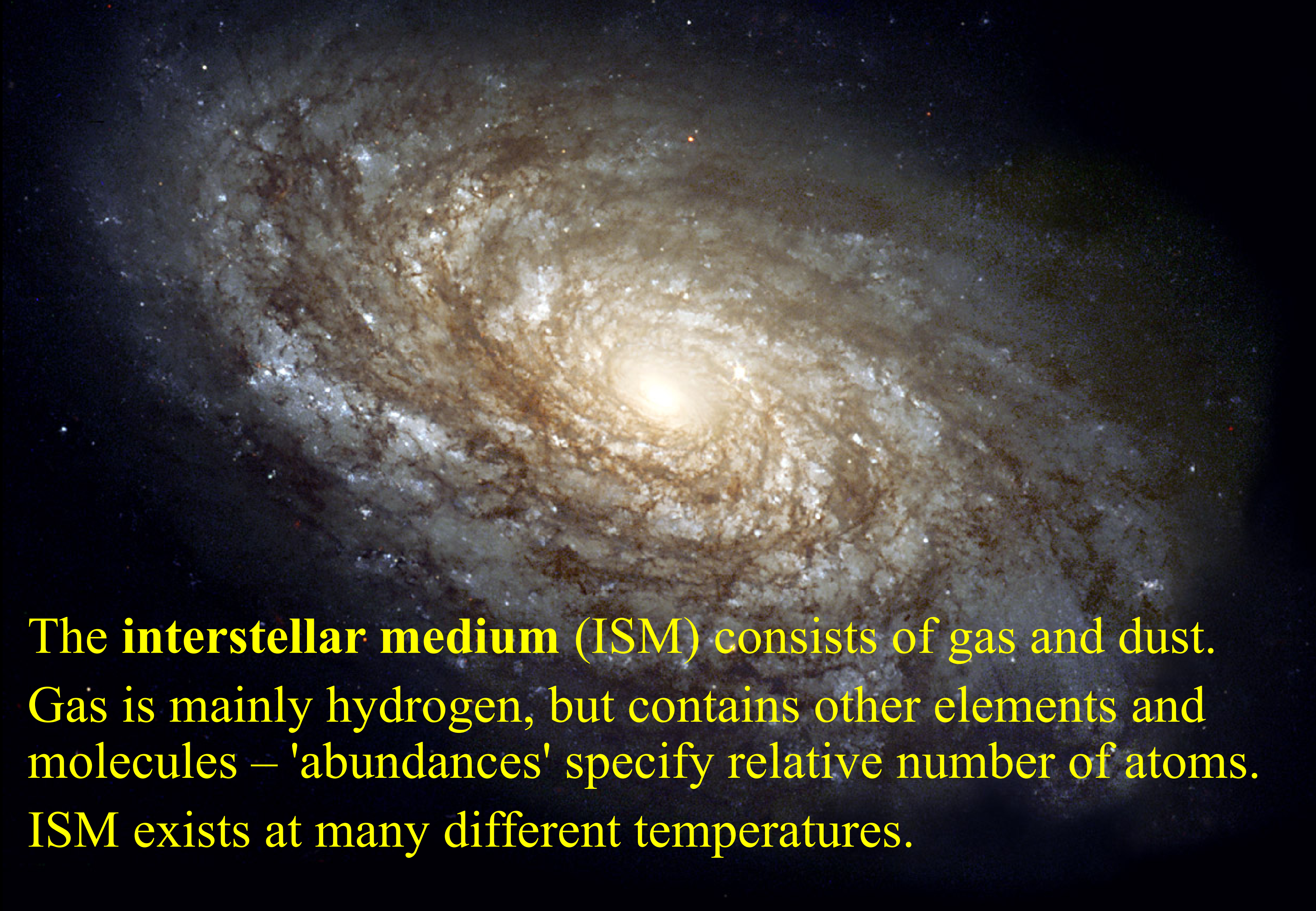
Milky Way and Interstellar Medium

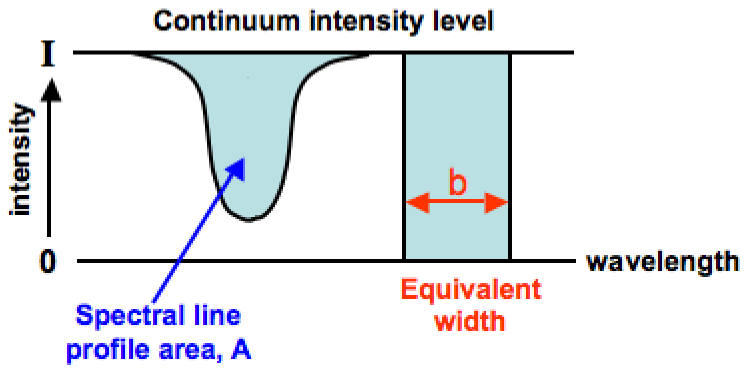
- Diffuse contents of the Milky Way
- Absorption lines from neutral and ionized gas
  - Equivalent width
- Ionized gas (plasma)
  - Thermal bremsstrahlung
  - Emission lines, permitted and forbidden
  - Dispersion measure of pulsars
- Overall picture of interstellar gas
  - Heating and cooling

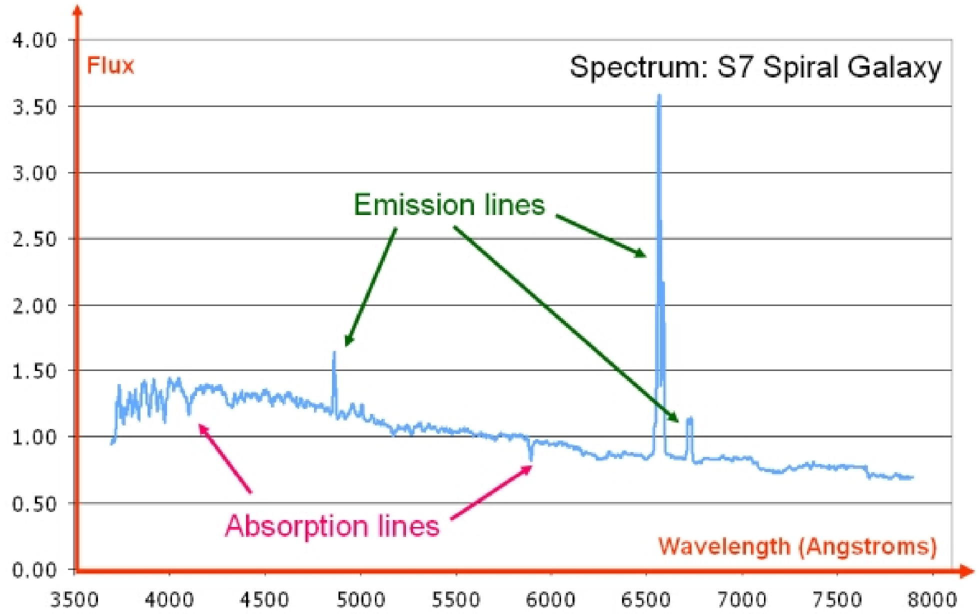
Interstellar Medium



- The **interstellar medium** (ISM) consists of gas and dust.
- Gas is mainly hydrogen, but contains other elements and molecules – 'abundances' specify relative number of atoms.
- ISM exists at many different temperatures.

Absorption Lines

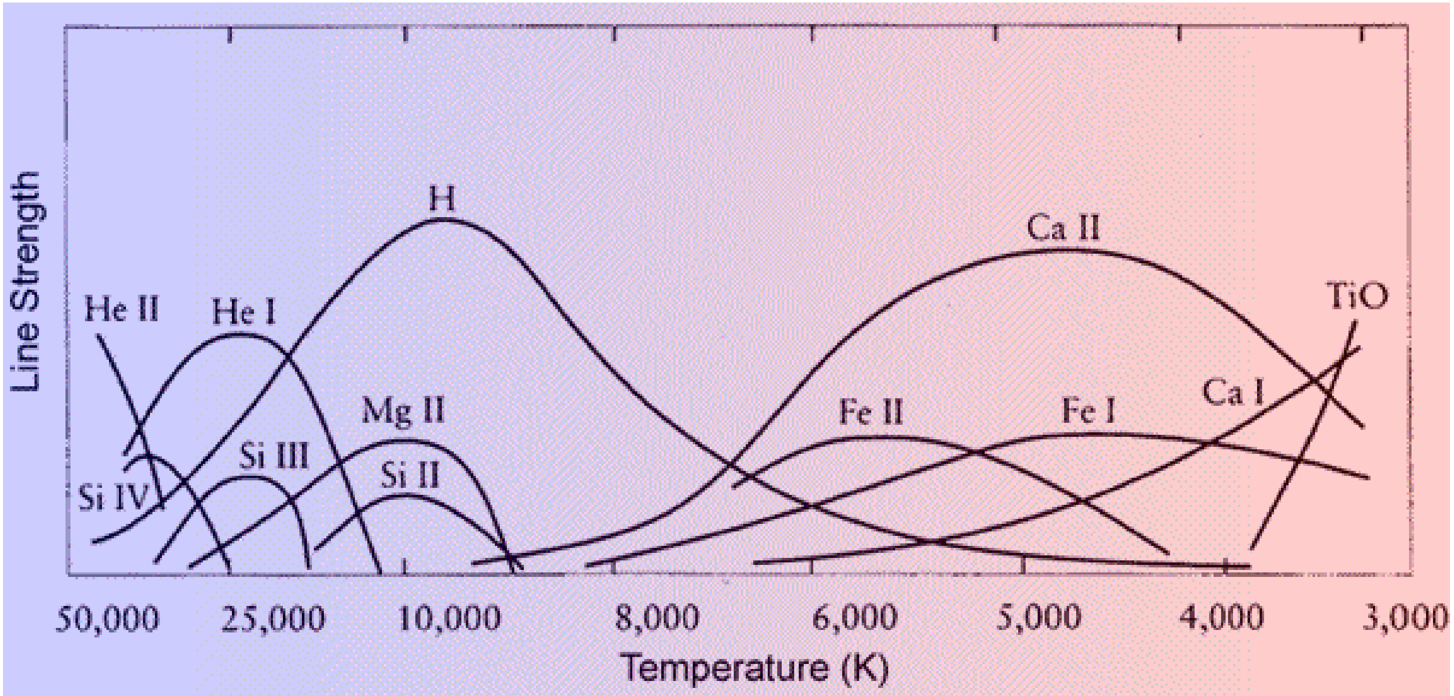




- Neutral atoms absorb photons at particular energies, corresponding to atomic transitions. This produces absorption lines in the spectra of objects more distant than the absorber.
- 'Equivalent width' indicates the strength of the line:

$$b = \int \left(1 - \frac{I_\nu}{I_{\nu c}}\right) d\nu$$

Absorption Lines



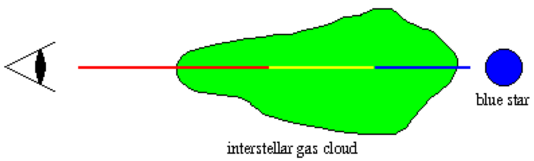
- Which absorption lines are present indicate the temperature of the absorbing gas.
- Different atoms will absorb different energies.
- Atoms have different ionization states, e.g. Si II, Si III, Si III
  - Si I = neutral, Si II = singly ionized = one missing electron, …
  - Atoms are more highly ionized at higher temperatures.

Ionization Levels

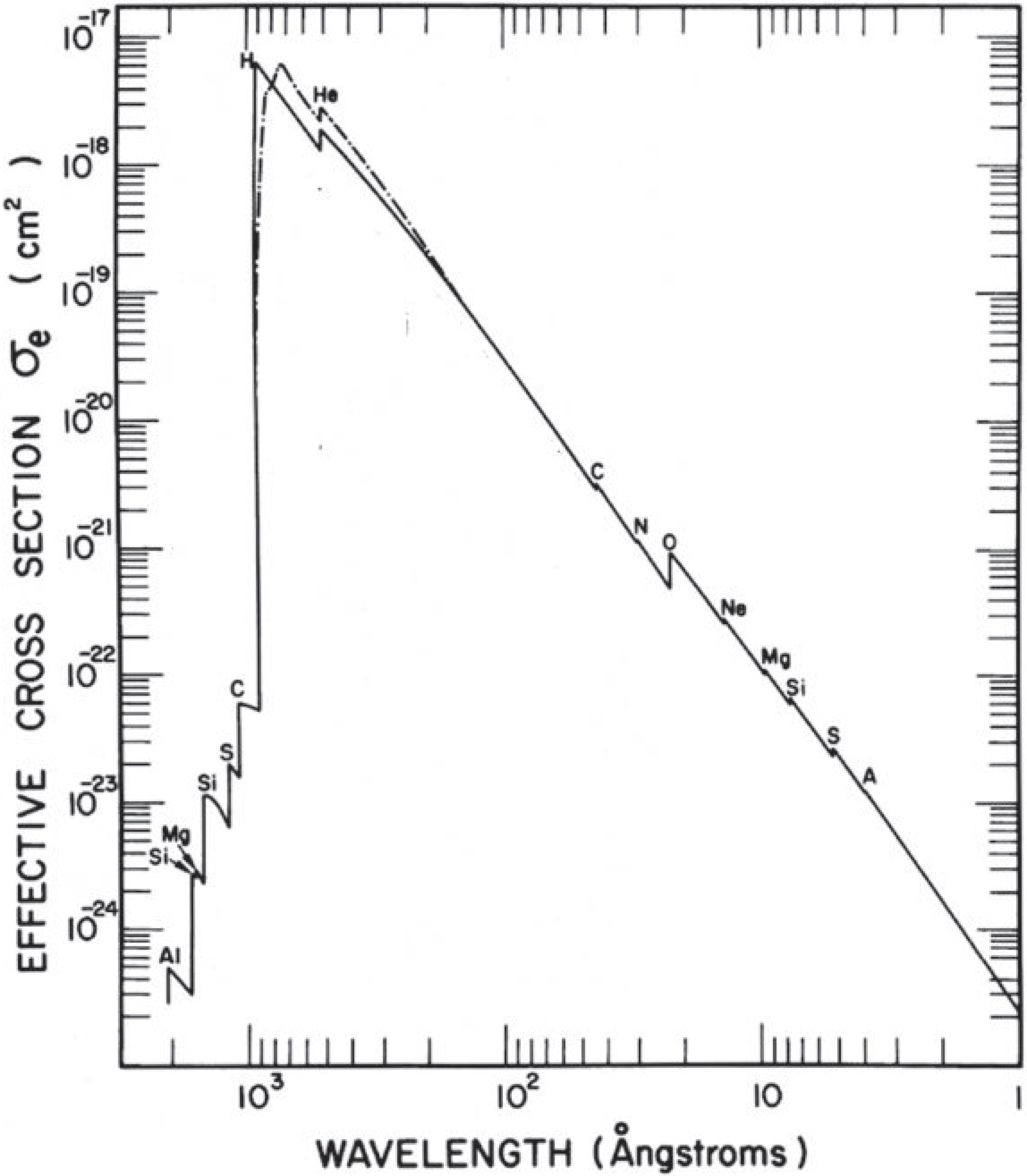
Roman numeral = # ionizations – 1.

- Hydrogen ($Z = 1$)
  - H I = neutral
  - H II = single ionized (= proton)
- Helium ($Z = 2$)
  - He I = neutral = 2 electrons
  - He II = single ionized = 1 electron
  - He III = doubly ionized = 0 electrons
- e.g. Oxygen ($Z = 8$)
  - O VII = oxygen with only 2 electrons

Interstellar absorption



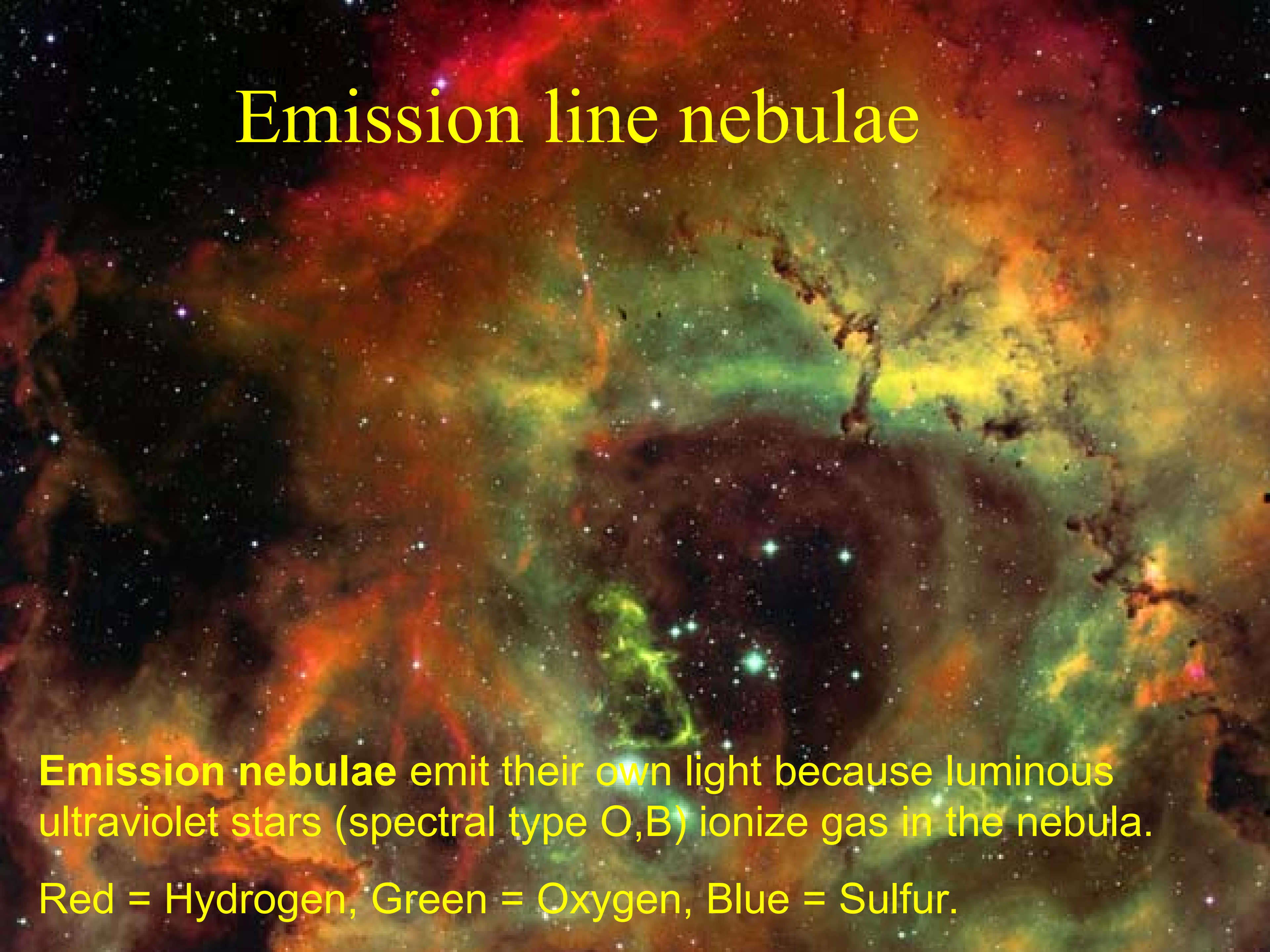
Cross section versus wavelength for material with 'cosmic' abundances, meaning ratio of each element to H equals that in the Sun.



Ionized Interstellar Gas

- Ionized gas (plasma) can produce
  - Thermal bremsstrahlung
  - Emission lines

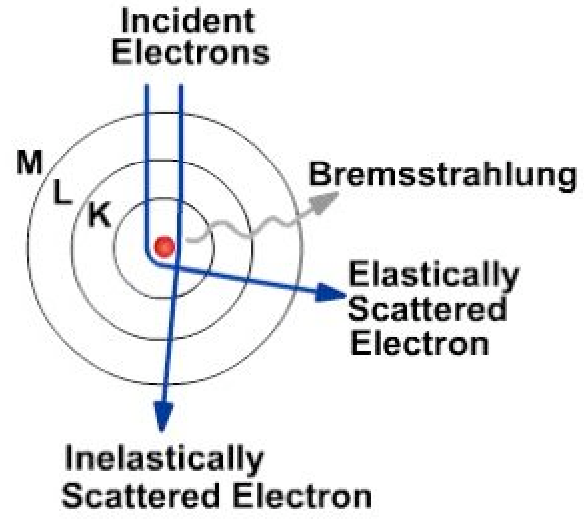
Emission line nebulae



Emission nebulae emit their own light because luminous ultraviolet stars (spectral type O,B) ionize gas in the nebula.

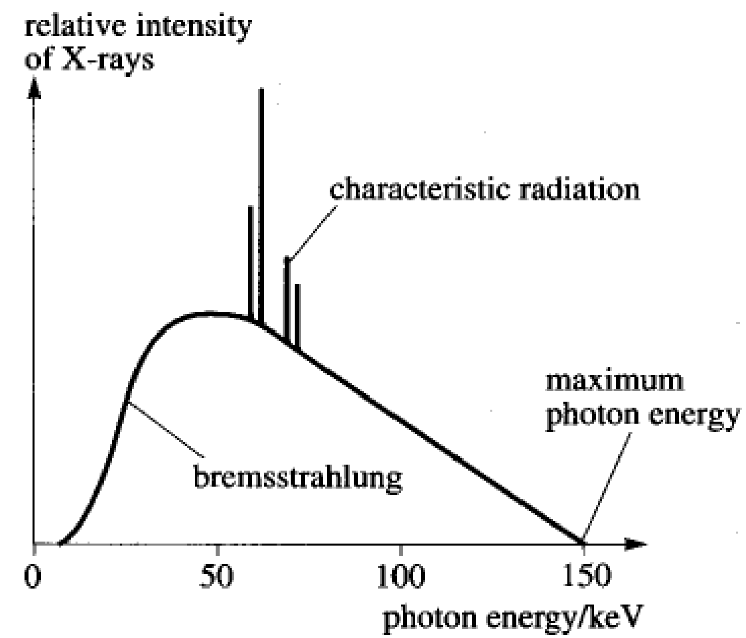
Red = Hydrogen, Green = Oxygen, Blue = Sulfur.

Thermal bremsstrahlung



- Bremsstrahlung = free electron scatters off an atom or another electron.
- Maximum photon energy = maximum electron energy.
- Intensity along line of sight:

$$I_\nu = A \int N_e^2 T^{-1/2} dr$$



- Can produce line emission if incident electron excited the atom.

Permitted and Forbidden Transitions

- From quantum mechanics, amplitude for transition from one state to another via some process is $T = \langle f | \hat{O} | i \rangle$
- The strongest atomic transitions are electric dipole transitions, the operator is $q\vec{x}$
- "Allowed" transitions are electric dipole transitions, need

$$T = \langle f | q\vec{x} | i \rangle = \int d^3x \;\; \psi_f^*(\vec{x})(q\vec{x})\psi_i(\vec{x}) \neq 0$$

- If electric dipole transition is not allowed, then the transition is "forbidden". Transition can still occur, but via some other process, e.g. magnetic dipole or electric quadrapole.

Spectral Line Notation

- Spectral lines specified by ionization state of atom (H I , O III, etc.)

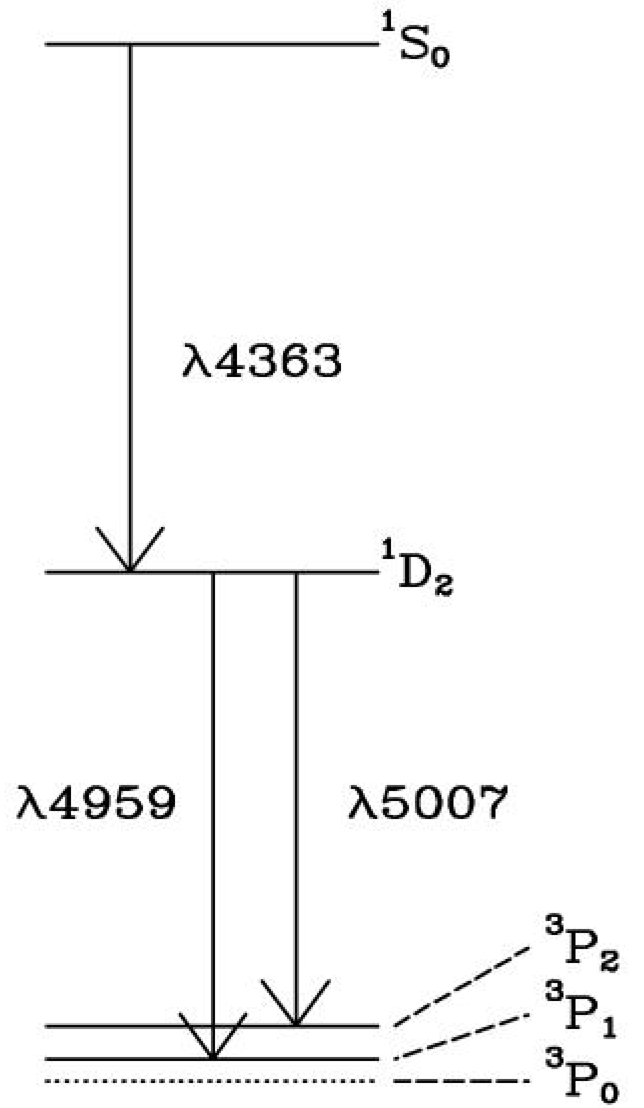
  Does line emission change ionization?

- Specify wavelength (in Å), e.g. λ4363.
- If the transition is “forbidden”, then add [] around the ionization state, e.g. [O III].
- If the transition is a “doublet”, two lines from the same excited state, then specify both wavelengths, e.g. λλ 4959, 5007.
- Figure shows transitions of O III:

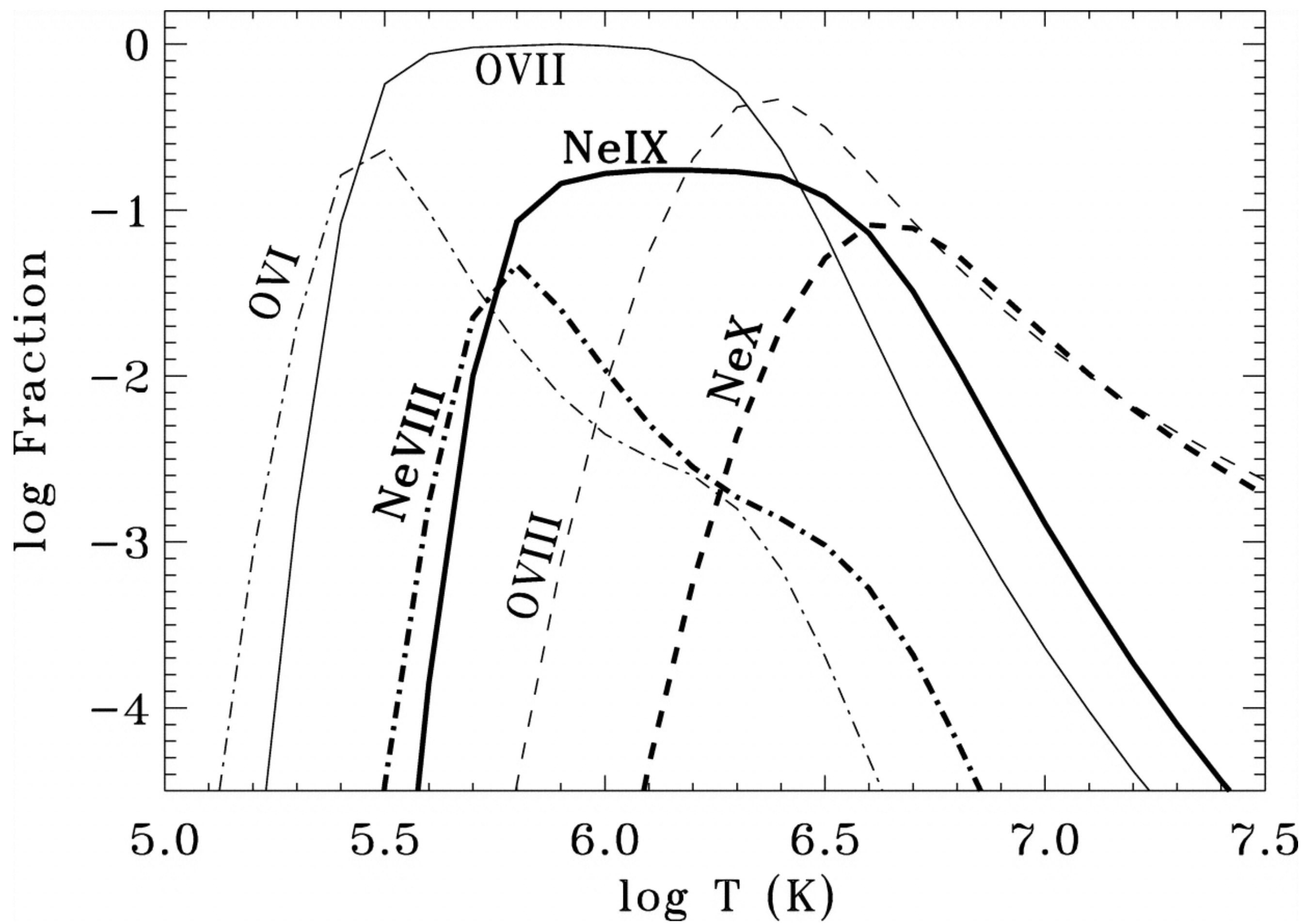
  [O III] λ4363

  [O III] λλ 4959, 5007

- Lines from H do not follow this pattern.



Emission Lines

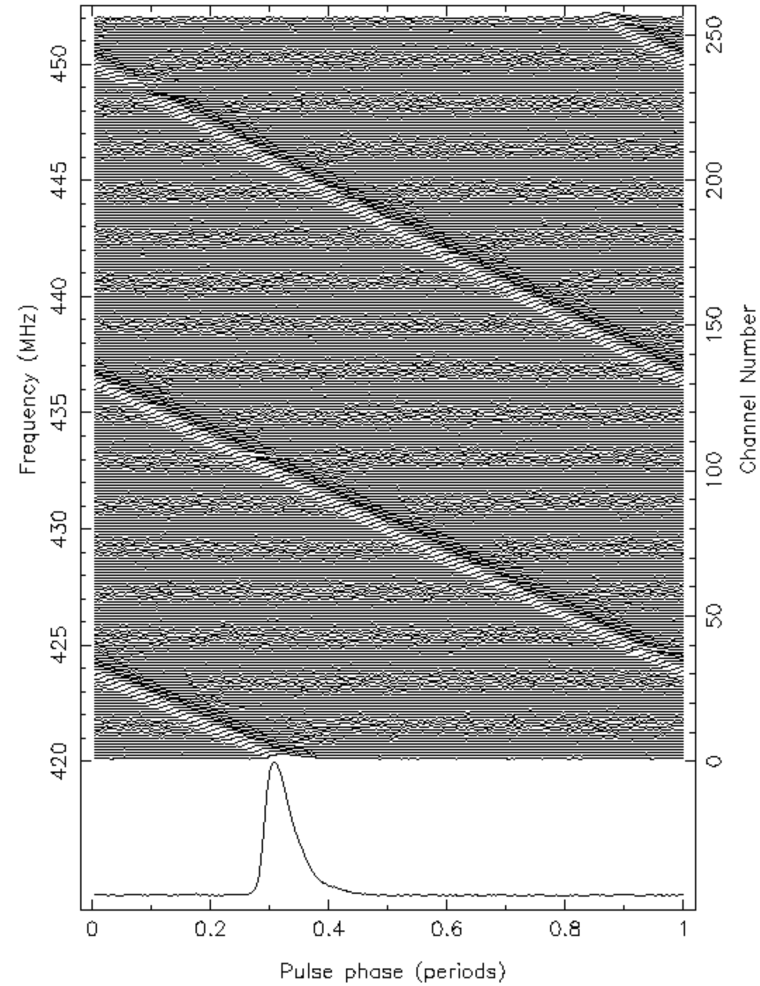


- Line intensity $I \propto \int N_e^2 T^{-3/2} dl$
- As for absorption lines, different ionization states occur at different temperatures, so line ratios can be used to find temperature.

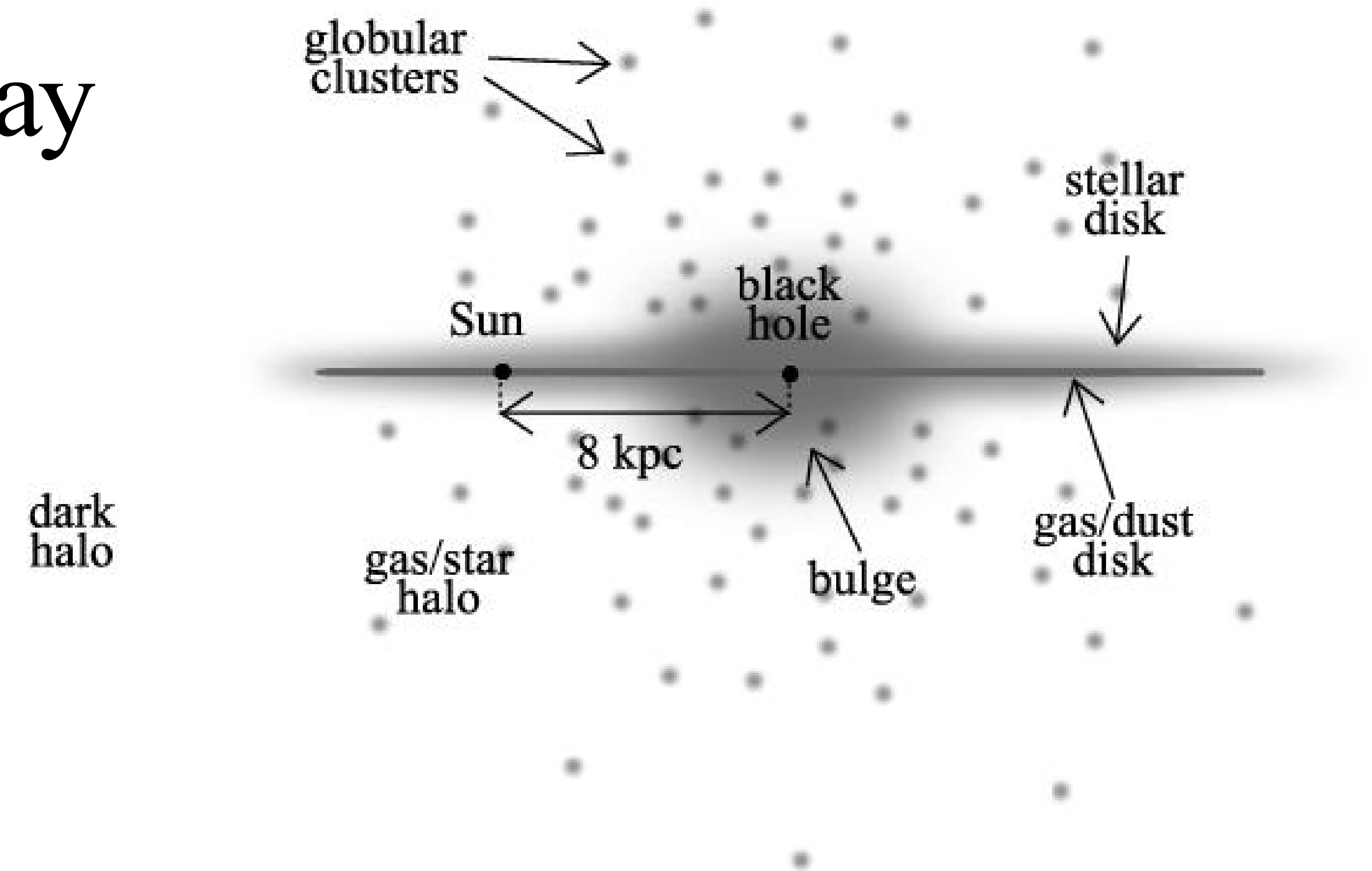
Pulsar Dispersion

- Free electrons slow down radio waves. Slowing is a function of frequency.
- Delay is $\Delta T \ \propto \ \frac{1}{\nu^2} \int N \, dl$

- Pulsars can be used to measure electron density in ISM.
- Dispersion ~ N vs emission ~ N^2
  - Can derive density

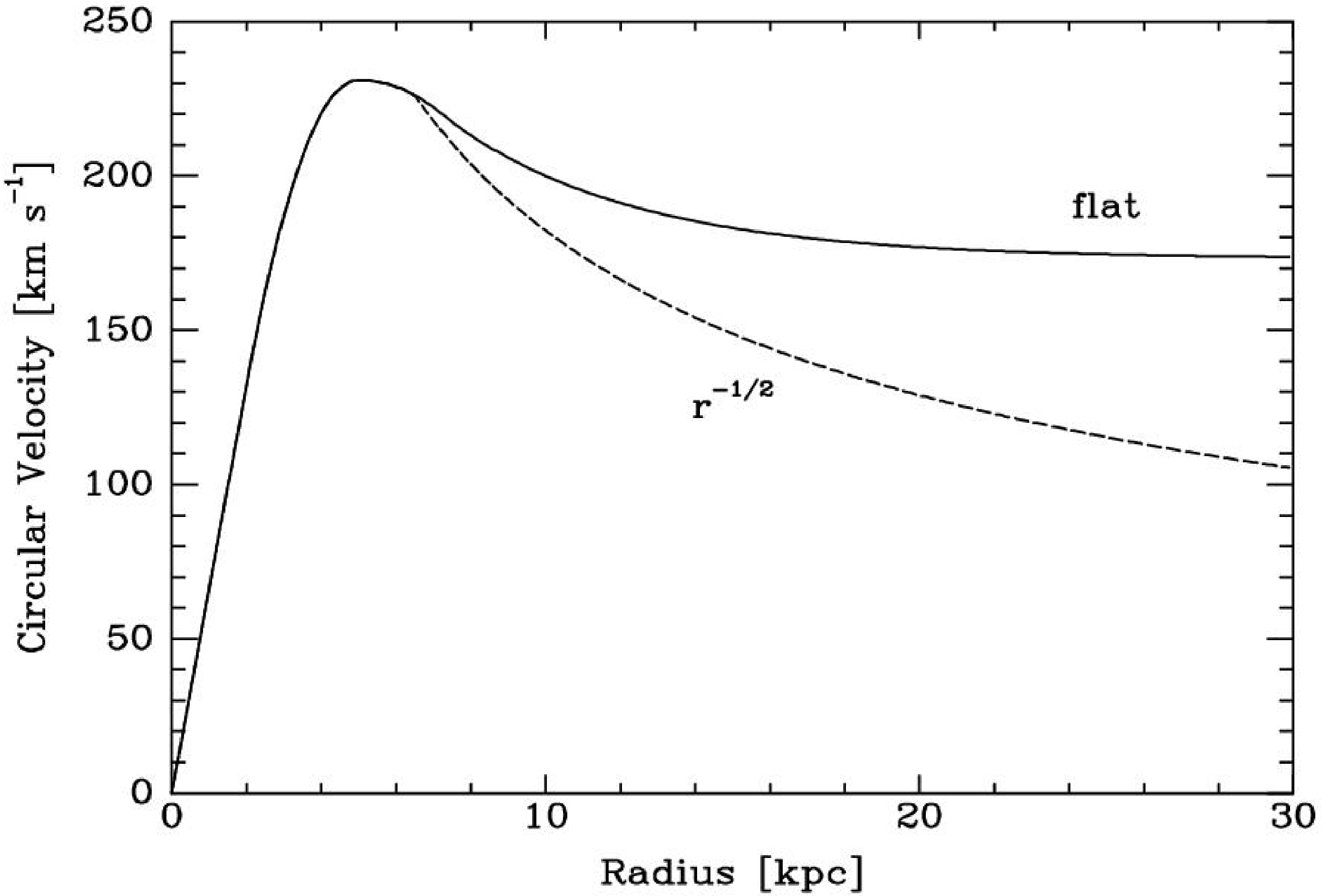


Milky Way



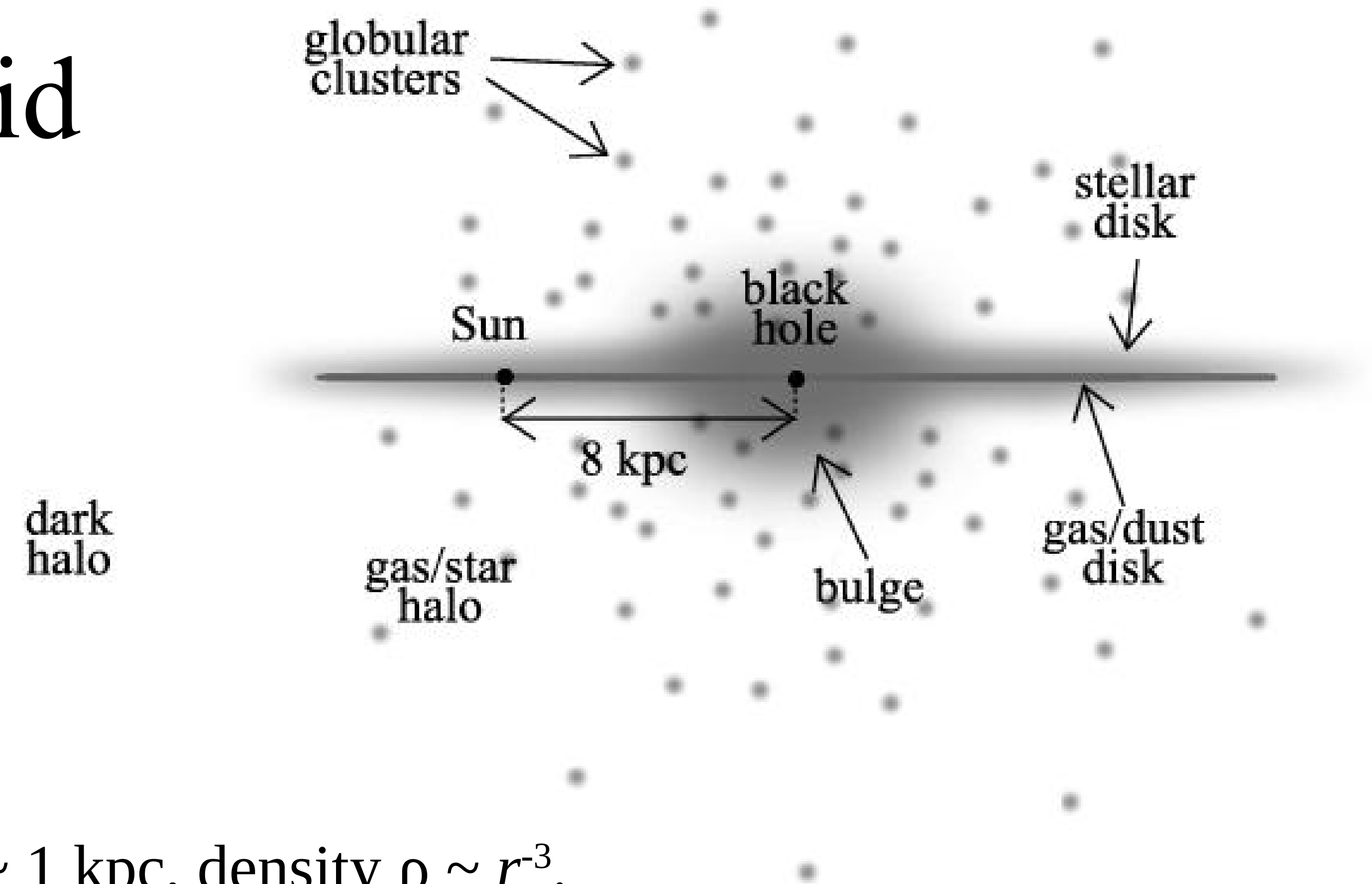
- Distance from Sun to Galactic center $R = 8.0 \pm 0.5$ kpc.
- Orbital velocity of Sun around Galactic center $v = 220$ km/s.
- Orbital period = $2\pi R/v = 2\times10^8$ years.
- Mass of MW internal to Sun = 1.8×10^{44} g = 10^{11} solar masses.

Dark Matter Halo



- Orbital speeds of stars at large Galactocentric radius are larger than expected if orbits are maintained only by gravitational pull of visible matter (stars+gas). Need “dark matter”.
- Rotation curve is flat at large radii. Thus, $M(< r) \sim r$.

Spheroid



- Bulge radius ~ 1 kpc, density $\rho \sim r^{-3}$.
- Halo radius ~ 50 kpc.
- Age of stars in bulge and halo 10-14 Gyr.
- Spheroid stars have lower metallicity (abundances of elements heavier than He) than Sun, as low as $10^{-4.5}$ solar.

Disk of the Milky Way

- Density profile:

$$\rho(r,z)=\rho_0\left[\exp\left(-\frac{r}{r_d}\right)\right]\left[\exp\left(-\frac{|z|}{h_d}\right)\right]$$

r = radial distance in center, z = distance above/below plane

- Scale length of disk R_d = 3.5 ± 0.5 kpc.
- Scale height of disk h_d = 330 pc for older (solar mass) stars.
- Scale height of disk h_d = 160 pc for gas and dust (why smaller?).
- About 10^{10} solar masses with "one scale radius".
- Estimate stellar density, mean separation, collision rate.

Spiral Arms

- Spiral arms have enhanced gas density and star formation rate.
- Stars form in arms, move out. Older stars pass through arms.
- Arms are density waves in stars and ISM.

Heating and Cooling of ISM

ISM cools via radiation.

ISM heats via:

- Supernova produce shock waves that heat the nearby gas to high temperatures ~ 10^6 K
- Young, high mass stars are hot (~10^4 K) and produce radiation that ionizes the ISM.
- High energy particles (cosmic rays) ionize the ISM.
- Stellar winds, infalling gas, intergalactic UV may also contribute to heating the ISM.

Dynamics of ISM

ISM is stable only if heating and cooling rates balance. ISM has two stable phases, one at ~8000 K, one at ~80 K. Gas at other temperatures is necessarily dynamic.

Table 12.3 The principal phases of the interstellar gas. (Courtesy of Dr. John Richer.)

Names	Main constituent	Detected by	Volume of interstellar medium	Fraction by mass	N (m^{-3})	Temperatu (K)
'Molecular clouds'	H_2, CO CS, etc	Molecular lines. Dust emission	~0.5%	40%	$\geq 10^9$	10–30
'Diffuse clouds' 'H I clouds' 'Cold neutral medium'	H, C, O with some ions, C^+, Ca^+	21-cm emission & absorption	5%	40%	10^6–10^8	80
'Intercloud medium'	H, H^+, e^- Ionisation fraction 10–20%	21-cm emission & absorption Hα emission	40%	20%	10^5–10^6	8000
'Coronal gas'	H^+, e^- Highly ionised species, O^{5+}, C^{+3}, etc	O VI Soft X-rays 0.1-2 keV	~50%	0.1%	$\sim 10^3$	$\sim 10^6$

Note approximate pressure equilibrium.

Young stars ionize the ISM