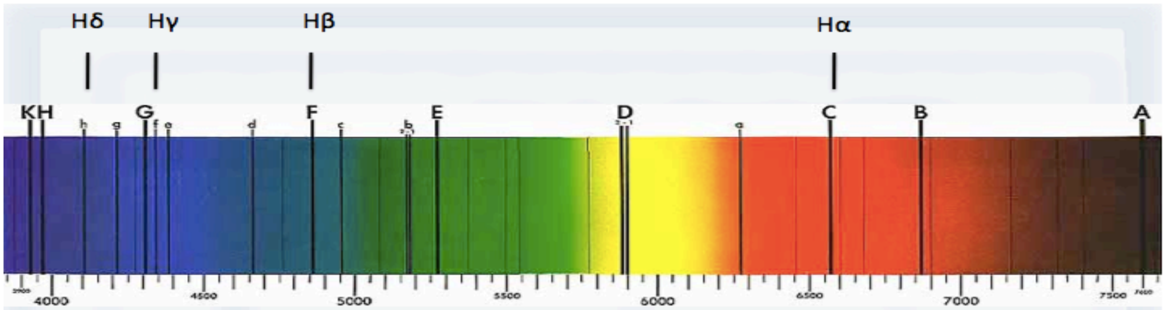
High Energy Spectroscopy
How does one get information about celestial objects

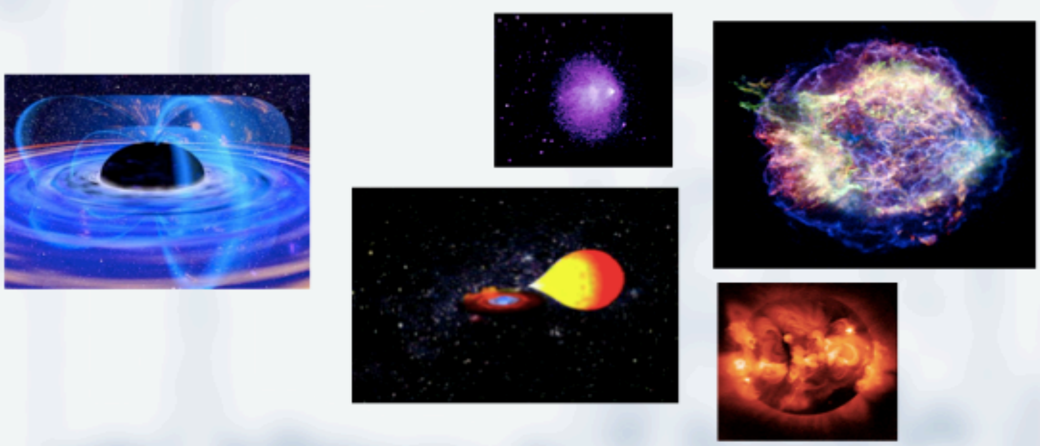


NB: $1\ \text{Å} = 10^{-8}$ cm
$E = hc/\lambda$: $E(\text{keV}) = 12.3985/\lambda(\text{Å})$

Astrophysical X-ray band: 0.1-100 keV (> 10 keV 'hard X-rays', no atomic spectroscopy)
0.1-10 keV corresponds to ~1-100 Å

Spectrum provides precise information on 'local' conditions in the plasma

element, ionization stage, ionization mechanism, temperature, density,
degree of relaxation and past history,
velocities (thermal, turbulent, bulk, nonthermal), ***E*** and ***B*** fields, ...



There are 4 sources of information in astrophysics- image, spectrum, time series and polarization. All of these are derived from observations- one cannot perform an experiment

This can be combined- imaging spectroscopy, or time resolved spectroscopy etc

3 energy (wavelength ranges)

All energy ranges have continuum process

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

- At 1Å < λ <50μ '**atomic processes**' dominate
  - In x-ray band most transitions from He or H-like ions (1-2 electrons). Also have features from Fe L shells (3-10 electrons).
    - Also have 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

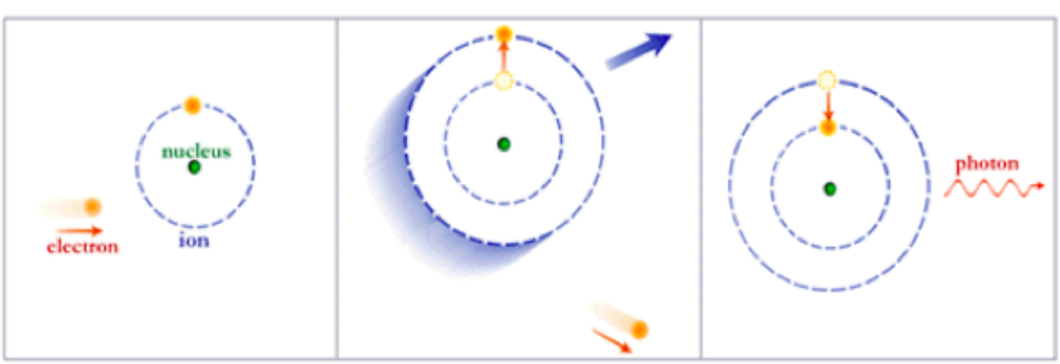
Notice mixed units (!)

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

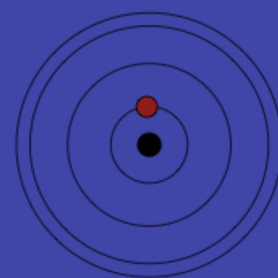
Radiative transition rate (aka "Einstein A value") is the expected number of spontaneous transitions per second/atom from one level to another $A_{ij}=1/t_{radiative}$



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.

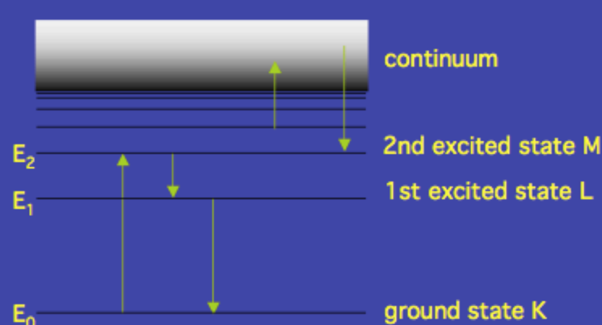
Each orbit is associated with an electron energy, so are sometimes called energy levels. An electron has to gain energy to move from an inner to an outer energy level. An electron loses energy when moving from an outer to an inner energy level.



Each element has its own unique set of energy levels:

$$E_N = -\frac{13.58Z^2}{N^2} \text{electron volts (eV)}$$

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)

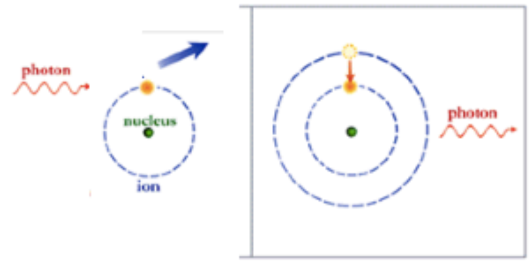
De-excitation: an electron jumps from level N to level M (M<N) and emits a quantum of radiation (a photon) of energy $E=E_N-E_M$

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.

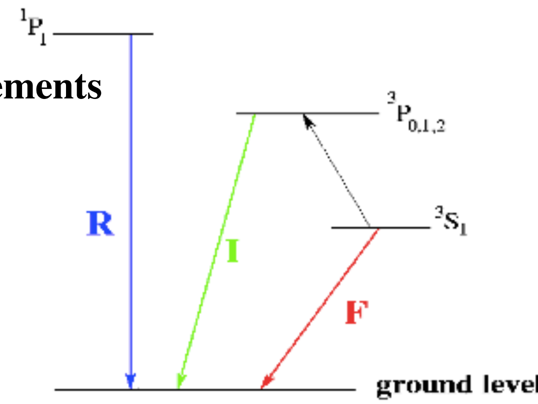
TYPES OF LINE EMISSION

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



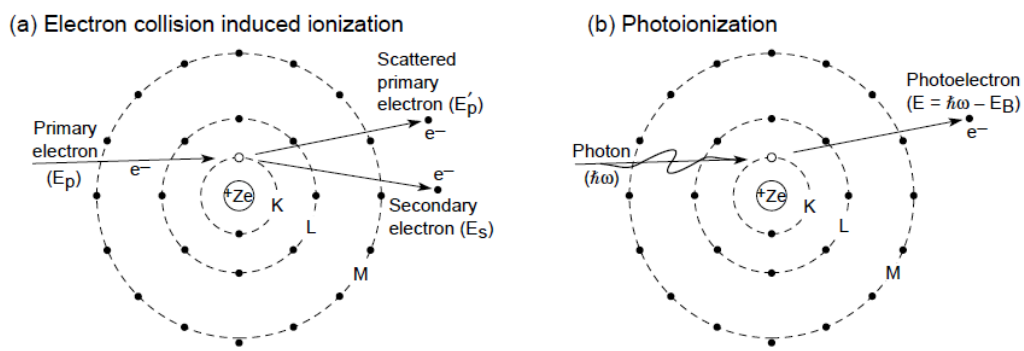
Yield~Z^4 **important for high Z elements**

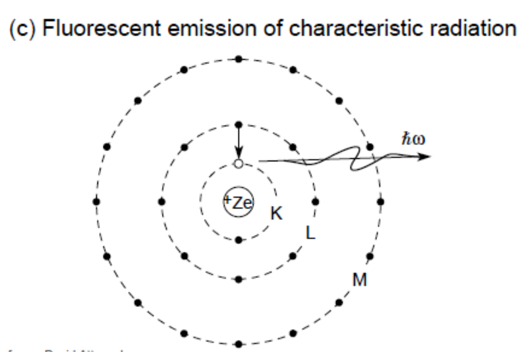
- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination



From R. Smith

3 Ways to Excite Atoms

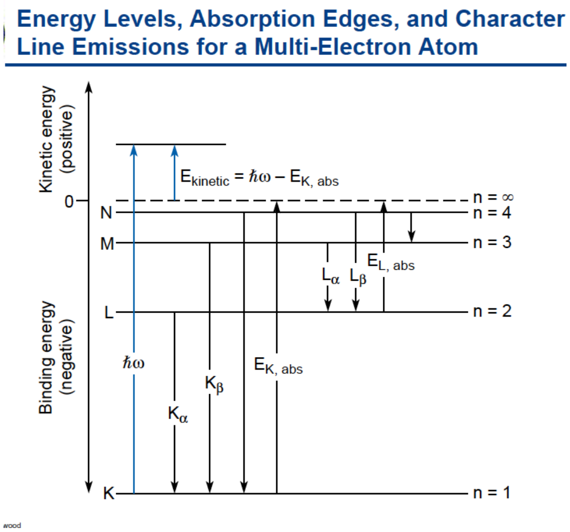


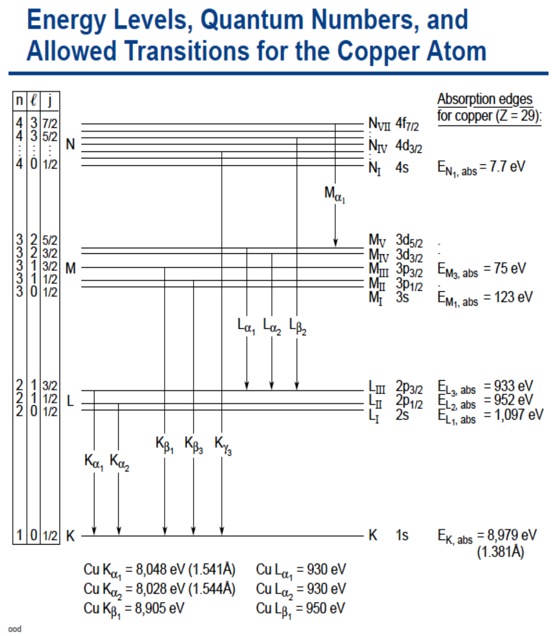


3 ways to produce a Photon via 'atomic' process (an incomplete set)

Professor David Attwood

- Generic Atom





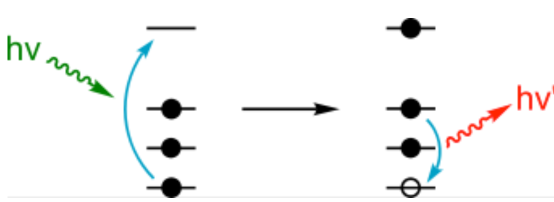
•Copper Atom

Fluorescence

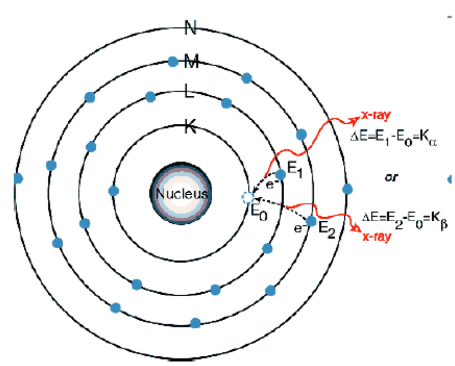
- Following removal of an inner electron by an energetic photon by radiation source, an electron from an outer shell drops into its place. -
- This process can produce x-ray line radiation even from totally unionized (cold) atoms
- L→K transition Kα,
- M→K Kβ, M→Lα etc
- Fluorescence involves a radiative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

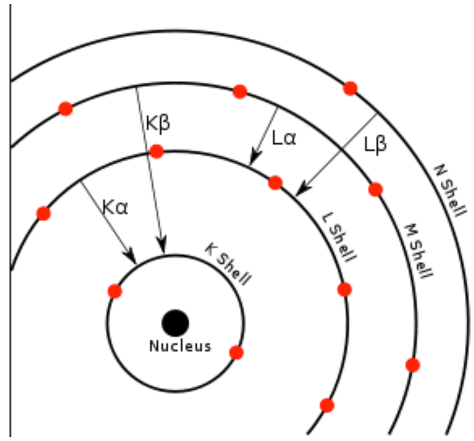
a transition of the form $1s2s^2 2p^k nl \rightarrow 1s^2 2s^2 2p^{k-1} nl$.

- **Very important in x-ray binaries and AGN**



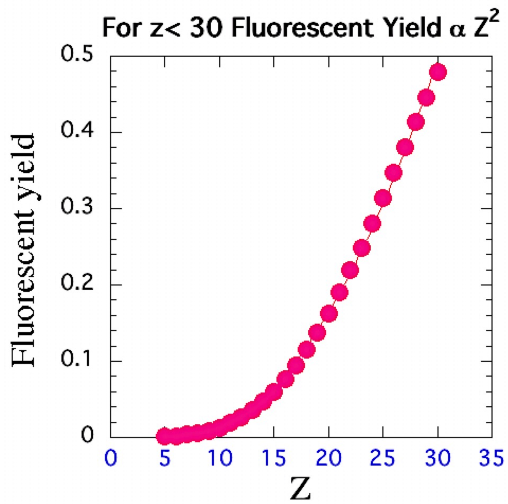
- X-ray fluorescence

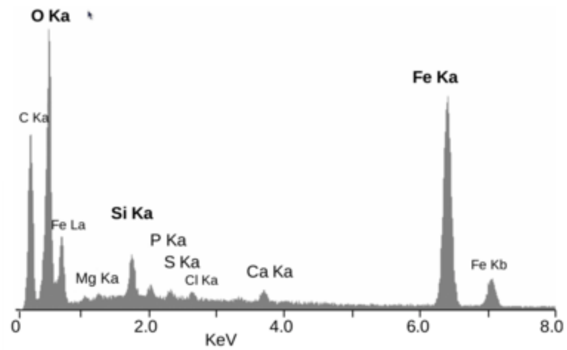




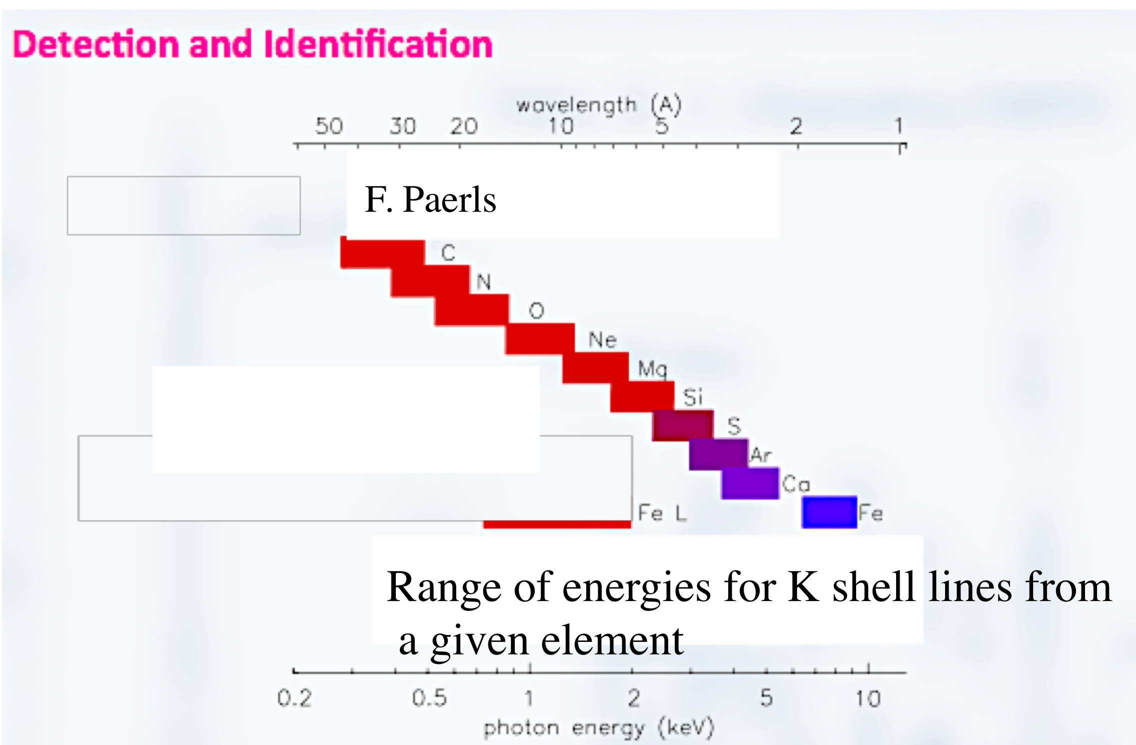
Fluorescence Spectroscopy

- Strength of lines is proportional to fluorescence yield x abundance

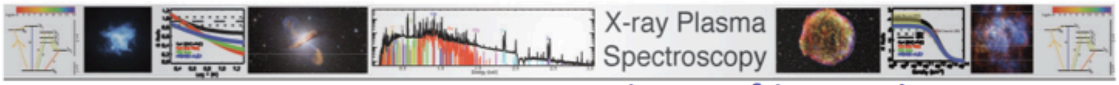




For many x-ray spectra Fe is the dominant fluorescent line- convolution of abundance of Fe and yield



Energy range of emission lines from different elements



Ions of Importance

In x-ray spectra

All ions are equally important.

...but some are more equal than others.

In collisional plasmas, three ions are of particular note:

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.

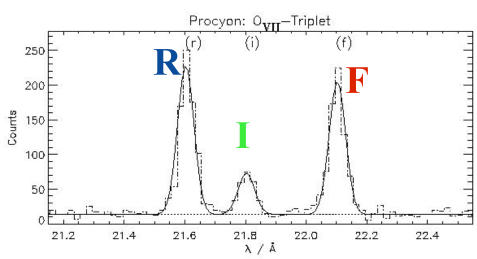
He-like: Δn≥1 transitions are all bright and in X-ray. The n=2→1 transitions have 4 transitions which are useful diagnostics, although R=300 required to separate them.

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.

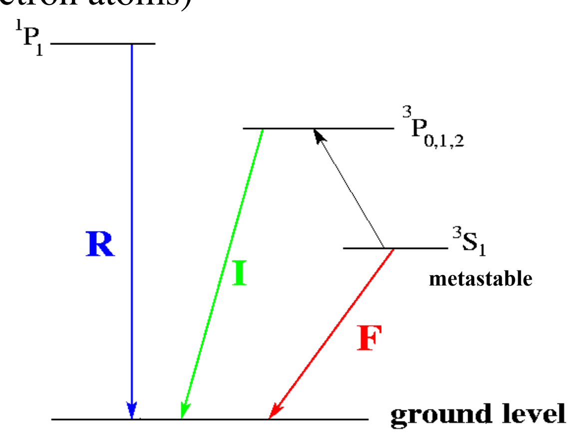
Energy Levels

Helium-like Atoms: Plasmas excited to x-ray emitting temperatures are dominated by He-like (2 electron) and H-like (1 electron atoms)

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



Ness et al. (2001)



lines from He-like atoms

Gabriel & Jordan (1969):

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

First widely used for solar plasma diagnostics.

Now: extra-solar objects: collisional (e.g., stellar coronae), photo-ionization (e.g., AGN, X-ray binaries), out-of-equilibrium (e.g., SNR)

A Little Bit About Atomic Spectral Nomenclature

He-like ions:

Two electrons: can have |↑↑>, |↓↓>, |↑↓>, |↓↑>. But these are not all eigenstates of ***J***. These ones are:
|↑↑>, |↓↓>, |↑↓> + |↓↑> (symmetric in the spins, total spin 1) **'triplet'**
|↑↓> – |↓↑> (antisymmetric in the spins, total spin 0) | **'singlet'**

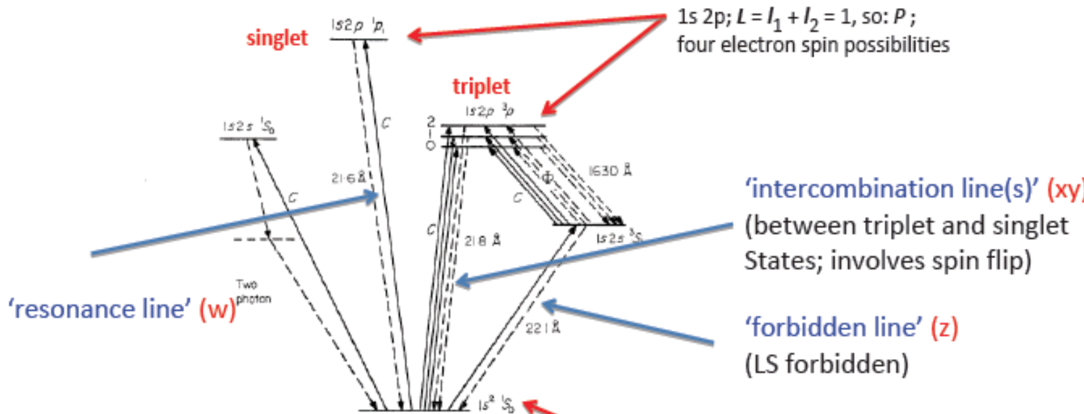


FIG. 1. *The He-like ion, showing those terms and processes involved in the present analysis. The wavelengths indicated apply to the case of oxygen VII.*

Ground: space-*symmetric*, must be spin-*antisymmetric*, so s = 0 (2s+1 = 1; **singlet**)

Gabriel and Jordan, 1969, *MNRAS*, **145**, 241

H- and He-like ions in practice: wavelengths

Lots of lines !

Courtesy Masao Sako, University of Pennsylvania

H-LIKE SPECIES

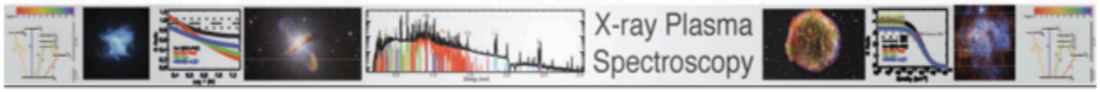
Ion	Lyα₁		Lyα₂		K-edge	
	λ (Å)	E (keV)	λ (Å)	E (keV)	λ (Å)	E (keV)
C VI	33.7342	0.36754	33.7396	0.36747	25.3033	0.489993
N VII	24.7792	0.50036	24.7846	0.50024	18.5871	0.667046
O VIII	18.9671	0.65368	18.9725	0.65348	14.2280	0.871410
Ne X	12.1321	1.02195	12.1375	1.02150	9.10177	1.36220
Na XI	10.0232	1.23697	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

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	3.96587	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

Lines: Drake, G. W. 1988, Can. J. Phys., 66, 586
Edges: HULLAC, except for Na & Al (Verner et al. 1996, ApJ, 465, 487)



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.

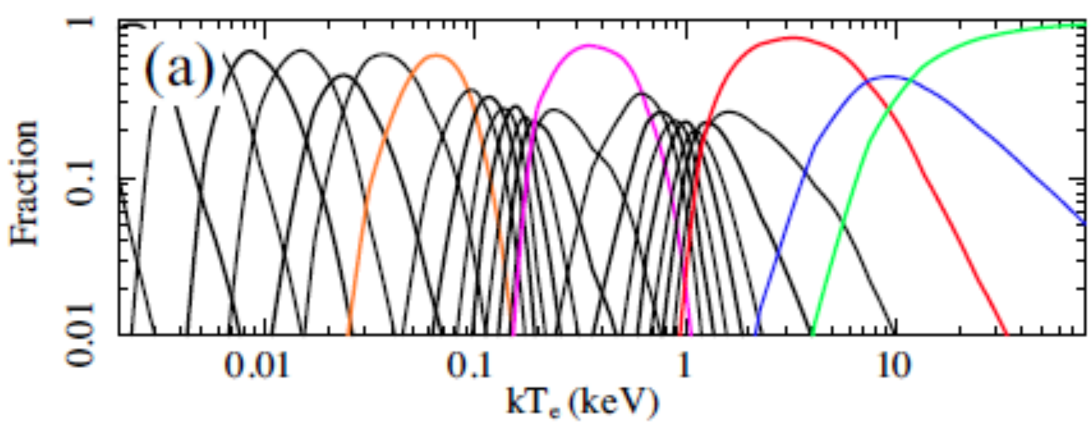
A consequence of this is that the plasmas can be separated into two categories:

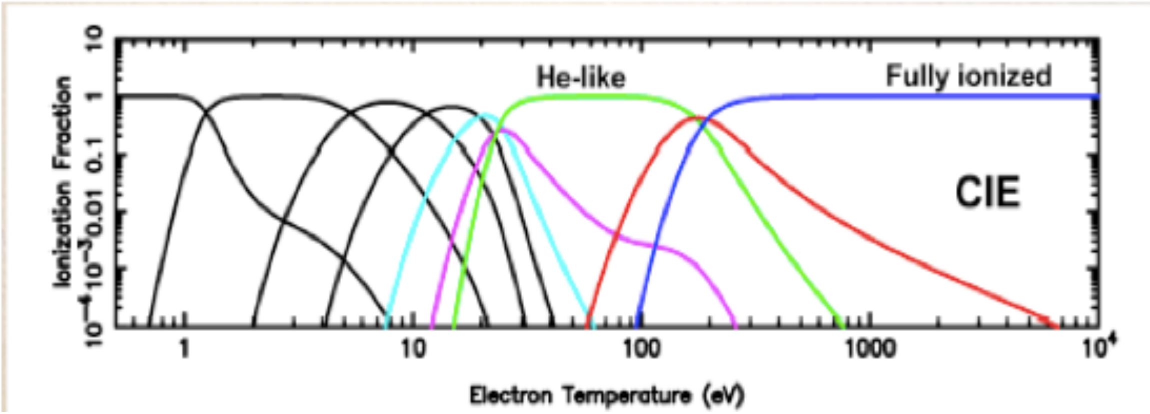
- Collisional:
  $k_B T_e$ ~ Ionization energy of plasma ions

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

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 is Ne-like (Fe+16), orange is Ar like,Fe+18)
- **As gas gets hotter it gets more ionized**

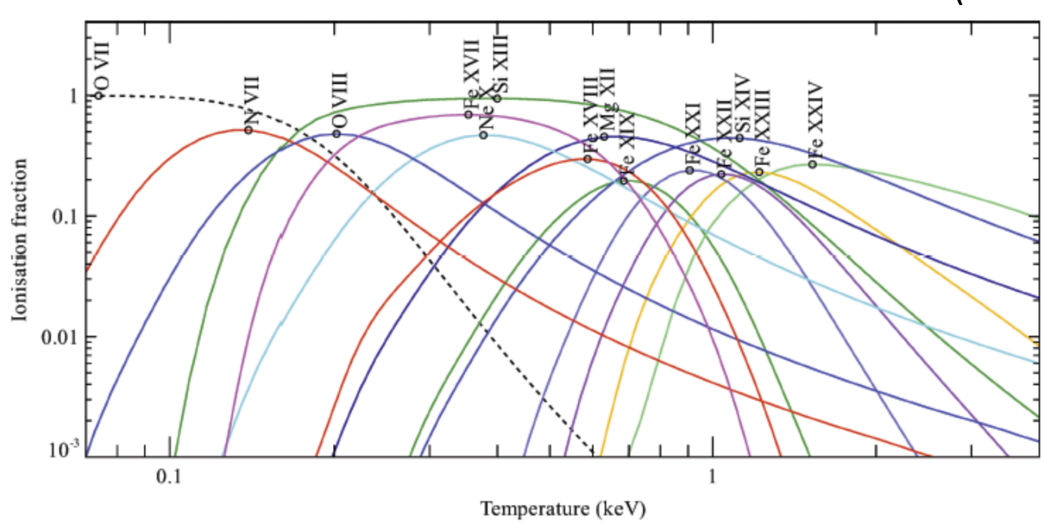




same graph , but now for Oxygen; 100eV=1.17x10^6k
(CIE- means gas is in Collisionally Ionized Equilibrium)

Strongest X-ray Lines as Function of kT

Sanders et al. (2008)



Flux of each line strongly depends on the plasma temperature
Line ratios are important to study the temperature structure

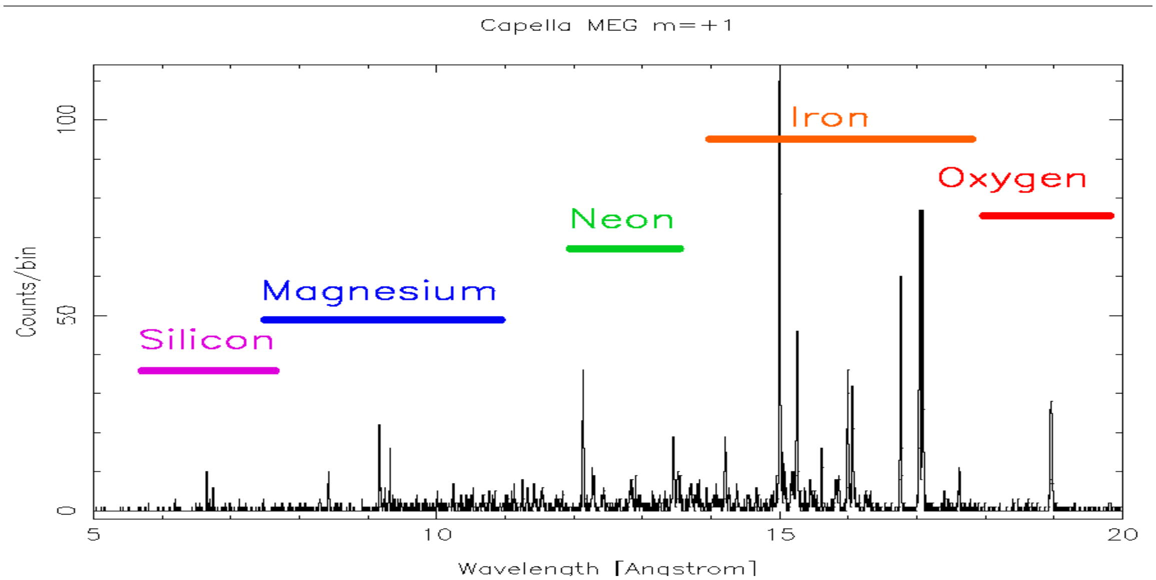
Plasma Codes

Understanding a collisional plasma requires a collisional 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

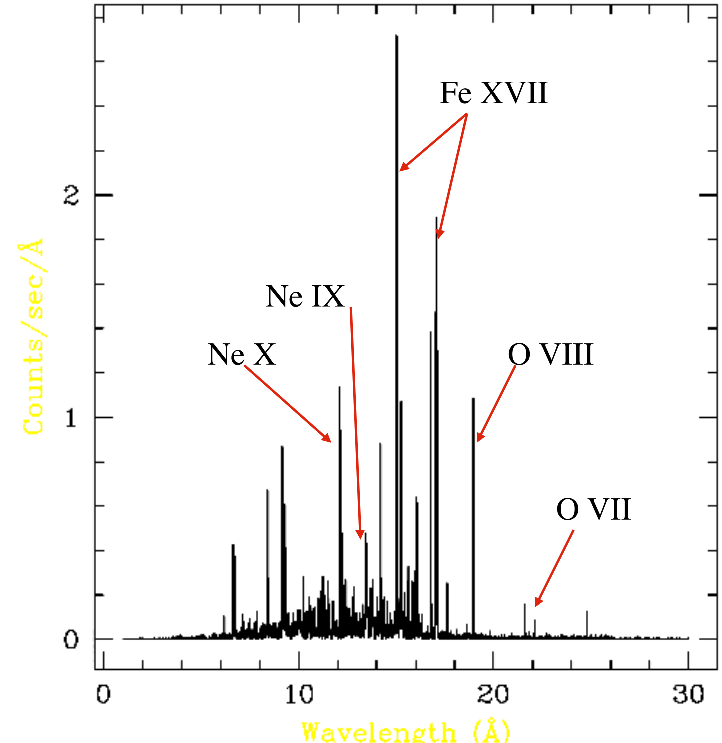
The calculated spectrum is also known as APEC, and the atomic database is called APED.

Chandra Grating Spectrum of Capella



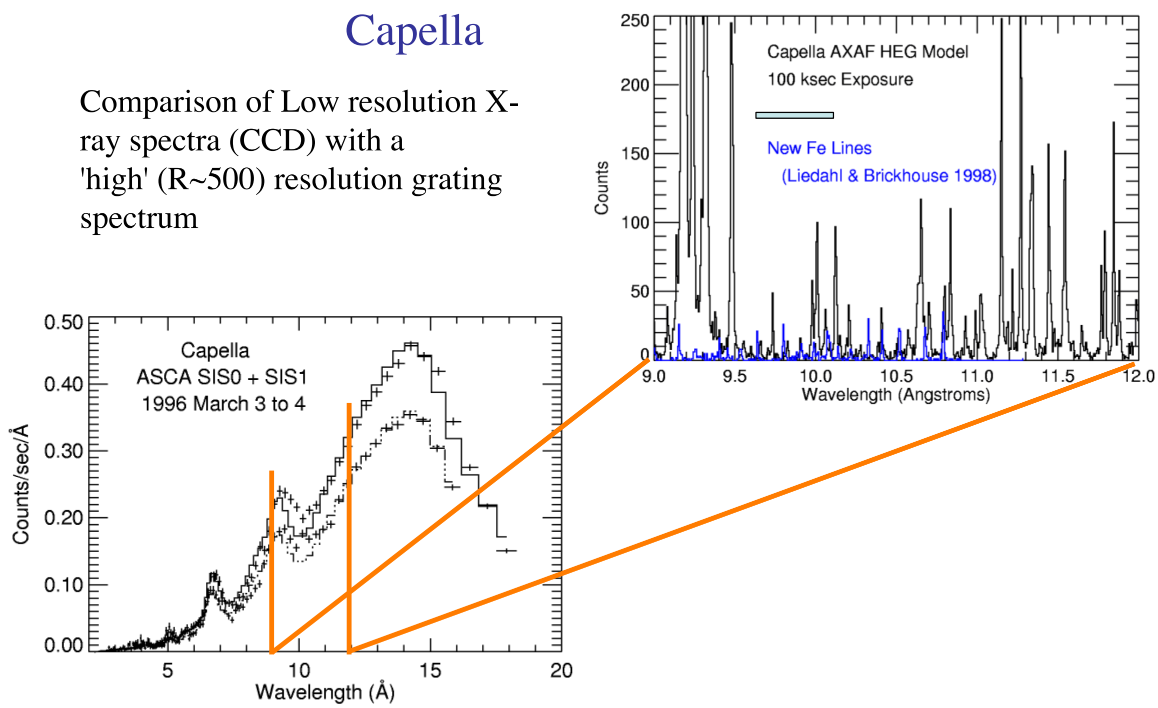
Ions of Importance

Capella observed with the Chandra HETG

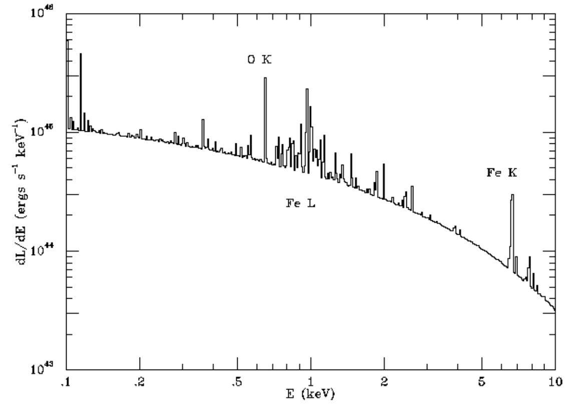


Collisionally Ionized Equilibrium Plasma- Capella

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



Physical Processes



- Continuum emission
  - Thermal bremsstrahlung, ~exp(-hν/kT)
  - Bound-free (recombination)
  - Two Photon
- Line Emission

  (line emission)

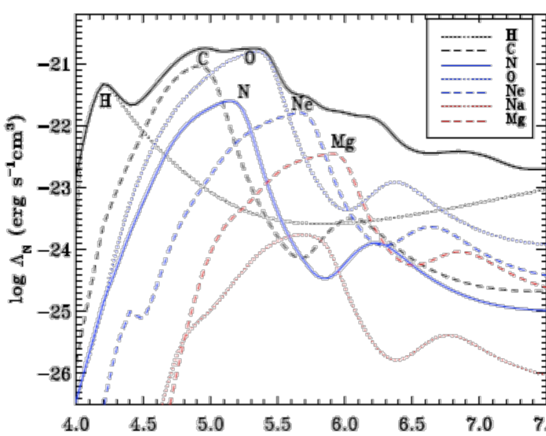
  $L_\nu \sim \varepsilon_\nu$ (T, abund) (n_e^2 V)

  $I_\nu \sim \varepsilon_\nu$ (T, abund) (n_e^2 l)

  Line emission dominates cooling at T<10^7 K

  Bremmstrahlung dominates at higher temperatures

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



Cooling Function

Determines how much energy is radiated by a parcel of gas as a function of temperature

the two panels show different elements

Notice that oxygen dominates cooling at logT~5.5, while Fe dominates at log T~6-7

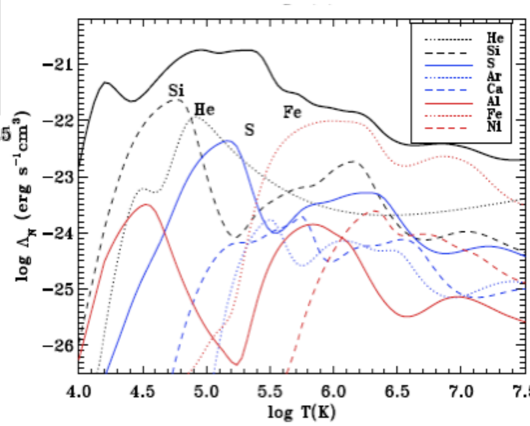
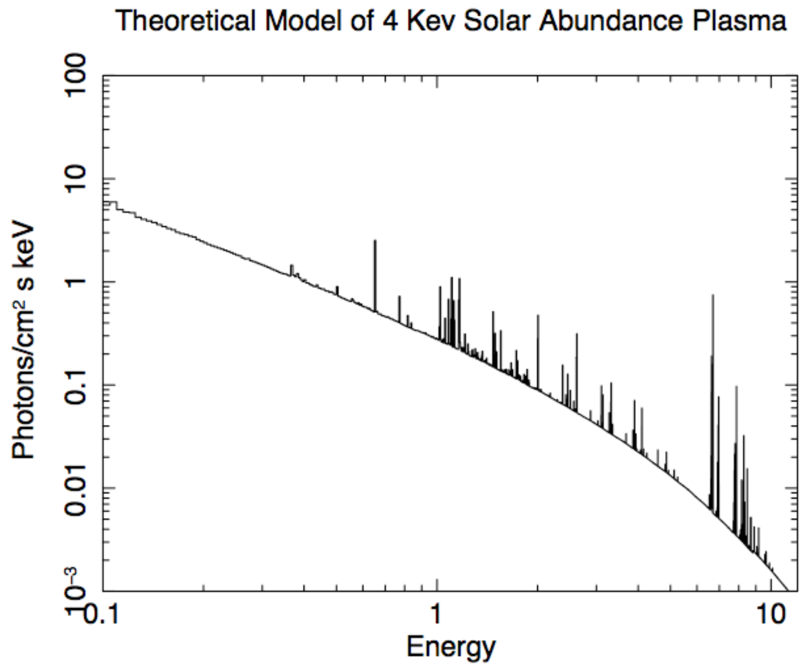


Fig. 2. Contributions of different elements to the cooling curve are given. Each of the plots shows a different set of elements. Important peaks are labelled with the name of the element. The total cooling curve (black solid line) is an addition of the individual elemental contributions.

- Theoretical model of a collisionally ionized plasma kT=4 keV with solar abundances
- The lines are 'narrow'
- Notice dynamic range of 10^4
- Lines are from a wide variety of elements, continuum from bremsstrahlung



Photoionized Plasmas

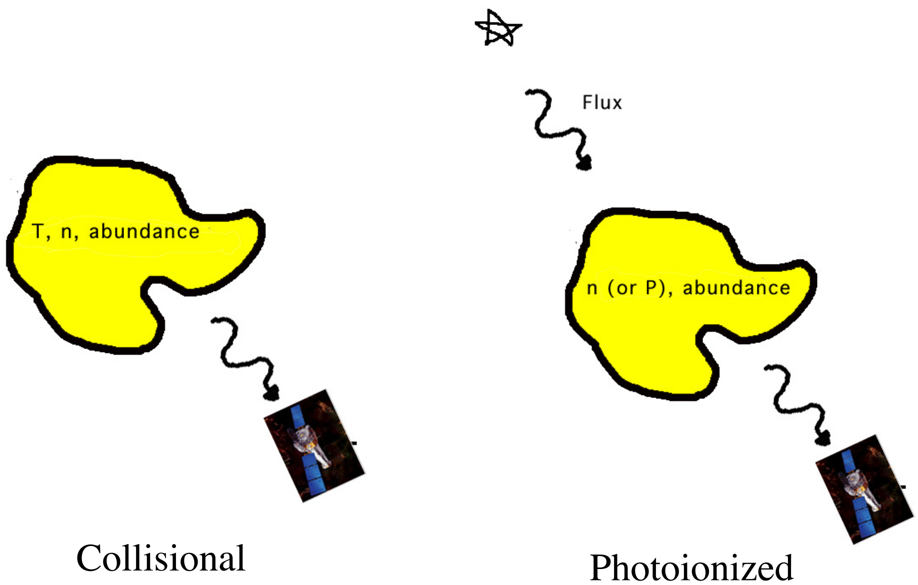
What happens when an external photon source illuminates the gas?

- 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*

R. Smith

Photoionized Plasmas



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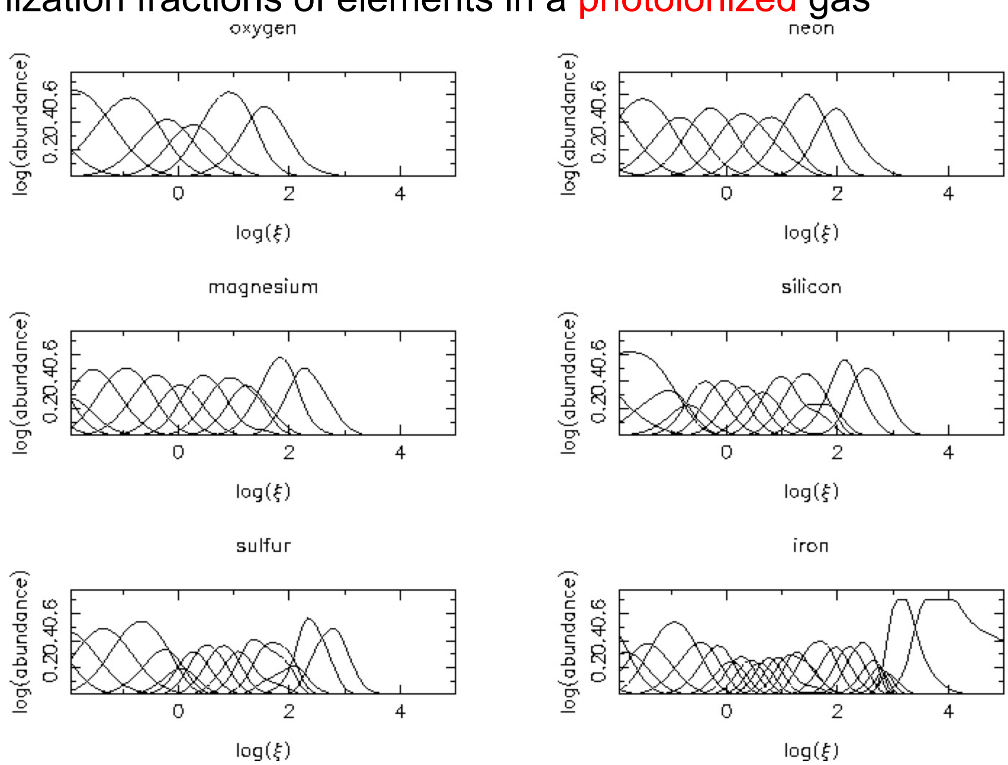
Ionization fractions of elements in a photoionized gas

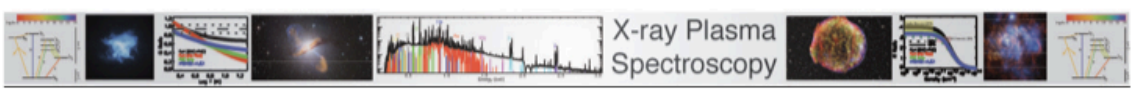


ξ=X-ray flux/gas density=$4\pi F/n$

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

Plasmas
R. Smith

	Photoionized	CIE
Dominant ionization	Photoionization hν+Z −>Z+1	Electron impact e^-+Z ->Z+1
Examples	Active galaxies(AGN) binary stars with collapsed companion H II regions	Stellar coronae Supernova remnant Clusters of galaxies
Spectral signature	Absorption,bound-free, bound-bound Emission: recombination	Emission lines, Δn=0,1,2 favored



Both collisional and photoionized plasmas may be in equilibrium or out of it.

- A collisional or photoionized plasma in ionization equilibrium (usually called a CIE or PIE plasma) has the property that

$$I_{rate}(Ion) + R_{rate}(Ion) = I_{rate}(Ion^-) + R_{rate}(Ion^+)$$

- A non-equilibrium ionization (NEI) plasma may be:
  - Ionizing $[\Sigma I_{rate}(I) > \Sigma R_{rate}(I)]$
  - Recombining $[\Sigma I_{rate}(I) < \Sigma R_{rate}(I)]$
  - Other

The Ionization Parameter

- The 'moral' equivalent of the temperature in a photoionized plasma is the ionization parameter

- **Ionization parameter (flux/density):**

$$\xi \equiv \frac{L_X}{n_e R^2}$$ Tarter, Tucker & Salpeter (1969)

$$U_X \equiv \frac{N_X}{4\pi R^2 n_e c}$$ Davidson (1974)

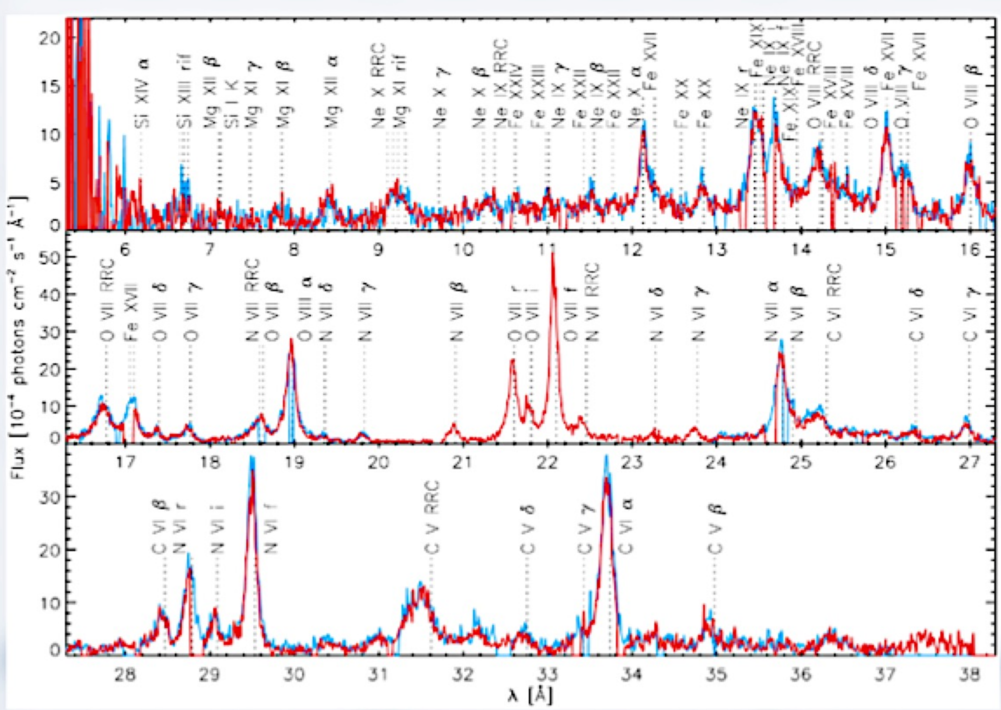
N_x= # of ionizing Photons

$$L_X \equiv \int_{E_{\min}}^{\infty} L(E)dE \qquad N_X \equiv \int_{E_{\min}}^{\infty} \frac{L(E)}{E} dE$$

$E_{\min}$ = 13.6eV, 0.1 keV, 0.7 keV (Davidson, Netzer, George)

The ionization parameter controls ionization state of a photoionized plasma

Emission from X-ray photoionized gas



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

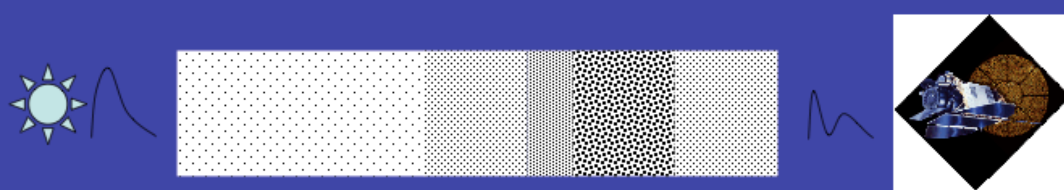
Absorption

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)

$$\tau = N\sigma$$

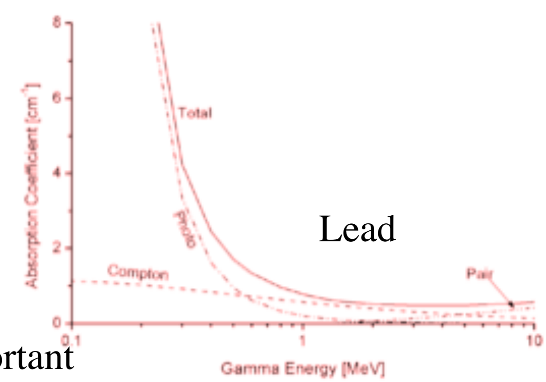


Absorption of X and γ-ray Photons

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

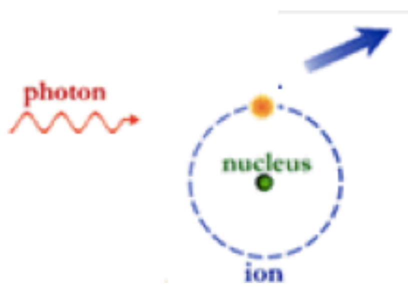


In γ-rays pair creation is also important

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) are light: absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

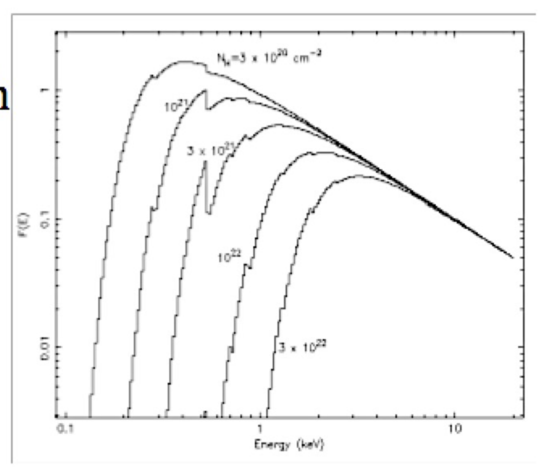
$N_H =$ Equivalent hydrogen column density (cm^{-2})

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

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

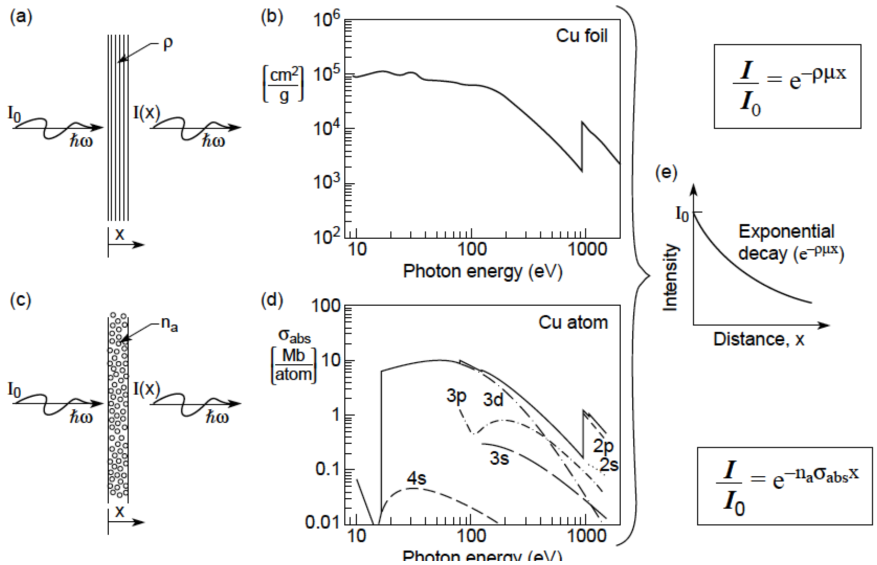
$$F(E) = A E^{-\Gamma} e^{-\sigma(E) N_H}$$

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



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

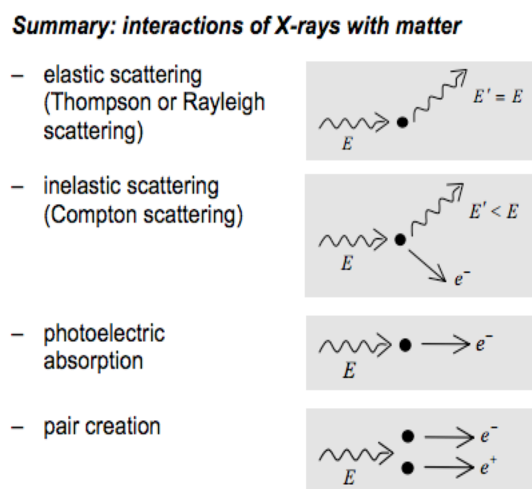
For normal materials

E<100 kev photoelectric absorption dominates

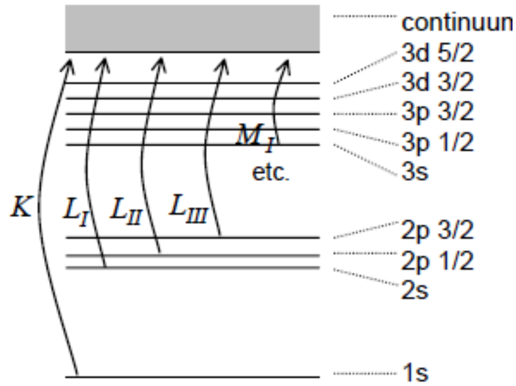
100 keV<E<1 MeV Thompson and Compton scattering dominate

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)

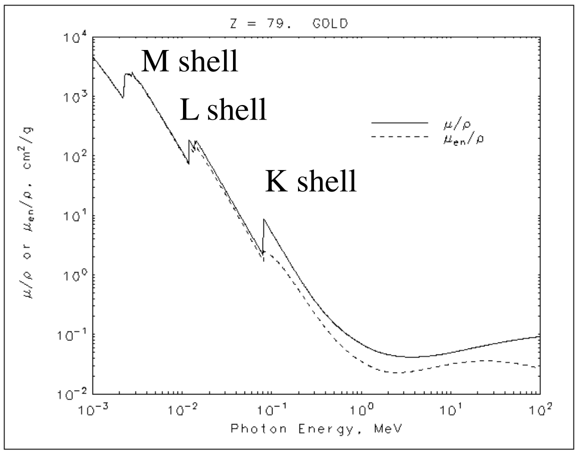


from
http://www2.fkf.mpg.de/keimer/lecture/Scattering_I/MS_6.pdf



energy of absorption edge is characteristic of specific element.
E.g. for *K*-edge:E_K~(Z(Z-1))13.58 eV
where *Z* = nuclear charge

Gold- Absorption Cross Section vs Energy

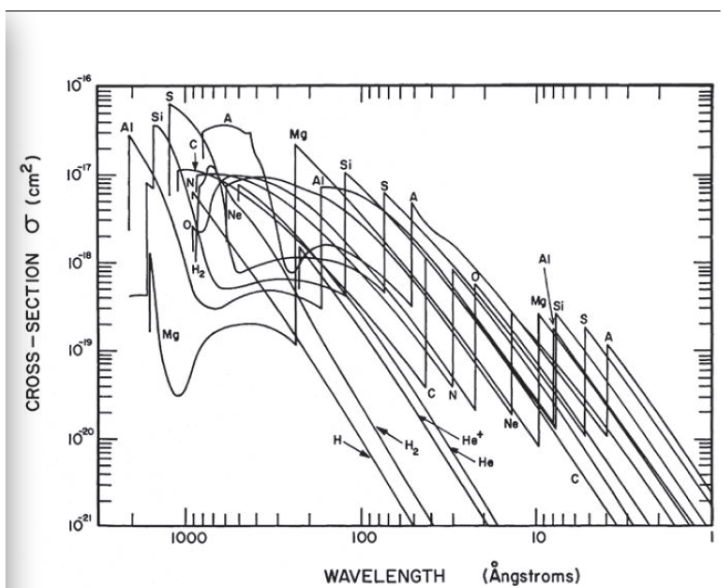


log Energy (MeV)

.
– 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 τ(E), photoelectric absorption is only important at energies *E*<10 keV

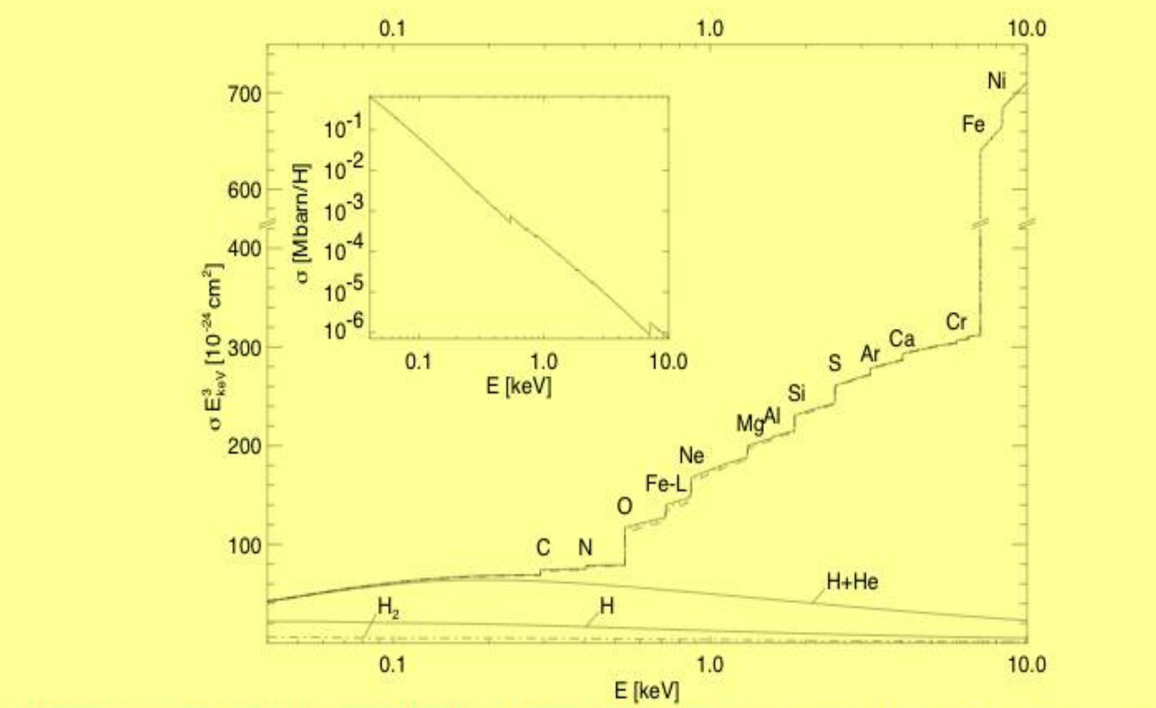


toabsorption cross-sections of the abundant elements in the interstellar medium as a function of wavelength

Fig 9.1 Longair

Photoelectric Absorption of ISM

-Multiplied by E^3 to 'flatten' the curve



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

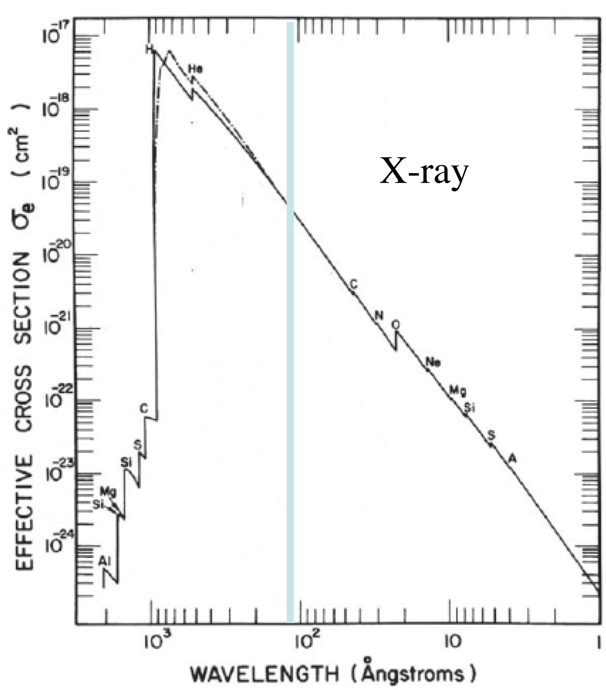
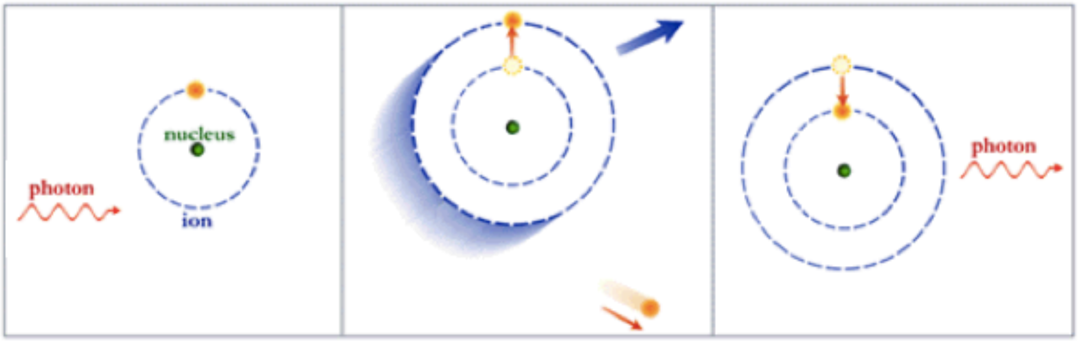


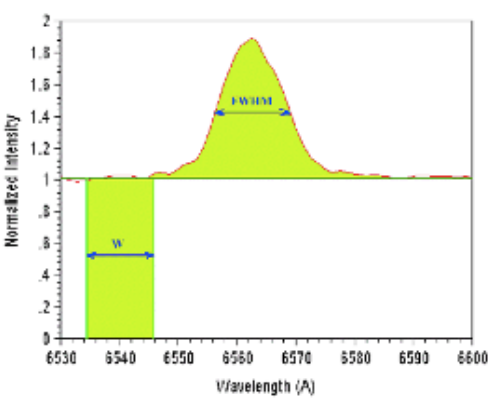
Fig. 9.2 The effective absorption cross-section per hydrogen atom for interstellar gas with typical cosmic abundances of the chemical elements. The solid line is for the gaseous component of the interstellar medium; the dot-dashed line includes molecular hydrogen. The discontinuities in the absorption 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.

ABSORPTION LINES



Equivalent width:

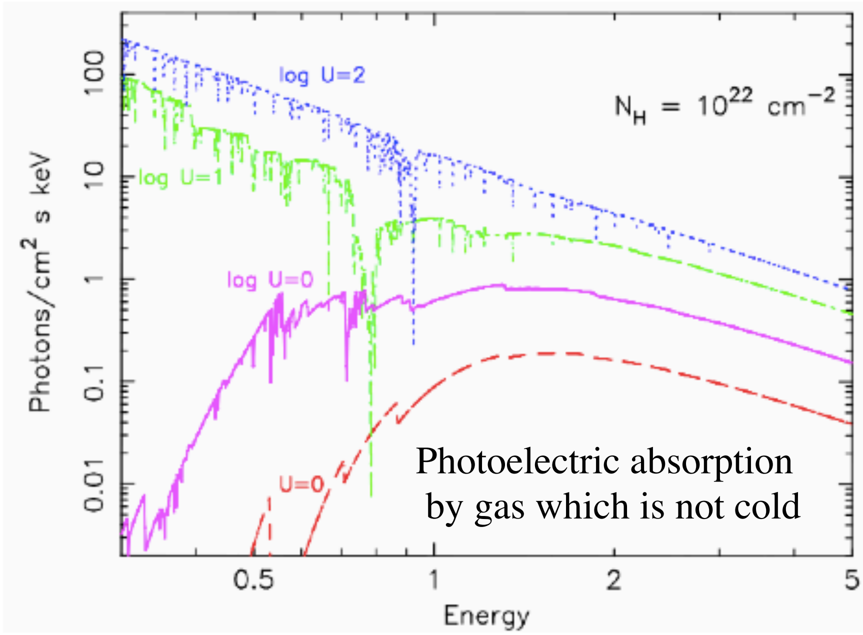
$$EW = \frac{\int_{-\infty}^{\infty} F_l(E)dE}{F_c(E_l)}$$

$F_l =$ line flux, $F_c =$ continuum flux,

$E_l =$ line energy

The EW is essentially how much of the continuum it takes to produce the flux in the line

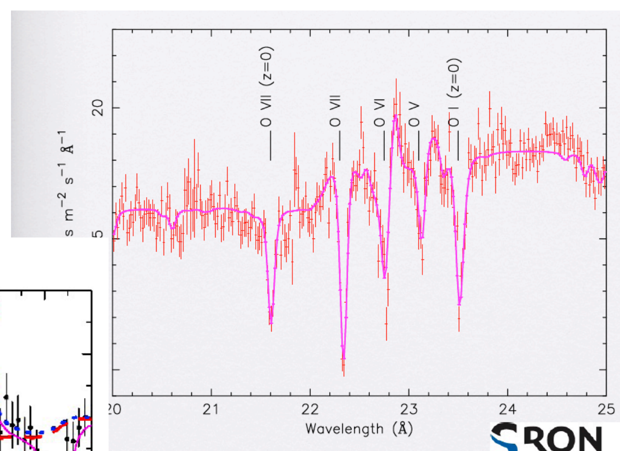
IONIZED ABSORPTION

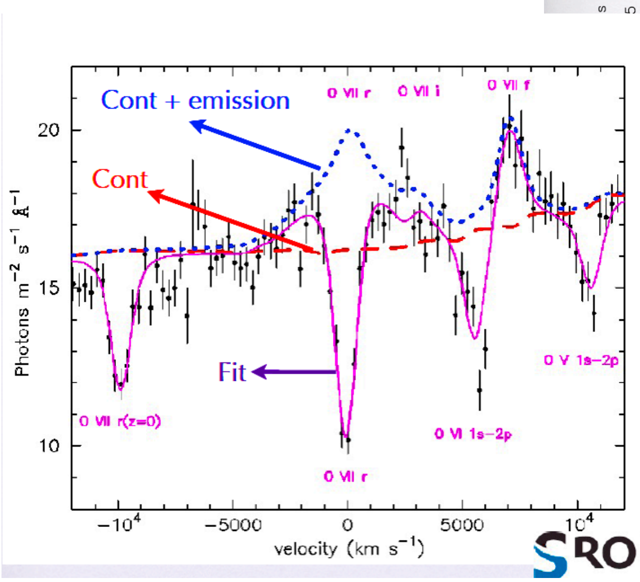


Continuum absorption profile still can be dominated by bound-free edges of abundant elements but…things get comple

Examples of Emission and Absorption Lines

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





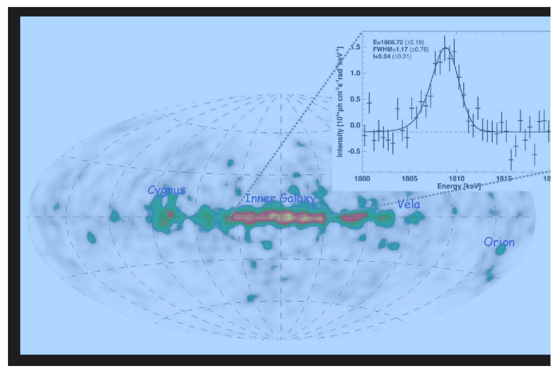
Gamma-Ray Spectroscopy Longair Sec 10.3

- Two types of nuclear processes producing γ -ray lines in astronomical sources:
  - the decay of radioactive species created in the processes of nucleosynthesis (e.g. ^{26}Al (1809 keV) and ^{60}Fe (see Diehl et al Nature 0601015.pdf and New Astron.Rev. 50 (2006) 534-539)
  - the collisional excitation of the nuclei by cosmic ray protons and nuclei (Πs at 70 MeV)

^{26}Al half life $T_{1/2}$~7.2×10^5 yrs created in SN

^{26}Al gamma-rays represent the massive star population

the amount of ^{26}Al, corresponds to a rate of supernovae from massive stars (i.e. "Types Ib/c and II") of two per100 years.



Solar Gamma-Ray Flare Spectrum

- Potential for lots of spectroscopy, but need much high sensitivity

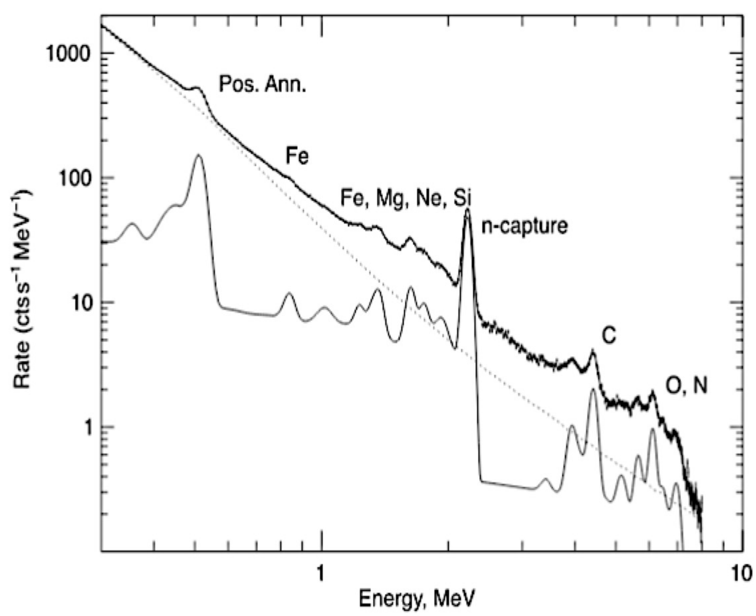


Fig. 2 Count spectrum derived from the sum of 19 flares observed with *SMM*. The *solid line* running through the data is the best-fitting count spectrum. The *dotted line* is the fitted electron bremsstrahlung component and the *other solid line* is the fitted narrow nuclear deexcitation line component

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
- charge exchange : ions hit neutrals, swap electrons
- bound-bound : electrons jump down quantum levels

Conclusions

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

- Line emission
  - Collisional ⇒ temperature, abundance, density, dynamics
  - Photoionized ⇒ photoionization parameter, abundance, density,dynamics
- Synchrotron emission ⇒ relativistic electrons, magnetic field
- Inverse Compton scattering ⇒ relativistic electrons
- Blackbody ⇒ temperature, size of emitting region / distance^2
- Absorption ⇒ abundance, density, velocity

•Γ-ray spectra are continuum dominated with Synchrotron emission and Inverse Compton scattering dominating- photoelectric absorption is unimportant.

Next Lecture

- Detectors