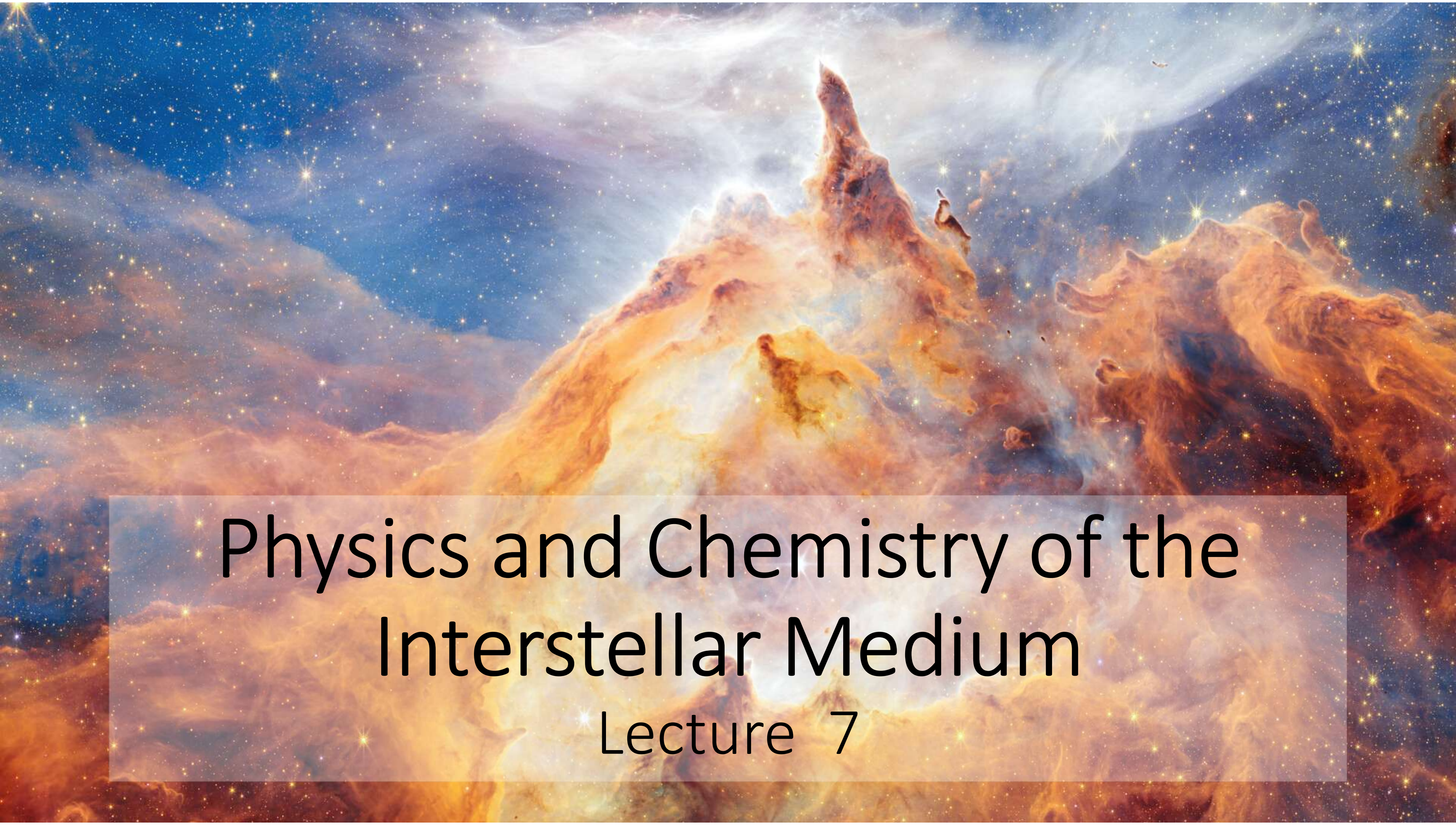


Physics and Chemistry of the Interstellar Medium

Lecture 7

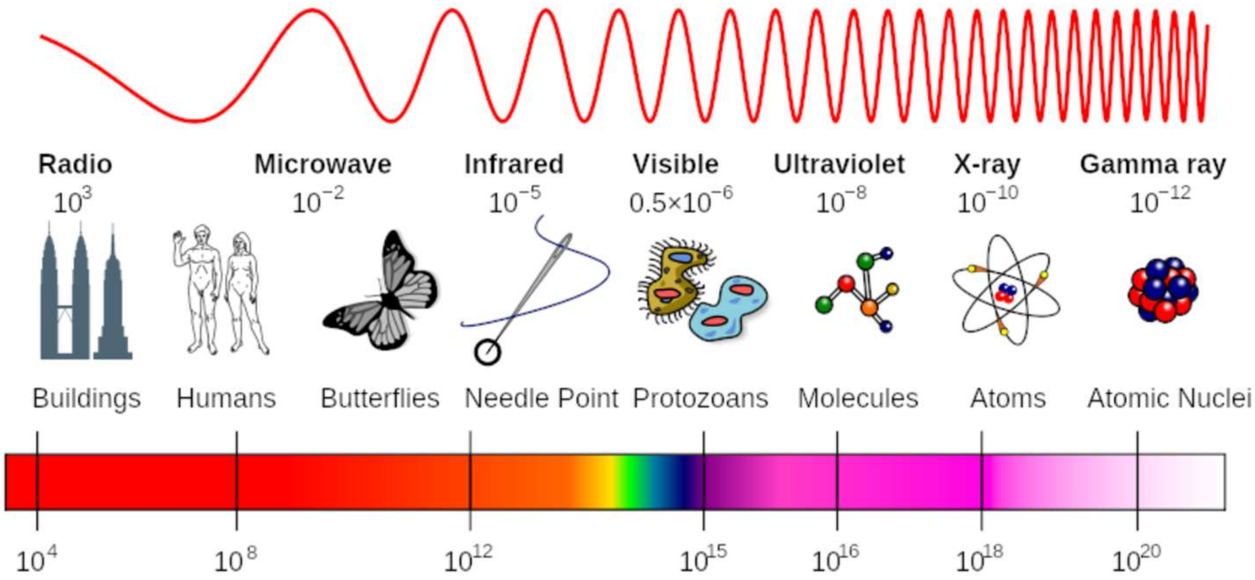
Radiation

Lecture VII

3.2. Discrete systems
- Atoms and Molecules
- Selection Rules

3.3. Excitations
- Collisions
- LTE

3.4. Discrete systems
- Escape Probability



Discrete Systems

Non-radiative transitions

- **Collisions**
  - Definition of rate coefficients equivalent to Einstein coefficients

$$C_{a,a'} = n_{coll}\,\gamma_{a,a'} = n_{coll}\langle \sigma v \rangle = n_{coll}\int_0^\infty \sigma_{a,a'}(v)\,p(v)\,dv$$

$\sigma(v)$ = collision cross section for the transition (depends on velocity)

  - For Maxwell-distribution of velocities p(v):

$$C_{a,a'} = n_{coll}\int_0^\infty \sigma_{a,a'}(v)\sqrt{\frac{2}{\pi}}\,v^2\left(\frac{m_r}{kT_{kin}}\right)^{3/2}\exp\left(-\frac{m_r v^2}{2kT_{kin}}\right)$$

m_r = reduced mass of the collision partners

  - Integral numerically solved in quantum-dynamical computation
  - $\gamma_{a,a'}$ tabulated for many transitions

Collision rates

- **Different rates for different collision partners**
  - Relevant H_2, H, He, e^- :

Table 5.1. Rate coefficients for de-exciting collisions by H atoms and H_2 molecules. For comparison the last column gives the values of $\overline{v} \cdot \overline{\sigma}$ for elastic collisions between H atoms, in which the total kinetic energy of the collision partners is the same before and after the collision. [After Spitzer (1978, 1968)]

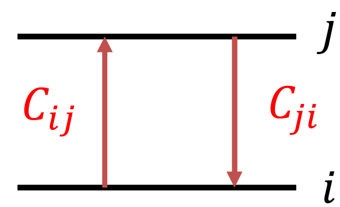
T [K]	Q_{nm} [cm^3 s^{-1}]				$\overline{v} \cdot \overline{\sigma}$ [cm^3 s^{-1}]
	H–H (Hyperfine structure levels $n = 1$)	$H-C^+$ ($^2P_{3/2}$-level)	$H-H_2$ ($J = 2$ of H_2)	H_2-CO ($J = 1$ of CO)	H–H
10	2.3×10^{-12}	7.7×10^{-10}	9.6×10^{-13}	1.8×10^{-12}	9.5×10^{-11}
100	9.5×10^{-11}	8.0×10^{-10}	3.0×10^{-12}	3.7×10^{-12}	3.2×10^{-10}
1000	2.5×10^{-10}	9.7×10^{-10}	4.2×10^{-11}		8.0×10^{-10}

Discrete Systems

Collision rates

- **Mutual dependence of upwards and downwards collision rates**
  - Energy conservation requires :

$$C_{ij} = C_{ji} \frac{g_j}{g_i} \exp\left(-\frac{h\nu_{ij}}{kT_{kin}}\right)$$



(Boltzmann distribution)

- Sum of collisional rate coefficients for different collision partners i_{coll} needed:

$$C_{ij} = \sum_{i_{coll}}^{n_{coll}} n_{i_{coll}} \gamma_{ij,i_{coll}}$$

(H_2, H, H^+, He, electrons, ...)

Collision rates

Beware!

- Rates can be different for ortho- and para-H2.
- Many important rates have not been computed yet

→ large uncertainty in models.

ortho

para

H_2 : J=1

Table 1. Rate coefficients, $q(J \rightarrow J')$, for rotational de-excitation of $^{12}C^{16}O$ by *para*-H_2, in units of $cm^3 s^{-1}$. Numbers in parentheses are powers of 10.

J	J'	T(K) 10	20	40	60	100	250
1	0	2.3(-11)	2.4(-11)	3.3(-11)	4.1(-11)	5.0(-11)	5.8(-11)
2	0	3.5(-11)	3.8(-11)	4.2(-11)	4.5(-11)	4.7(-11)	5.1(-11)
3	0	2.8(-12)	3.8(-12)	4.9(-12)	5.8(-12)	7.2(-12)	1.0(-11)
4	0	3.8(-12)	4.7(-12)	5.7(-12)	6.2(-12)	6.8(-12)	8.1(-12)
5	0	6.2(-13)	7.4(-13)	1.0(-12)	1.3(-12)	2.0(-12)	4.2(-12)
6	0	5.9(-13)	7.0(-13)	9.1(-13)	1.1(-12)	1.4(-12)	2.1(-12)
7	0	1.8(-13)	2.1(-13)	2.8(-13)	3.6(-13)	5.8(-13)	1.6(-12)
8	0	1.3(-13)	1.7(-13)	2.2(-13)	2.8(-13)	4.0(-13)	8.6(-13)
9	0	4.1(-14)	5.7(-14)	7.8(-14)	1.0(-13)	1.8(-13)	6.0(-13)
10	0	2.4(-14)	3.5(-14)	5.0(-14)	6.7(-14)	1.1(-13)	3.6(-13)
11	0	9.3(-15)	1.4(-14)	2.2(-14)	3.2(-14)	6.0(-14)	2.2(-13)
2	1	2.8(-11)	3.5(-11)	4.9(-11)	6.0(-11)	7.3(-11)	8.7(-11)
3	1	6.2(-11)	6.6(-11)	7.1(-11)	7.3(-11)	7.5(-11)	8.1(-11)

Table 2. Rate coefficients, $q(J \rightarrow J')$, for rotational de-excitation of $^{12}C^{16}O$ by *ortho*-H_2, in units of $cm^3 s^{-1}$. Numbers in parentheses are powers of 10.

J	J'	T(K) 10	20	40	60	80	100
1	0	5.5(-11)	4.5(-11)	4.5(-11)	4.9(-11)	5.3(-11)	5.7(-11)
2	0	7.7(-11)	7.4(-11)	6.9(-11)	6.6(-11)	6.5(-11)	6.4(-11)
3	0	5.3(-12)	5.9(-12)	6.6(-12)	7.0(-12)	7.4(-12)	7.7(-12)
4	0	1.1(-11)	1.1(-11)	1.1(-11)	1.1(-11)	1.1(-11)	1.1(-11)
5	0	1.5(-12)	1.8(-12)	2.2(-12)	2.5(-12)	2.7(-12)	2.9(-12)
6	0	1.5(-12)	1.7(-12)	2.0(-12)	2.2(-12)	2.4(-12)	2.6(-12)
2	1	6.6(-11)	6.4(-11)	6.7(-11)	7.2(-11)	7.7(-11)	8.2(-11)
3	1	1.1(-10)	1.1(-10)	1.1(-10)	1.1(-10)	1.1(-10)	1.0(-10)
4	1	9.9(-12)	1.3(-11)	1.5(-11)	1.5(-11)	1.6(-11)	1.6(-11)
5	1	1.8(-11)	1.9(-11)	1.9(-11)	2.0(-11)	2.0(-11)	2.0(-11)
6	1	2.8(-12)	3.5(-12)	4.6(-12)	5.5(-12)	6.2(-12)	6.8(-12)