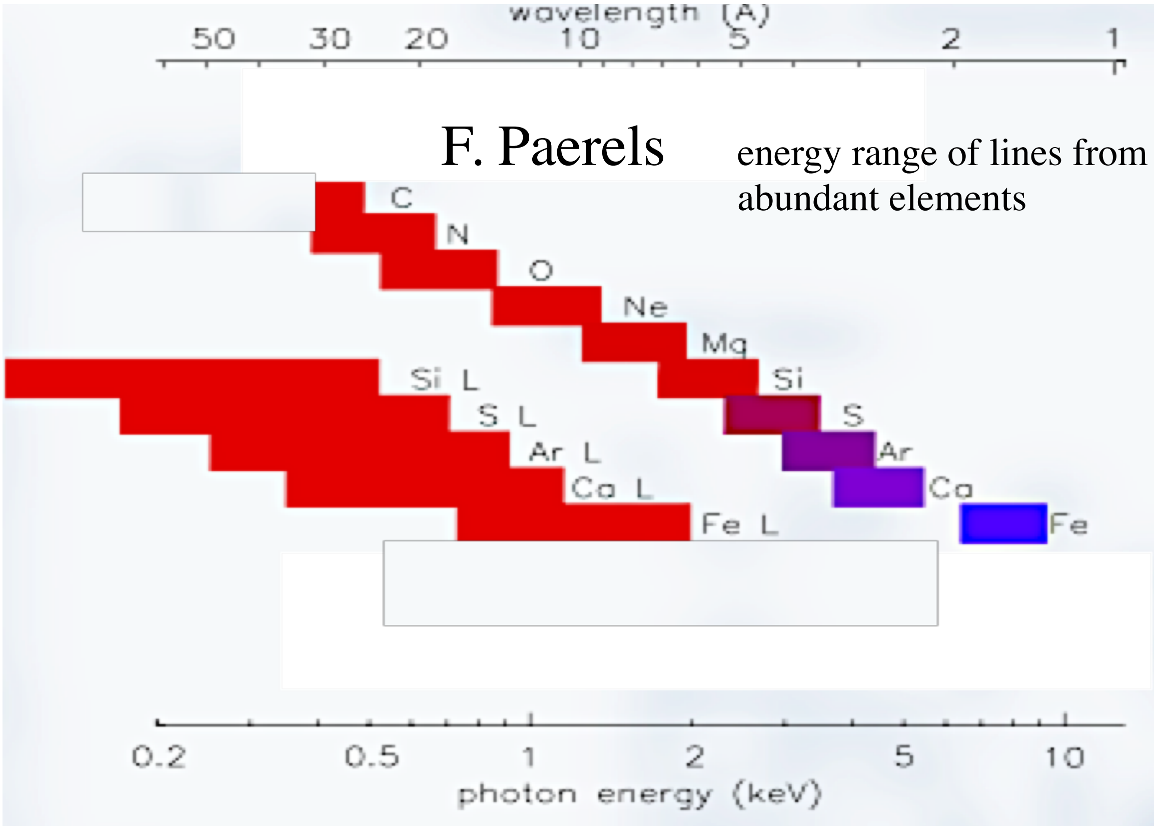
Fluorescence Spectroscopy

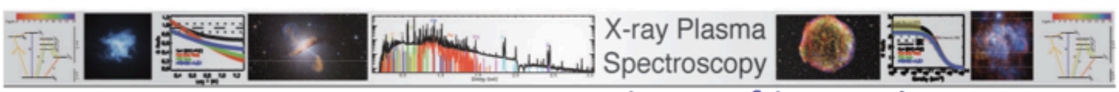
- Strength of lines is α to fluorescence yield x abundance
- fluorescence yield α to Z^4





For most x-ray spectra Fe is the dominant fluorescent line





Ions of Importance

In x-ray spectra

All ions are equally important.

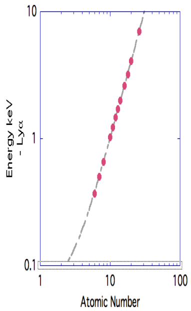
...but some are more equal than others.

In collisional plasmas, <u>three ions are of particular note:</u>

H-like : All transitions of astrophysically abundant metals (C→Ni) are in the X-ray band. Lyα/Lyβ is a useful temperature diagnostic; Lyα is quite bright.

He-like: Δn≥1 transitions are all bright and in X-ray. The n=2→1 transitions have 4 transitions which are useful diagnostics, although R=300 required to separate them.

Ne-like: Primarily Fe XVII; two groups of bright emission lines at 15Å and 17Å; ionization state and density diagnostics, although there are atomic physics problems.



H-LIKE SPECIES

Ion	$Ly\alpha_1$		$Ly\alpha_2$		K-edge	
	λ (Å)	E (keV)	λ (Å)	E (keV)	λ (Å)	E (keV)
C VI	33.7342	0.36754	33.7396	0.36747	25.3033	0.489993
N VII	24.7792	0.50036	24.7846	0.50024	18.5871	0.667046
O VIII	18.9671	0.65368	18.9725	0.65348	14.2280	0.871410
Ne X	12.1321	1.02195	12.1375	1.02150	9.10177	1.36220
Na XI	10.0232	1.23697	10.0286	1.23631	7.52011	1.64870
Mg XII	8.41920	1.47264	8.42461	1.47169	6.31714	1.96266
Al XIII	7.17091	1.72899	7.17632	1.72769	5.38093	2.30414
Si XIV	6.18043	2.00608	6.18584	2.00432	4.63808	2.67318
S XVI	4.72735	2.62270	4.73276	2.61970	3.54830	3.49419
Ar XVIII	3.73110	3.32299	3.73652	3.31817	2.80113	4.42622
Ca XX	3.01848	4.10750	3.02390	4.10014	2.26668	5.46986
Fe XXVI	1.77802	6.97316	1.78344	6.95197	1.33637	9.27760

Lines: Johnson, W. R., & Soff, G. 1985, Atom. Data Nucl. Data Tables, 33, 405

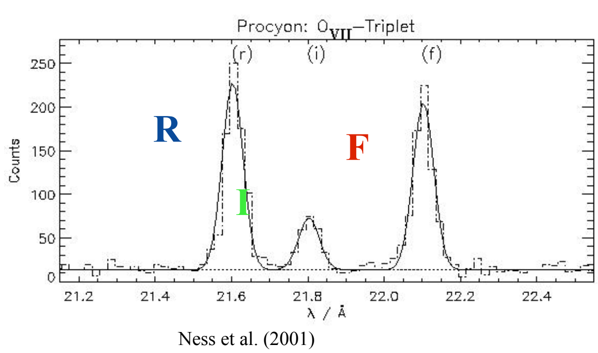
Notice ~30 range in energies

HE-LIKE SPECIES

Ion	w(resonance)		x(intercombo)		y(intercombo)		z(forbidden)		K-edge	
	λ (Å)	E (keV)	λ (Å)	E (keV)	λ (Å)	E (keV)	λ (Å)	E (keV)	λ (Å)	E (keV)
C V	40.2674	0.307902	40.7280	0.304420	40.7302	0.304404	41.4718	0.298960	31.63	0.392
N VI	28.7800	0.430800	29.0819	0.426328	29.0843	0.426293	29.5346	0.419793	22.46	0.552
O VII	21.6015	0.573961	21.8010	0.568709	21.8036	0.568641	22.0974	0.561080	16.78	0.739
Ne IX	13.4473	0.922001	13.5503	0.914992	13.5531	0.914803	13.6984	0.905100	10.37	1.196
Na X	11.0029	1.12683	11.0802	1.11897	11.0832	1.11867	11.1918	1.10781	8.463	1.465
Mg XI	9.16875	1.35225	9.22817	1.34354	9.23121	1.34310	9.31362	1.33121	7.037	1.762
Al XII	7.75730	1.59829	7.80384	1.58876	7.80696	1.58812	7.87212	1.57498	5.944	2.086
Si XIII	6.64795	1.86500	6.68499	1.85467	6.68819	1.85378	6.73949	1.83967	5.085	2.438
S XV	5.03873	2.46062	5.06314	2.44876	5.06649	2.44714	5.10067	2.43074	3.846	3.224
Ar XVII	3.94907	3.13958	3.96557	3.12628	3.96936	3.12353	3.99415	3.10414	3.009	4.121
Ca XIX	3.17715	3.90237	3.18910	3.88775	3.19275	3.88330	3.21103	3.86120	2.417	5.129
Fe XXV	1.85040	6.70040	1.85541	6.68231	1.85952	6.66754	1.86819	6.63659	1.404	8.828

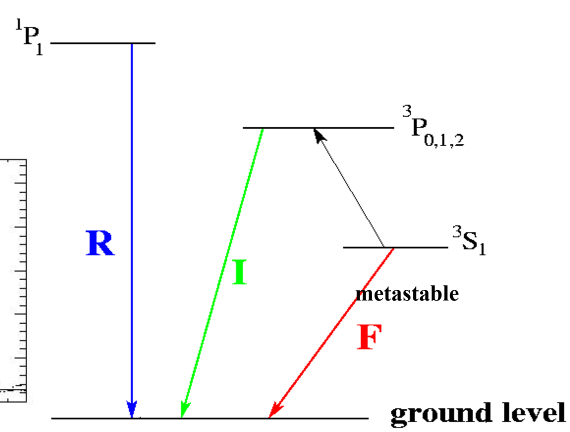
Diagnostics − He Like Ions

R: resonance line (permitted, w)
I: Intercombination line (x+y)
F: Forbidden line (z)



Ness et al. (2001)

Energy Levels



Gabriel & Jordan (1969):

- **Density:** $R(n_e)$ = **Forbidden** / **Intercombination**
- **Temperature:** $G(T_e)$ = **(F + I)** / **Resonance**

widely used for solar plasma diagnostics. collisional plasmas (e.g., stellar coronae),

photo-ionization (e.g., AGN, X-ray binaries), out-of-equilibrium (e.g., SNR)

"Two Types" of Ionized Gas

- Photoionized
  - in ISM O and B stars ionize gas and produce HII regions and Planetary Nebulae
    - gas properties determined by density and spectrum of stars
  - Photoionization by the stellar radiation field is balanced by recombination into *excited* states of H.
  - (Total # of ionizing photons/sec emitted)=Total # of recombination into excited levels of H per second
- Collisional Ionization
  - Gas is heated by some process and ionization balance is controlled by collisions (ISM in elliptical galaxies)

The basic atomic processes in astrophysical X-ray emitting plasmas are two-body collisional excitation & ionization, photoexcitation & ionization, spontaneous radiative decay, and two-body recombination.

A consequence of this is that the plasmas can be separated into two categories:

- Collisional:
  $k_B T_e$ ~ Ionization energy of plasma ions

- Photoionized:
  $k_B T_e$ << Ionization energy of plasma ions

Ionization Balance

- In <u>collisional Ionization equilibrium</u> the fraction of a given element in a given ionization state is solely a function of **temperature**

Oxygen Fe

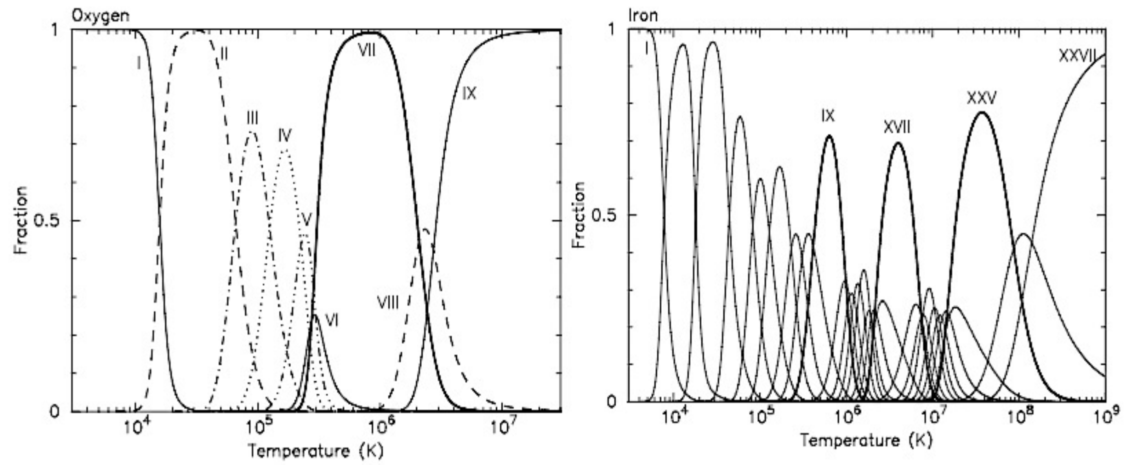
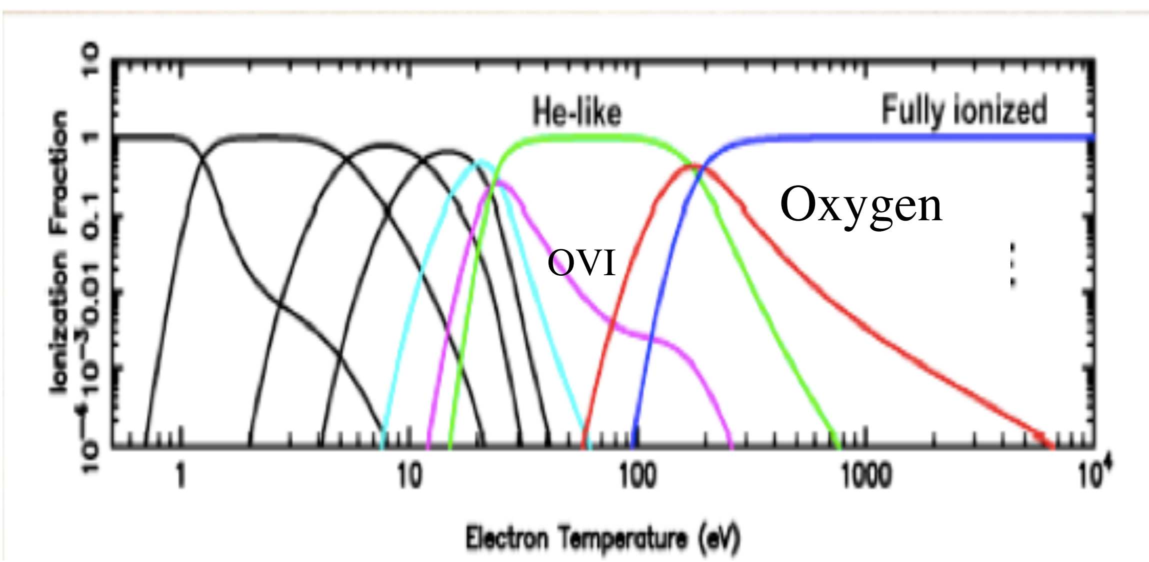


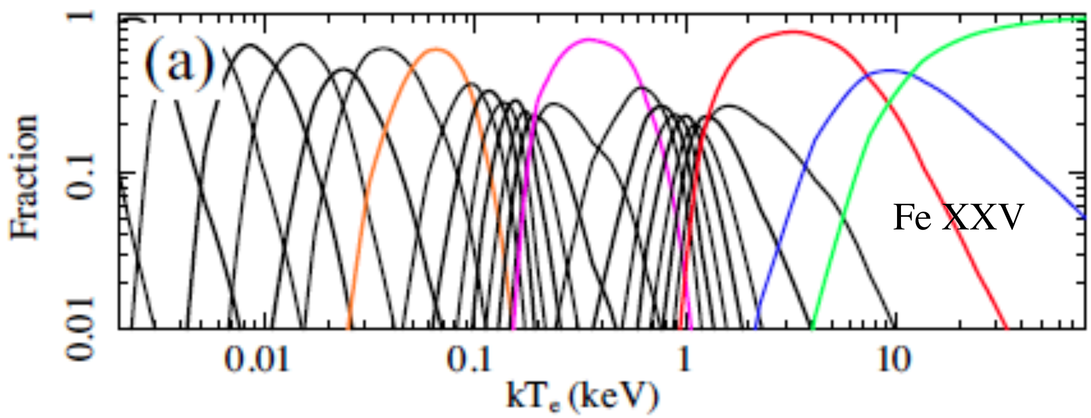
Fig. 7 Ion concentration of oxygen ions (left panel) and iron ions (right panel) as a function of temperature in a plasma in Collisional Ionisation Equilibrium (CIE). Ions with completely



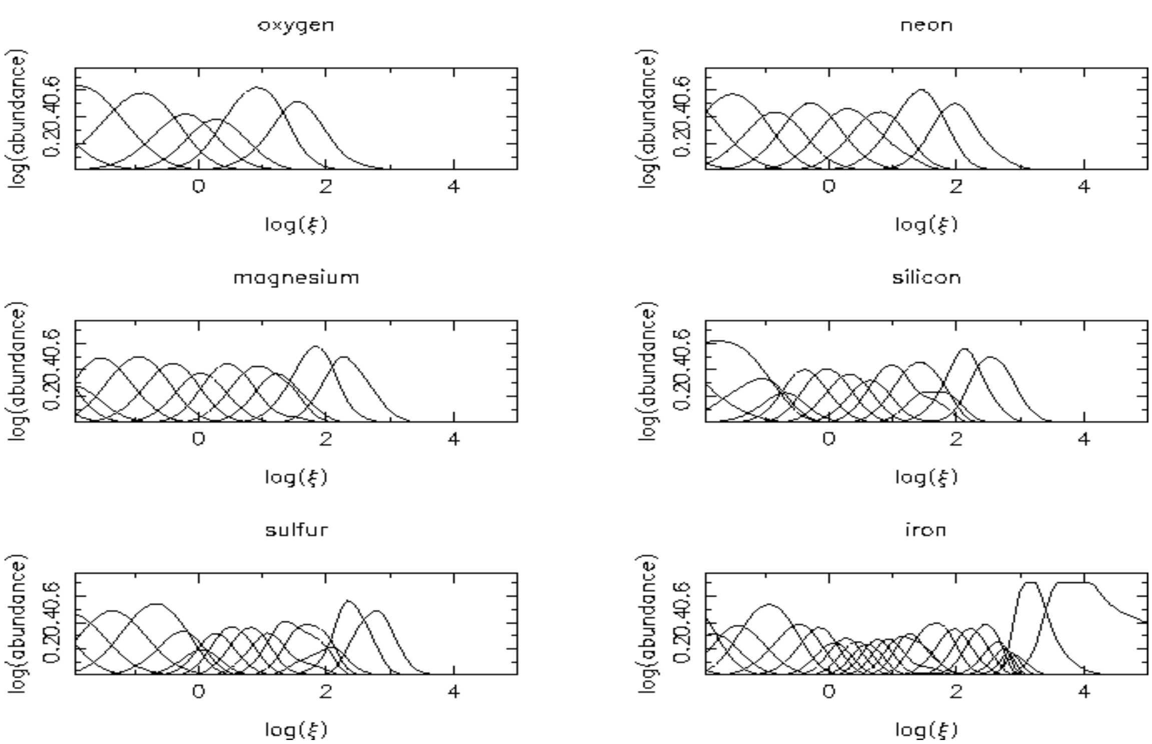
For temperatures > 1keV (1.17x107k) oxygen is completely ionized, x-ray lines are from He and H-like oxygen and are produced at kT ~30-700eV (3×10^5-8×10^6 degrees kelvin)

Collionsially Ionized Plasma

- The fraction of **Fe** that is in a given ionization state as a function of the **temperature** (red is He-like Fe, blue is H-like Fe, magenta is Ne-like (Fe+16), orange is Ar like, Fe+8)
- **As gas gets hotter it gets more ionized**



Ionization fractions of elements in a photoionized gas



ξ=X-ray flux/gas density=4πF/n

Neutral <----------->fully stripped

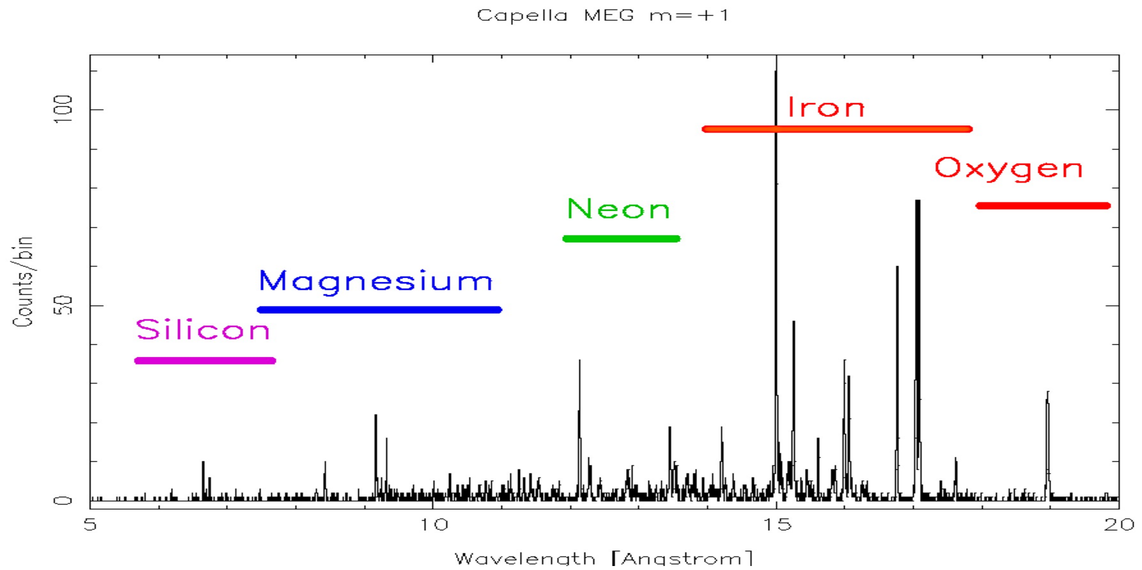
Plasma Codes

Understanding a collisional/photoionized plasma requires a collisional/photoionized plasma model. Since even a simple model requires considering hundreds of lines, and modern codes track millions, most people select one of the precalculated codes:

Code	Source
Raymond-Smith	ftp://legacy.gsfc.nasa.gov/software/plasma_codes/raymond
SPEX	http://saturn.sron.nl/general/projects/spex
Chianti	http://wwwsolar.nrl.navy.mil/chianti.html
ATOMDB	http://cxc.harvard.edu/ATOMDB

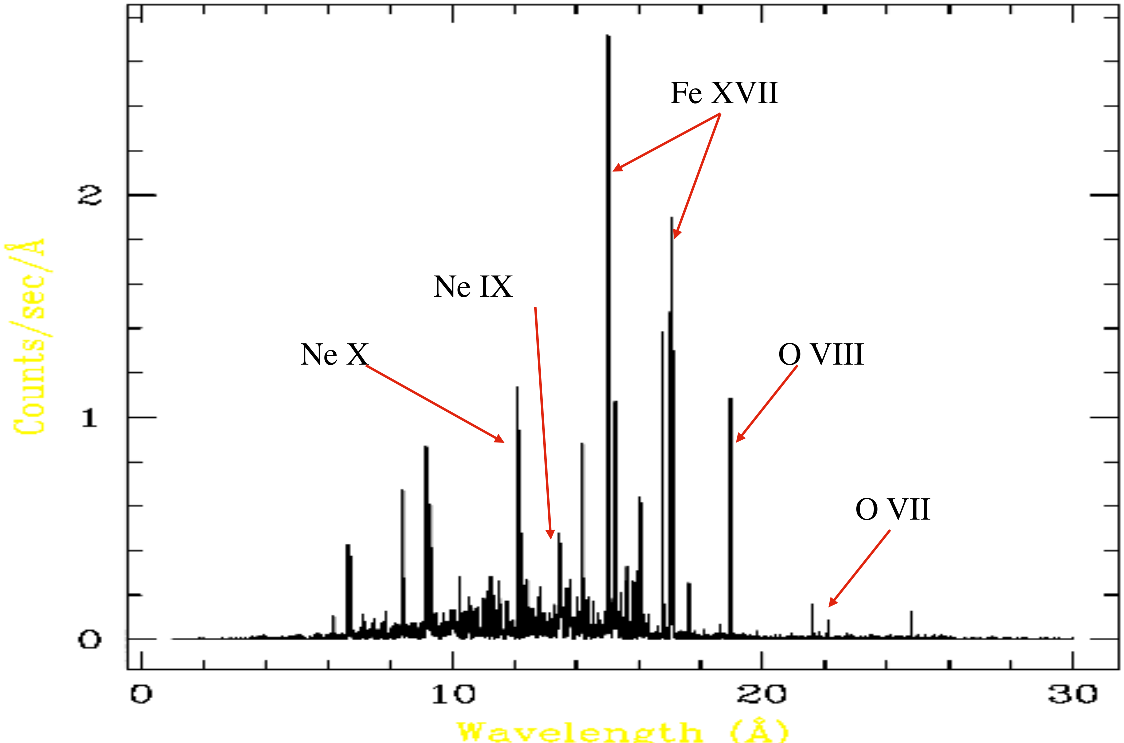
The calculated spectrum is known as APEC, and the atomic database is called APED.

Chandra Grating Spectrum of Capella



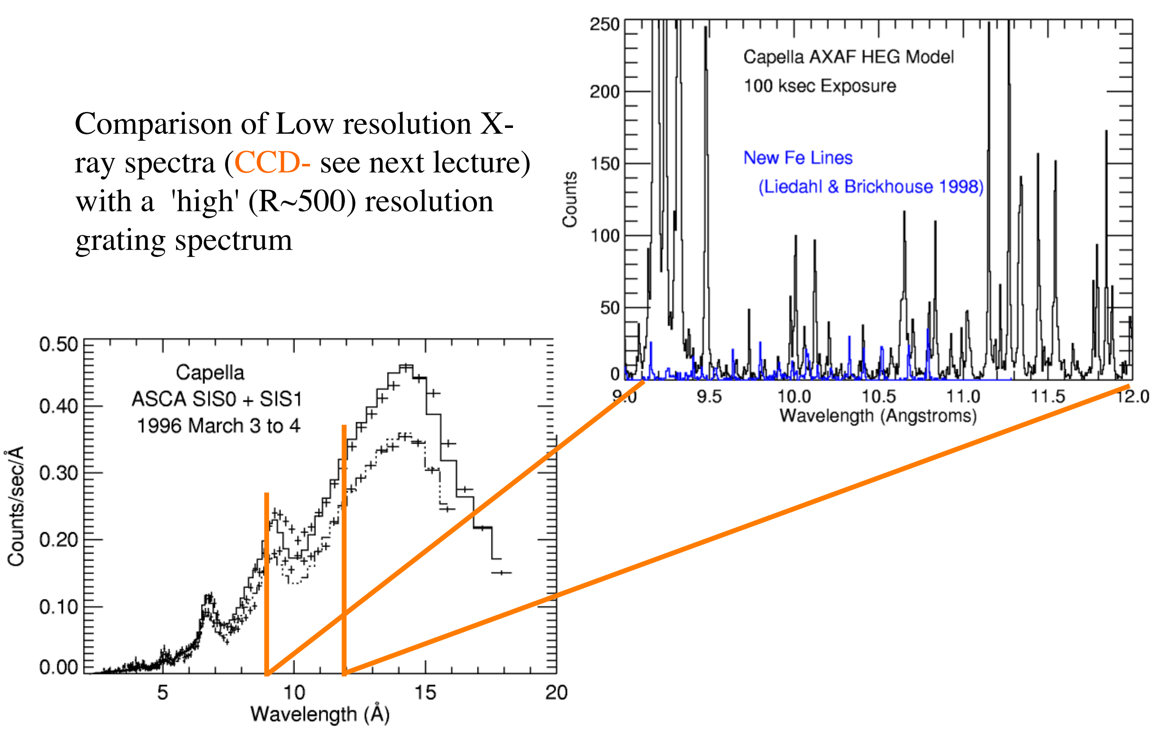
Capella Chandra HETG Data

Ions of Importance



Collisionally Ionized Equilibrium Plasma-Capella

Comparison of Low resolution X-ray spectra (CCD- see next lecture) with a 'high' (R~500) resolution grating spectrum



Physical Processes

- Continuum emission
  - Thermal bremsstrahlung, ~exp(-hν/kT)

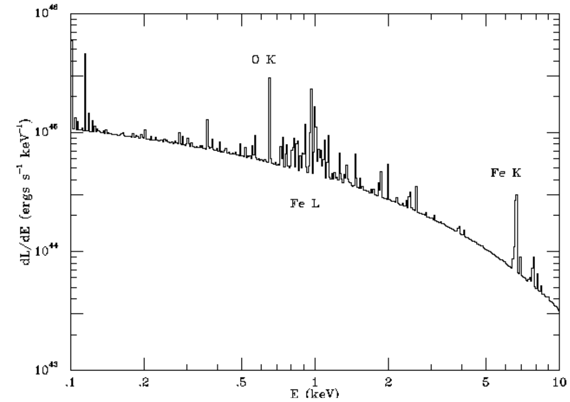
- Line Emission

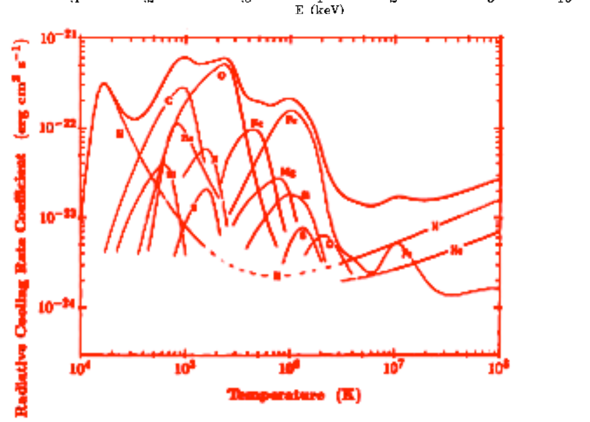
  (line emission)

  $L_\nu \sim \varepsilon_\nu$ (T, abund) $(n_e^2\, V)$

  Line emission dominates cooling at T<10^7 K

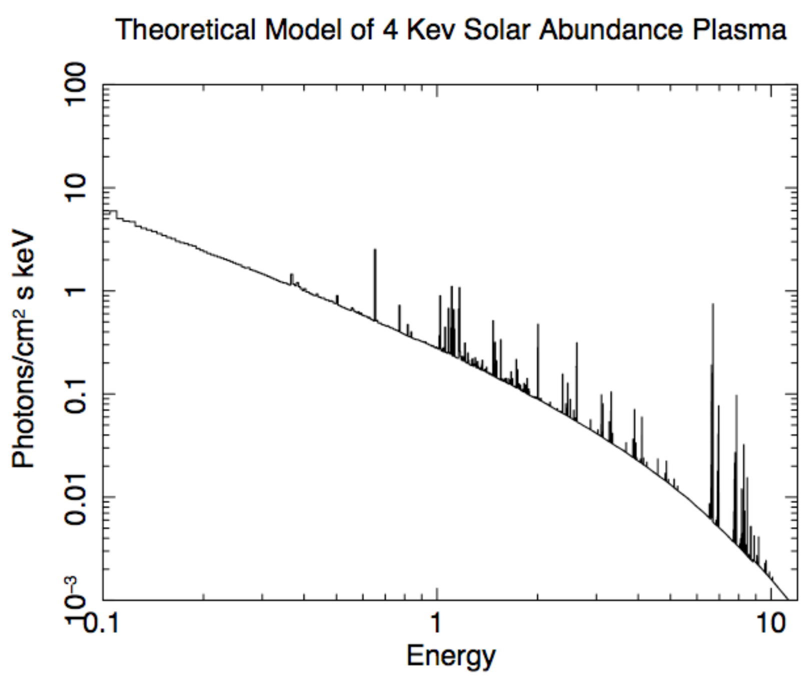
  Bremmstrahlung at higher temperatures





$$\epsilon(\nu) = \frac{16\, e^6}{3\, m_e\, c^2} \left(\frac{2\pi}{3 m_e\, k_B T_X}\right)^{1/2} n_e n_i\, Z^2\, g_{ff}(Z, T_X, \nu)\, \exp\left(\frac{-h\nu}{k_B T_X}\right),$$

...oling rate of hot plasma as a function of the plasma temperature. The contribution to the cooling ...s of different important abundant elements is indicated (Böhringer and Hensler 1989). Most of

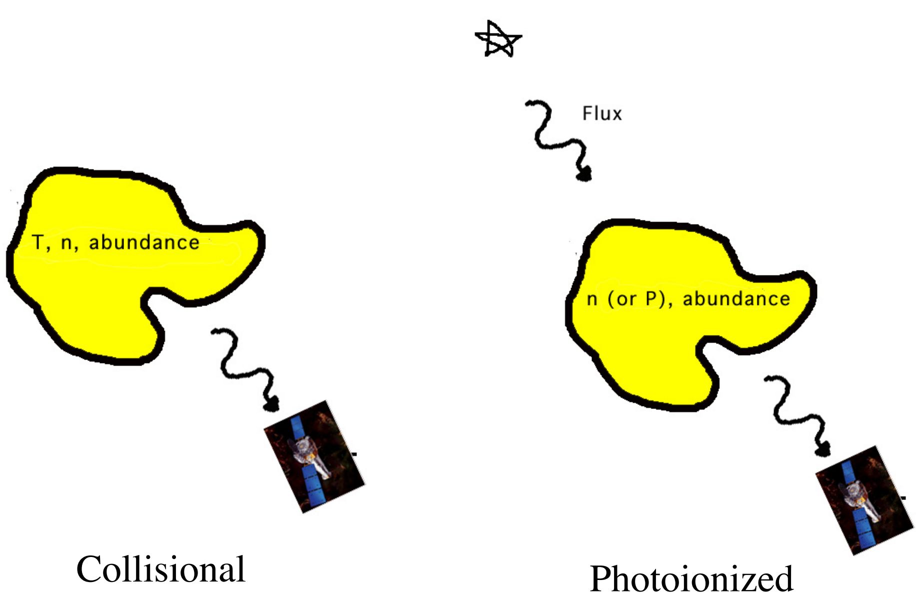


- Theoretical model of a <u>collisionally ionized</u> plasma kT=4 keV with solar abundances
- The lines are 'narrow'
- Notice dynamic range of 10^4

Plasmas
R. Smith

	Photoionized	Coronal
Dominant ionization	Photoionization $h\nu$+Z ->Z+1	Electron impact e^-+Z ->Z+1
Examples	Active galaxies(AGN) x-ray binaries	Stellar coronae Supernova remnant Clusters of galaxies
Spectral signature	Absorption,bound-free, bound-bound Emission: recombination	Emission lines, Δn=0,1,2 favored

Photoionized Plasmas



R. Smith

R. Smith

Photoionized Plasmas

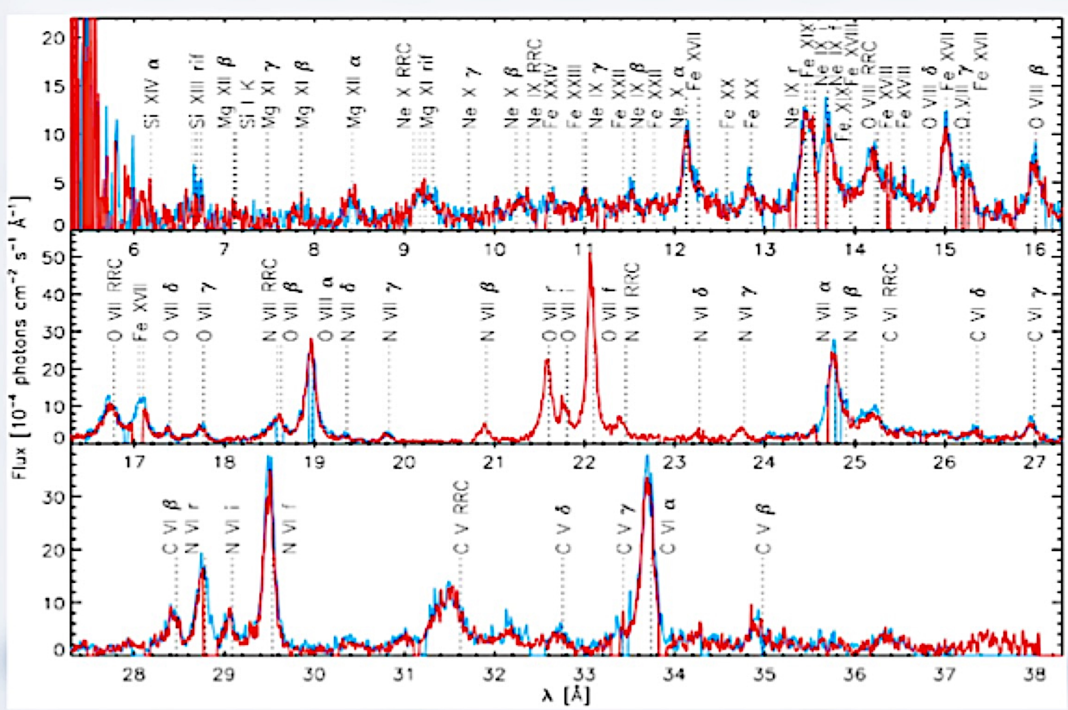
What happens when an external photon source illuminates the gas?

- The photons ionize the atoms in the gas.
- The electrons 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*

ξ=X-ray flux/gas density=4πF/n

Emission from X-ray photoionized gas



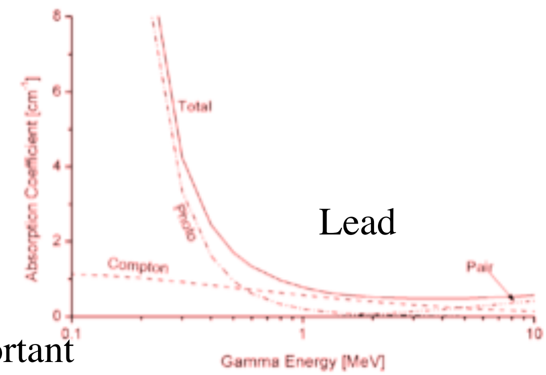
NGC 1068 (Seyfert 2); *XMM-Newton* RGS; Kinkhabwala et al., 2002, *ApJ*, **575**, 732

Absorption of X and γ-ray Photons

- Absorption processes
  - Photoelectric absorption Longair 9.1
  - Ionized gas: warm absorbers
  - Absorption lines

absorption of γ-rays via pair creation, photoelectric effect, Compton scattering (photons reduced in energy, not absorbed).

X-ray and γ-rays are very penetrating radiation -but a 1 keV x-ray is totally absorbed by ~0.01gm of material (~10^{22} atms/cm^2)



In γ-rays pair creation is also important

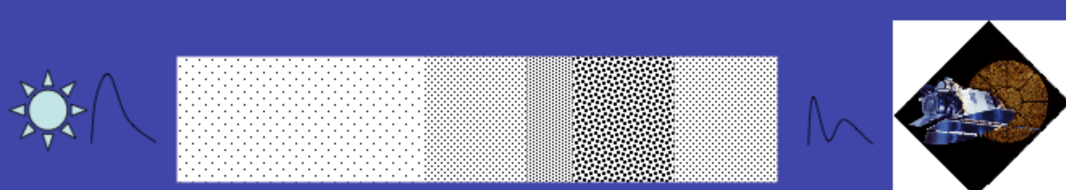
Absorption

As radiation passes through a medium, in general the medium will absorb some of the radiation, and emit some radiation. Thus the radiation received at a detector will be different from that emitted by the source. For a source of intensity I_0 whose light passes through an absorbing medium, the observed intensity I is

$$I = I_0 \exp^{-\tau}$$

where τ is the optical depth of the medium. τ is sometimes expressed in terms of an absorption cross-section σ and a column density N (the number of particles in a cylindrical column of unit area in the medium)

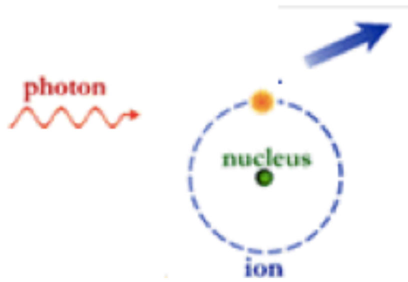
$$\tau = N\sigma$$



PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O)
absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

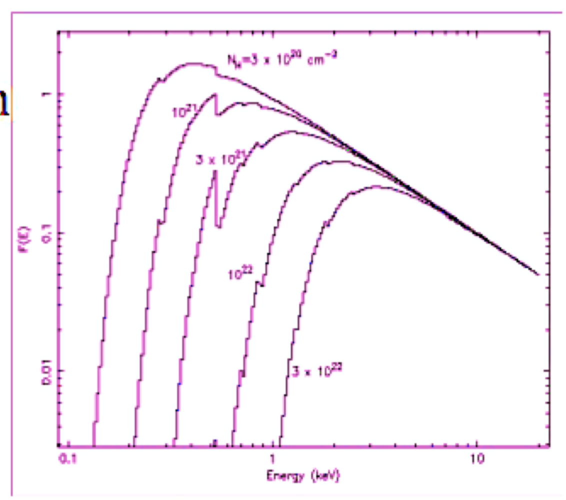
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

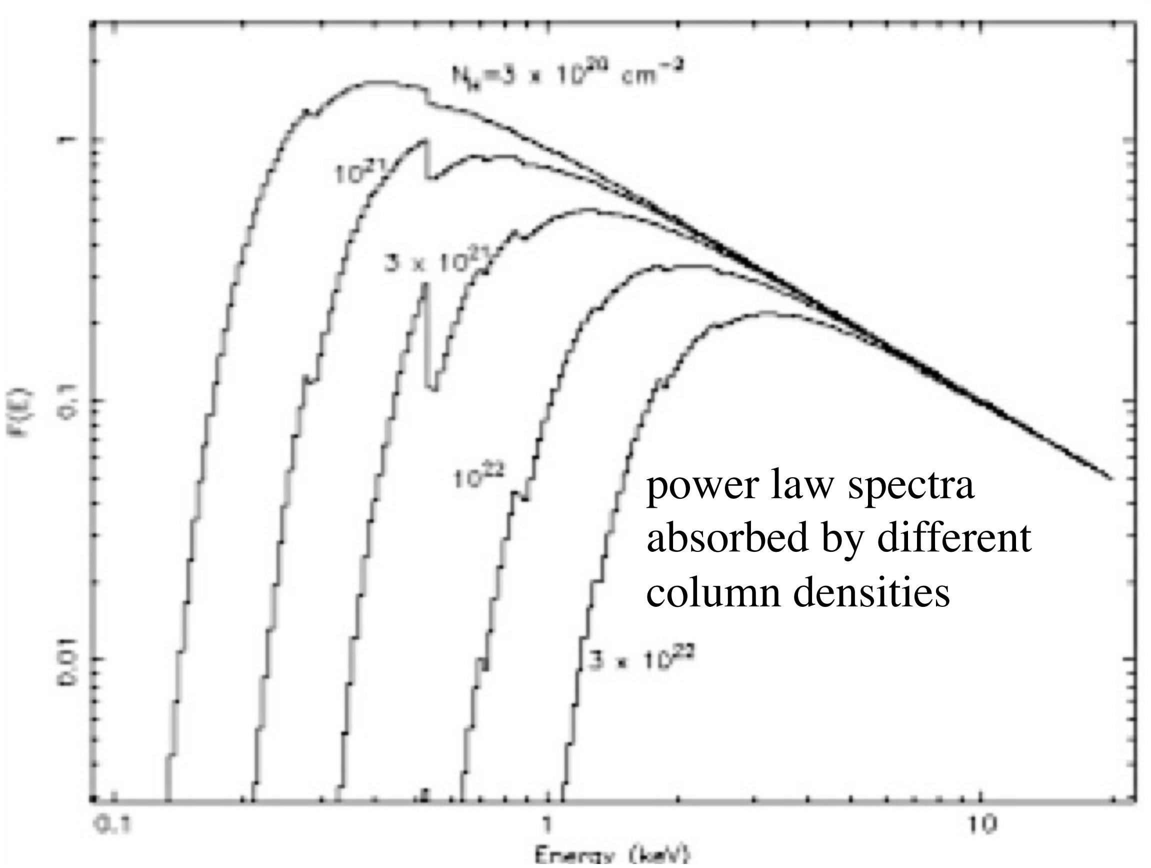
$\tau = \sigma(E) N_H =$ optical depth

$$F(E) = AE^{-\Gamma} e^{-\sigma(E) N_H}$$

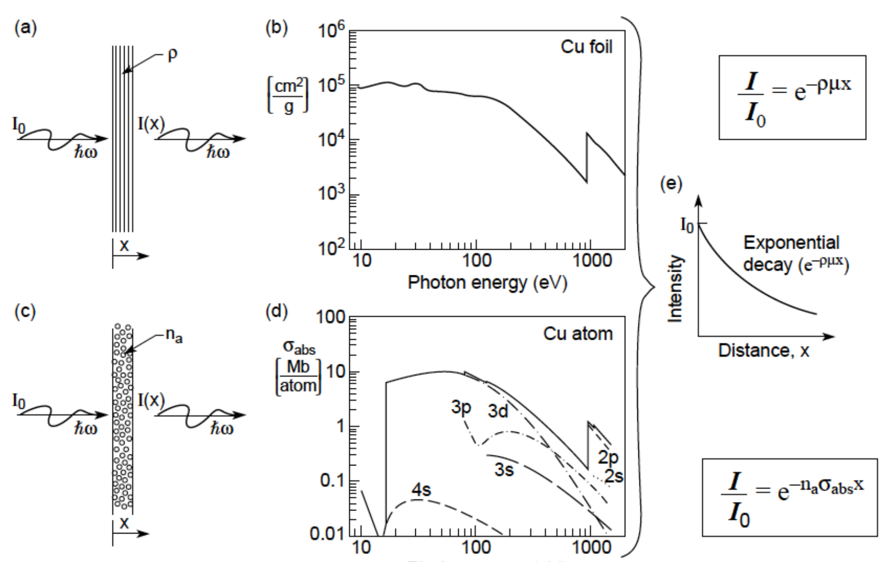
$$\sigma(E) \approx E^{-3}$$



Profile dominated by bound-free edges of abundant elements



Photoabsorption by Thin Foils and Isolated Atoms



David Atwood UCB Course Ast 210

X-ray Absorption

I=I(0,E)exp(-σn);σ is the cross section per atom as a function of energy; n is the number of atoms

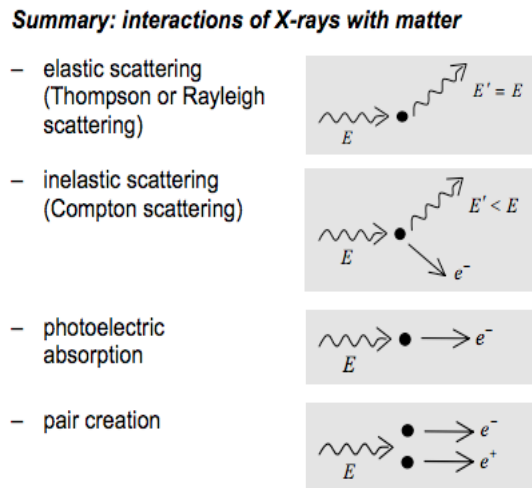
For normal materials

E<100 kev photoelectric absorption dominates

100 keV<E<1 MeV Thompson and Compton scattering dominate

E> 1 MeV ($2m_ec^2$) pair production dominates

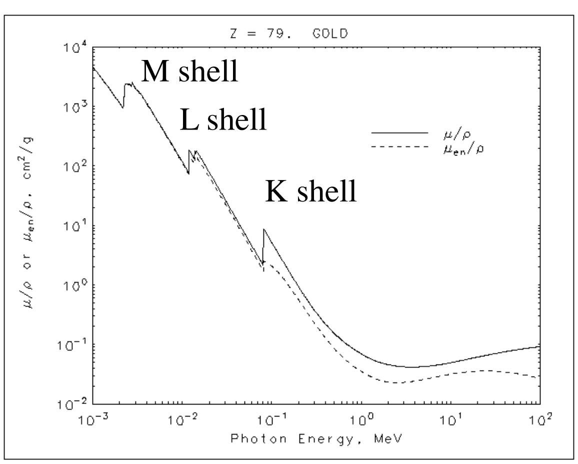
when photoelectric absorption dominates there are prominent "absorption edges" characteristic of the binding energies of electrons in specific atoms (or ions)



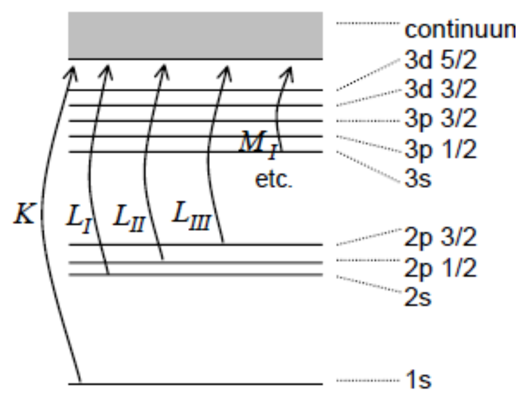
from http://www2.fkf.mpg.de/keimer/lecture/Scattering_I/MS_6.pdf

energy of absorption edge is characteristic of specific element.
E.g. for *K* edge:
E_K~(Z(Z-1))13.6eV where *Z* = nuclear charge

Gold- Absorption Cross Section vs Energy



log Energy (MeV)

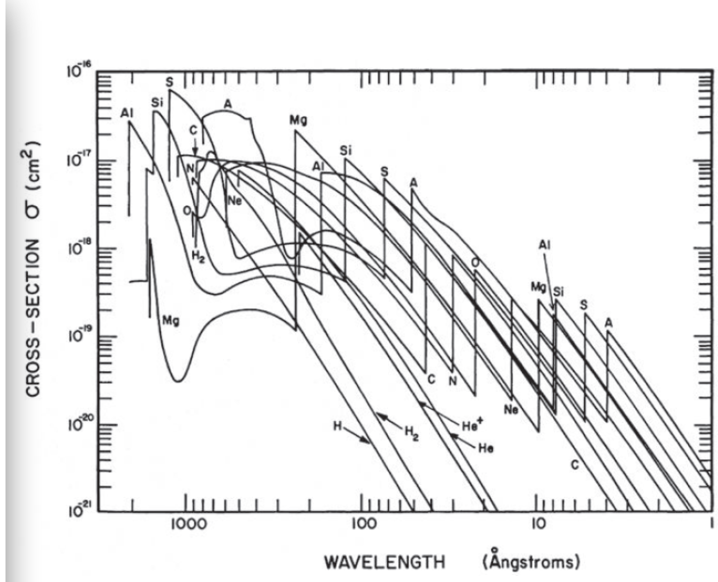


.

– strong ***energy dependence*** of absorption coefficient.
This is the origin of the diminishing relative importance of photoelectric absorption with increasing energy.
– ***absolute magnitude*** of *cross section* depends strongly on *Z*.

Photo-electric Cross Sections

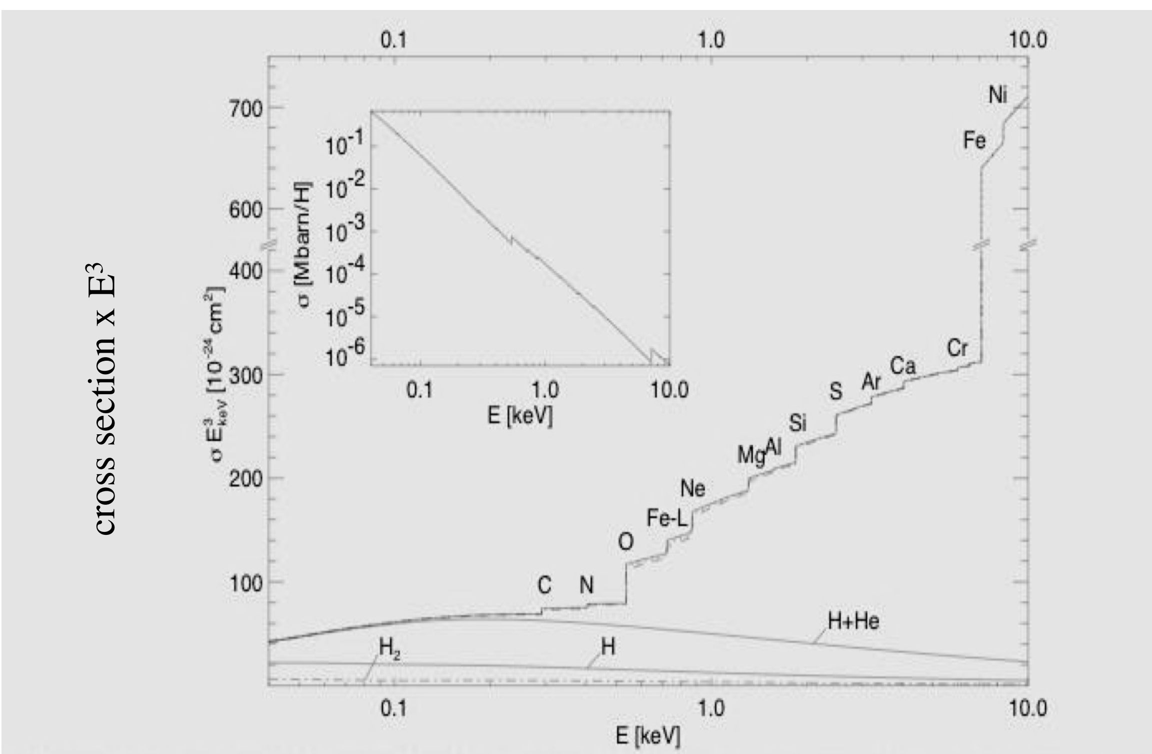
- Notice the strong change with energy
- these cross sections need to be multiplied by the total column density in a given element which is proportional to the abundance of that element
- the spectra of many X-ray sources *turn over* at about 1 keV because of interstellar photoelectric absorption.
- Because of the steep energy dependence of $\tau(E)$, photoelectric absorption is only important at energies $E<10$ keV



toabsorption cross-sections of the abundant elements in the interstellar medium as a function of wavelength

Fig 9.1 Longair

Photoelectric Absorption of ISM



Absorption cross section for material of cosmic abundances (Wilms, Allen & McCray, 2000),

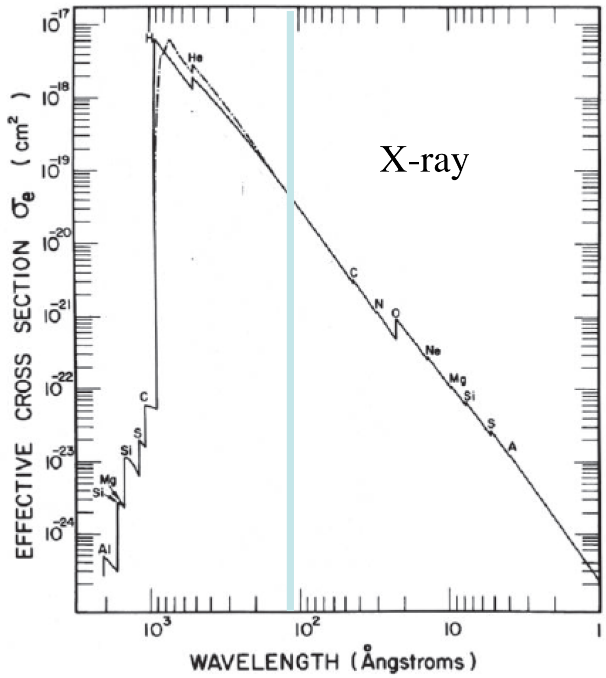
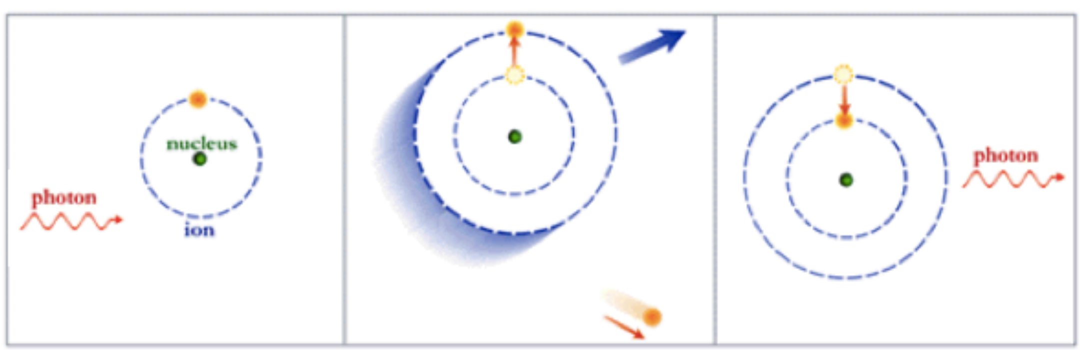


Fig. 9.2 The effective absorption cross-section per hydrogen atom for interstellar gas with typical cosmic abundances of the chemical elements. The solid line is for the gaseous component of the interstellar medium; the dot-dashed line includes molecular hydrogen. The discontinuities in the absorption cross-section as a function of energy are associated with the K-shell absorption edges of the elements indicated. The optical depth of the medium is $\tau_e = \int \sigma_e(\varepsilon) N_H \, dl$ where N_H is the number density of hydrogen atoms (Cruddace *et al.*, 1974). Note that the cross-section is presented in units of cm^2. For reference, 1 Å ≡ 12.4 keV and 100 Å ≡ 0.124 keV.

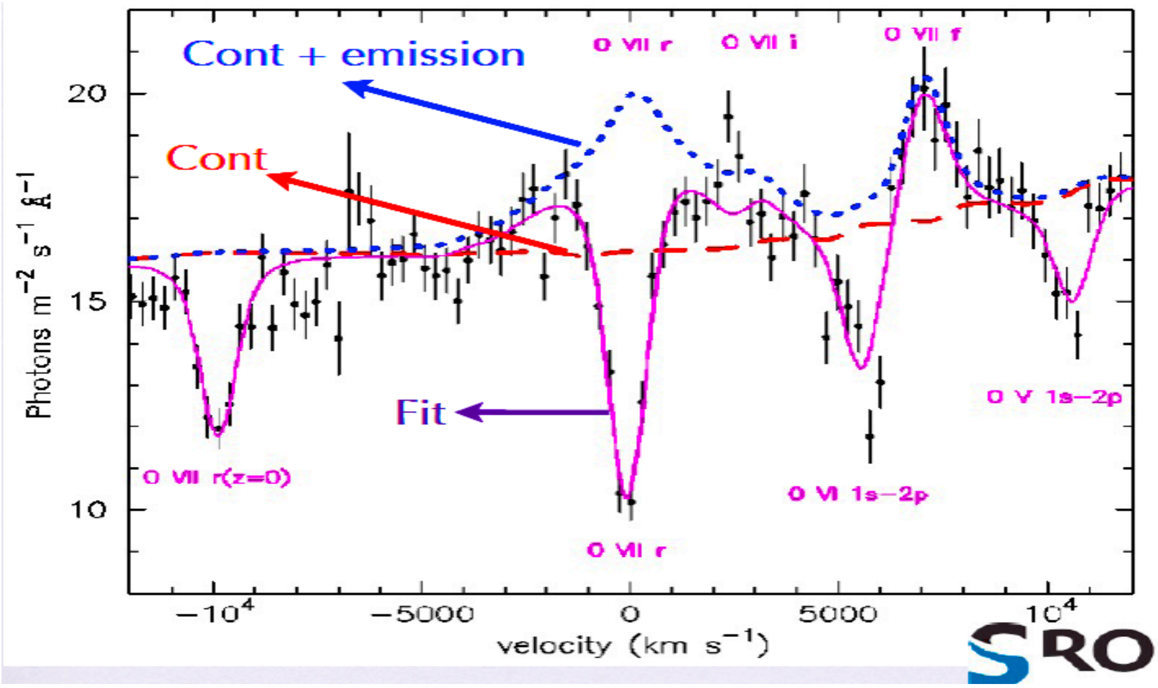
ABSORPTION LINES



- Absorption by a specific transition in atom
- Cross-sections larger than photoelectric
- But only over a small wavelength range
- Strength depends on Doppler parameter *b*
- Can measure N_H, U, velocity etc.

Examples of Emission and Absorption Lines

- Mkn509 - section of the x-ray spectrum
- Notice the wide range of ionization



Conclusions

There are relatively few processes that dominate X-ray emission; analyzing the observed spectrum from each can reveal the underlying parameters.

- Line emission
  - Collisional ⇒ temperature, abundance, density, dynamics
  - Photoionized ⇒ photoionization parameter, abundance, density, dynamics

- Continuum processes
- Synchrotron emission ⇒ relativistic electrons, magnetic field
- Inverse Compton scattering ⇒ relativistic electrons
- Blackbody ⇒ temperature, size of emitting region / distance^2
- Bremmstrahlung- temperature, density

- Photoelectric absorption – material in line of sight.

•γ−ray spectra are continuum dominated with Synchrotron emission and Inverse Compton scattering dominating- solar γ-ray spectrum shows lines

Summary

- blackbody : everything hits everything, many times- equilibrium
- synchrotron : electrons bend in magnetic fields
- bremmstrahlung (free-free) : electrons bend in electric fields
- Compton scattering : photons hit electrons
- inverse Compton : photons hit energetic electrons
- free-bound : electrons hit atoms, get captured
- photoionization : photons hit atoms, electrons escape
- bound-bound : electrons jump down quantum levels

Next Lectures

- How are high energy photons detected?
  - X-ray imaging and spectroscopic detectors
  - γ-ray detectors
- X-ray telescopes