Emission III: Photoionized Plasmas (and continuum processes)

Randall K. Smith

NASA/GSFC & JHU

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Introduction

We have now covered the basic X-ray emitting atomic processes as well as **collisional plasmas**. Now we will cover:

- Synchrotron Radiation
- Compton/Inverse Compton Radiation
- Absorption *and*
- **Photoionized Plasmas**

  (where $k_B T_e$ **<<** Ionization energy of plasma ions)

We will again make some initial assumptions about our "astrophysical plasmas":

- They are dominated by H and He, with trace metals.
- Nuclear transitions are insignificant.

However, now magnetic fields will play an important role, and it will not always be true that electrons have a Maxwellian velocity distribution!

Cyclotron/Synchrotron Radiation

Radiation emitted by charge moving in a magnetic field.

First discussed by Schott (1912). Revived after 1945 in connection with problems on radiation from electron accelerators.

Very important in astrophysics: Galactic radio emission (radiation from the halo and the disk), radio emission from the shell of supernova remnants, X-ray synchrotron from PWN in SNRs…

Cyclotron/Synchrotron Radiation

Cyclotron radiation comes from a non-relativistic electron, gyrating in a magnetic field, while synchrotron radiation is by definition relativistic.

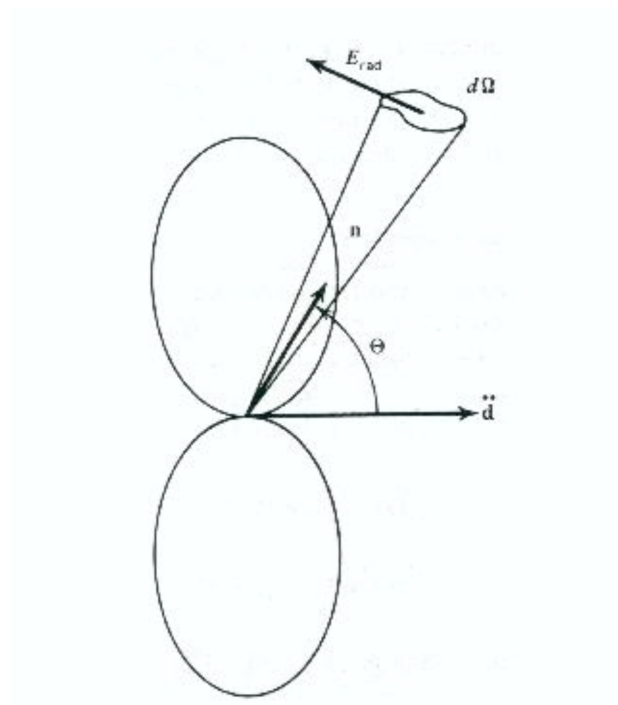
(As with Bremsstrahlung, a rigorous derivation is quite tricky.)

In the non-relativistic case, the frequency of gyration in the magnetic field is

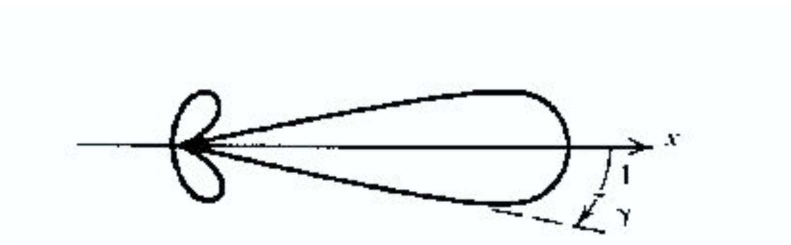
$$\omega_L = eB/m_e c$$

$$= 2.8\ B_{1G}\ \text{MHz (Larmor)}$$

And the frequency of the emitted radiation is $\boldsymbol{\omega_L}$



Synchrotron Radiation



Angular distribution of radiation (acceleration ⊥ velocity).

Rybicki & Lightman

Synchrotron radiation comes from relativistic electrons interacting with a magnetic field. In this case, the emitted radiation is "beamed" along the velocity vector, with an opening angle

$$\Delta\theta \sim 1/\gamma$$

Gyration frequency $\omega_B = \omega_L/\gamma$

Observer sees radiation for duration $\Delta t \lll T = 2\pi/\omega_B$

This means that the spectrum includes higher harmonics of ω_B.

The maximum is at a characteristic frequency which is:

$$\omega_c \sim 1/\Delta t \sim \gamma^2 e B_\perp / mc$$

Synchrotron Radiation

The total emitted power is:

$$P = \frac{2e^4 B_\perp^2}{3m_e^2 c^3 \beta^2 \gamma^2} = \frac{2}{3} r_0^2 c \gamma^2 B_\perp^2 \qquad \text{when } \gamma >> 1$$

Or, alternatively $P \propto \gamma^2 c \sigma_T U_B \sin^2\theta$ (where U_B is the magnetic energy density

and so $P \sim 1.6 \times 10^{-15} \gamma^2 B^2 \sin^2\theta \text{ erg/s}$

Electron lifetime: $\tau \propto E/P \sim 20/(\gamma B^2)$ yr

This is sometimes called "electron burn-off"; in the Crab Nebula, the lifetime of an X-ray producing electron is only 20 years (!)

Note that $P \propto 1/m^2$: synchrotron is negligible for massive particles.

Synchrotron Radiation

Synchrotron radiation comes from relativistic electrons spiraling around magnetic fields. Can we use X-ray measurements to determine either the:

- electron distribution?
- magnetic field?

Synchrotron Radiation

Assume the energy spectrum of the electrons between energy E_1 and E_2 can be approximated by a power-law:

$$N(E) = K\, E^{-\rho}\, dE \quad \text{(isotropic, homegeneous).}$$

where N(E) is the number of e^- per unit volume

Intensity of radiation in a homogeneous magnetic field:

$$I(\nu, k) = \frac{\sqrt{3}}{\rho + 1} \Gamma(\frac{3\rho - 1}{12}) \Gamma(\frac{3\rho + 19}{12}) \frac{e^3}{mc^2} (\frac{3e}{2\pi m_e^2 c^5})^{(\rho-1)/2} K [B \sin\theta]^{(\rho+1)/2} \nu^{-(\rho-1)/2}$$

This complex result does lead to one simple conclusion:

$$I(\nu) \propto \nu^{-(\rho-1)/2}$$

or, equivalently $I(E) \propto E^{-(\rho-1)/2}$

Synchrotron Radiation

$$N(E) = K\, E^{-\rho}\, dE \quad \text{for } E_1 < E < E_2$$

We know ρ; can we get K, E_1,E_2, or B?

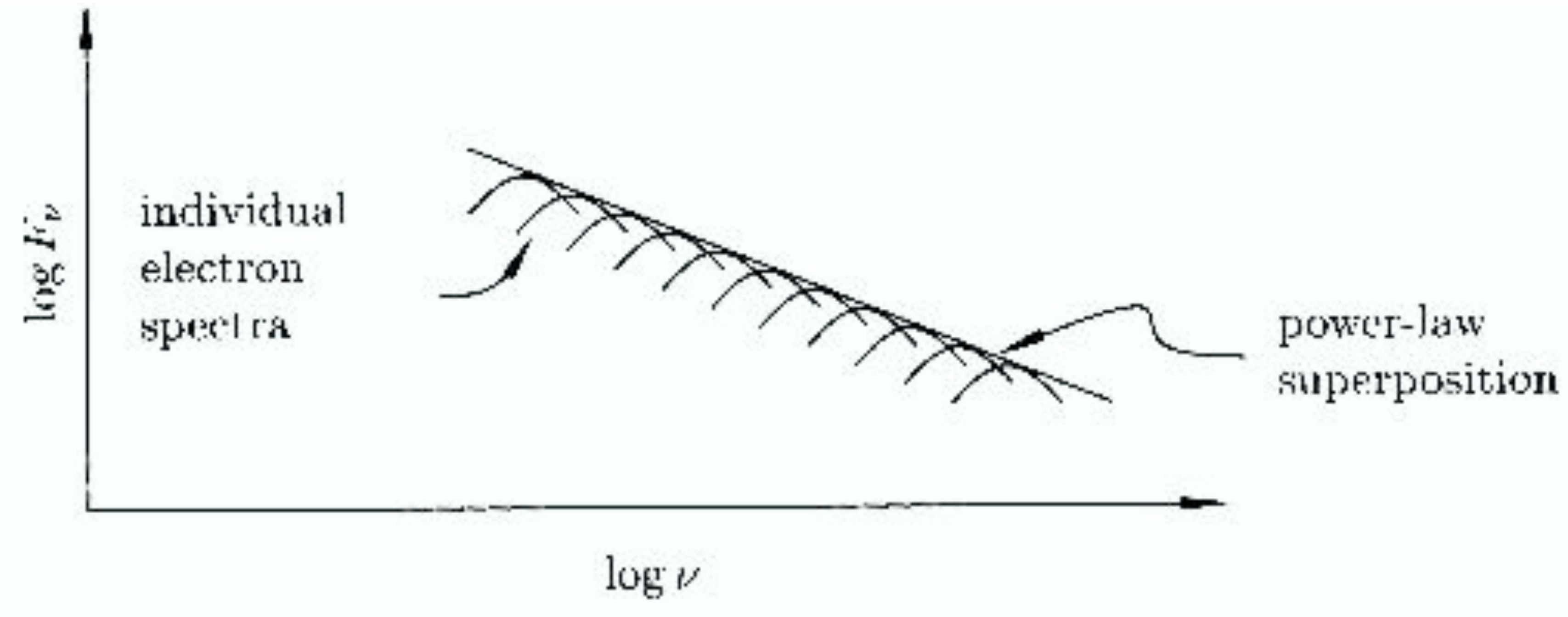
Average the previous equations over all directions of magnetic field (for astrophysical applications), where L is the size of the radiating region:

$$I(\nu) = a(\rho)\frac{e^3}{m_e c^2}\left(\frac{3e}{4\pi m_e^3 c^5}\right)^{(\rho-1)/2} B^{(\rho+1)/2} K L \nu^{-(\rho-1)/2}\ \text{erg cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\ \text{Hz}^{-1}$$

where $$a(\rho) = \sqrt{\frac{3\cdot 2^{(\rho-1)}}{\pi}}\frac{\Gamma(\frac{3\rho-1}{12})\Gamma(\frac{3\rho+19}{19})\Gamma(\frac{\rho+5}{4})}{8(\rho+1)\Gamma(\frac{\rho+7}{4})}$$

Synchrotron Radiation

The spectrum from a single electron is **not** a power-law, but if the energy distribution of the electrons is a power distribution, the result appears to be one:



(from Shu, Part II, p 178)

Synchrotron Radiation

Estimating the two boundaries energies E_1 and E_2 of electrons radiating between ν_1 and ν_2 can be done using the following results:

$$E_1(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_1}{3eBy_1(\rho)}} = 250\sqrt{\frac{\nu_1}{By_1(\rho)}}\mathrm{eV}$$

$$E_2(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_2}{3eBy_2(\rho)}} = 250\sqrt{\frac{\nu_2}{By_2(\rho)}}\mathrm{eV}$$

Tabulations of $y_1(\rho)$ and $y_2(\rho)$ are available. Note that if

$\nu_2/\nu_1 << y_1(\rho)/y_2(\rho)$ or if $\rho<1.5$ this is only rough estimate

Synchrotron Radiation

As one might expect, synchrotron radiation can be quite polarized. The total polarization:

$$\frac{P_\perp(\omega) - P_{||}(\omega)}{P_\perp(\omega) + P_{||}(\omega)} = \frac{\rho + 1}{\rho + 7/3}$$

can be very high (more than 70%).

Synchrotron Self-absorption

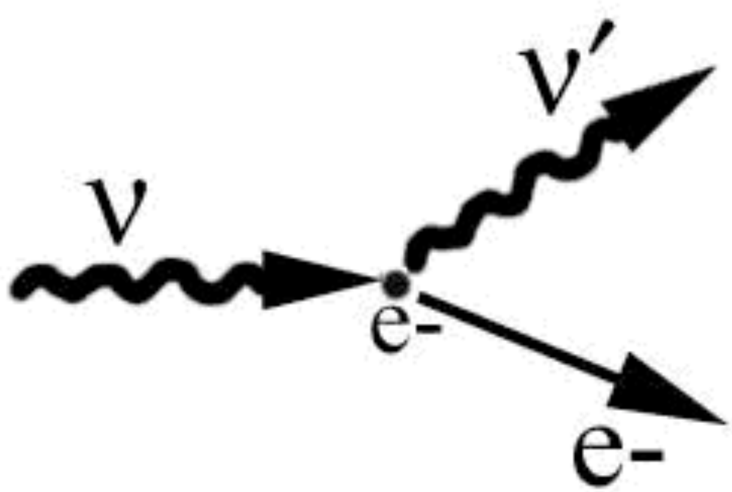
The principal of invariance under time reversal suggests that any emission process can also be an absorption process.

Here, a photon interacts with a charged particle in a magnetic field and is absorbed; the process is stronger at low frequencies/energies. Below the "break frequency" ν_m, we have the result that

$$F \propto \frac{\nu^{5/2}}{\sqrt{B}}$$

independent of the spectral index.

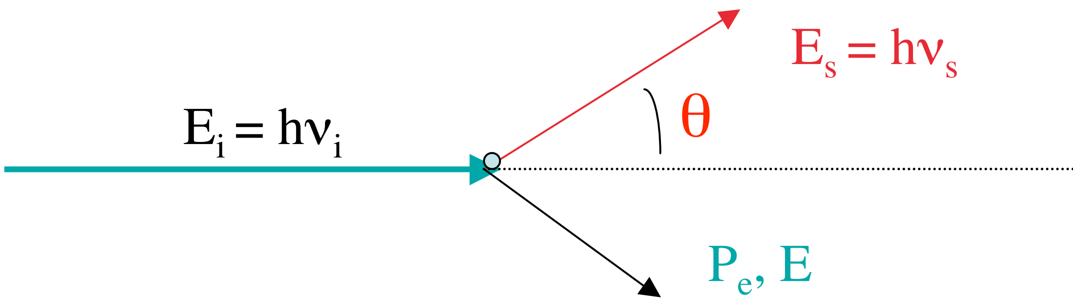
Compton Scattering



$$\nu' < \nu$$

Compton Scattering

For low energy photons ($h\nu << mc^2$), scattering is classical Thomson scattering (E_i=E_s; $\sigma_T = 8\pi/3\ r_0^2$)



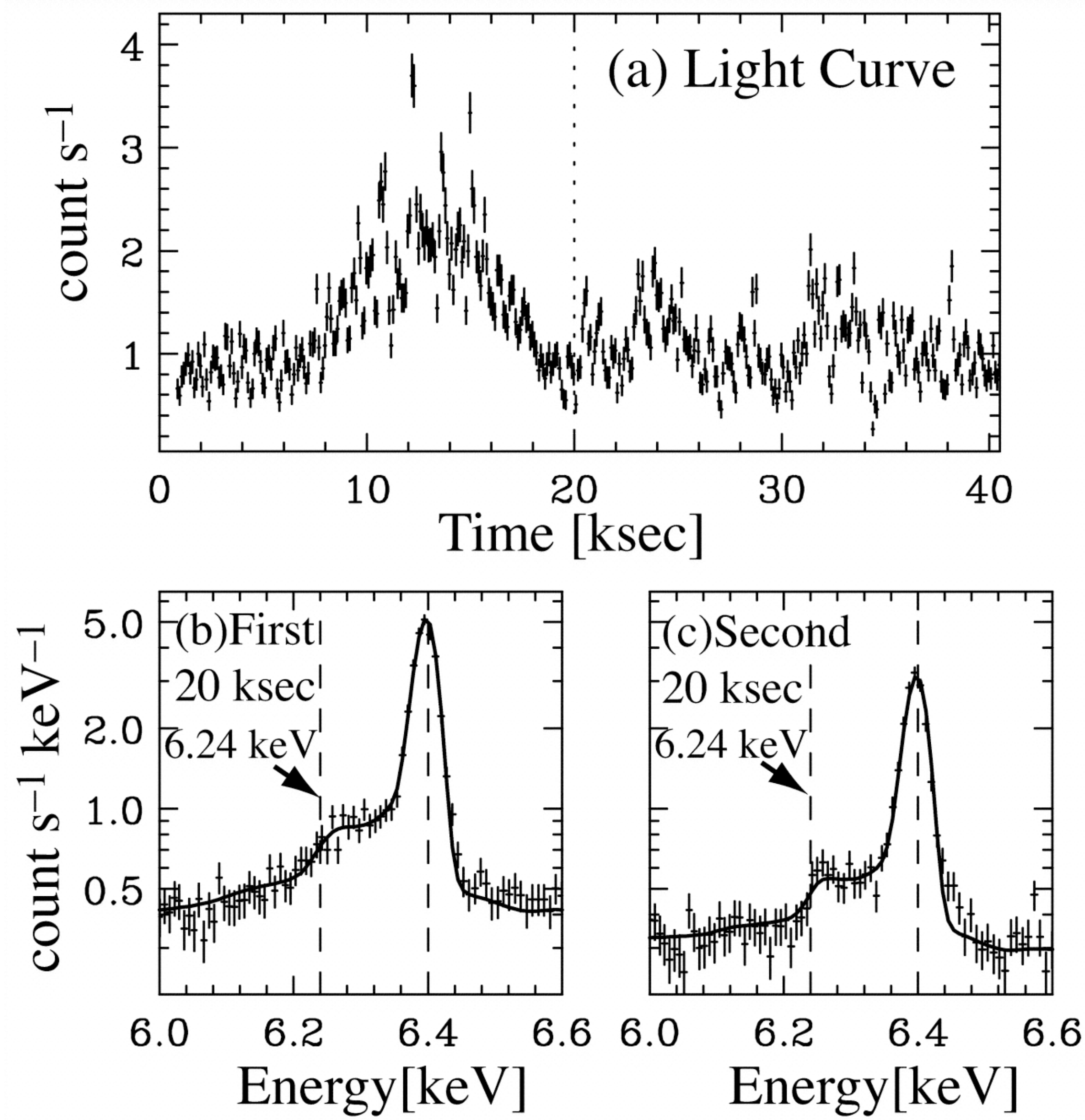
where $$E_s = \frac{E_i}{1 + \frac{E_i}{m_e c^2}(1 - \cos\theta)}$$ or

$$\lambda_s - \lambda_i = \lambda_c(1 - \cos\theta) \qquad \lambda_c \equiv \frac{h}{m_e c} = 0.02426\,\text{Å}$$

Note that E_s is always smaller than E_i

Compton Scattering

This has been detected using the Chandra HETG and the Fe K 6.4 keV fluorescence line from the XRB GX301-2 (Watanabe et al. 2003)

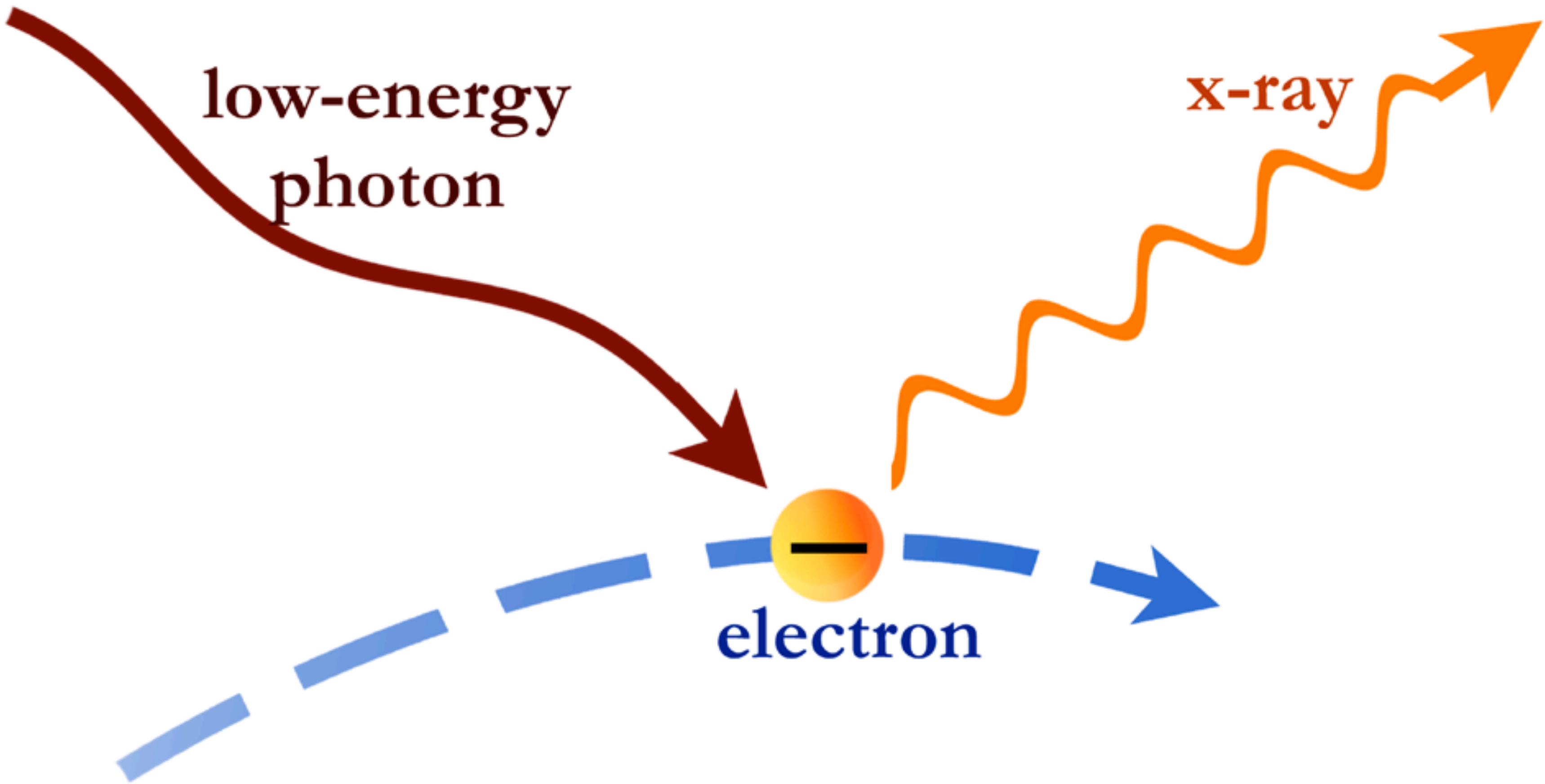


Here E = 6.4 keV, so
$\lambda = 12.398/E = 1.937$Å

$$\lambda_s - \lambda_i = \lambda_c(1 - \cos\theta)$$

$\lambda_s = \lambda + 2\lambda_c = 1.986$ Å or
$E = 6.24$ keV (if $\Theta = 180^o$)

Inverse Compton Scattering



Inverse Compton Scattering

If the electron kinetic energy is large enough, energy can be transferred from the electron to the photon:

Inverse Compton

Use the previous formula (valid in the rest frame of the electron) and then Lorentz transform:

$$E_i^{foe} = E_i^{lab}\gamma(1 - \beta\cos\theta)$$

$$E_s^{foe} = f_{comp}(E_i^{foe})$$

$$E_s^{lab} = E_s^{foe}\gamma(1+\beta\cos\theta')$$

which means that $E_s^{lab} \propto E_i^{lab}\,\gamma^2$ (potentially quite large!)

Inverse Compton Scattering

The total power emitted via this process is:

$$\mathrm{P}_{\mathrm{comp}} = \frac{4}{3}\sigma_T c \gamma^2 U_{\mathrm{ph}}(1 - f(\gamma, E_i^{\mathrm{lab}}))$$

or $$\mathrm{P}_{\mathrm{comp}} \sim \frac{4}{3}\sigma_T c \gamma^2 \beta^2 U_{\mathrm{ph}}$$

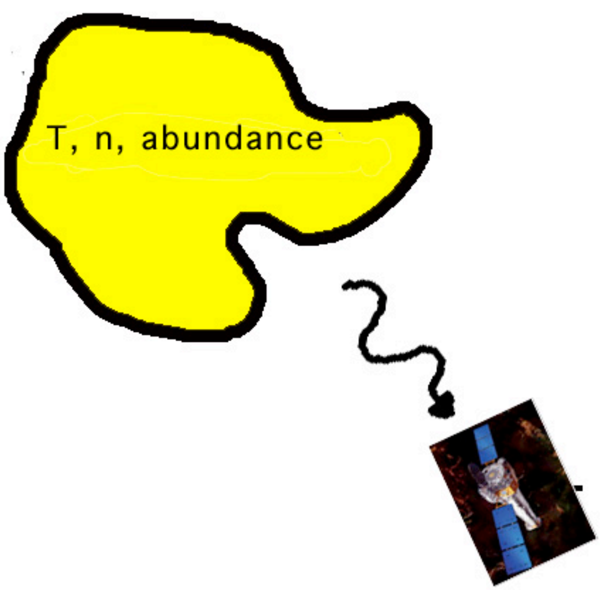
where U_{ph} is the initial photon energy density

Remember that $\mathrm{P}_{\mathrm{sync}} \propto \gamma^2 c \sigma_T U_B$

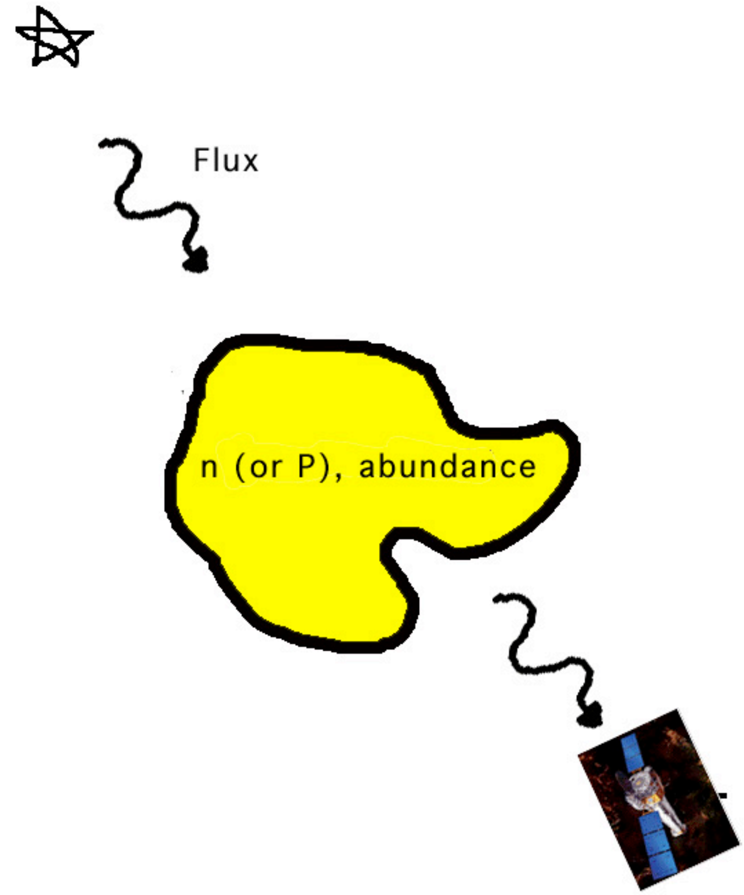
So: $$\frac{\mathrm{P}_{\mathrm{sync}}}{\mathrm{P}_{\mathrm{comp}}} = \frac{U_B}{U_{ph}}$$

So synchrotron radiation can be thought of as inverse Compton radiation from the “virtual” photons in the magnetic field.

Photoionized Plasmas



Collisional



Photoionized

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*

Photoionized Plasmas

	Photoionized	Coronal
Dominant ionization	Photoionization $h\nu+Z \rightarrow Z+1$	Electron impact $e^-+Z \rightarrow Z+1$
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, $\Delta n=0,1,2$ favored

Consequences of Photoionization

- Temperature lower for same ionization than coronal, $T \sim 0.1\ E_{th}/k$
- 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

Photoionized Plasmas

- In coronal gas, need $kT_e \sim \Delta E$ 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.

Parameter definitions:

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

$$U_x \equiv \frac{N_X}{4\pi R^2 nc}$$ Davidson (1974)

$$\Gamma \equiv \frac{L_X(> 13.6 \text{ eV})}{8\pi R^2 nc}$$ Kwan & Krolik (1981)

$$\Xi \equiv \frac{L}{4\pi n_e ckTR^2}$$ Krolik, McKee & Tarter (1982)

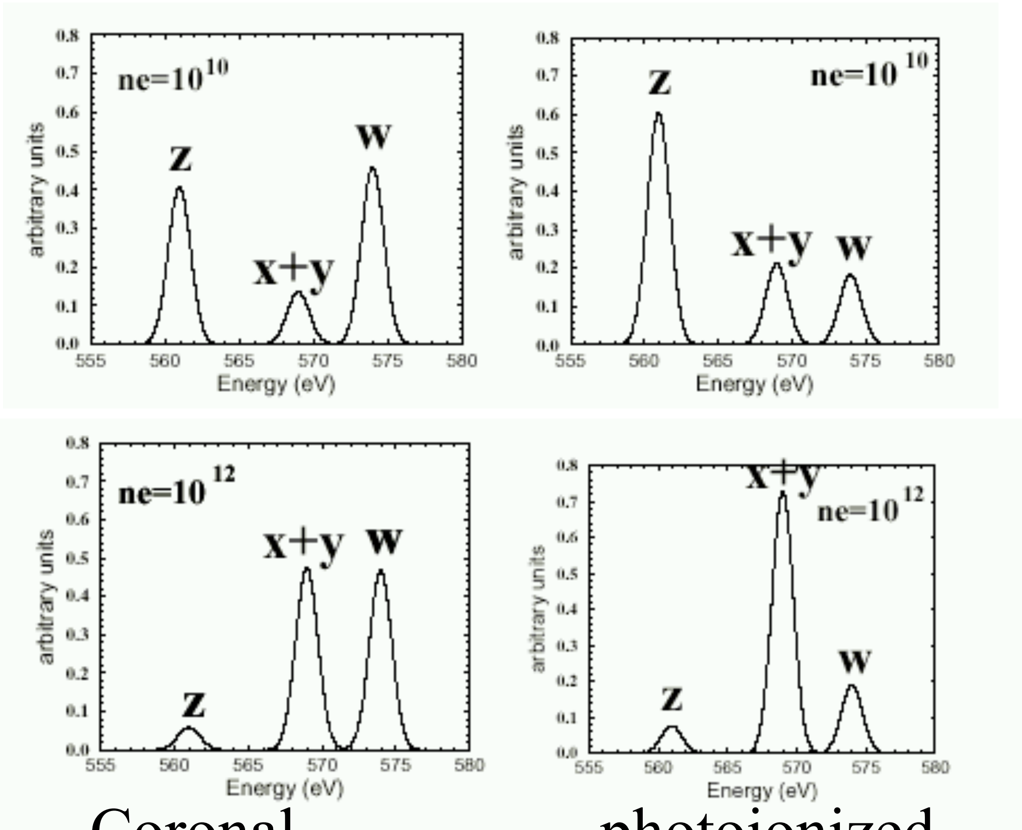
$$U_1 \equiv \frac{N}{4\pi R^2 nc}$$ Netzer (1994)

where:

$$L \equiv \int_{13.6 \text{ eV}}^{\infty} L(E)\,dE \qquad N \equiv \int_{13.6 \text{ eV}}^{\infty} L(E)\frac{dE}{E} \qquad N_X \equiv \int_{100 \text{ eV}}^{\infty} L(E)\frac{dE}{E}$$

Photoioinized Plasmas

Density dependence of He-like lines



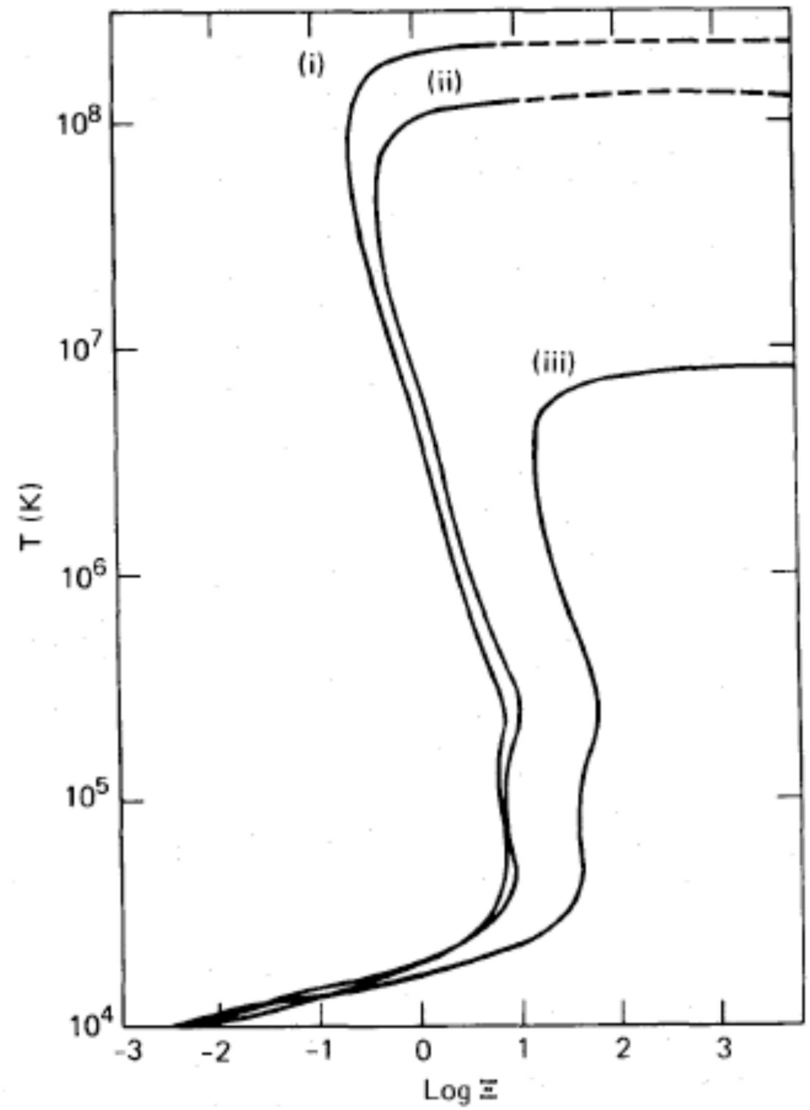
Coronal photoionized

(Porquet and Dubau 1998)

Photoionized Plasmas

'Thermal Instability'

- For gas at constant pressure, thermal equilibrium can be multiple-valued if the net cooling rate varies more slowly than $\Lambda(T) \sim T$
- This suggests the possibility of 2 or more phases coexisting in pressure equilibrium
- The details depend on atomic cooling, abundances, shape of ionizing spectrum.

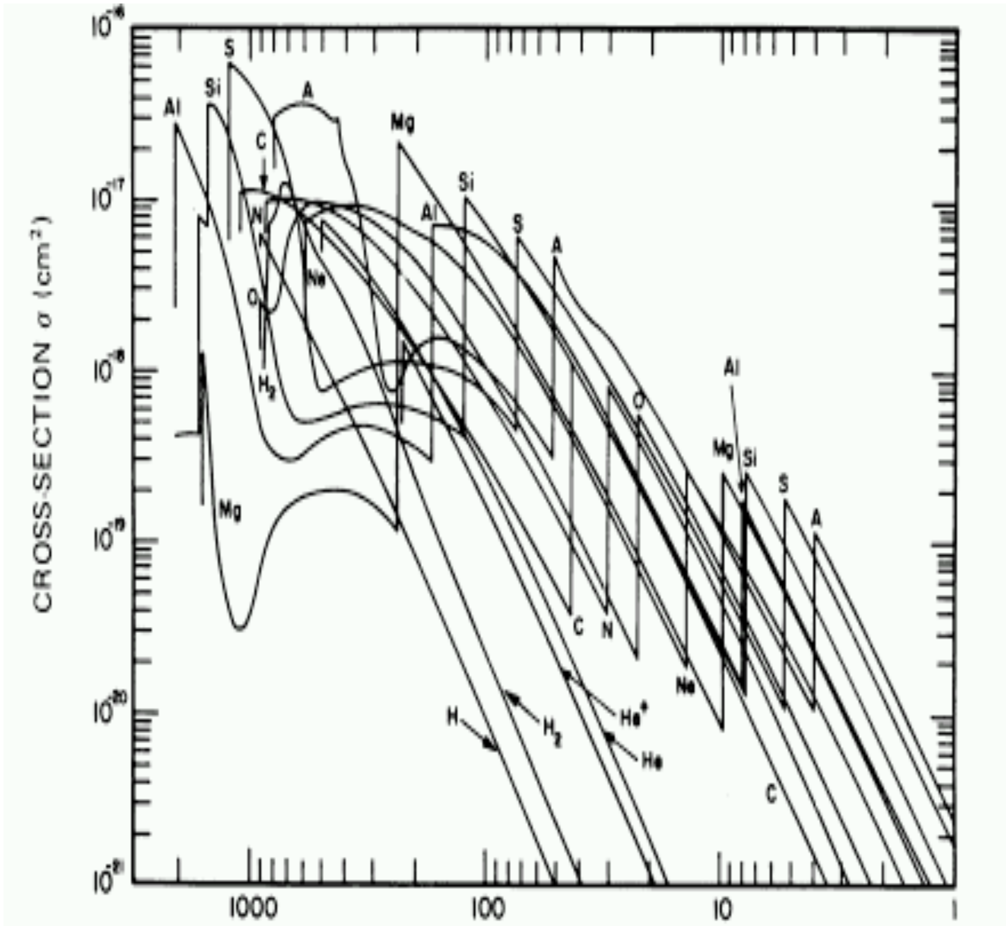


Krolik, McKee and Tarter 1981

Absorption

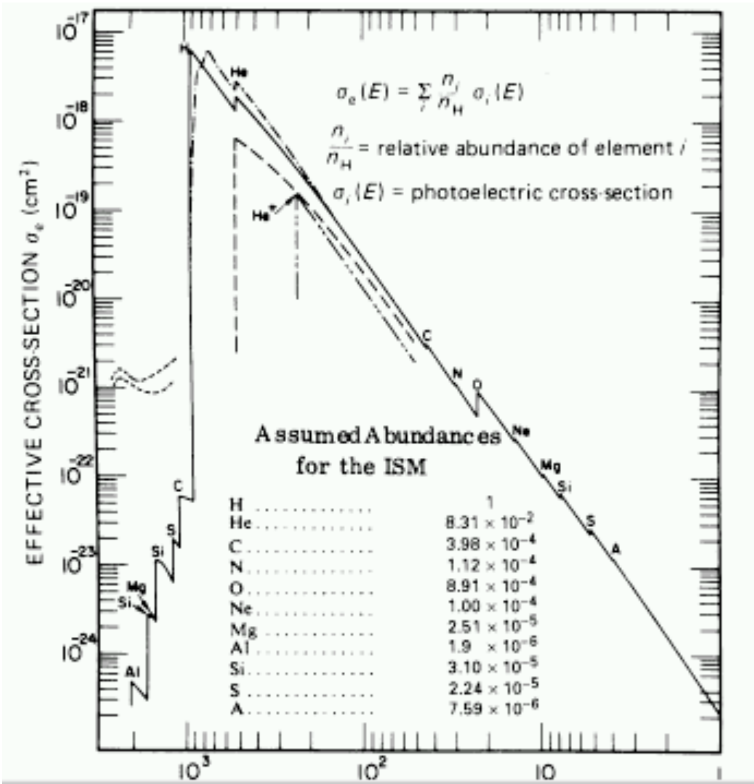
- Absorption by interstellar material is in every spectrum, but absorption is uniquely associated with photoionized sources.
- A crude approximation for the photoabsorption cross section of a hydrogenic ion is that the cross section is $\sim Z^{-2}$ at the threshold energy, and that the threshold energy 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

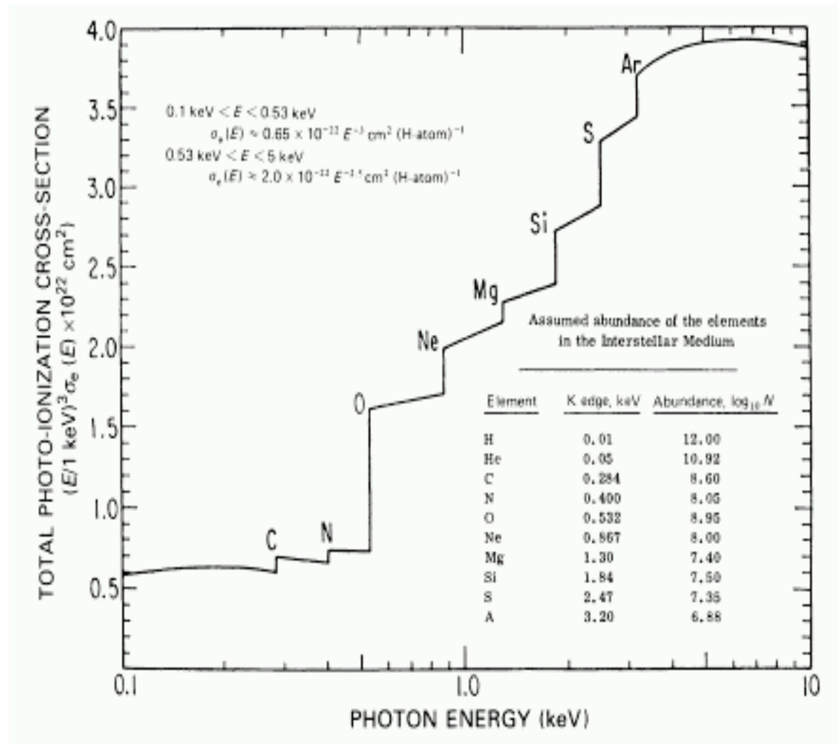
Absorption



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

Absorption

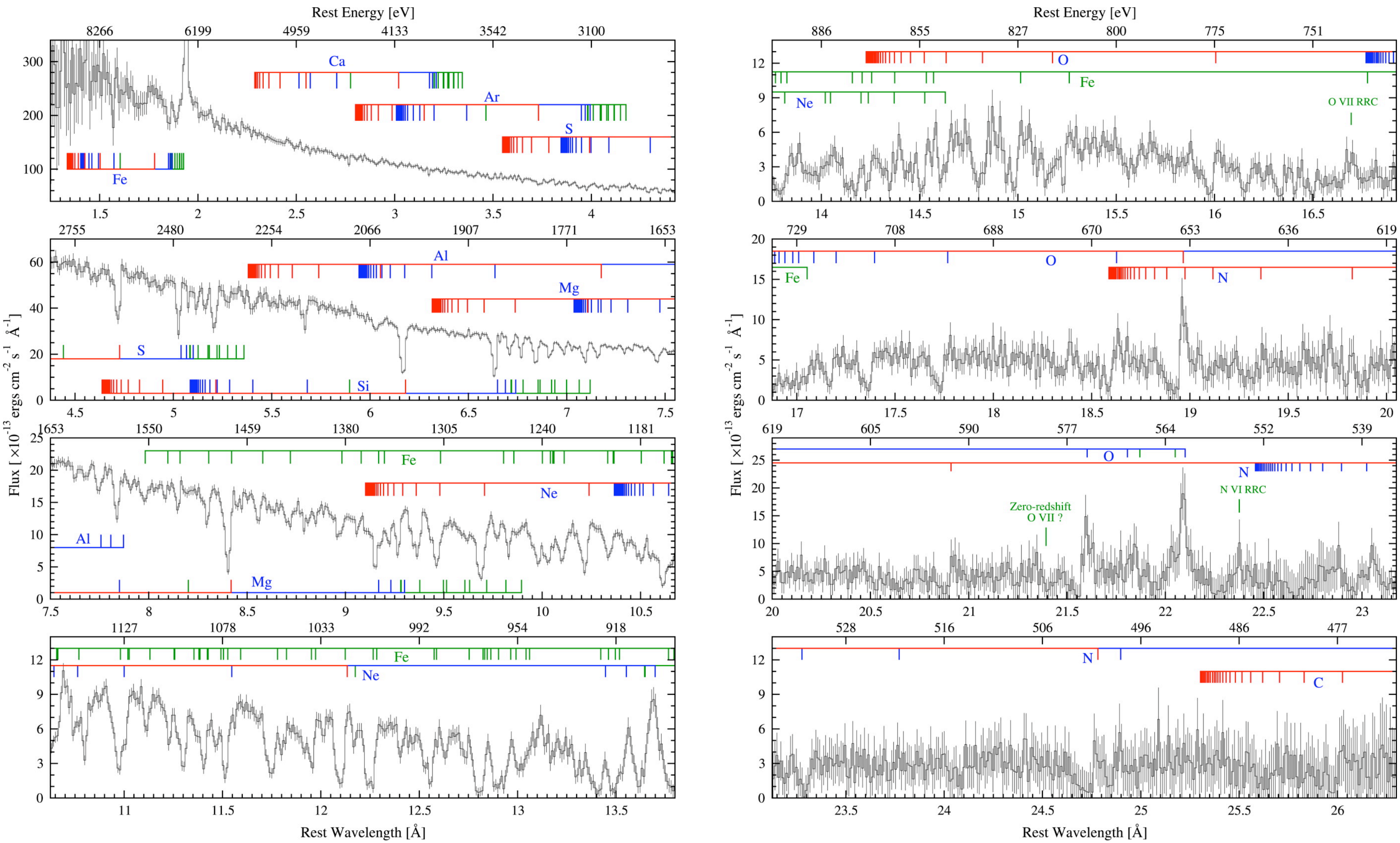




Interstellar absorption (Morrison and McCammon; Zombeck)

NGC 3783 900 ksec Chandra observation

Absorption



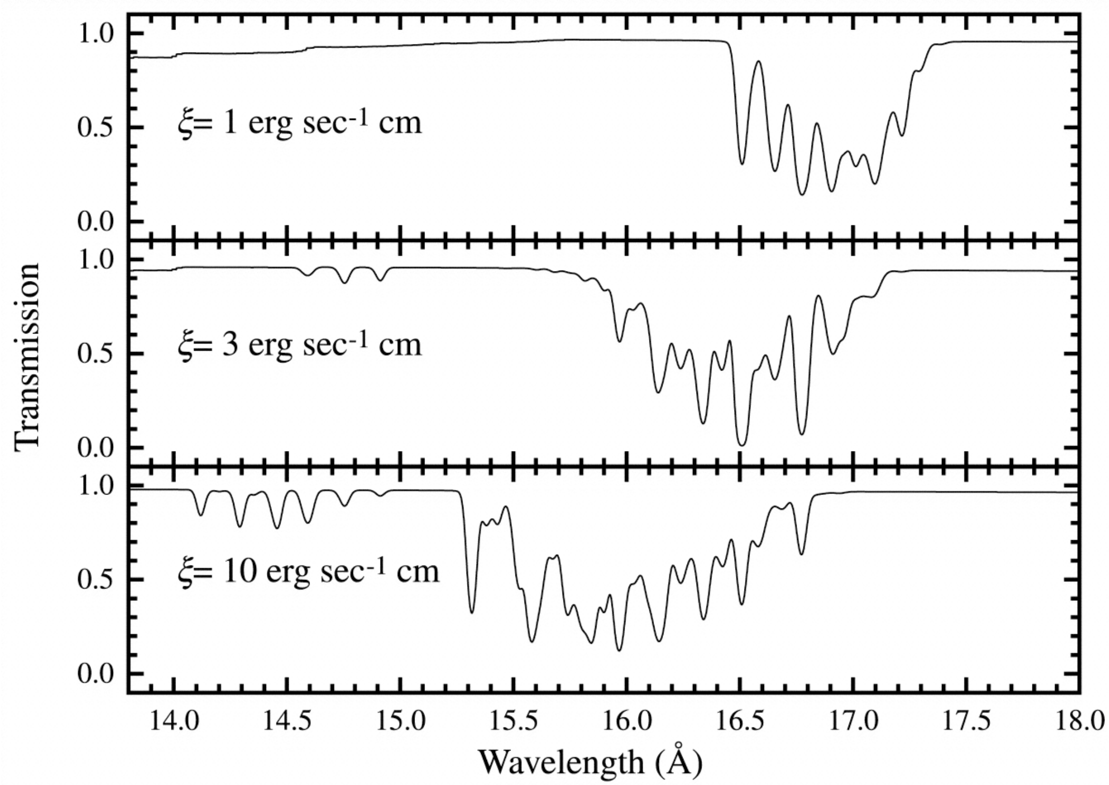
135 absorption lines identified

Kaspi et al. 2003

Absorption

Unresolved Transition Arrays (UTAs)

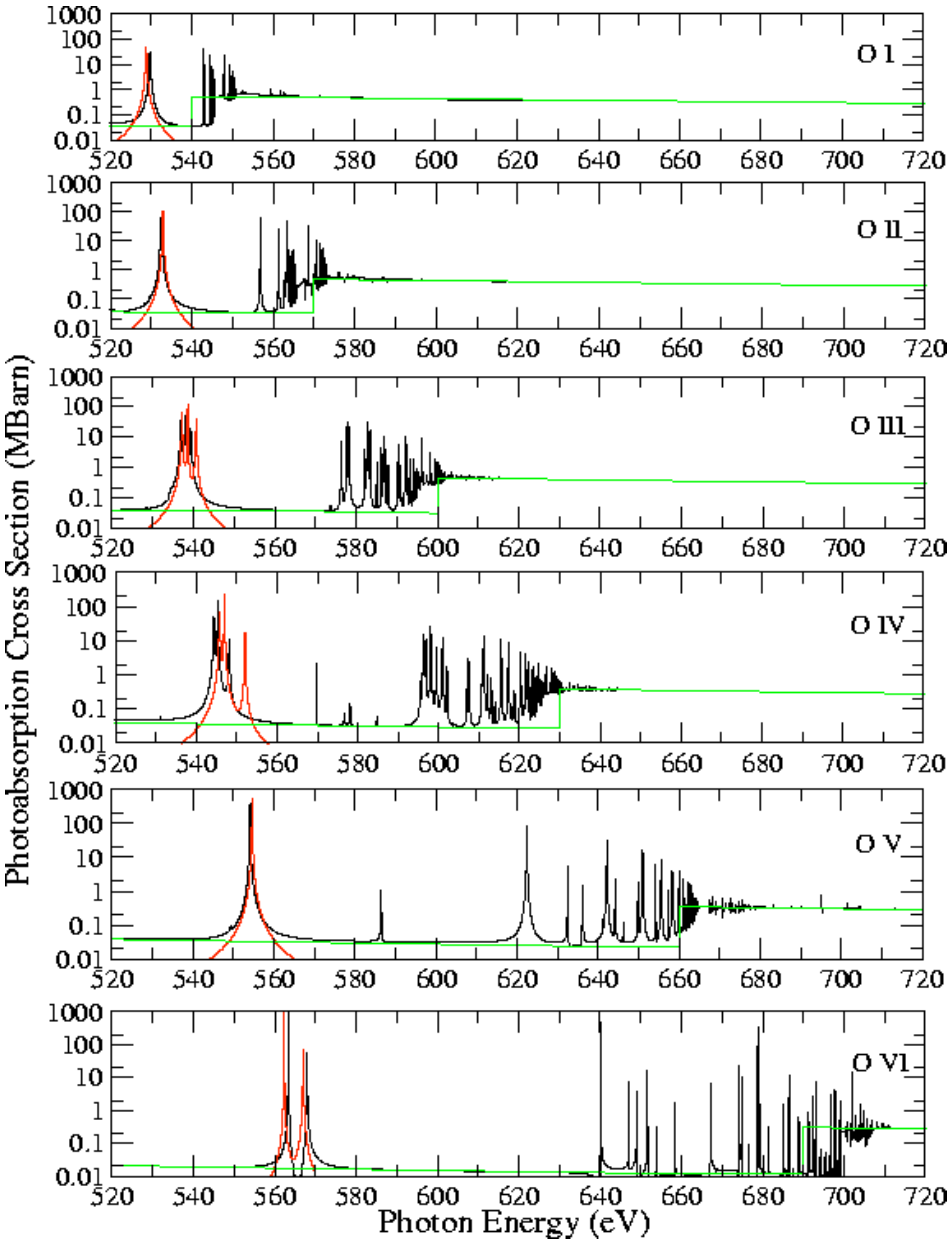
- Appears in absorption spectra of AGN, eg. NGC 3783
- Comes from 2p-3s or 2p-3d transitions --> requires iron less than 9 times ionized
- Potential diagnostic of ionization balance



(Behar, Sako and Kahn 2002)

Absorption

K shell Photoabsorption (Oxygen)



In theory, could diagnose ionization balance in the ISM or other absorbing material. This data uses semi-empirical corrections to energy levels in the optimization of wavefunctions, based on the experiment, plus multi-code approach

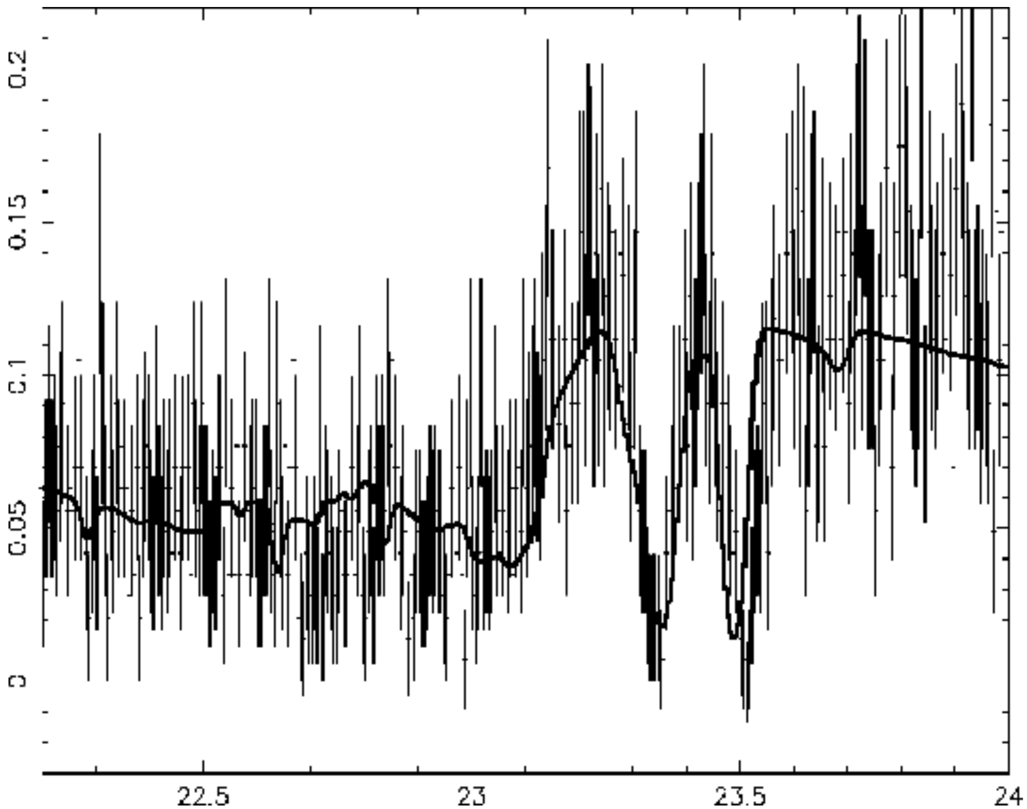
Red: Pradhan et al (2003)

Green: Verner and Yakovlev (1995)

Black: Garcia et al. (2005)

Absorption

Spectrum of Cyg X-2 fit with O K edge data



Using these cross sections, no ad hoc offset is needed to fit to the Chandra spectrum of Cyg X-2

Garcia et al. 2005

Experimental wavelengths can be used to optimize calculated absorption cross sections, and thereby improve accuracy of more transitions than just those for which measurements exist

Conclusions

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

Books and references

- Rybicki & Lightman "Radiative processes in Astrophysics"
- Longair "High Energy Astrophysics"
- Shu "Physics of Astrophysics"
- Tucker "Radiation processes in Astrophysics"
- Jackson "Classical Electrodynamics"
- Pacholczyk "Radio Astrophysics"
- Ginzburg & Syrovatskii "Cosmic Magnetobremmstrahlung" 1965 Ann. Rev. Astr. Ap. 3, 297
- Ginzburg & Tsytovitch "Transition radiation"