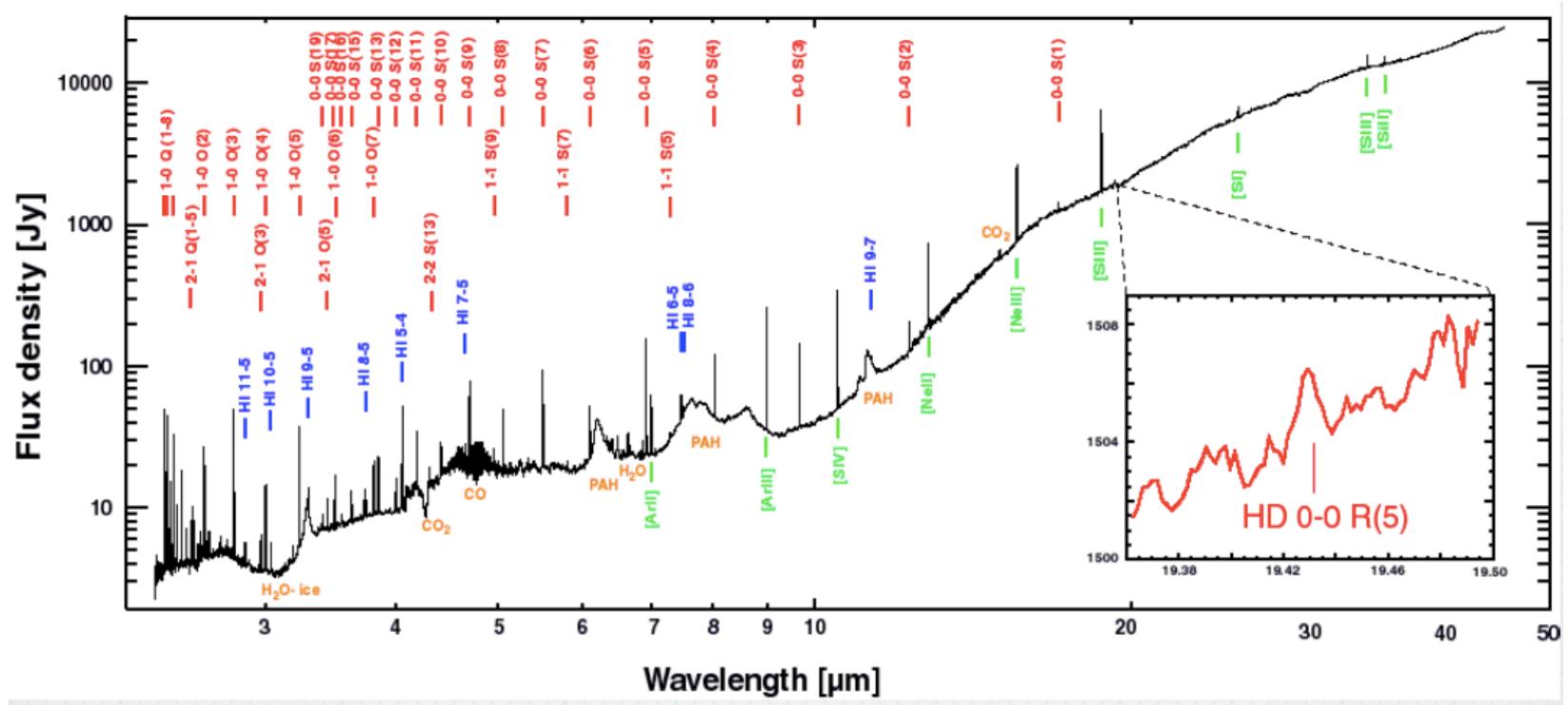
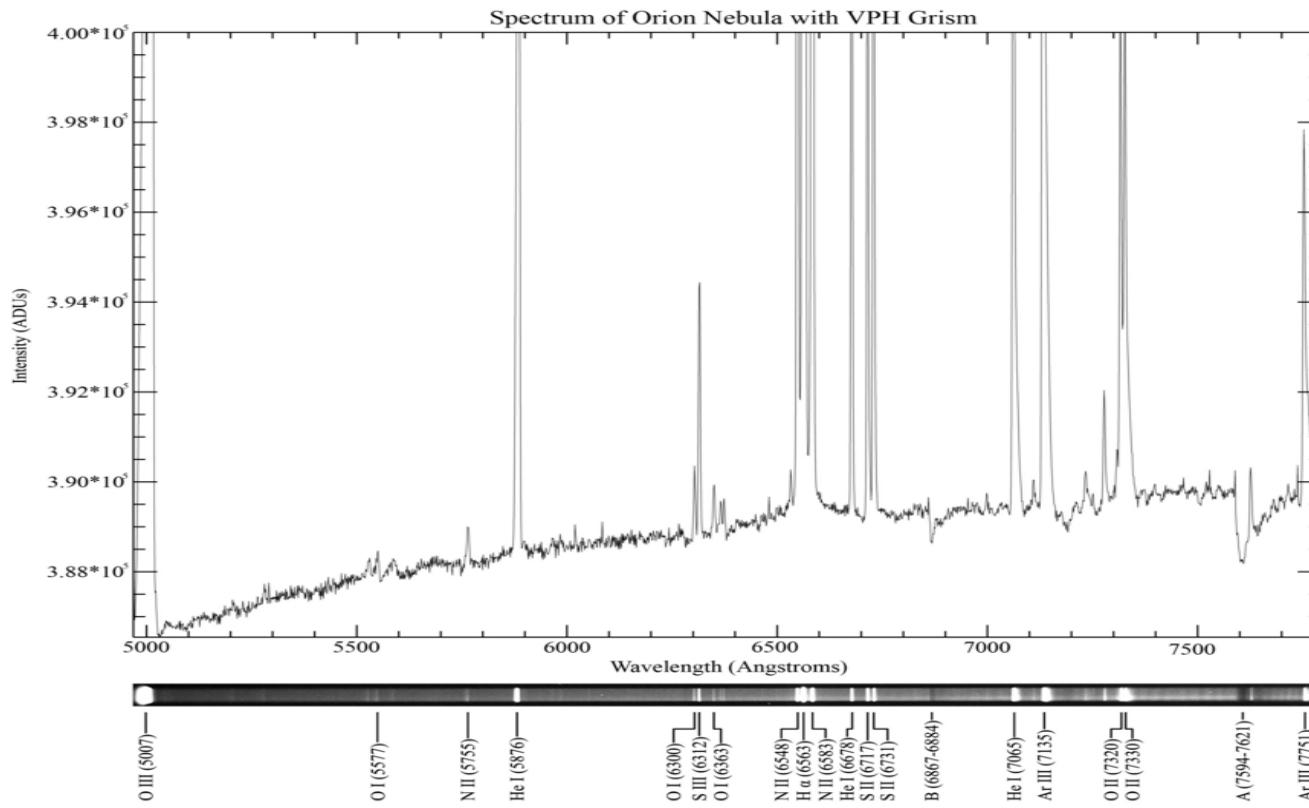


# Collisionally Excited Spectral Lines (Cont'd)



# Please Note:

Contrast the collisionally excited lines with the H and He lines in the Orion Nebula spectrum.



# Preview: Pure Recombination Lines

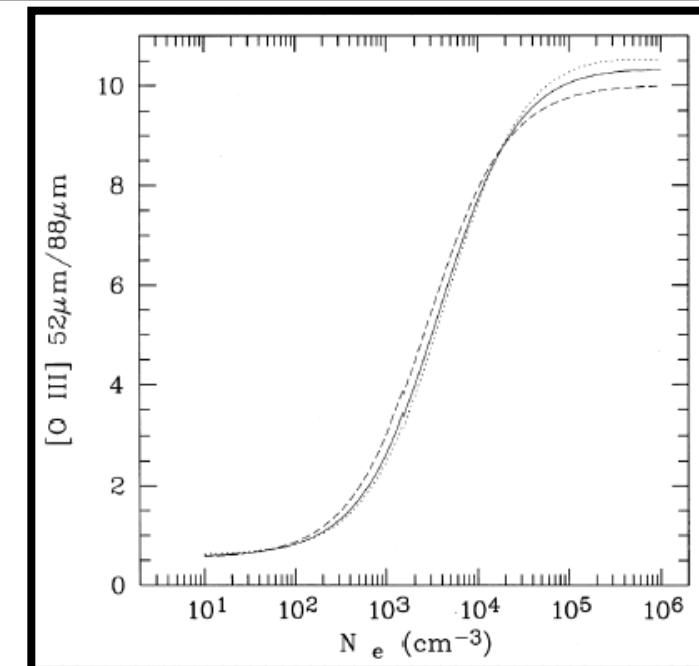
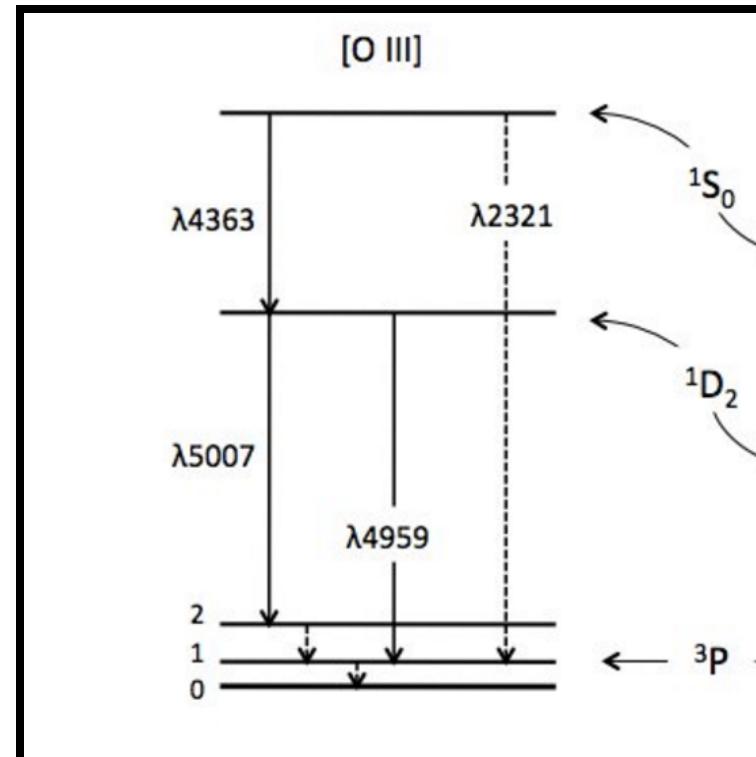
- Recombination of an ion and electron forms an ion an excited state.
- The electron cascades through many possible energy levels back down to the ground state
- Why is this more complicated than the two-level resonance line transitions?
- Calculation of the cascade process requires precision; See [DS] 2.1.2 for the QM approach.
- Hydrogen recombination spectrum

# Multiphase Structure in HII regions: Impact on T & n diagnostics

- HII regions: T and density diagnostics
  - Real ISM is clumpy; measure  $n_{e,c}$
  - Emission measure  $\sim \langle n_e^2 \rangle * \text{length}$
  - Define a volume filling factor for the clumps such that  $\langle n_e^2 \rangle \sim f * n_{e,c}^2$
- $f \sim 0.01$  to  $0.1$  typically

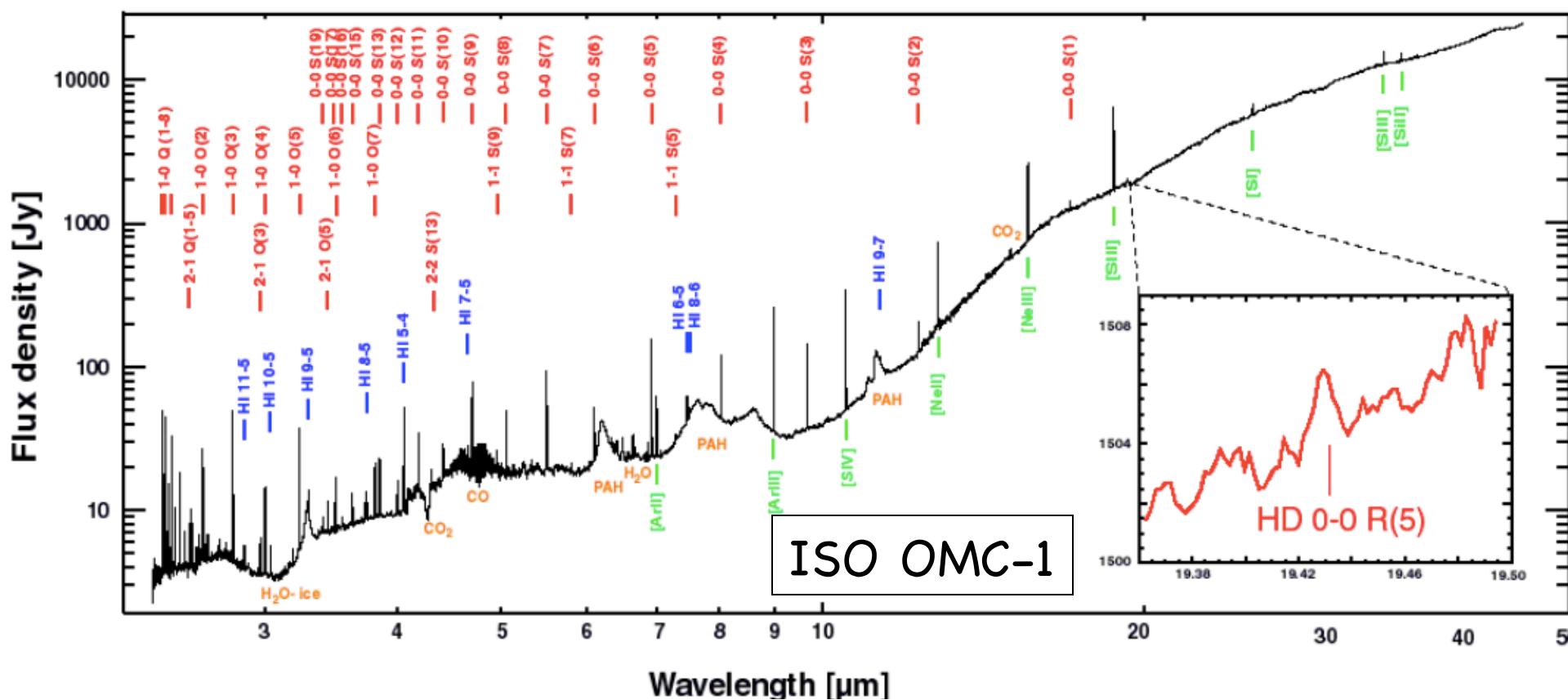
# Please Note: Fine Structure Lines

- Examples for [OIII] :
  - $^3P_2 \rightarrow ^3P_1$  transition produces a photon at 52um
  - $^3P_1 \rightarrow ^3P_0$  transition produces a photon at 88um
- $I(52 \text{ um})/I(88 \text{ um})$  depends on  $n_e$  because the  $n_{\text{cr}}(^3P) \ll n_{\text{cr}}(^1D)$ .
- $I(5007 \text{ A})/I(52 \text{ um})$  depends on T via collisional excitation.



# Mid/Far-infrared Fine Structure Lines

- Transitions between fine-structure levels of p<sup>2</sup> and p<sup>4</sup> ions are dominant coolants of gas at 100 – 3000 K. See DS Table 3.3.
- E.g., [CII] 158 um; [OIII] 88.36, 51.81 um
- Atmospheric water vapor blocks 25–300 um
  - Infrared Space Observatory (ISO); Spitzer IRS; Herschel; ALMA (for high redshift galaxies)



# Spectroscopic Notation [bb]

- Notation for ions
- Electron configuration
- Spectroscopic term
- Pauli exclusion principle
  - One active electron (e.g., Mg II, Na I)
  - Two electrons with LS coupling (e.g., Mg I)
  - Heavier ions can have JJ coupling
  - Real coupling usually intermediate to these limiting cases

# Terms for ns and np Subshells

E config.	Terms	Examples
...ns <sup>1</sup>	$^2S_{1/2}$	H I, HeII, C IV, N V, O VI
...ns <sup>2</sup>	$^1S_0$	He I, C III, N IV, O V
...np <sup>1</sup>	$^2P_{1/2, 3/2}$	C II, N III, O IV
...np <sup>2</sup>	$^3P_{0,1,2}$ $^1D_2$ $^1S_0$	C I, N II, O III, Ne V, S III
...np <sup>3</sup>	$^4S_{3/2}$ $^2D_{3/2, 5/2}$ $^2P_{1/2, 3/2}$	N I, O II, Ne IV, S II, Ar IV
...np <sup>4</sup>	$^3P_{2,1,0}$ $^1D_2$ $^1S_0$	O I, Ne III, Mg V, Ar III
...np <sup>5</sup>	$^2P_{3/2, 1/2}$	Ne II, Na III, Mg IV, Ar IV
...np <sup>6</sup>	$^1S_0$	Ne I, Na II, Mg III, Ar III

# Atomic Spectra: Selection Rules

- Governed by rules of quantum mechanics
  - Wave function of individual electrons (in a spherically symmetric potential)  
$$\Psi(r,\theta,\phi) = R_{nl}(r) \Theta_{lm}(\theta) \Phi_m(\phi)$$
  - Principal  $n = 1, 2, 3, \dots$
  - Electron spin  $s = 1/2$
  - Angular momentum  $l = 0, 1, 2, \dots, (n-1)$
  - Magnetic  $m = -l, -(l-1), \dots, 0, \dots, (l-1), l$

# Reminder: Einstein Coefficients

- Transition probability (from the excited state) given by Einstein relation  $A_{21} \sim 10^{8-9} \text{ s}^{-1}$
- $A_{21}$  calculated from the overlap of the wave functions for the initial and final states
  - Favors the bluer transition when there are multiple paths for decay,  $A_{21} \sim (\text{Dipole matrix element}) * v_{12}^3$
  - Stimulated emission important when the upper level has a high population compared to the ground level
  - Probability of photon absorption (by an atom in the ground state) depends on the energy density of the electromagnetic field,  $B_{12}U(v_{12})$ , where  $B_{12}$  is the Einstein coefficient for absorption

# Selection Rules I.

## Resonance Lines

- Einstein Coefficient  $A_{21} \sim 10^{8-9} \text{ s}^{-1}$
- Electric dipole transition selection rules
  - Only 1 electron involved in the transition
  - Initial and final states have different parity
  - Emitted photon carries 1 unit of angular momentum, so  $\Delta l = +/- 1$
  - Electron spin does not change
  - Change in the total angular momentum of the active electron is  $\Delta J = +/- 1, 0$  (with  $J=0$  to  $J=0$  forbidden)
- Statistical weight of any level is  $g = 2J + 1$

# Forbidden Lines

- Magnetic dipole transitions
- A of 1 to  $10^{-4} \text{ s}^{-1}$
- How long do electrons involved in forbidden transitions rest in their excited states?
- Clearly the densities must be very low indeed for the atom to avoid a collision on this timescale.
- The emitted photon is very unlikely to be reabsorbed by another ion. Why?
- Forbidden line photons usually escape from a nebula, so they are very important coolants.
- Examples [OIII] 4959, 5007; [OII] 3726,29,
  - What makes  ${}^1\text{D}_2 \rightarrow {}^3\text{P}_2$  forbidden?

# Selection Rules III.

## Intercombination or Semi-forbidden Lines

- Departure from pure LS coupling means that electric quadrupole transitions between states of different multiplicity can occur
- But at much lower probability,  $A$  of  $10^3 \text{ s}^{-1}$
- At typical ISM density and temperature, these transitions are still more probable than a collision with another atom.
- Example: CIII]

# Selection Rules: Summary

		Electric dipole (E1)	Magnetic dipole (M1)	Electric quadrupole (E2)	Magnetic quadrupole (M2)
Rigorous rules	(1)	$\Delta J = 0, \pm 1$ $(J = 0 \not\leftrightarrow 0)$		$\Delta J = 0, \pm 1, \pm 2$ $(J = 0 \not\leftrightarrow 0, 1; \frac{1}{2}, \frac{3}{2})$	
	(2)	$\Delta M_J = 0, \pm 1$		$\Delta M_J = 0, \pm 1, \pm 2$	
	(3)	$\pi_f = -\pi_i$	$\pi_f = \pi_i$		
LS coupling	(4)	One electron jump $\Delta l = \pm 1$	No electron jump $\Delta l = 0,$ $\Delta n = 0$	None or one electron jump $\Delta l = 0, \pm 2$	One ele $\Delta l = 0, \pm 1$
	(5)	If $\Delta S = 0$ $\Delta L = 0, \pm 1$ $(L = 0 \not\leftrightarrow 0)$	If $\Delta S = 0$ $\Delta L = 0$	If $\Delta S = 0$ $\Delta L = 0, \pm 1, \pm 2$ $(L = 0 \not\leftrightarrow 0, 1)$	
Intermediate coupling	(6)	If $\Delta S = \pm 1$ $\Delta L = 0, \pm 1, \pm 2$		If $\Delta S = \pm 1$ $\Delta L = 0, \pm 1, \pm 2, \pm 3$ $(L = 0 \not\leftrightarrow 0)$	If $\Delta S = \pm 1$ $\Delta L = 0, \pm 1, \pm 2, \pm 3$ $(L = 0 \not\leftrightarrow 0)$

# Molecular Spectra

- Rotating Molecules
- Vibrating Molecules
- Ro-Vibrational Spectra
- Electronic Molecular Spectra

# Rotating Molecules

- Quantized rotational energy levels related to the moments of inertia of the molecules along the various axes of symmetry
- Example: Linear (Diatomic) molecules
  - Roughly a rigid rotator with constant spacing between atoms
  - Solutions quantized in the z component of the angular momentum,  $m_j$ , and the rotational quantum number,  $J$ , analogous to “l” in one electron atoms [BB]
  - $E_J \sim J(J+1)$
  - Lines are linearly spaced

# Molecular Hydrogen

- Does H<sub>2</sub> radiate strongly?
- To produce electric dipole line emission in these rotational transitions requires a heterogeneous linear molecule like CO.
- Transitions occur via electric quadrupole interaction. The least energetic transition is J=0 to J=2
- Lifetimes of excited states are much, much longer than for the ions, e.g., about 1000 years for the J=2 level.
- Hence the rotational levels are populated by collisions

# Vibrating Molecules

- Equilibrium distance  $r_0$  at potential minimum, I.e., repulsion of the nuclei vs. attractive force of the bond [BB]
- Stretching
- 1 frequency!
- Higher E

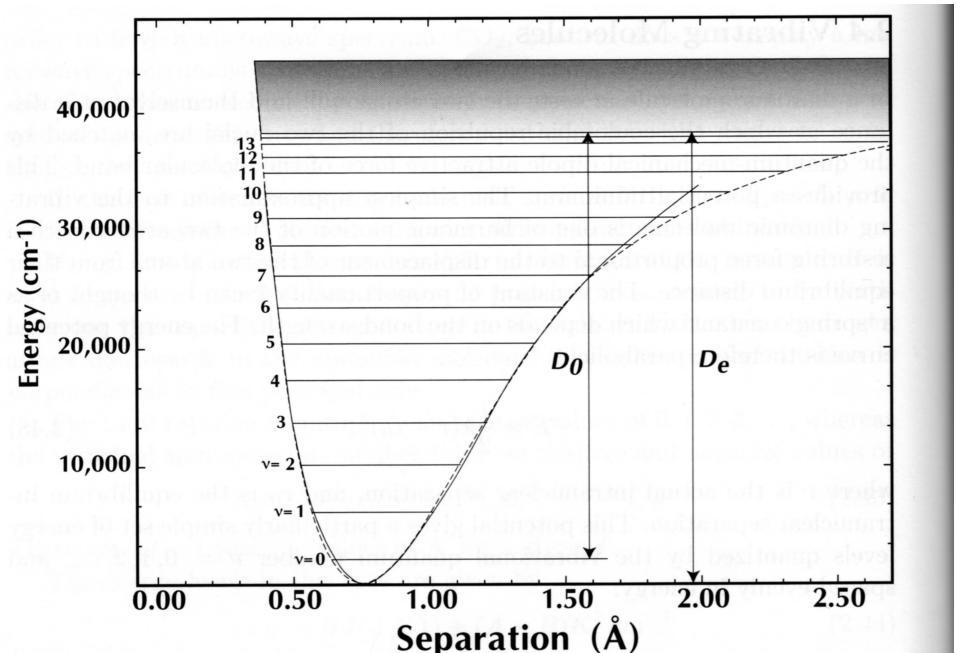
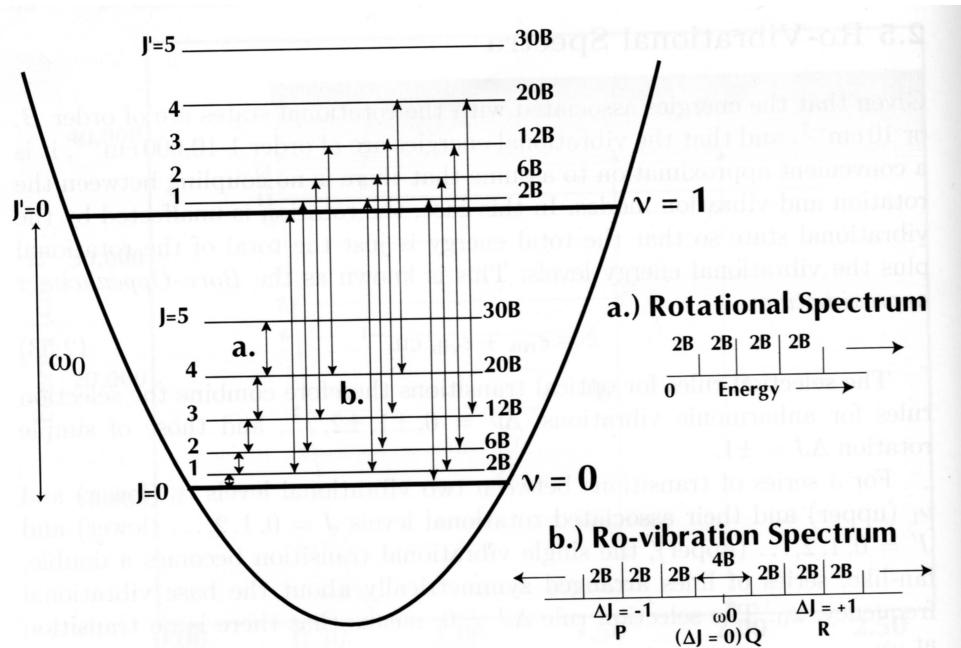
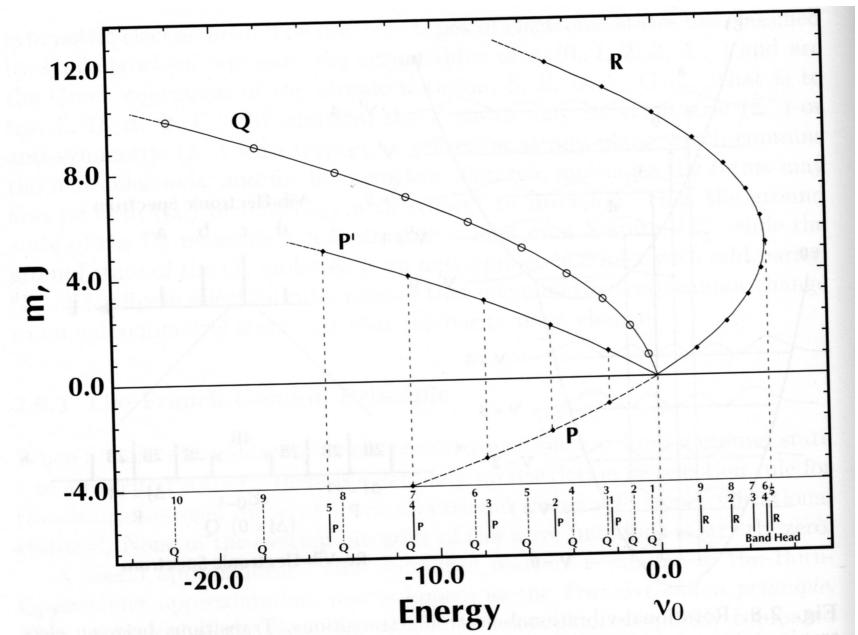


Fig. 2.6. The Morse potential for H<sub>2</sub>. The actual potential inferred from detailed spectroscopy is the solid curve, the Morse potential is given by the dashed curve.

# Ro-vibrational levels

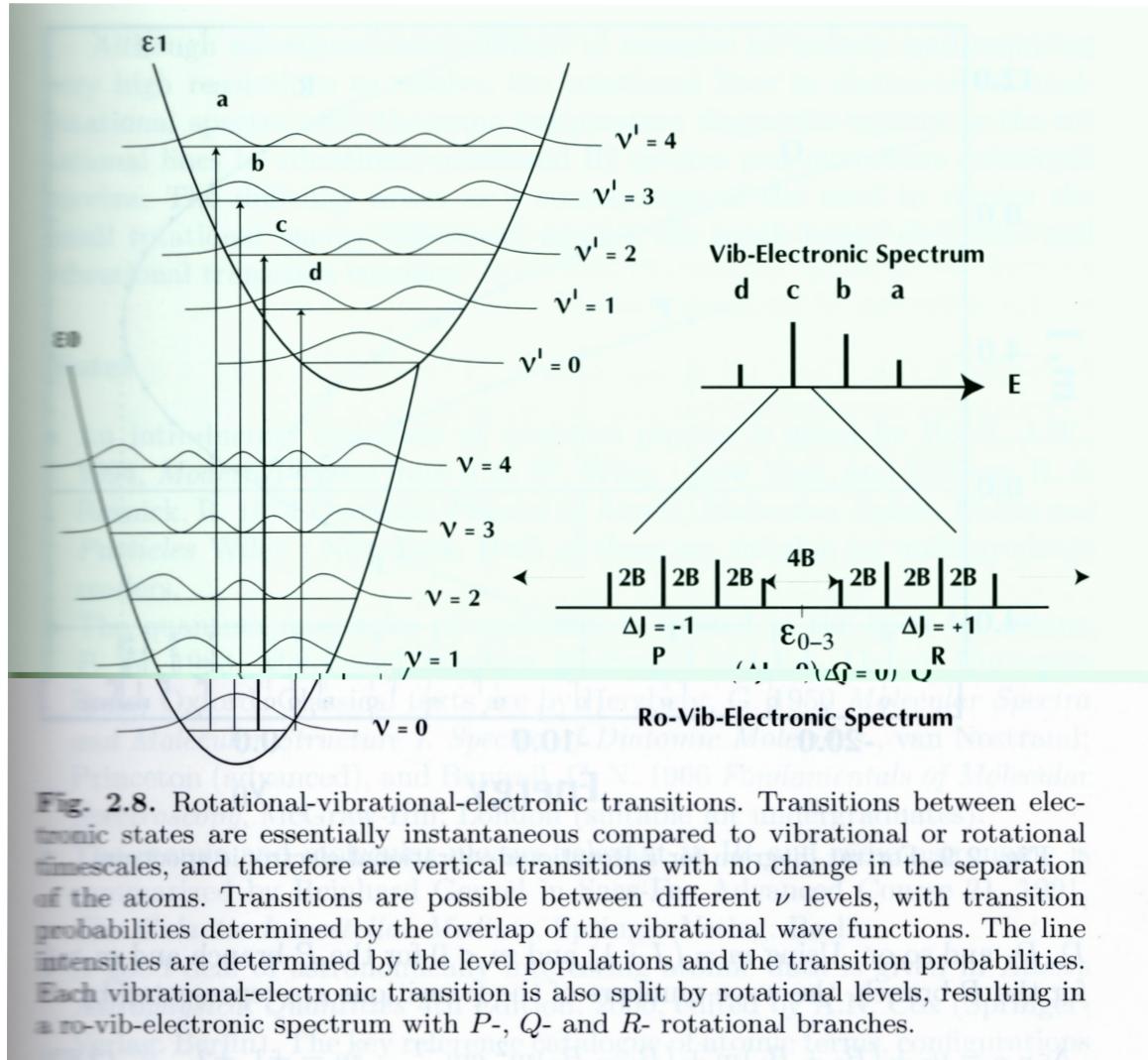


**Fig. 2.7.** Rotational-vibrational levels. Within each vibrational level of a diatomic molecule, a series of rotational levels occur, here magnified by a factor of several hundred for illustrative purposes. Transitions within the rotational levels (a.) produce a microwave spectrum with a spacing of  $2B$  in energy. Transitions between rotational levels across vibrational levels, (b.), produce an infrared line at  $\omega_0$  that is split into rotational series spectral lines ( $P$ - and  $R$ - branches) that are also separated by an energy of  $2B$ . If  $\Delta J = 0$  is permitted by out-of-line bending vibrations, a series of lines called the  $Q$  branch can appear at  $\omega_0$  with zero spacing because the energy differences for  $\Delta J = 0$  are constant.



**Fig. 2.9.** Fortrat diagram for a Rotational-vibrational-electronic spectrum.

# Electronic Transitions



**Fig. 2.8.** Rotational-vibrational-electronic transitions. Transitions between electronic states are essentially instantaneous compared to vibrational or rotational timescales, and therefore are vertical transitions with no change in the separation of the atoms. Transitions are possible between different  $\nu$  levels, with transition probabilities determined by the overlap of the vibrational wave functions. The line intensities are determined by the level populations and the transition probabilities. Each vibrational-electronic transition is also split by rotational levels, resulting in a ro-vib-electronic spectrum with  $P$ -,  $Q$ - and  $R$ - rotational branches.

# End of Lecture 4

- “I ask you to look both ways. For the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been reached through the stars.”

-- Sir Arthur Eddington (*Stars & Atoms*, 1928)
- Assigned Reading
  - Same as Lecture 3
  - Please work HW problem 2 which asks you to apply the 3 level atom model.

# Introduction to Radiative Transfer

- Specific Intensity - constant along a ray
- Mean Intensity - zeroth moment
- Flux - 1st moment
- Radiation pressure - 2nd moment
- Quiz - Compute the flux from a uniformly bright source
- Reading
  - D: ch 7
  - Rybicki & Lightman ch 1