Microscopic Processes in the ISM

(Based on Chapter 3 of Dyson & Williams' "The Physics of the ISM")

Three categories of microscopic processes in the ISM are discussed:
(1) heating of the ISM,
(2) cooling of the ISM, and
(3) formation of molecules.

1. Heating of the ISM

Heating of the ISM can be provided by
– starlight
– X-rays and cosmic rays
– shocks (stellar winds, novae, supernovae, etc.)
– compressional and frictional heating.

1.1. Heating by Starlight

The heating by starlight is done by absorbing a UV photon, freeing a particle with excess kinetic energy, for example, photoionization and photodissociation.

Photoionization: $A + h\nu \rightarrow A^+ + e^-$

If the absorbed photon has an energy greater than the ionization potential (IP), the excess energy will be carried by the free electron as its kinetic energy; K.E. of the $e^- = h\nu$ - IP. Energy is injected into the ISM.

The ISM contains the following elements in the order of decreasing abundances:
H, He, O, C, N, Ne, Mg, Si, Fe, S, ... H is the most abundant element in the ISM, so it absorbs most of the UV photons with $h\nu \geq 13.6$ eV.

The IP of H is 13.6 eV. 1 eV = 1.6×10^{-12} ergs.
$hc/\lambda = 13.6$ eV $\rightarrow$ $\lambda = 912$ Å.
$kT = 13.6$ eV $\rightarrow$ $T = 1.6\times10^5$ K.

Abundant elements with ionization potentials less than 13.6 eV can also heat the ISM. For example, C has an IP of 11.26 eV. A 13.5 eV photon, which cannot ionize H, can ionize a C atom and give the free electron a kinetic energy of 13.5 - 11.26 = 2.24 eV.

$h\nu =$	$\leftarrow$ 13.6 eV		24.6 eV $\rightarrow$
heating by	C, Mg, Si, Fe, S... |	H |	H and He

Photodissociation of H_2.

H_2 can absorb a photon and make a transition from the ground state X to an excited B. It radiatively cascades down to the vibrational continuum of the ground state X, where molecules may dissociate. ∼10% of the excitations lead to dissociation.

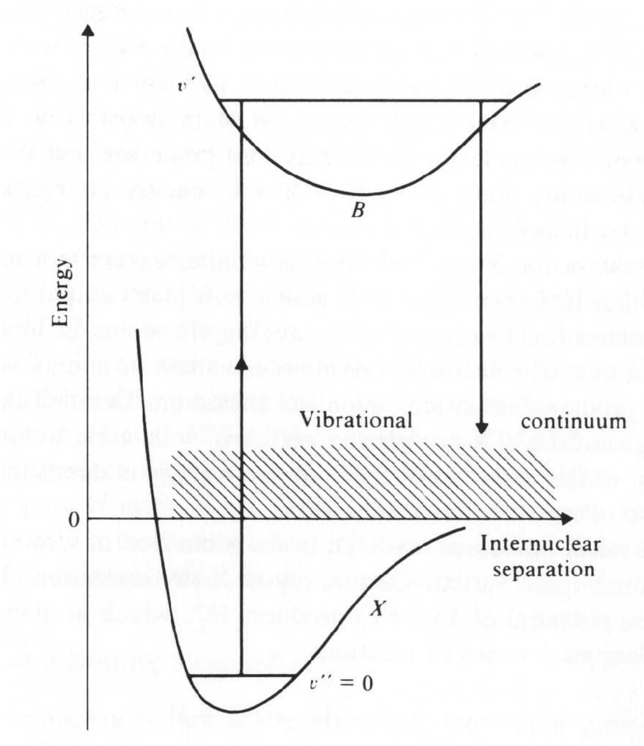

Fig. 1.— Potential energy curves of the H_2 molecule ground state X and excited state B. The molecule in the vibrational continuum "falls apart," with about 0.4 eV of energy in the dissociating atoms.

1.2. Heating by Cosmic Rays and X-rays

$\mathrm{X} + \mathrm{H} \;\rightarrow\; \mathrm{X}' + \mathrm{H}^+ + \mathrm{e}^-$ [X: an X-ray photon]

$\mathrm{p} + \mathrm{H} \;\rightarrow\; \mathrm{p}' + \mathrm{H}^+ + \mathrm{e}^-$ [p: a cosmic ray proton]

Cosmic ray particles consist of primarily protons and electrons. Most of them have energies of a few MeV (the ones that are detected on Earth). Soft X-rays peak at 0.1 keV.

For a 2 MeV proton, the electron released can have a wide range of energies, but the mean is ∼30 eV. This electron can collide with a neutral atom to cause excitation or ionization:

$$\mathrm{e}^- + \mathrm{H}(1s) \;\rightarrow\; \mathrm{e}^- + \mathrm{H}(2p) \;\rightarrow\; \mathrm{e}^- + \mathrm{H}(1s) + \mathrm{h}\nu$$

$$\mathrm{e}^- + \mathrm{H}(1s) \;\rightarrow\; \mathrm{e}^- + \mathrm{H}^+ + \mathrm{e}^-$$

Electrons with energies > 13.6 eV can ionize a H atom. Electrons with energy >10.2 eV can excite H(1s) to H(2p). [E(2p) - E(1s) = 10.2 eV]
Energy is lost through radiative de-excitation. About 3.4 eV of kinetic energy is injected per electron (primary or secondary) produced by a 2 MeV proton.

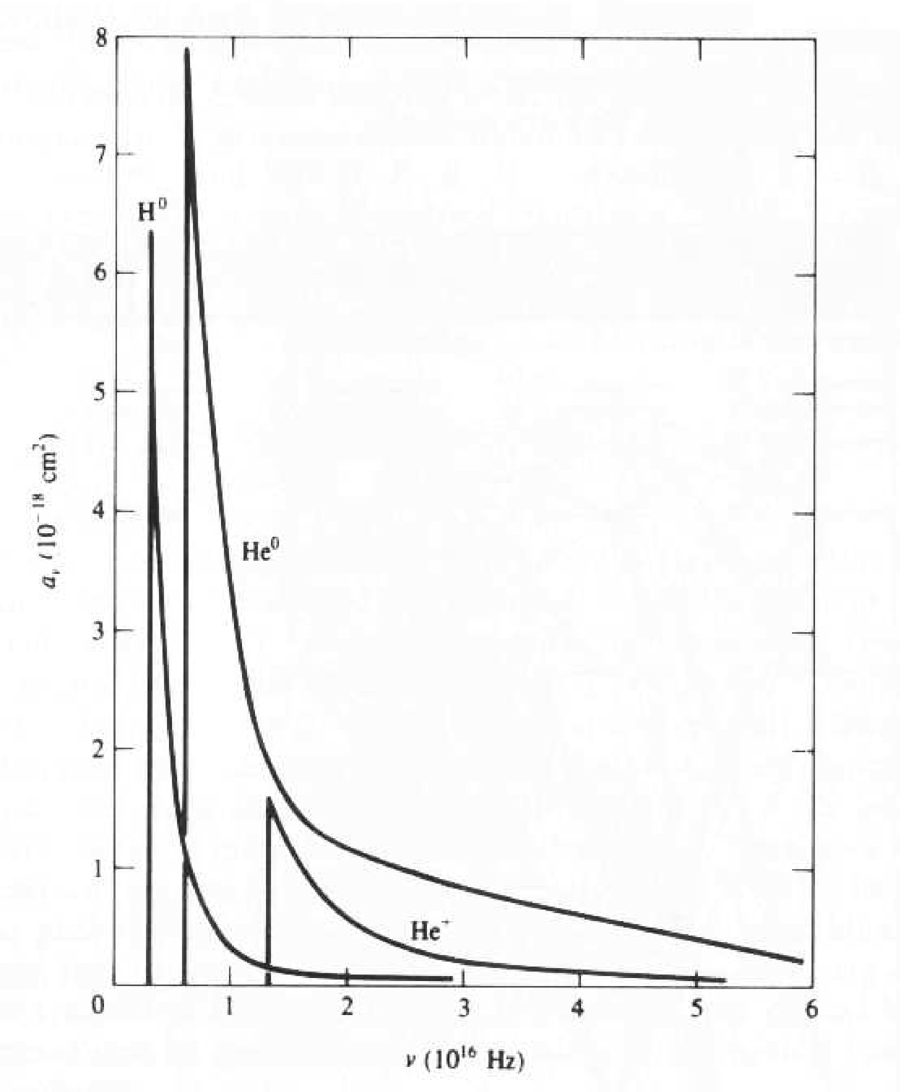

Fig. 2.— Photoionization absorption cross sections of H^0, He^0, and He$^+$.

For X-ray ionization, He plays a more important role because its photoionization absorption cross section is larger than H. For example, at 50 eV, the absorption cross section of He^0 is $\sim$10 times that of H^0.

X(50eV) + He $\rightarrow$ He$^+$ + e$^-$, energy of the e$^-$ = 50 - 24.6 = 25.4 eV.
The electron generated can further ionize He or H. For each 50 eV photon, only $\sim$6 eV is deposited as heat in the limiting case of a neutral medium.

Cosmic ray or X-ray ionization of H_2 produces H_2^+.

$H_2^+ + H_2 \rightarrow H_3^+ + H$

$H_3^+ + e^- \rightarrow 3H$ or $H_2 + H$

Both of these two reactions are exothermic; ∼11 eV of excess energy is contained in the products. Some of this energy is locked in the molecules; about 2/3 of the energy is available for heating.

The free electron released can also interact with H_2:

$e^- + H_2 \rightarrow e^- + H_2$ elastic scattering

$e^- + H_2 \rightarrow e^- + H_2^*$ inelastic scattering

$e^- + H_2 \rightarrow e^- + H_2^+ + e^-$ ionization

$e^- + H_2 \rightarrow e^- + H + H$ dissociation

$H_2^* \rightarrow H_2 + h\nu$ generates a UV photon.

Cosmic ray heating is very important for molecular clouds.

2. Cooling of the ISM

Useful tips: Interstellar clouds cool by radiating photons.

Excitation energy ΔE ∼ thermal kinetic energy kT ∼ photon energy $h\nu$

Ions/atoms/molecules are collisionally excited to higher energy states, then emit photons to drop down to lower energy states. If the photons leave the cloud, the cloud has successfully converted some kinetic energy to photons and lost them. The cloud has cooled.

$A + B \rightarrow A + B^*$ collisional excitation

$B^* \rightarrow B + h\nu$ radiative de-excitation

To have an efficient cooling process, the following criteria have to be met:

(1) frequent collisions; implying a high abundance

(2) excitation energy ≤ thermal kinetic energy

(3) a high probability of excitation during the collision

(4) a photon is emitted before a collisional de-excitation of B^*

(5) the photons emitted are not re-absorbed; i.e., the gas is "optically thin".

2.1. Cooling by Ions and Atoms

Abundant ions and atoms with energy levels requiring excitation energies comparable to the thermal kinetic energies can be excited collisionally. For example, the $^2P_{1/2} \rightarrow {}^2P_{3/2}$ transition of C^+ has $\Delta E = 1.4\times10^{-14}$ erg = kT at 92 K. This transition may be important for cooling clouds at 100 K, but not for clouds at 20 K.

Table: Important Cooling Transitions

Transition	Colliding Partners	$\Delta E/k$
C^+ ($^2P_{1/2} \to {}^2P_{3/2}$)	H, e^-, H_2	92 K
Si^+ ($^2P_{1/2} \to {}^2P_{3/2}$)	e^-	413 K
O ($^3P_2 \to {}^3P_{1,0}$)	H, e^-	228 K, 326 K
O^+ ($^4P_{3/2} \to {}^2P_{5/2,3/2}$)	e^-	3.8×10^4 K
N^+ ($^3P \to {}^1D$)	e^-	2.2×10^4 K

The first column contains the "coolant" (B), and the second column the colliding partner (A), where A + B $\rightarrow$ A + B* $\rightarrow$ A + B + hν.

Note that all these transitions are "forbidden".

2.2. Cooling by Molecules

Molecules rotate and vibrate. The transitions between rotation energy levels are in the mm radio wavelength range, and the transitions between vibration energy levels are in the UV wavelength range.

A rigid rotator has energy levels $E_J = BJ(J+1)$, where J = 0, 1, 2..., $B = \frac{h^2}{8\pi^2 I}$, and I is the molecule's moment of inertia.

H_2, the most abundant molecule, does not have a dipole moment, so $\Delta J = \pm1$ transitions are not allowed. Only $\Delta J = \pm2$ transitions occur. $J = 0 \to 2$, ΔE = 510 K = 7×10^{-14} ergs. The lifetime of the $J = 2$ level is 3×10^{10} s = 951 yr. The populations at the rotational levels are determined by collisions. Typical intervals between collisions are $\sim 10^{11}/n$ s. For a density $n \sim 10^3$ cm^{-3}, the collision timescale is shorter than the radiative relaxation timescale, so collisions will establish a population $N_J \propto (2J+1)e^{-E_J/kT}$, the Boltzmann distribution, where T is the kinetic temperature. The radiation of $J = 2 \to 0$ transition , leaking out slowly, is not effective in cooling the clouds.

The molecule HD has a dipole moment, so $\Delta J = \pm1$ transitions are allowed. However, $n(\mathrm{HD}) \leq 10^{-5} n(\mathrm{H_2})$, so HD is efficient, but not significant, in cooling.

The molecule CO is the most important coolant in dense molecular clouds, although $n(\mathrm{CO}) \sim 10^{-5} n(\mathrm{H_2})$. CO ($J = 0 \to 1$) transition has $\Delta E = kT$ at T = 5.5 K. Therefore, CO can be easily excited collisionally at typical temperatures of molecular clouds.

Table: Main Cooling Mechanisms at Different Temperatures

Temperature (K)	Main Coolants	Cooling Rates (J m^{-3} s^{-1})	Cooling Rates (ergs cm^{-3} s^{-1})
10	CO	10^{-45} n^2	10^{-32} n^2
10^2	H_2, C^+	10^{-40} n^2	10^{-27} n^2
10^3	metastable ions	10^{-38} n^2	10^{-25} n^2
10^4	H, H^+ + e	10^{-35} n^2	10^{-22} n^2

E_{high} ———————

atom/ion/molecule X

hν

E_{low} ———————

The transition of X from E_{high} to E_{low} emits a photon with energy h$\nu = \Delta E$. If the abundance of X at E_{low} level is low, the ISM is optically thin to this spectral line. This is true for most spectral lines.

The ISM is optically thick to Lyman Series of H because H is the most abundant element and most H atoms are in the ground state ready to absorb a Lyman photon.

The ISM is optically thick to ^{12}CO ($J = 1 \rightarrow 0$) transition for dense molecular clouds. ^{13}CO ($J = 1 \rightarrow 0$) transition is optically thin because of its lower abundances.

3. Formation of Molecules

Molecules can be formed either by gas phase chemistry or with the help of dust grains. Often ions are involved to speed up the reaction rate.