Radiative Processes in the Interstellar Medium

(II) Shocks & PDRs

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Radiative rate terms: $$\frac{dN_2}{dt} = -A_{21}N_2 + \bar{J}(B_{12}N_1 - B_{21}N_2)$$

$$= -A_{21}N_2\left[1 - \bar{J}\frac{B_{21}}{A_{21}}\frac{n_1 - n_2}{n_2}\right]$$

$$= -A_{21}N_2\underbrace{\left[1 - \frac{\bar{J}}{S}\right]}_{\beta_1}$$

$$\boxed{\frac{dN_2}{dt} = -\beta_1 A_{21}N_2}$$

$$A \rightarrow \beta A$$

$$N_{cr} \rightarrow \beta N_{cr}$$

Rotational transitions: $A \sim 10^{-5}\ s^{-1}$ $\langle\sigma v\rangle \sim 10^{-10}\ cm^3 s^{-1}$

$N_{cr} \sim 10^5\ cm^{-3}$

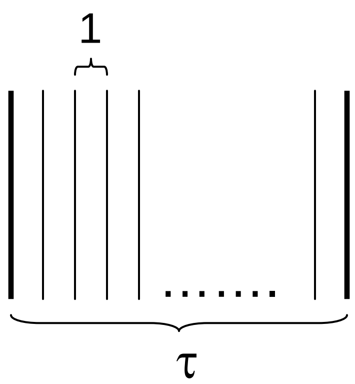
Naïve Escape Probability

I in $Ie^{-\tau}$ out $\Rightarrow$ probability to escape from τ is $e^{-\tau}$

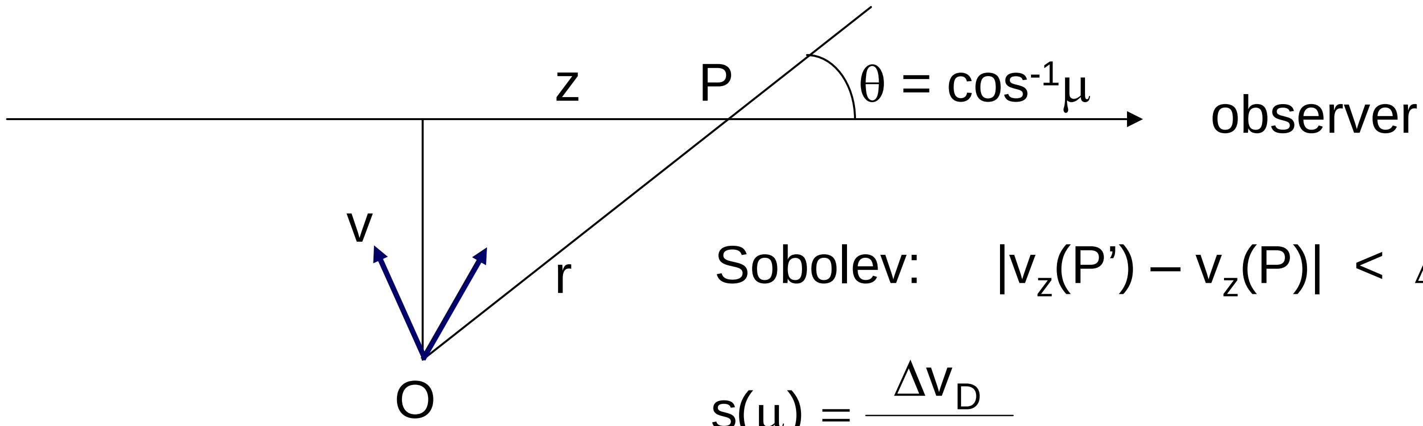
Mean escape probability:

$$\beta = \langle e^{-\tau} \rangle = \frac{1}{\tau}\int_0^{\tau} e^{-\tau'} d\tau' = \frac{1 - e^{-\tau}}{\tau}$$

$$\beta \approx \begin{cases} 1 & \tau << 1 \\ 1/\tau & \tau >> 1 \end{cases}$$



Large Velocity Gradients (LVG)



Sobolev: $|v_z(P') - v_z(P)| < \Delta v_D$

$$s(\mu) = \frac{\Delta v_D}{\partial v_z / \partial z}$$

$$= r\frac{\Delta v_D}{v}\frac{1}{1-\mu^2(1-d\ln v/d\ln r)}$$

$$\bar{J} = S(1-\beta)$$

$$\beta = \int \frac{d\Omega}{4\pi}\frac{1-e^{-\tau(\mu)}}{\tau(\mu)}$$

$$\tau(\mu) = \kappa s$$

Back to the radiative rate terms:

$$\frac{dN_2}{dt} = -\beta A_{21} N_2$$

$$\beta \propto 1/\tau$$

$\Rightarrow$ <u>dN/dt independent of A</u>!!!

two-sided line flux:	$j = h\nu\,\beta A_{21} N_2\, d$
optically thin:	$j = h\nu\, A_{21} N_2\, d$
optically thick:	$j = 4\pi\Delta\nu_D\, S(T_x)$

HEATING

kinetic energy redistribution; T

$\Downarrow$

line excitations; internal energy redistribution

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line emission

COOLING

Interstellar Shocks

- Generated by supersonic motions
- Effects — heating, compression and velocity structure

SHOCK ENVIRONMENTS

- cloud collisions
- outflows from YSOs
- OB stars — winds and HII region expansion
- PN ejection
- Wolf-Rayet winds
- supernovae

Hydrodynamics — mean free path << system dimensions

Basic "macro" equations:

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\nabla\vec{u}$$

$$\rho\frac{d\vec{u}}{dt} = -\nabla p$$

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \vec{u}\cdot\nabla$$

Basic "micro" equations:

$$p = p(\rho, T);$$

$$c^2 \equiv \left(\frac{\partial p}{\partial \rho}\right)_{\text{adiabatic}}$$

1-d, small adiabatic perturbation:

$\rho = \rho_0 \Rightarrow \rho_0 + \delta\rho;$ $\delta\rho << \rho_0$

$p = p_0 \Rightarrow p_0 + \delta p;$ $\delta p = c^2\delta\rho << p_0$

$u = 0 \Rightarrow \delta u;$ $\delta u << ?$

Linearize:

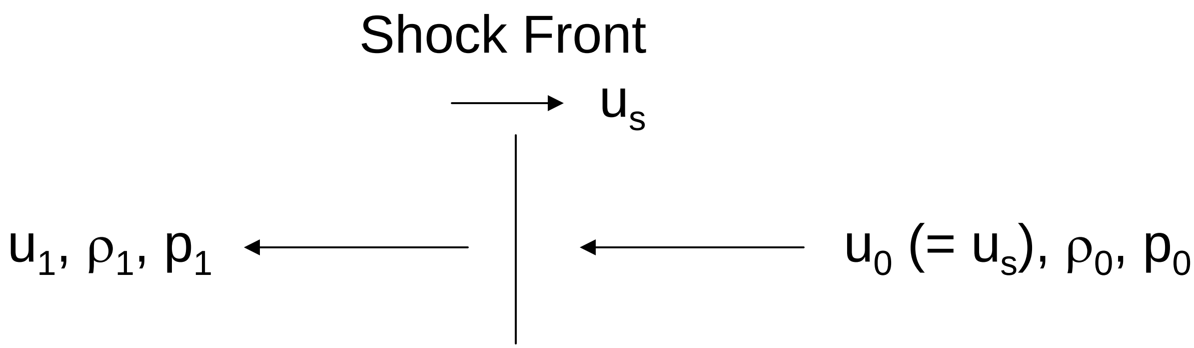
$$\delta\rho = \delta\rho(x \pm ct)$$

$$\delta p = c^2\delta\rho$$

$$\delta u = \pm c\frac{\delta\rho}{\rho_0} << c$$

Ideal gas: $p = \frac{\rho}{m}kT = \tfrac{1}{2}\rho u_{th}^2;$ $c = \sqrt{\tfrac{1}{2}\gamma}\, u_{th}$

Supersonic disturbance $\Rightarrow$ Shock!



Steady-state ($\partial/\partial t = 0$), shock frame:

$$\rho_0 u_0 = \rho_1 u_1$$

$$p_0 + \rho_0 u_0^2 = p_1 + \rho_1 u_1^2$$

$$t_{elastic} << t << t_{cool} = t_{inelastic}$$

Adiabatic phase:

$$U_0 + \frac{p_0}{\rho_0} + \tfrac{1}{2}u_0^2 = U_1 + \frac{p_1}{\rho_1} + \tfrac{1}{2}u_1^2$$

Strong shocks ($M = u_0/c_0 >> 1$):

$$\frac{\rho_1}{\rho_0} = \frac{\gamma + 1}{\gamma - 1} = 4 \quad (\gamma = 5/3)$$

Not much of a compression!

Ordered $\Rightarrow$ Thermal motions

$$u_{th,1} = \sqrt{\tfrac{3}{8}}\, u_s$$

Overall pressure: $\Pi = p + \rho u^2 = p + \frac{1}{\rho}(\rho u)^2$

pre-shock: $c_0 << u_0 \Rightarrow p << \rho u^2$ $\qquad \Pi \approx \rho_0 u_s^2$

post-shock: $\rho_1 u_1^2 = \frac{1}{4\rho_0}\left(\rho_0 u_0\right)^2 = \frac{1}{4}\rho_0 u_s^2 = \frac{1}{4}\Pi$ $\qquad \Pi \approx p_1$

pre-shock ram pressure $= \rho_0 u_s^2 \quad \approx \quad ½\rho_1 u_{th,1}^2 =$ post-shock thermal pressure

Shocks — High Temperatures:

$$T \approx 10^5 \left(\frac{u_s}{100\ \mathrm{km\,s^{-1}}} \right)^2\ \mathrm{K}$$

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Dissociation, ionization

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Cooling at constant pressure

$\Downarrow$

isothermal compression

$$\rho_1 c_0^2 = \rho_0 u_s^2 \qquad \frac{\rho_1}{\rho_0} = M^2$$

Magnetic Fields

Flux freezing: $$\frac{B_0}{\rho_0} = \frac{B_1}{\rho_1}$$

Full pressure: $$\Pi = p + \rho u^2 + \frac{B^2}{8\pi}$$

$$= p + \frac{1}{\rho}(\rho u)^2 + \frac{\rho^2}{8\pi}\left(\frac{B}{\rho}\right)^2$$

Magnetic cushioning: $B_1 = u_s(8\pi\rho_0)^{1/2}$

Low ionization — ion-neutral drifts; C shocks

Shock Diagnostics

- High-excitation molecular lines:
  - H_2: vib-rot ($\lambda \sim 2–5\ \mu m$, $12\ \mu m$)
  - CO: high J ($\lambda > 100\ \mu m$), $v = 1 \rightarrow 0$ ($4.7\ \mu m$)
  - OH: low J ($\lambda \sim 50–160\ \mu m$)
- Atomic fine structure & forbidden:
  - FeII($1.64\ \mu m$)
  - SiII($35\ \mu m$)
  - OI($63\ \mu m$)
- Hydrogen Brα, Brγ

n-T profiles: $T = T_a f(t)$ $n = n_a T_a / T$

Probing the ISM cooling function!

Enhanced Abundances

High temperatures — overcome endothermicity & energy barriers:

$$C^+ + H_2 + 0.4\ \text{eV} \rightarrow CH^+ + H$$

Similarly, can channel all O not in CO into OH, H_2O

Photon Dominated Regions

PhotoDissociation Regions

- Radiation induced
  - Ionization
  - Dissociation
  - Heating

Ionization Heating

Ionization equilibrium: $N_+ N_e \alpha(T) = N_0 \int_{\nu_0}^{\infty} 4\pi \mathcal{N}_\nu \sigma_\nu d\nu$ $\mathcal{N}_\nu = J_\nu / h\nu$

Ionization heating: $H = N_0 \int_{\nu_0}^{\infty} 4\pi \mathcal{N}_\nu h(\nu - \nu_0) \sigma_\nu d\nu$

$$H = N_+ N_e \alpha(T)\, kT_i$$

$$kT_i = \frac{\int_{\nu_0}^{\infty} h(\nu - \nu_0) \mathcal{N}_\nu \sigma_\nu d\nu}{\int_{\nu_0}^{\infty} \mathcal{N}_\nu \sigma_\nu d\nu}$$

Characteristic T_i determined from spectral shape

independent of intensity!

Recombination Cooling

$$C = N_+ N_e \sum \int_0^\infty v\sigma_r(v)\tfrac{1}{2}mv^2 f(v)dv$$

$$C = N_+ N_e \beta(T) kT$$

$$\beta(T) = \sum \frac{1}{kT}\int_0^\infty \tfrac{1}{2}mv^2 \cdot v\sigma_r(v) f(v)dv \approx \alpha(T)$$

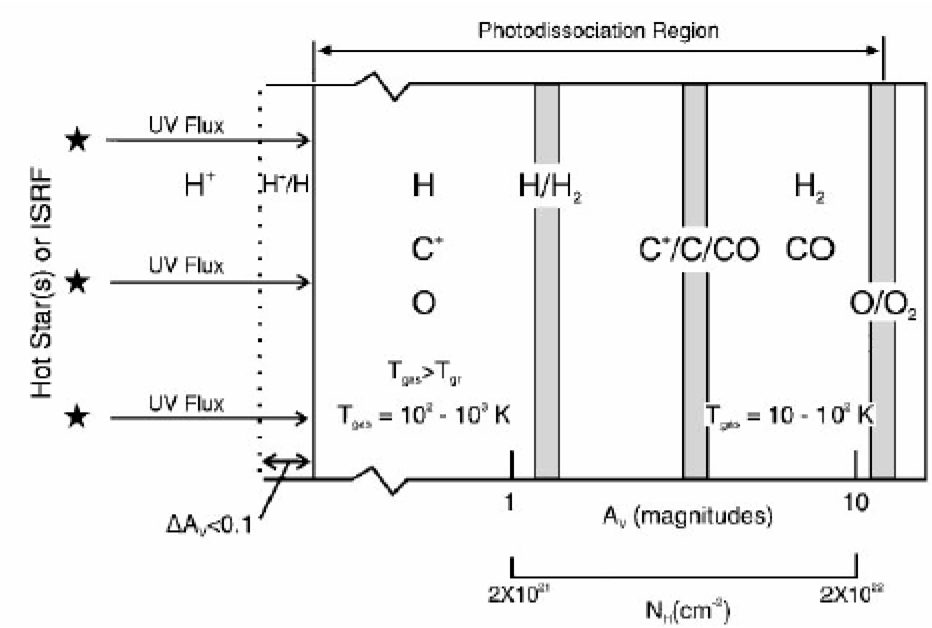
Thermal Equilibrium:

$T = T_i\, \alpha/\beta$

T depends only on shape of ionizing spectrum

HII regions: T ~ 8,000 – 10,000 K

AGN clouds: T ~ 8,000 – 20,000 K



- Radiation (6–13.6 eV) dominated heating and/or composition
- All molecular clouds are PDRs to a depth A_v ~ 4 from surface!
- Main heating:
  - grain photoelectric: FUV (~ 6–10 eV) electron ejection from grain; e^- kinetic energy ~ 1 eV
  - H_2 pumping: FUV (11–13.6 eV) electronic excitation of H_2

Shocks vs PDRs

- Most line & IR cont. emission of a galaxy is from PDRs
- shocks — only specific regions or lines
- PDRs have larger:
  - linewidths
  - line-to-continuum ratios
  - OI(63 μm):CII(158 μm)

The FUV flux in PDRs may regulate low- and high-mass star formation in galaxies, and the column density of gravitationally-bound, star-forming molecular clouds