# Heating and Cooling

# Further reading

- Lequeux “The Interstellar Medium” Springer 2005
- Wolfire et al. 1995, ApJ 443, 152
- E. van Dishoek 2006, ISM Lecture 4, Leiden University
- E. van Dishoek 2006, ISM Lecture 9, Leiden University



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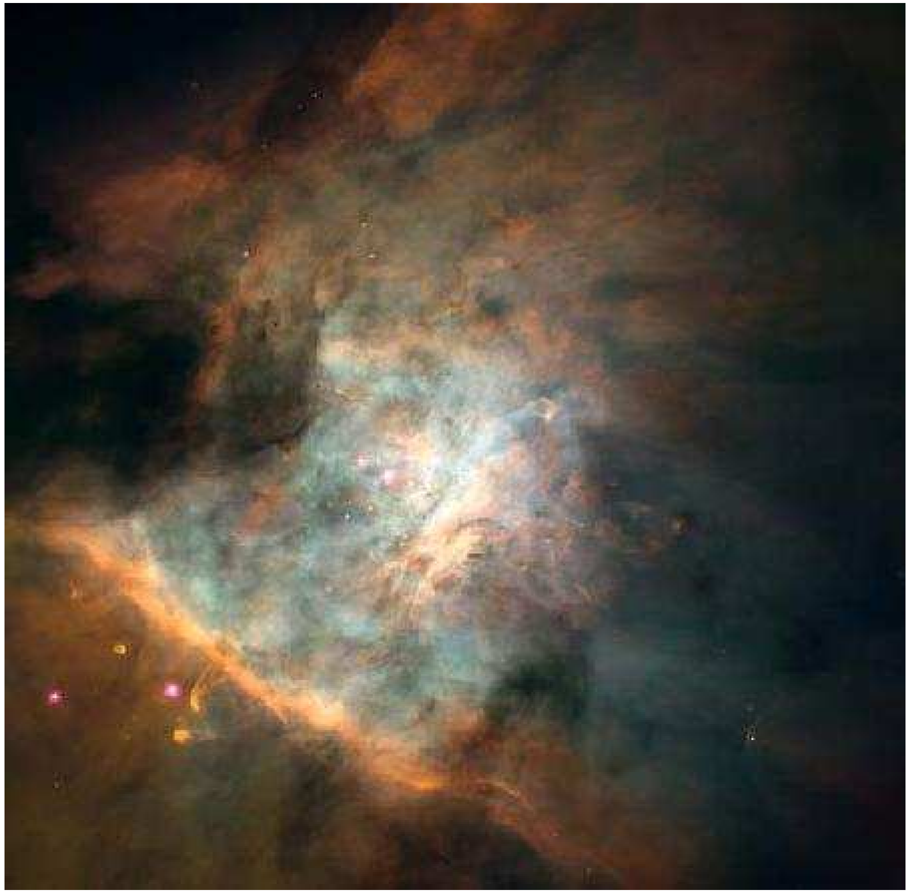
# Sources of ionization and excitation

**Picture:**
optical observation of the Orion star formation region M42

**Processes:**
Photo-ionization

**Origin:**
Massive stars

# Sources of ionization and excitation



**Picture:**
optical observation of the Orion star formation region M42

**Processes:**
Photo-ionization
Shocks

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Massive stars

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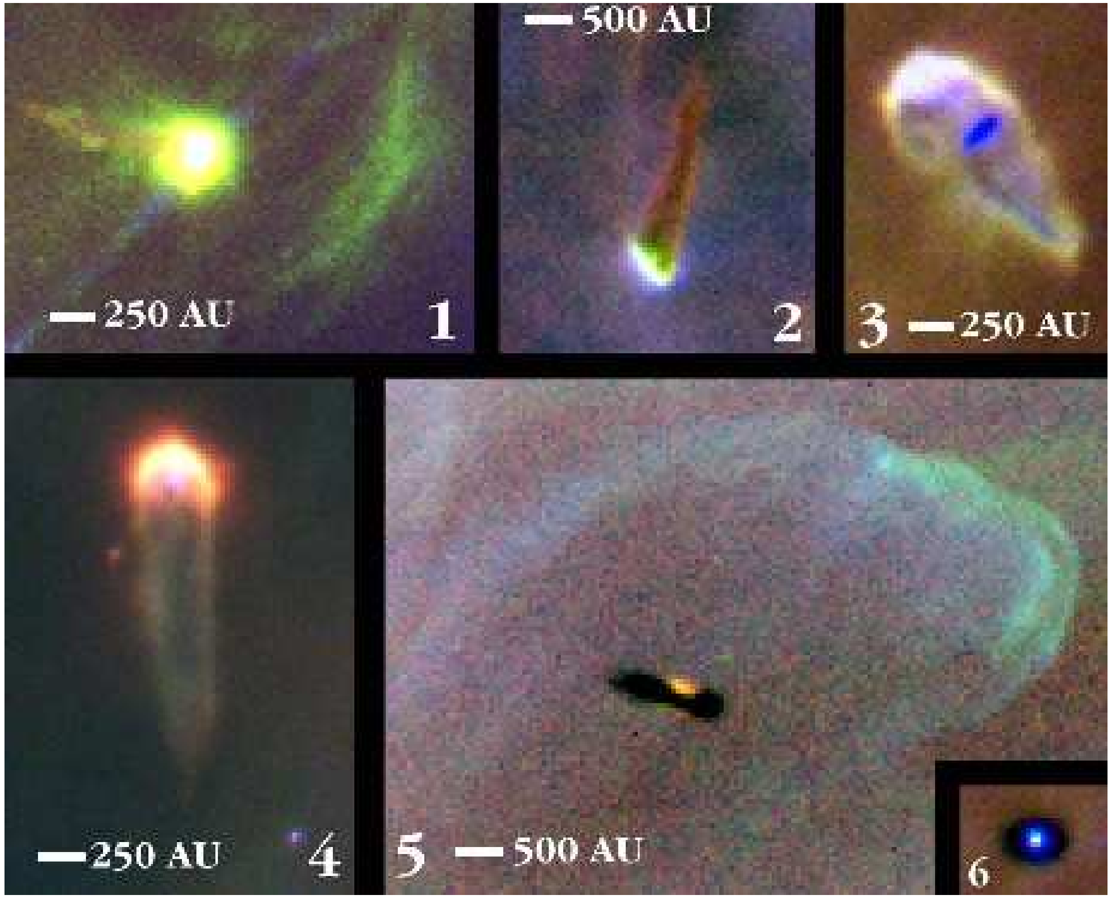
# Sources of ionization and excitation

**Picture:**
HST- observation of a young stellar cluster

**Processes:**
Photo-ionization
Stellar winds
Shocks

**Origin:**
Massive stars
Stellar evolution

# Sources of ionization and excitation

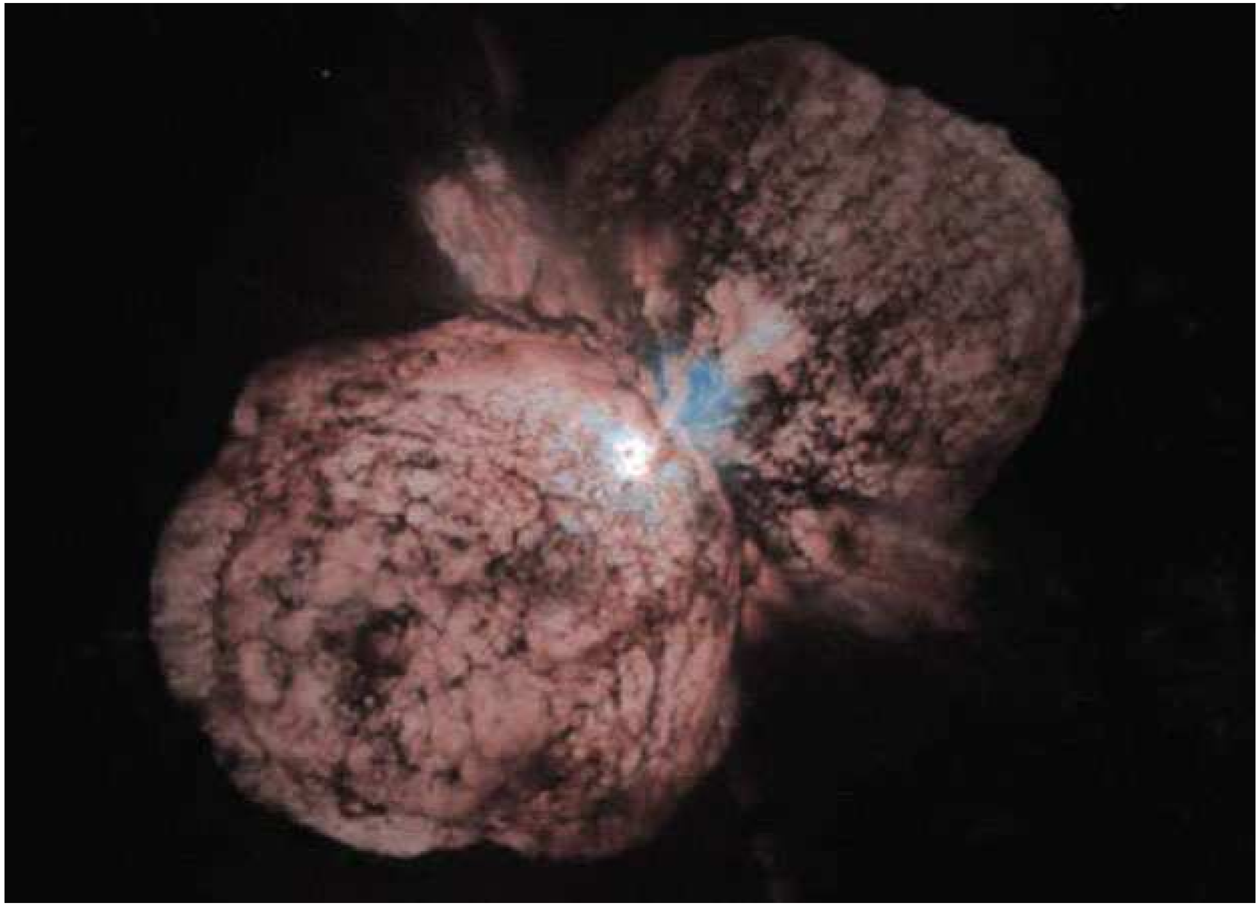



**Picture:**
HST- observation of molecular clouds in the Orion star formation region M42

**Processes:**
Stellar winds
Photo-ionization
shocks

**Origin:**
Massive stars

# Sources of ionization and excitation



**Picture:**
HST- observation of the massive Eta-Carina

**Processes:**
Shocks
Stellar winds
Photo-ionization

**Origin:**
Stellar evolution

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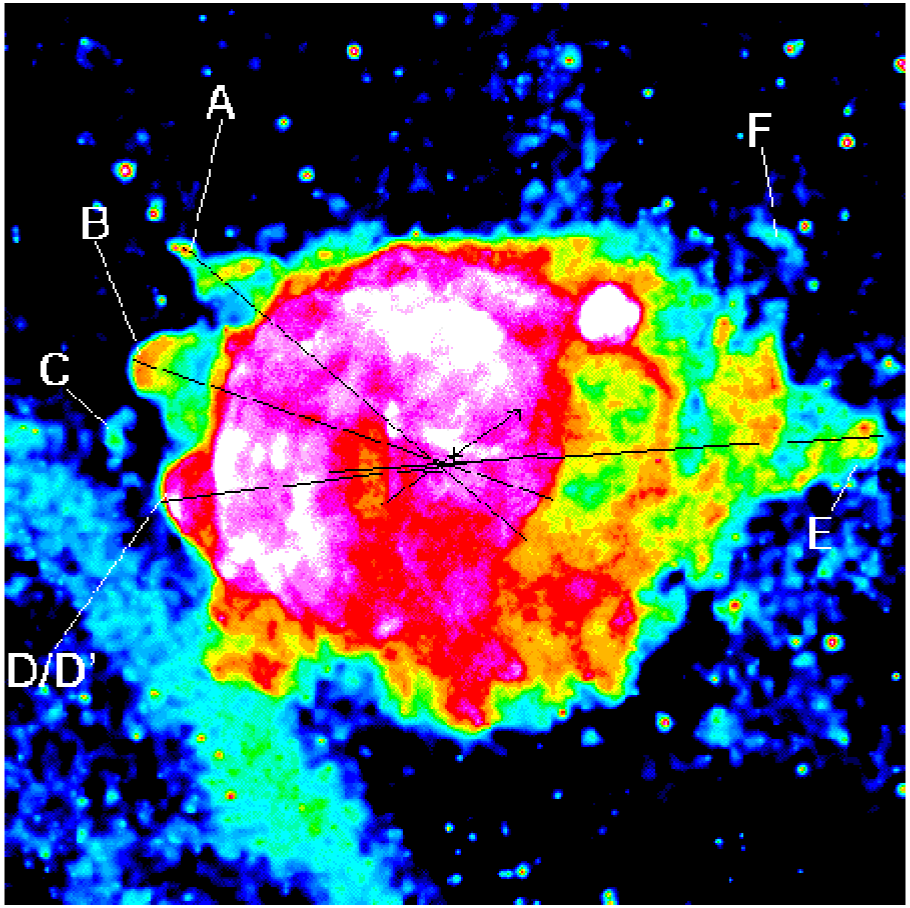
# Sources of ionization and excitation

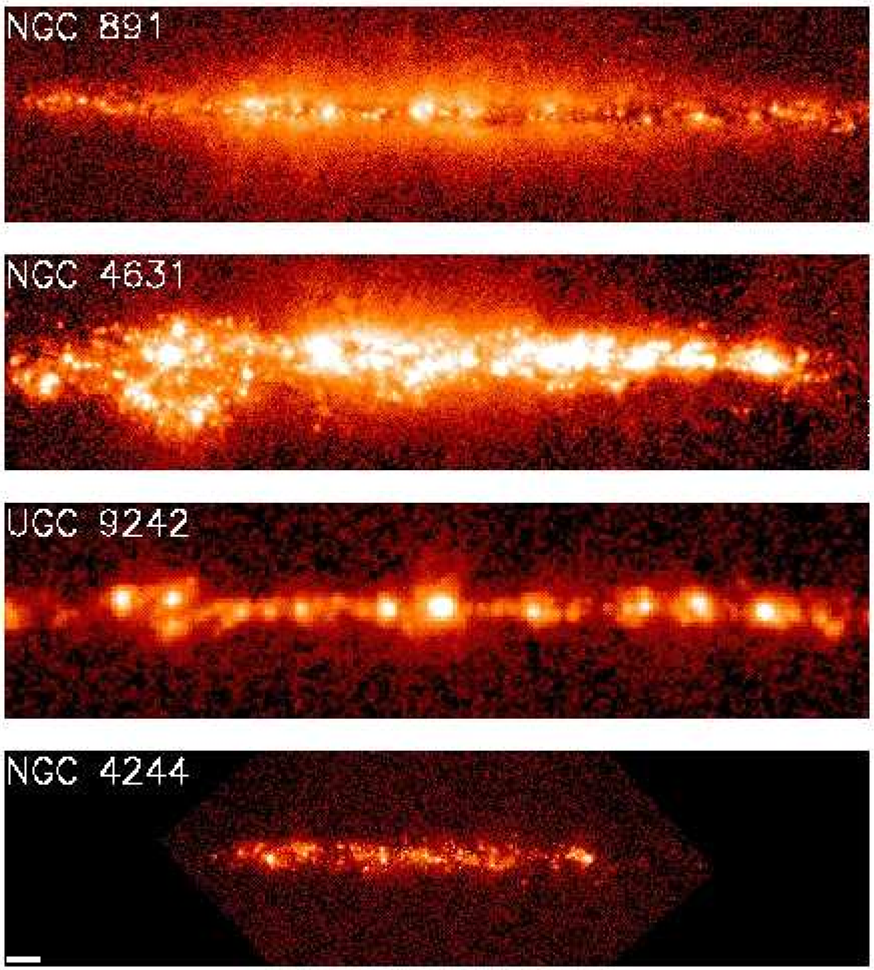



**Picture:**
Soft X-ray observation of the Vela supernova remnant

**Processes:**
Shocks

**Origin:**
Stellar evolution

# Sources of ionization and excitation




**Picture:**
Hα-observation of „edge-on“ galaxies with different star formation rates masses

**Processes:**
Photo-ionization

**Origin:**
Massive stars
Stellar evolution

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# Quick summary

- The **stellar evolution** is one source of energy which **heats** the interstellar matter
  - Stellar winds
  - Shocks
  - Ionizing photons
- The **radiation** observed from the gaseous distribution traces the primary **cooling** process of the interstellar matter
  - X-rays, UV
  - Optical
  - Near-infrared
  - Infrared
  - Radio

Mean free path ↓

# Composition of the ISM

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# Composition of the ISM

- The **total cooling rate** of the ISM depends strongly on the composition of the gas
  - Heavier elements than hydrogen and helium potentially contribute numerous electrons with ionization potentials of a few eV. These electrons can be freed by ionization and collisions and contribute to a high electron density (emission measure $n_e^2$)
- All constituents of the ISM are evaluated in number relative to the density of hydrogen atoms

$$A_i = \frac{n_i}{n_H} \text{ with } n_H = n\left(H^+\right) + n\left(H^0\right) + 2n_H\left(H_2\right)$$

- Carbon is under-abundant, because it is highly depleted on dust grains, yielding a gas phase under abundance of a factor 1.4 to 2.7
- Oxygen appears to be under abundant in the gas phase by factor of 2

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# Composition of the ISM (log!)

| Element | Gas-phase abundance | Element abundance |
|---|---|---|
| He | -1.0 | -1.00 |
| C | -3.52 | -3.44 |
| O | -3.34 | -3.34 |
| Si | -5.45-0.45x(lg n + 0.5) | -4.45 |
| Mg | -4.84-0.28x(lg n + 0.5) | -4.41 |
| Fe | -6.15-0.38x(lg n + 0.5) | -4.49 |
| S | -5.1 | -4.73 |
| N | … | -3.95 |
| Ne | … | -3.91 |

Wolfire et al. 1995

# Composition of the ISM

- The chemical composition and evolution of the ISM is in first order a function of the distance to the galactic plane ($1/r^2$, sources of ionization and shocks)
  - Molecular clouds with super-solar abundances
  - The general interstellar medium with solar abundances
  - The cold neutral medium without any molecular species
  - The warm neutral medium, diffuse HI gas
  - The warm ionized medium with sub-solar abundances
  - The hot ionized medium with a few metals located within the galactic plane and the halo of the Milky Way

z

- There exist radial abundance gradients across the Milky Way. They are associated with the decreasing feedback processes of the star formation at large galactocentric distances

# Physical processes

# Physical processes

- To heat the gas it is necessary to transfer energy into the gaseous medium
  - Collisions/interaction with energetic particles and photons
    - Photoelectric heating by grains
    - Photoelectric heating by the photo-ionization of atom and molecules
    - photoelectric heating by soft X-rays
    - Heating by low-energy cosmic-rays
  - Chemical heating
  - Heating by grain-gas thermal exchange
  - Hydrodynamic and magneto-hydrodynamic heating
  - Interstellar shocks

# Physical processes: photo-ionization

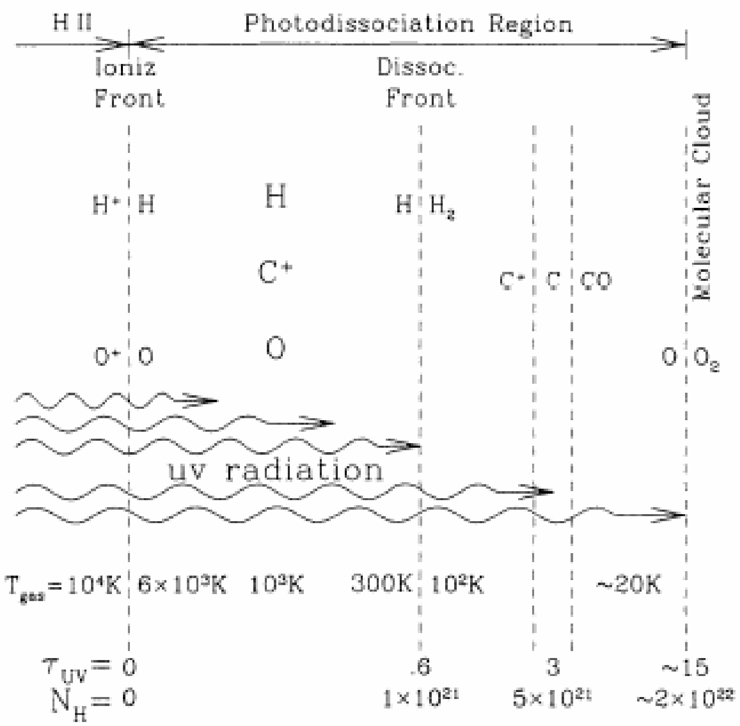
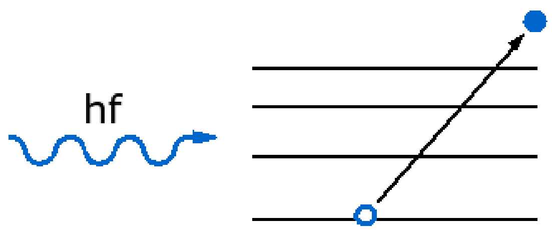



*Figure 1. The structure of a PDR produced by radiation from a star which also emits enough ionizing photons to produce an HII region. The ionization front separates the HII region from the PDR. Typical values of the effective far-ultraviolet optical depth, and H nucleon column density are shown.*




Photoeffect

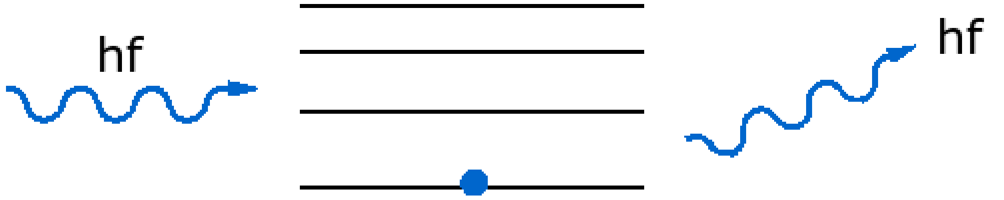
$$I = I_0 \cdot e^{-\int_0^S \sigma \cdot n(s) ds}$$

$$I = I_0 \cdot e^{-\sigma \cdot N_H}$$

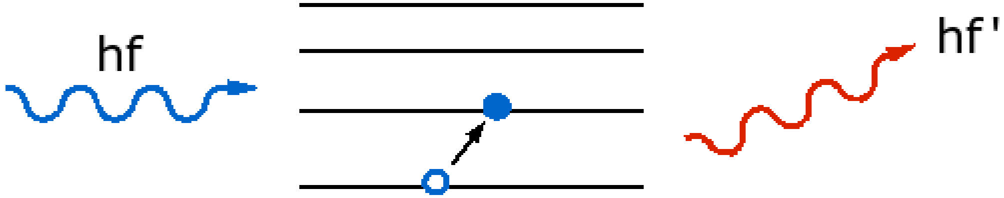
$$I = I_0 \cdot e^{-\tau}$$

Draine & Bertoldi 1999

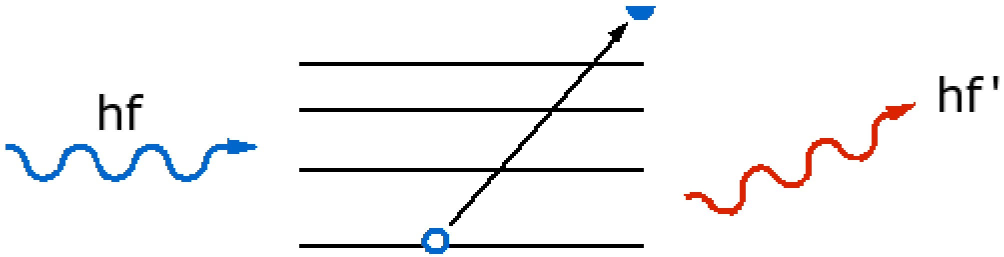
# Physical processes: Collisions




elastic scattering




inelastic scattering




Compton scattering



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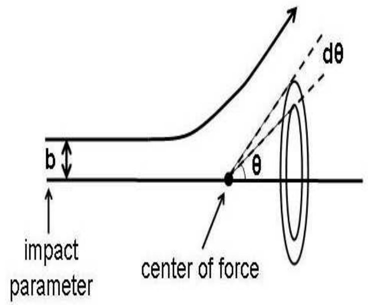
# Physical processes: Collisions

- Assume a source of particles with intensity I
- The cross section is defined by

$$\sigma(\Omega)d\Omega = \frac{\text{No. of particles scatter in } d\Omega}{\text{No. of incident particles}}$$

- The total cross-section is

$$\sigma = \int \sigma(\Omega)d\Omega = 2\pi\int_0^\pi \sigma(\theta)d\theta$$



# Physical processes: Collisions

- The cross section needs to be weighted by the velocity distribution of the electrons, which we assume to be described by the Maxwell-distribution

$$q = \int_0^\infty \upsilon \sigma(\upsilon) f(\upsilon) d\upsilon \text{ with}$$

$$f(\upsilon) = \frac{4}{\sqrt{\pi}} \left( \frac{m}{2kT} \right)^{3/2} \upsilon^2 e^{-\frac{m\upsilon^2}{2kT}}$$

# Physical processes: Collisions

- Balance equation

$$n_b n_l \sigma_{lu}(\upsilon_l) f(\upsilon_l) d\upsilon_l = n_b n_u \sigma_{ul}(\upsilon_u) f(\upsilon_u) d\upsilon_u$$

- Thermal equilibrium

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{\Delta E}{kT}}$$

- This gives

$$\sigma_{lu}(\upsilon_l)\upsilon_l^2 = \frac{g_u}{g_l}\sigma_{ul}(\upsilon_u)\upsilon_u^2$$

$$q_{lu} = \frac{g_u}{g_l} q_{ul} e^{-\frac{\Delta E}{kT}}$$

# Physical processes: Collisions

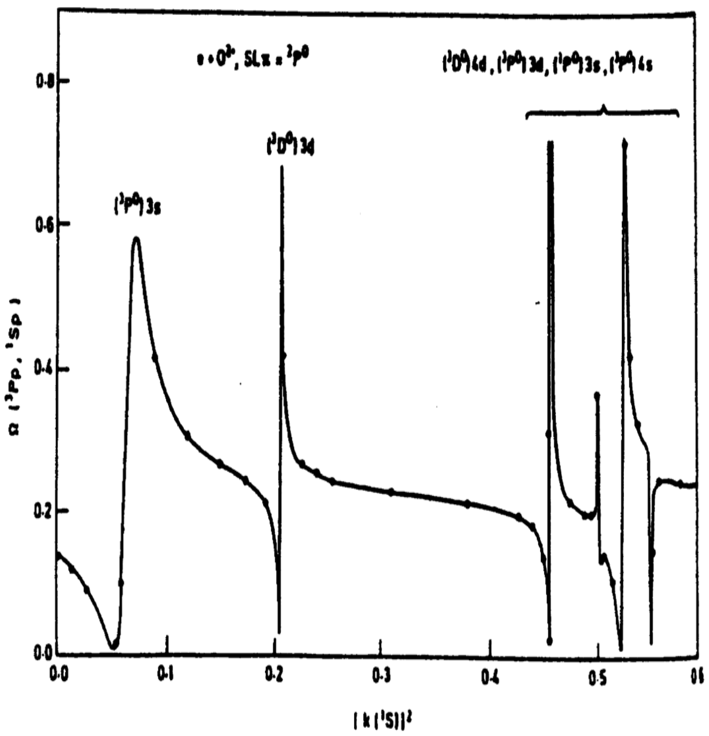
- Collisions can be quantified by the quantity “collision cross section”. The cross section can be calculated using quantum-mechanically methods
- The cross sections are tabulated for numerous species
- The quantity collision strength Ω is defined to show up only a weak dependence on the velocity of the collision partners. It is defined via

$$\sigma_{lu}(\upsilon_l) = \frac{\pi\hbar^2}{m^2\upsilon_l^2}\frac{\Omega(l,u)}{g_l}$$

# Physical processes: Collisions/Resonances

- Collision cross sections are not steady functions of the velocity of the colliding partners, but show up with some extreme variations called **resonances**
- The resonances needs to be accounted by the calculation of the quantity "collision strength" $\Omega$
- Integrated across the velocity distribution of interest (energy distribution) the contribution of resonances to the collision strength is minimized or even "averaged out"

# Resonances: OIII($^3$P) + e$^-$ -> OIII($^1$S)+e$^-$



Energy

E. van Dishoeck Lecture 4

# Heating

# Heating: dust grains

# Dominant thermal ionization processes: heating by dust grains

- Depending on the mass and size distribution of the dust grains, the ionizing radiation can free different amounts of electrons from the surface of the grains.
  - These grains show up with an effective positively charge, they can capture electrons from the gas phase leading to cooling of the gas
- The PAHs (size < 1.5nm) absorb according to Bakes & Tielens (1994) about 10% of the far ultraviolet field

$$\Gamma_{Pe} = 10^{-24} \varepsilon \chi n_H \ \mathrm{erg\,s^{-1}cm^{-3}}$$

- Here ε denotes the heating efficiency and χ is the scaling factor for the strength of the UV radiation field (100- 1000 of a classical PDR)
- 90% of the radiation is absorbed by dust grains of sizes ranging between 1.5 nm and 30 nm. **Small grains have larger photoelectric efficiencies and contribute about half of the net photoelectric heating**
- Extinction becomes important at hydrogen column densities in excess of $1.2 \times 10^{21}$ $cm^{-2}$

# Dominant thermal ionization processes: heating by dust grains

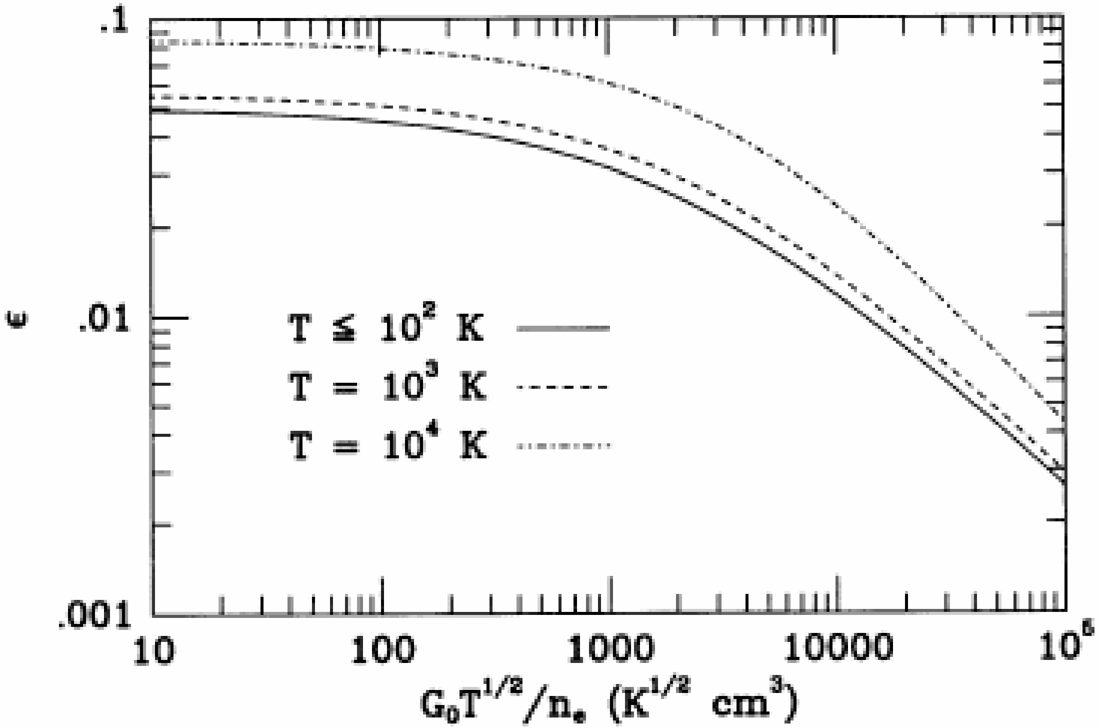
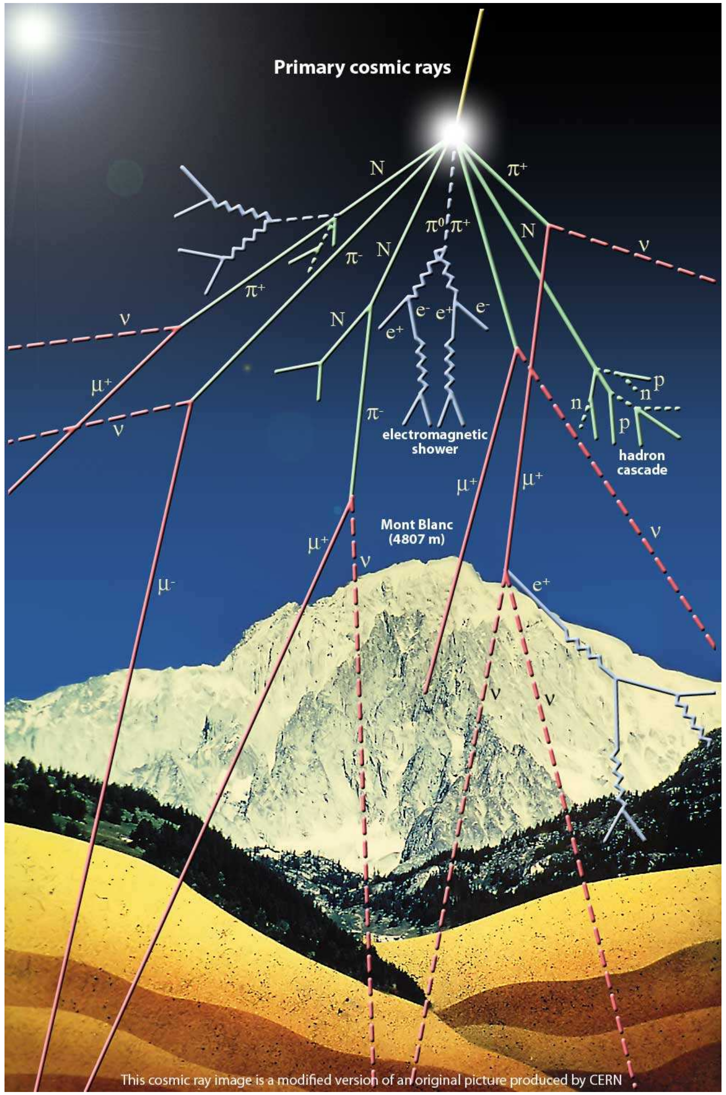



FIG. 1.—Photoelectric heating efficiency $\epsilon$ of small grains and PAHs (from Bakes & Tielens 1994) plotted as a function of $G_0 T^{1/2}/n_e$. Curves are shown for gas temperatures $T \leq 10^2$ K (*solid*), $T = 10^3$ K (*dash*), $T = 10^4$ K (*dash-dot*). At small values of $G_0 T^{1/2}/n_e$ ($\ll 5 \times 10^3$ $K^{1/2}$ $cm^3$) grains are mainly neutral and the efficiency is at a maximum. At larger values of $G_0 T^{1/2}/n_e$ the efficiency drops due to grain charging.

Wolfire et al. 1995, ApJ 443, 152

# Heating: cosmic-rays

# Dominant thermal ionization processes: heating by cosmic-rays





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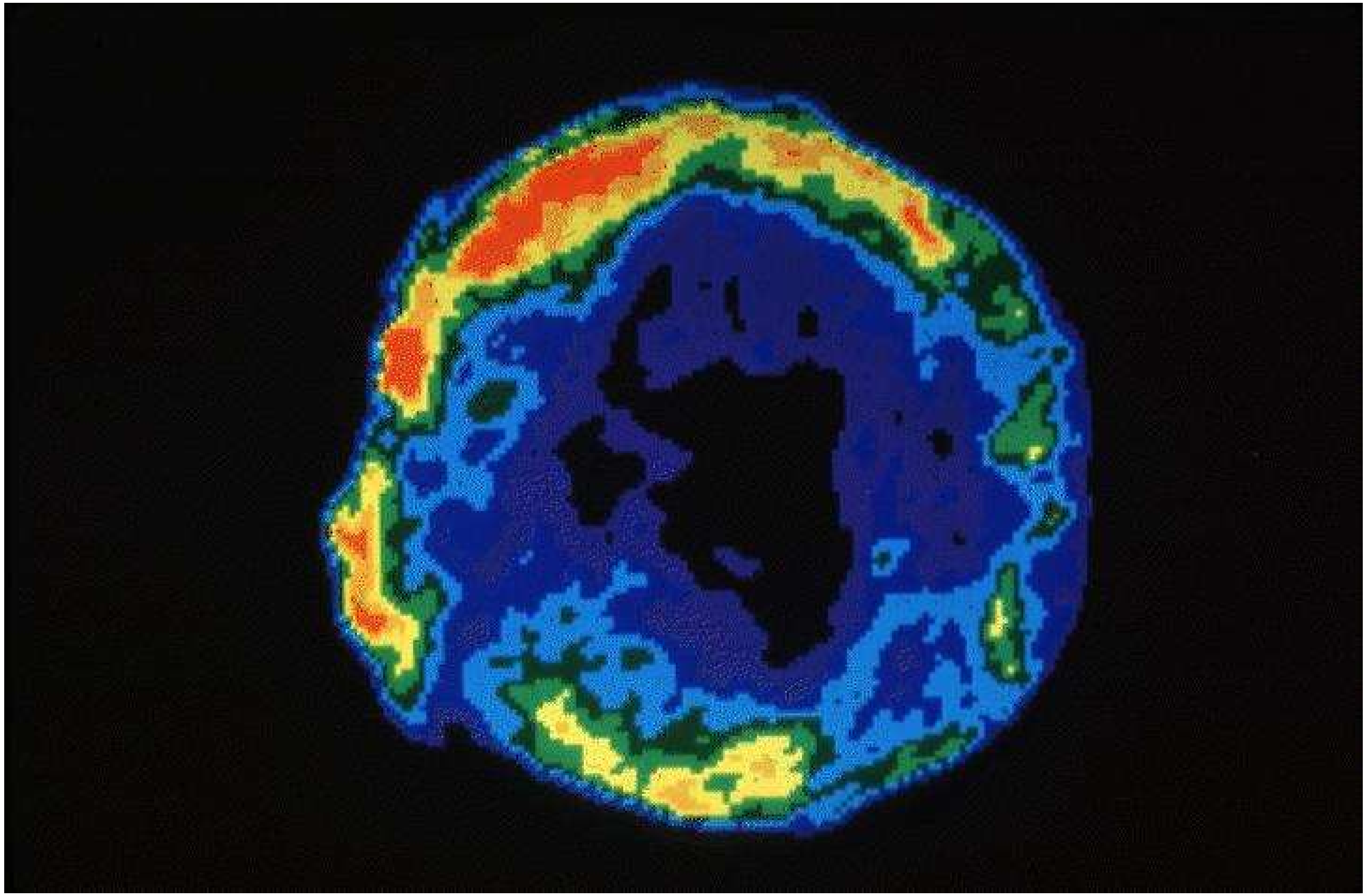
# Dominant thermal ionization processes: heating by cosmic-rays



www.astro.psu.edu, Tycho supernova remnant

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# Dominant thermal ionization processes: heating by cosmic-rays

- Cosmic-rays (CR) transform energy to bound electrons of atoms and ions
- Depending on the geometry of the interaction process, CR free electrons which lead to secondary excitation processes within the gas
- The CR interaction with the gas is determined by Coulomb interactions and the excitation of plasma waves in the gas
- The relative velocity difference between the CR and the collision partner is huge, accordingly the velocity of the CR is of minor importance
- Because of the power-law type spectrum of the energy distribution of CR only the low-energy CR (few MeV) are sufficiently abundant to account for significant ionization

# Dominant thermal ionization processes: heating by cosmic-rays

- The ionization rate can be described by

$$\varsigma = \sum_z \int_0^\infty 4\pi I_Z \sigma_{Ion,z(\upsilon)} d\upsilon \text{ with}$$

$$\mathrm{E} = \mathrm{m_H} c^2 \left[ \frac{1}{\sqrt{1 - \frac{\upsilon^2}{c^2}}} - 1 \right] \text{gives}$$

$$\varsigma = \sum_Z \int_0^\infty \mathrm{I}(\mathrm{E},\mathrm{Z}) \sigma_{ion}(E,Z) dE$$

# Dominant thermal ionization processes: heating by cosmic-rays

- The amount of energy released can be calculated according to the Bethe-Bloch formula to

$$-\left(\frac{dE}{dx}\right)_{ion} = nz\frac{4\pi e^4 Z^2}{m_e \upsilon}\left\{\ln\left[\frac{2m_e\upsilon^2}{\Delta E_{eff}}\left(1+\frac{E}{M_{CR}c^2}\right)^2\right]-\frac{\upsilon^2}{c^2}\right\} \text{ and}$$

$$-\left(\frac{dE}{dx}\right)_{el} = n_e\frac{4\pi e^4 Z^2}{m_e \upsilon}\left\{\ln\left[\frac{2m_e\upsilon^2}{\hbar\omega_p}\left(1+\frac{E}{M_{CR}c^2}\right)^2\right]-\frac{\upsilon^2}{c^2}\right\}$$

# Dominant thermal ionization processes: heating by cosmic-rays

- The cosmic-ray ionization rate is $n\zeta_{CR} = 1.8 \cdot 10^{-17}$ n cm$^{-3}$ s$^{-1}$
- The energy spectrum can be approximated by interstellar shock physics
- Total ionization rate of cosmic-rays is

  $n\zeta_{CR} = n\zeta_{CR}[1+\Phi^{H}(E,n_e/n)+\Phi^{He}(E,n_e/n)] \sim 3.0 \cdot 10^{-17}$ n cm$^{-3}$ s$^{-1}$
- The resulting heating rate is $n\Gamma = n\zeta_{CR}E_h(E,n_e/n) \sim 1.7\text{x}10^{-28}$ n ergs s$^{-1}$ cm$^{-3}$ with $E_h(E,n_e/n)$ gives the heat deposit for each primary electron of energy E
- **Obviously the cosmic-rays need high densities, accordingly, they are best absorbed in dense molecular clouds!**

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# Heating: photo-ionization

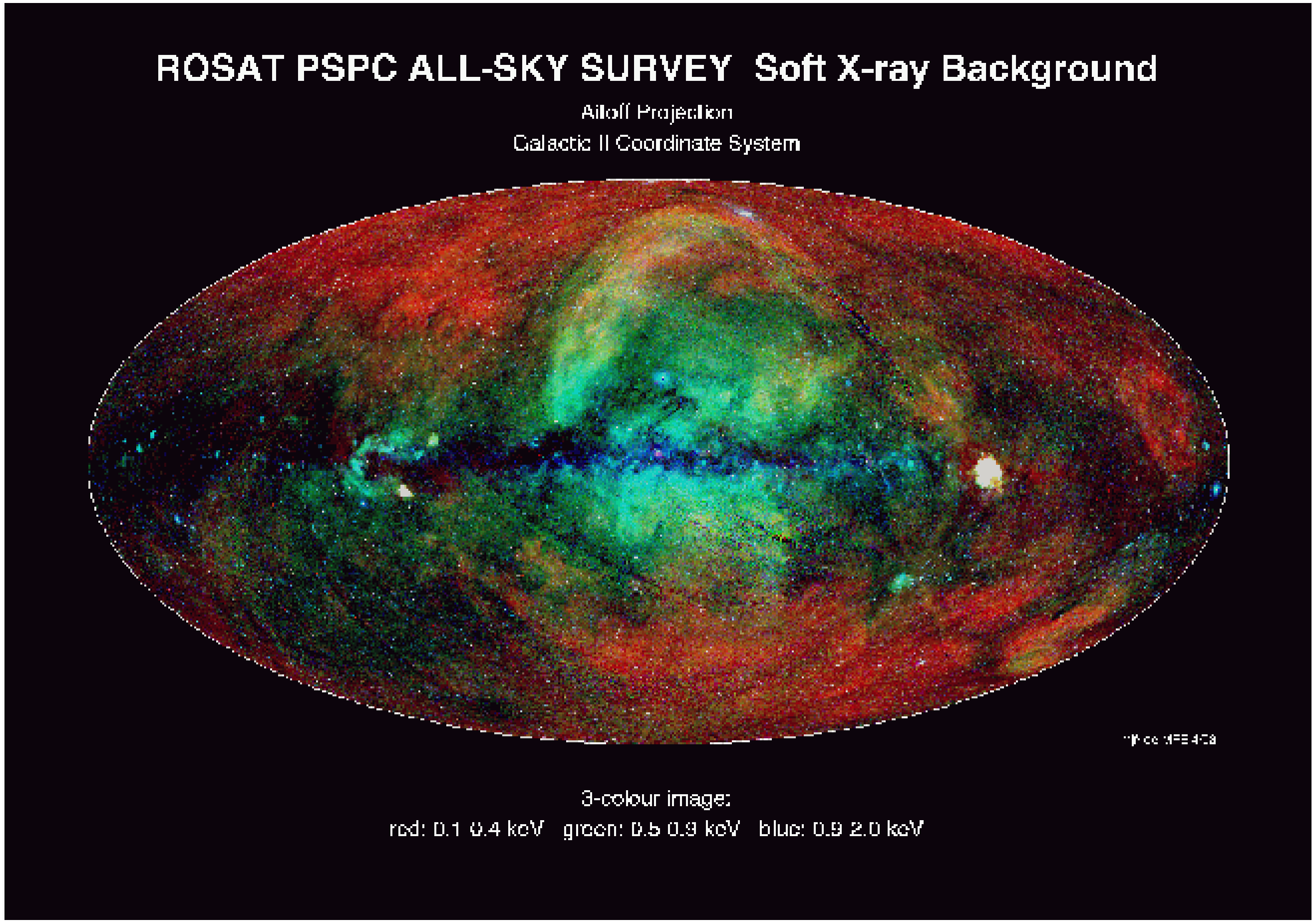
# Dominant thermal ionization processes: photo-ionization by atoms and molecules

- UV photons can free electrons from atoms and ions and provide sufficient amount of kinetic energy to the electron population
- The highest photon energy is 13.6 eV (hydrogen). The heating rate for a 11.2 eV photon which ionizes neutral carbon can be estimated to

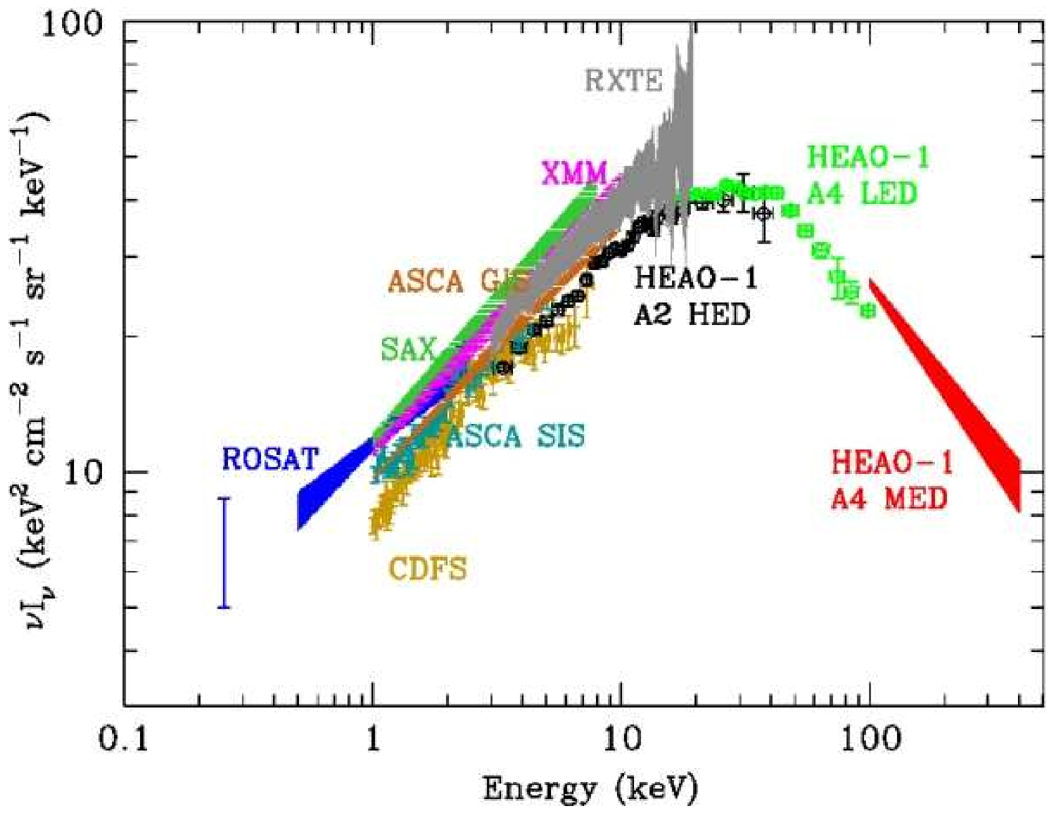
$$\Gamma_C = 2 \cdot 10^{-22} n\left(C^0\right) \mathrm{ergs\,s^{-1}cm^{-3}}$$

$$\approx 4 \cdot 10^{-28} \mathrm{ergs\,s^{-1}cm^{-3}}$$

# Dominant thermal ionization processes: heating by soft X-rays



# Dominant thermal ionization processes: heating by soft X-rays



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# Dominant thermal and ionization processes: heating by soft X-rays

- The X-ray background emission consists mainly of three components
  - The Local Bubble
  - The Milky Way X-ray halo
  - The extragalactic background
- intensity = $\frac{1}{2}[\Lambda(T_{LHB})EM_{LB} + \Lambda(T_{Halo})EM_{Halo}e^{-\sigma N} + C1e^{-\sigma N}]$
- $\Lambda$ represents the temperature emissivity based on a Raymond & Smith (1977, 1993) model
- Heating rate

$$n\Gamma_{X-ray} = 4\pi n \sum_i \int \frac{J}{h\nu} e^{-\sigma N} \sigma_\nu^i E_h\left(E^i, n_e / n\right) d\nu$$

$$\sim 10^{-26} \,\mathrm{ergs\, s^{-1} H^{-1}}$$

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# Heating: chemical heating

# Dominant thermal ionization processes: chemical heating

- On the surface of dust grains two hydrogen atoms can form a hydrogen molecule
- The energy released by the process of 4.48 eV will provide energy for the excitation of the new formed hydrogen molecule, its kinetic energy and heat the dust grain.
- About 4.2 eV will be transformed into excitation and 0.2 eV into kinetic energy, the dust grain will not be heated significantly!

$$\Gamma_{H_2} = R_f n^2 x_H \left(0.2 + 4.2\eta\right) \mathrm{eV\ s^{-1}\ cm^{-3}}$$

- $R_f$ is the hydrogen molecule formation rate and $x_H$ the gas abundance of hydrogen
- The heating rate is proportional only to the square of the volume density

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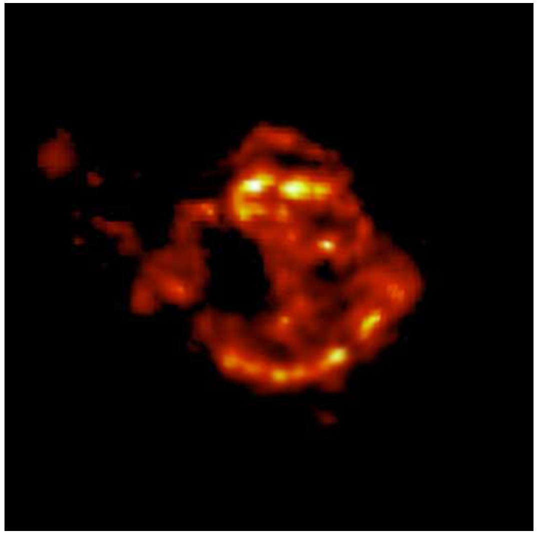
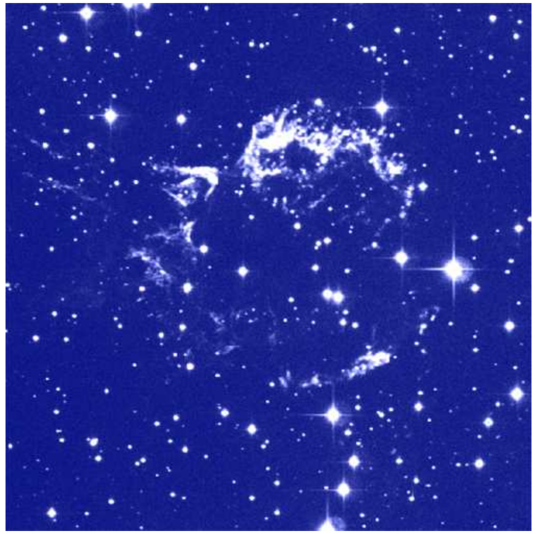
# Dominant thermal ionization processes: chemical heating

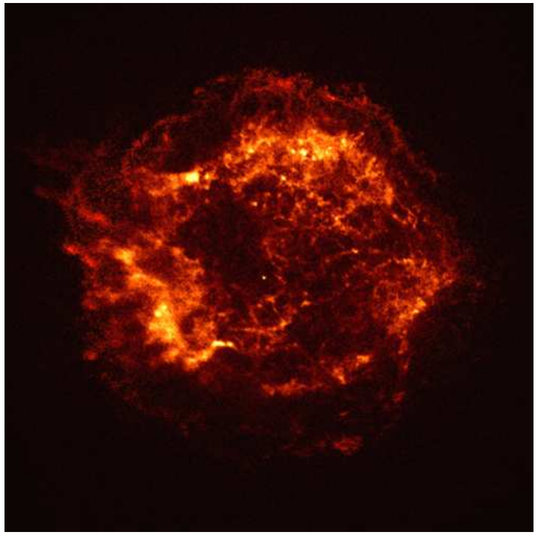
- The hydrogen molecule is able to absorb UV photons and its vibrational and rotational energy can efficiently heat the gas in the vicinity of stars bright in the UV range.
- Chemical heating is efficient only in shock regions and dense photo-dissociation regions

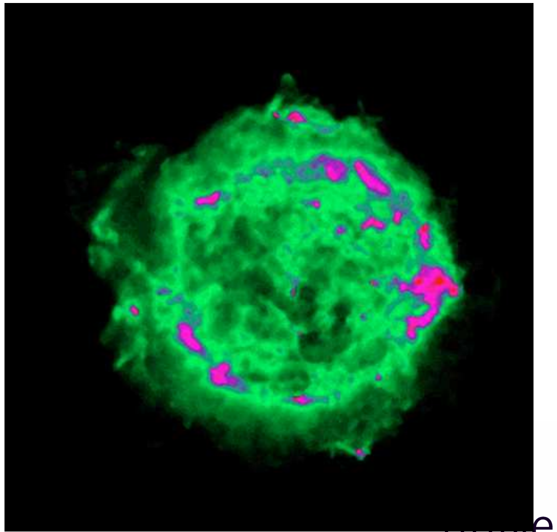
# Heating: dust-gas thermal exchange

# Dominant thermal ionization processes: dust grain – gas thermal exchange









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# Dominant thermal ionization processes: dust grain – gas thermal exchange

- Within a sufficiently warm environment the dust grains are warmer than the gas, yielding a heating source for gas atoms and molecules.
- In giant molecular clouds the far-infrared radiation coming from out-side the cloud can heat the dust grains. 100µm emission becomes an opacity of unity only on a level of visual extinction of about 300 magnitudes.
- The heating rate is

$$\Gamma_{gas,grain} \approx 1.6 \cdot 10^{-33} n_H^2 T^{-\frac{1}{2}} \left(T_d - T\right) \mathrm{erg\ s^{-1}\ cm^{-3}}$$

- The minimum grain temperature in the Milky Way is according to this process never less than 8K

# Dominant thermal ionization processes: dust grain – gas thermal exchange

- Comparing the process with heating by photoelectrons released by dust-grains

$$\frac{\Gamma_{gas,grains}}{\Gamma_{pe}} = 1.3 \cdot 10^{-7} n_{H_2} (T - T_d)$$

- Comparing the process with the heating by cosmic-rays

$$\frac{\Gamma_{gas,grains}}{\Gamma_{CR}} = 4 \cdot 10^{-5} n_{H_2} (T - T_d)$$

- **The process dominates in molecular clouds with densities in excess of $2 \times 10^4$ molecules $cm^{-3}$**

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# Heating: hydrodynamic heating and shocks

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# Dominant thermal ionization processes: hydrodynamic and magneto-hydrodynamic heating

- Supernovae, stellar winds and HII regions re-arranges the surrounding medium, yielding dissipative processes which heat the gas
- The ISM can be considered as a good conductor, accordingly magnetic fields can be dissipated via viscous dissipation of Alfven waves.
  - The Alfven waves are introduced within the ISM via cosmic-rays, the differential rotation of the gas and the shear of different magnetic fields
  - Relative motions between the ionized and the neutral gas components of a weakly ionized plasma produces via viscosity an effective heating

$$\Gamma_{hydro} = \rho P \frac{d}{dt}\left(\frac{1}{\rho}\right) \cong 2.6 \cdot 10^{-31} n_H T \ \mathrm{erg\ s^{-1} cm^{-3}}$$

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# Dominant thermal ionization processes: shocks

- A shock defines a pressure driven disturbance propagating with a higher velocity than the sound speed of the gas phase
- Shocks change the entropy of the system and are associated accordingly with irreversible processes

$$C_s \approx \sqrt{\frac{kT}{m}} \approx 1\,\mathrm{km\,s^{-1}}$$ **Cold neutral gas**

- Mach number

$$M \equiv \frac{v}{C_s}$$

# Dominant thermal ionization processes: shocks

- M<1 subsonic
- M>1 supersonic -> shock
- If magnetic fields are present, the propagation velocity of the undisturbed medium is given by the Alfven velocity

$$\upsilon_A^2 \equiv \frac{B^2}{4\pi\rho}$$

$$\upsilon_A^2 \approx \frac{\left(1\mu G \cdot \sqrt{n_H}\right)^2}{4\pi n_H} \qquad 10 < \mathrm{n_H} < 10^6\ \mathrm{cm^{-3}}$$

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# Dominant thermal ionization processes: shocks

- Sources of shocks in the ISM
  - Cloud collisions
  - HII regions
  - Stellar winds
  - Supernovae
  - Star formation and evolution
  - Spiral structure

- Typical sound speed values
  - $c_S$ ~ 1.2 km/s @ T=100 K
  - $c_S$ ~ 14 km/s @ T=10.000 K

$$c_S = \left( \frac{\gamma k T}{\mu m_H} \right)^{\frac{1}{2}}$$

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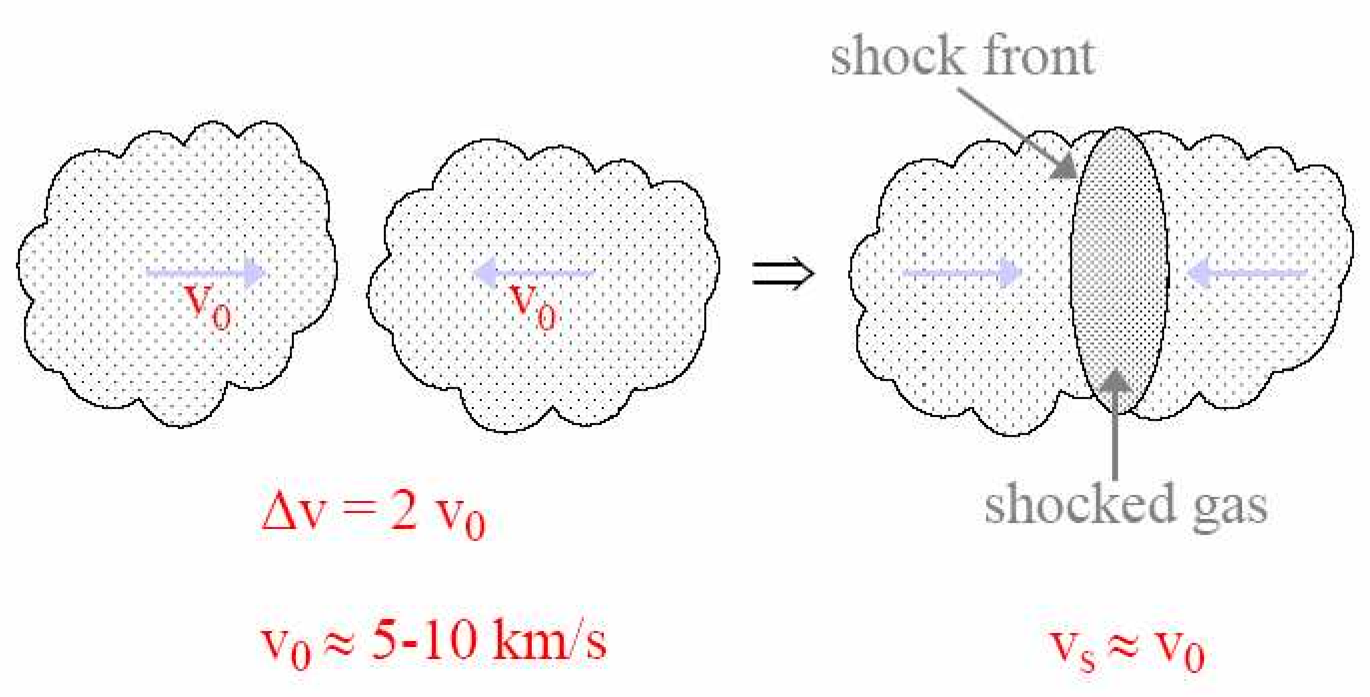
# Dominant thermal ionization processes: shocks

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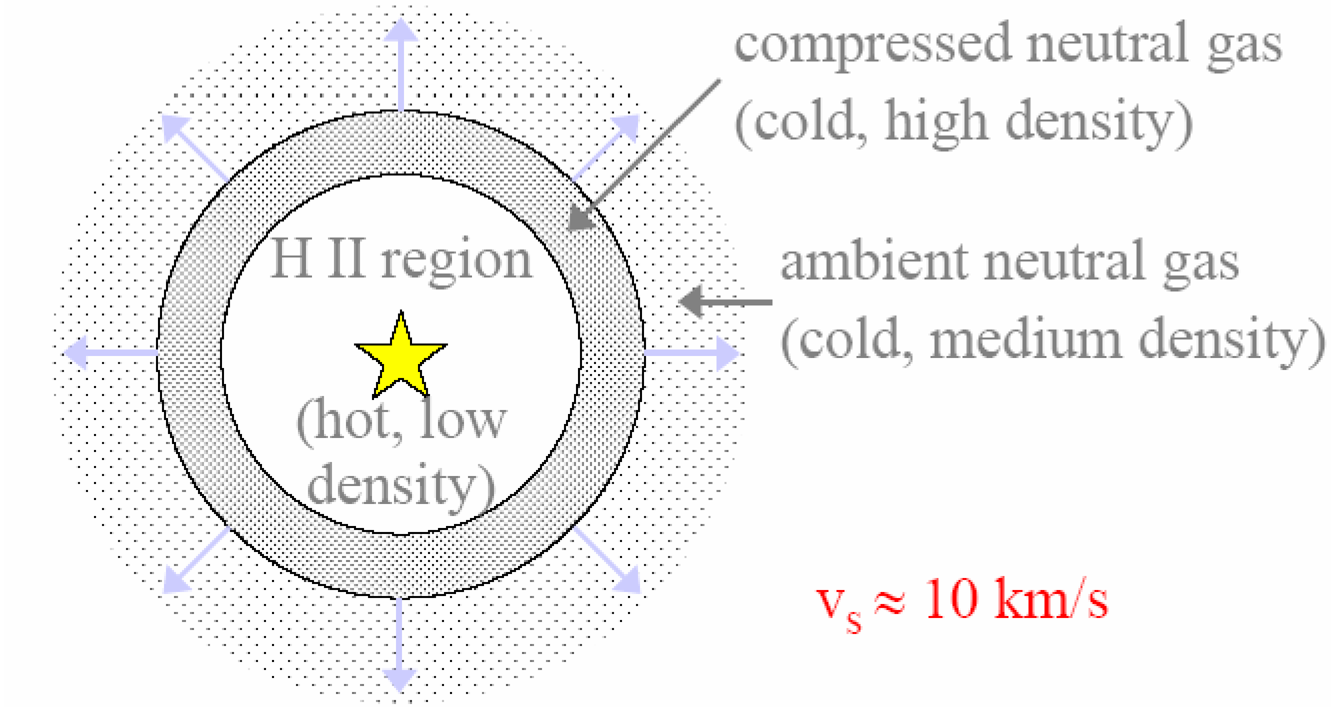
# Dominant thermal ionization processes: shocks

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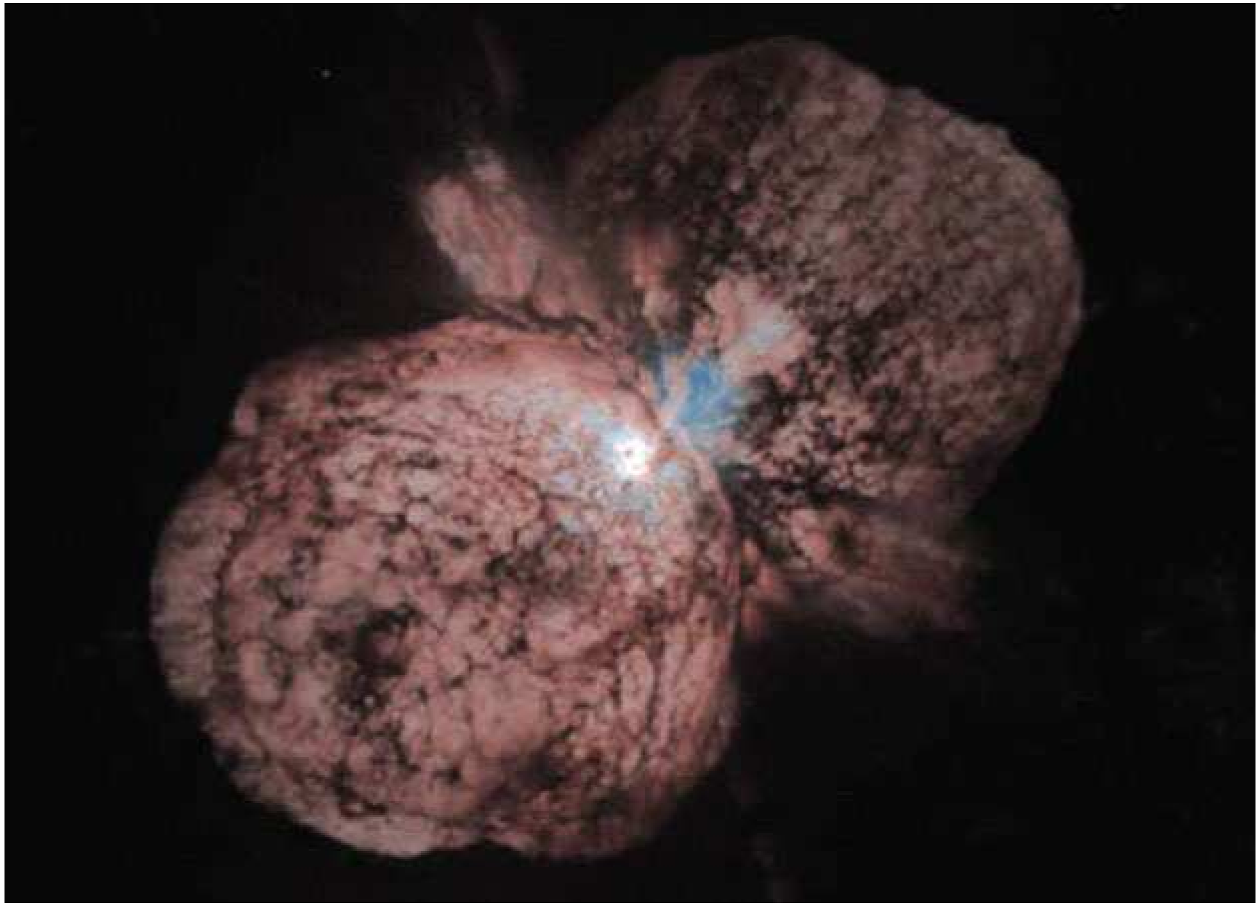
# Dominant thermal ionization processes: shocks



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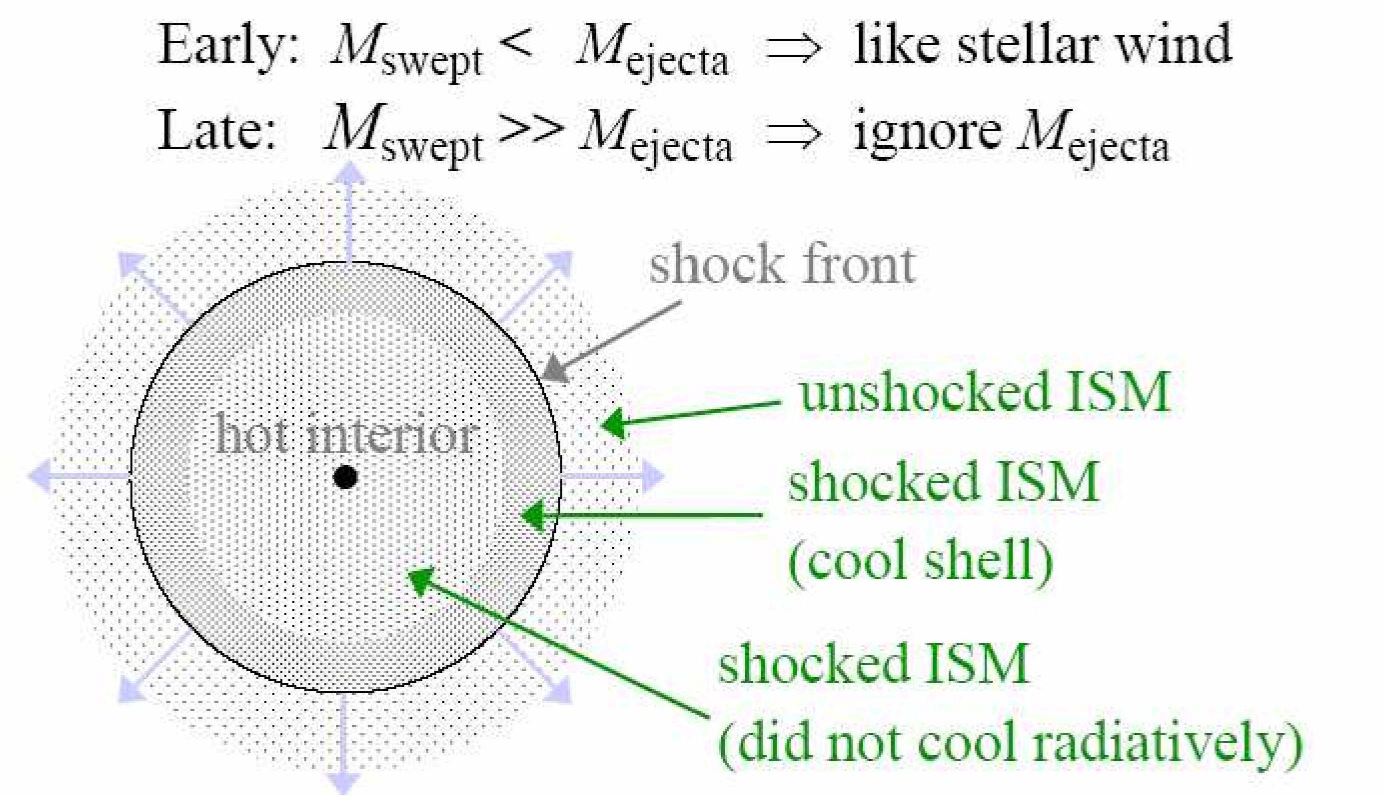
# Dominant thermal ionization processes: shocks

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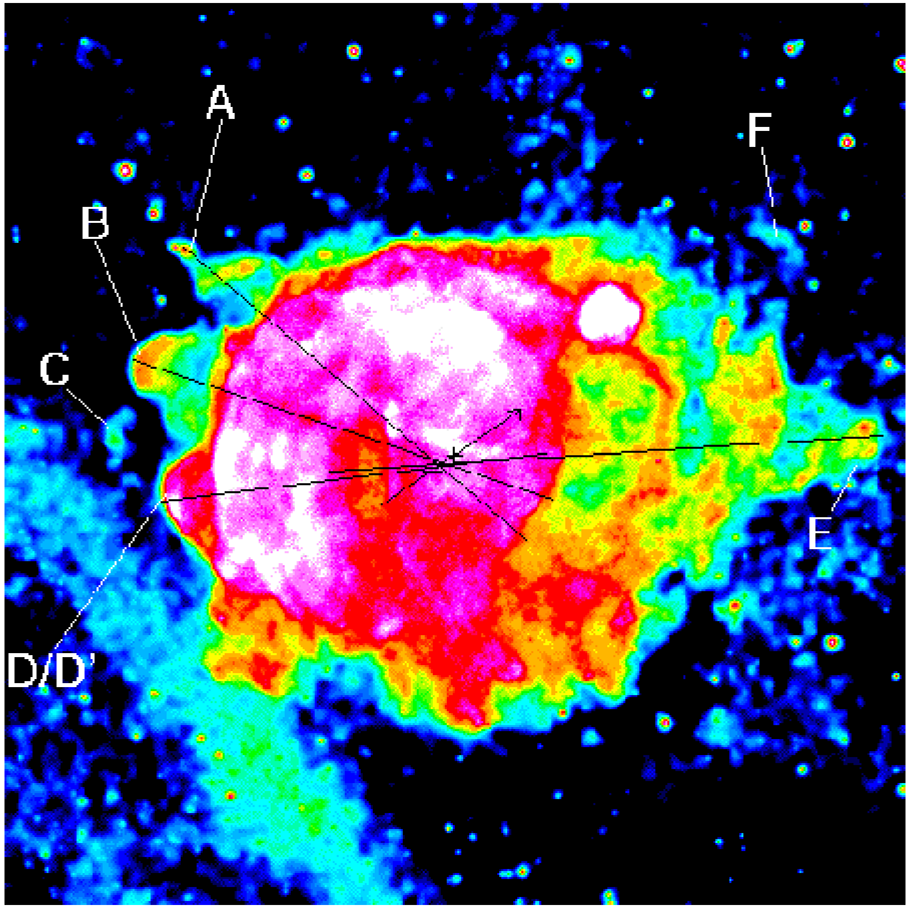


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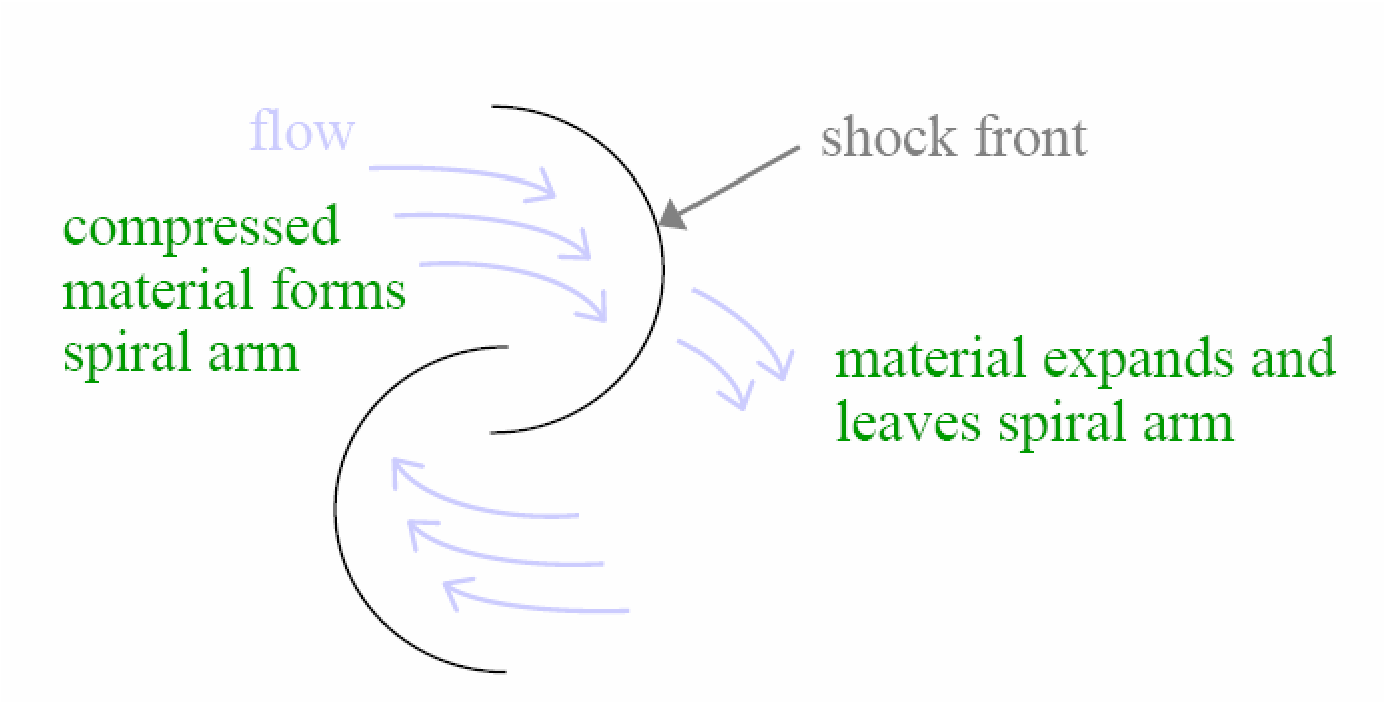
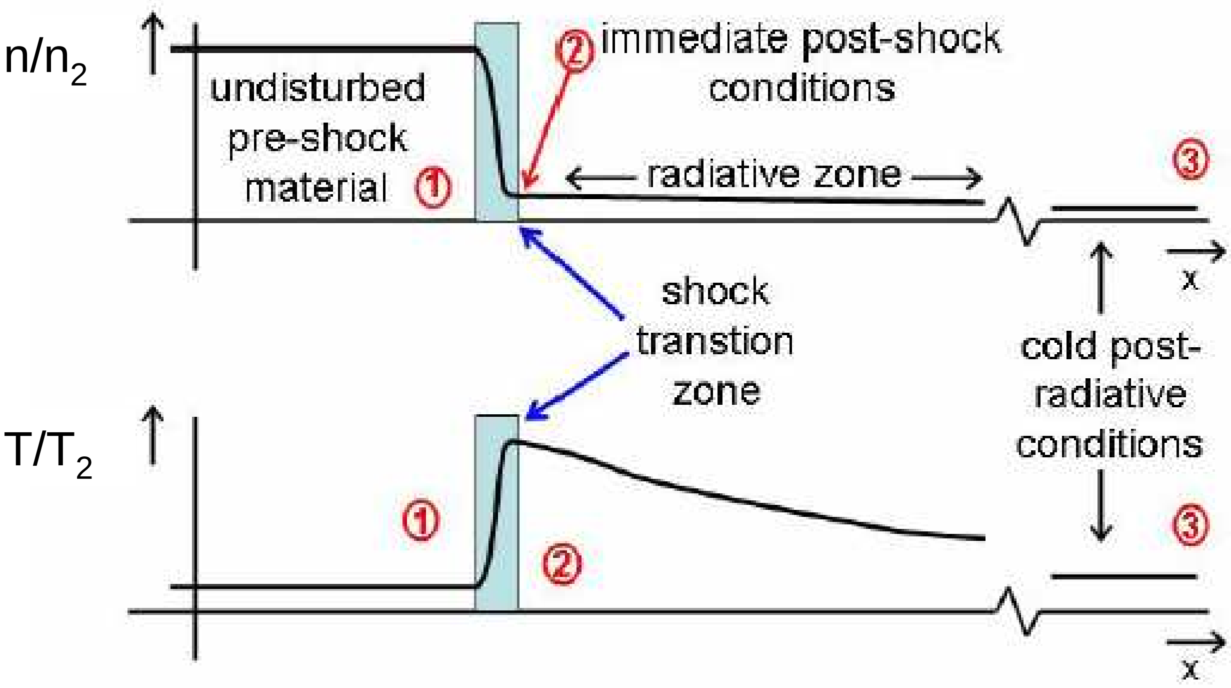
# Dominant thermal ionization processes: shocks




E. van Dishoeck 2006

# Dominant thermal ionization processes: shocks

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# Dominant thermal ionization processes: shocks

- Properties of strong shocks
  - Density ratio of shocked vs. un-shocked gas about 4
  - The magnetic pressure increases by the square of the volume density, in maximum about a factor of 16
  - The post-shock flow is subsonic
- Adiabatic and radiative shocks
  - **Adiabatic shock** denotes the situation that the energy of the system is conserved
  - **Radiative shock** denotes the situation that via photons the shocked gas cools
  - A shock is denoted as "**isothermal shock**" if the un-shocked gas has the same temperature as the post-shock gas

# Dominant thermal ionization processes: shocks

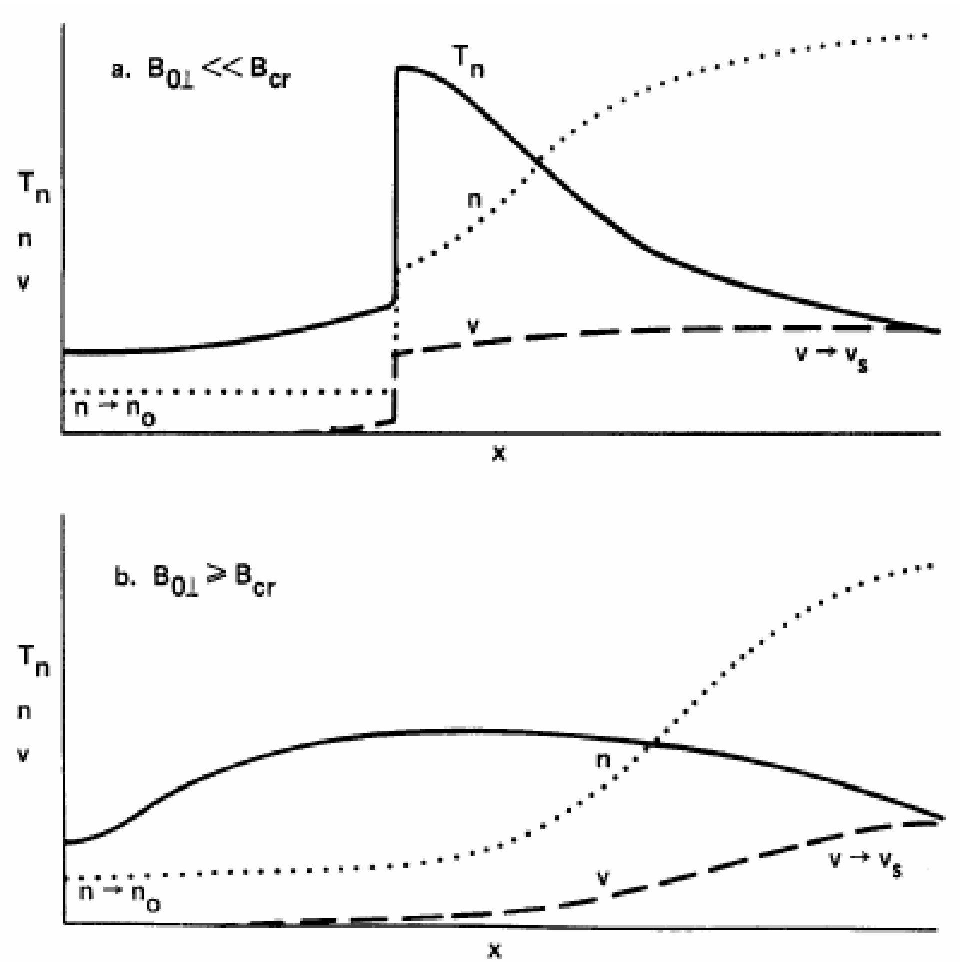
- Isothermal shocks $T_{post} = T_{pre}$ but $\rho_{pre} >> \rho_{post}$
  - Accordingly, the volume density ratio can be much larger than a factor of four!
  - Accounting also for magnetic fields, the compression of matter can be as large as a factor of 100!
- J- and C-shocks
  - Up to now the shocked gas has been considered as an homogeneous fluid, this situation is denoted as J-shock
  - The ISM consists of neutrals, ions and electrons. Moreover, magnetic fields are present yielding magneto-hydrodynamic waves (MHD)

$$\upsilon_{\varepsilon} = \sqrt{c_s^2 + \upsilon_A^2}$$

# Dominant thermal ionization processes: shocks

- J("jump")-shocks: $v_s > 50$ km/s
  - The shock can be considered as a discontinuity
  - Neutral atoms and ions occupy the same volume
  - The temperature of the post-shock gas is high
  - Strong UV radiation
- C("continuous")-shocks: $v_s < 50$ km/s
- Smooth variation of density, temperature and pressure function
- Separation between ions and neutral atoms (MHD-waves)
- The ions and neutral atoms have different temperatures
- Bulk of the radiation in the infrared regime

# J-shock

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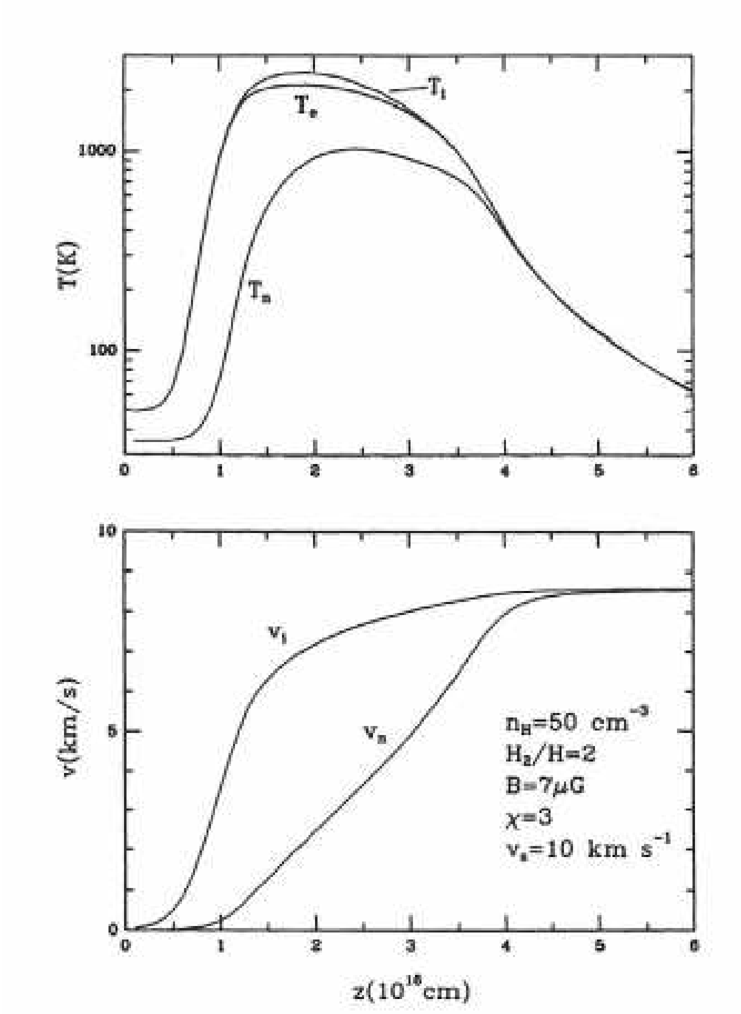
# C-shock




Draine & Katz 1986

# Summary of heating processes

- Heating by low-energy cosmic-rays
  - Dense molecular clouds
- Photoelectric heating by grains
  - Dense molecular clouds, supernova remnants
- Photoelectric heating by the photo-ionization of atoms and molecules
  - HII regions
- photoelectric heating by soft X-rays
  - Warm diffuse interstellar medium, cold interstellar medium
- Chemical heating
  - Dense molecular clouds
- Heating by grain-gas thermal exchange
  - Dense molecular cloud
- Hydrodynamic and magneto-hydrodynamic heating
  - Large- and small-scale shocks, supernova remnants
- Interstellar shocks
  - Large- and small scales, supernova remnants

# Summary of heating processes

J. Le Bourlot et al.: Infrared and submillimetric emission lines from the envelopes of dark clouds 235

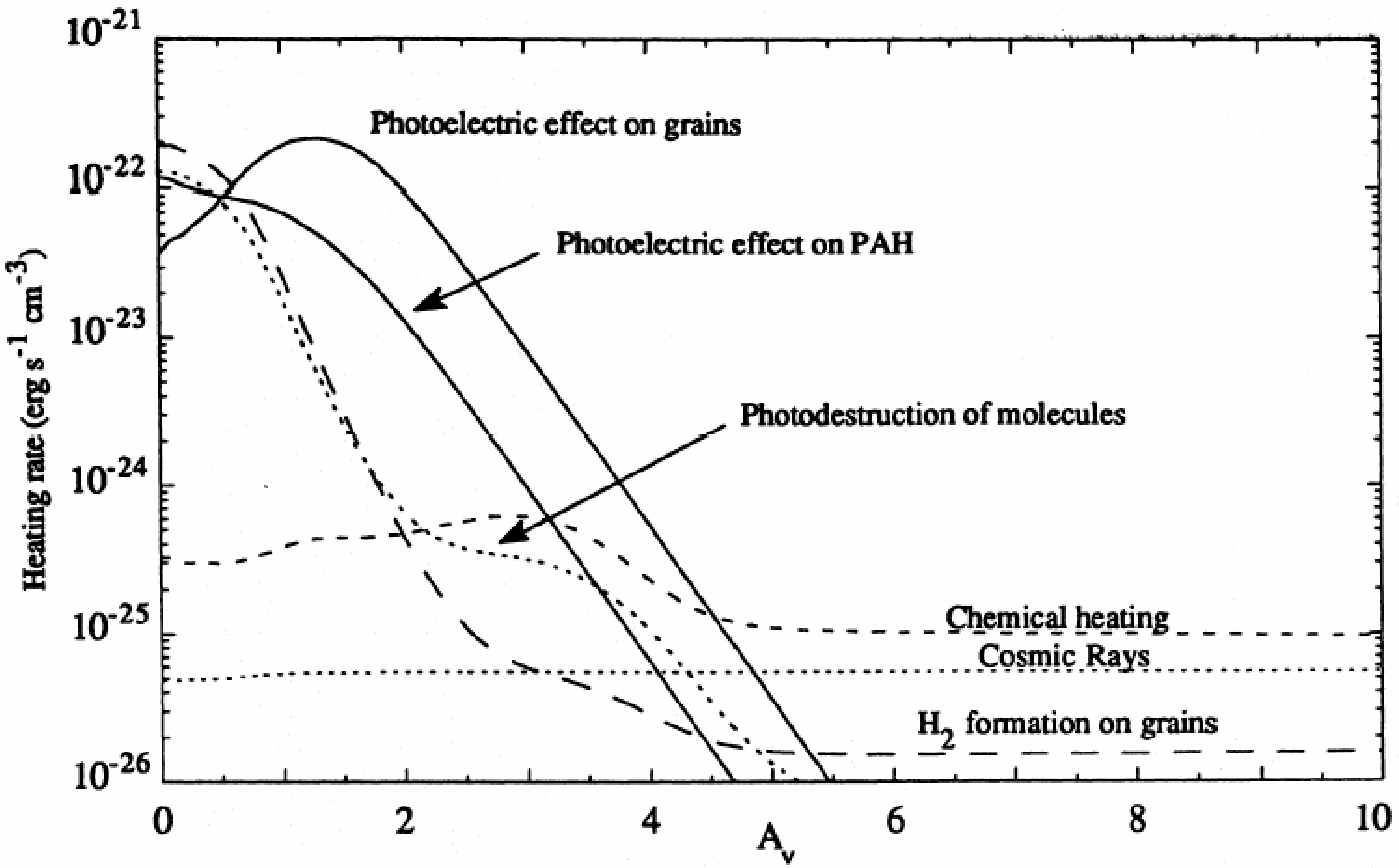



**Fig. 1a.** Contributions to the rate of heating of the gas for an isochoric model in which $n_H = 10^3\ \mathrm{cm^{-3}}$ and $\chi = 1000$. The fractional elemental abundances of C and O are C/H = 3.62 $10^{-5}$ and O/H = 8.53 $10^{-5}$ (see text, Sect. 2.3)

U. Klein/J.Kerp
ISM 2009

# Cooling

# Cooling

- Fine structure line cooling is almost everywhere in the ISM the dominant physical process
- Efficient cooling by fine structure lines needs
  - High element abundance
  - A fine-structure level close to the fundamental level
- In neutral regions CII and OI dominate
- In ionized regions OII, OIII, NII, NIII, NeII and NeIII dominate the cooling



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# Line diagnostic (temperature)

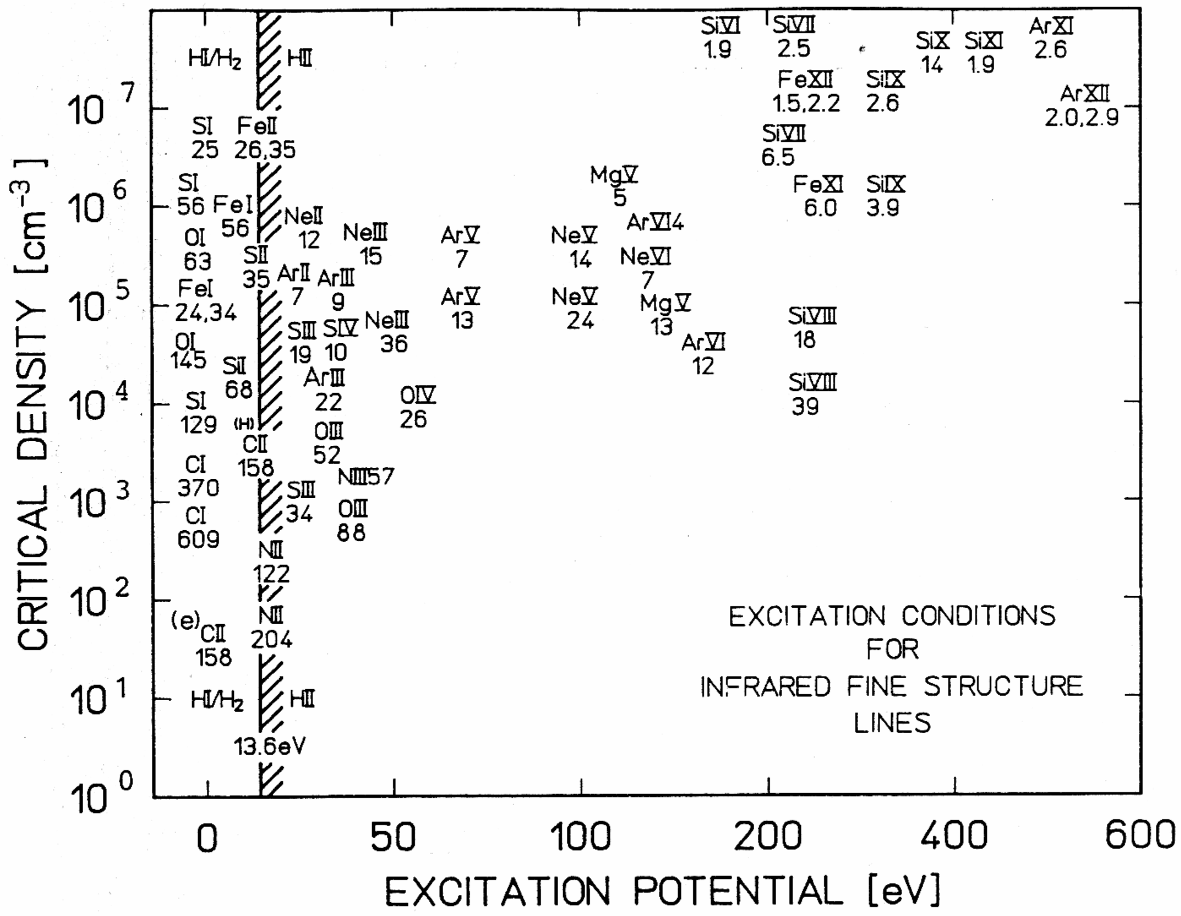


**Fig. 7.** Infrared fine structure lines as probes of physical conditions in interstellar clouds

Genzel, Saas-Fee Advanced Course 21



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# Line diagnostic (temperature)

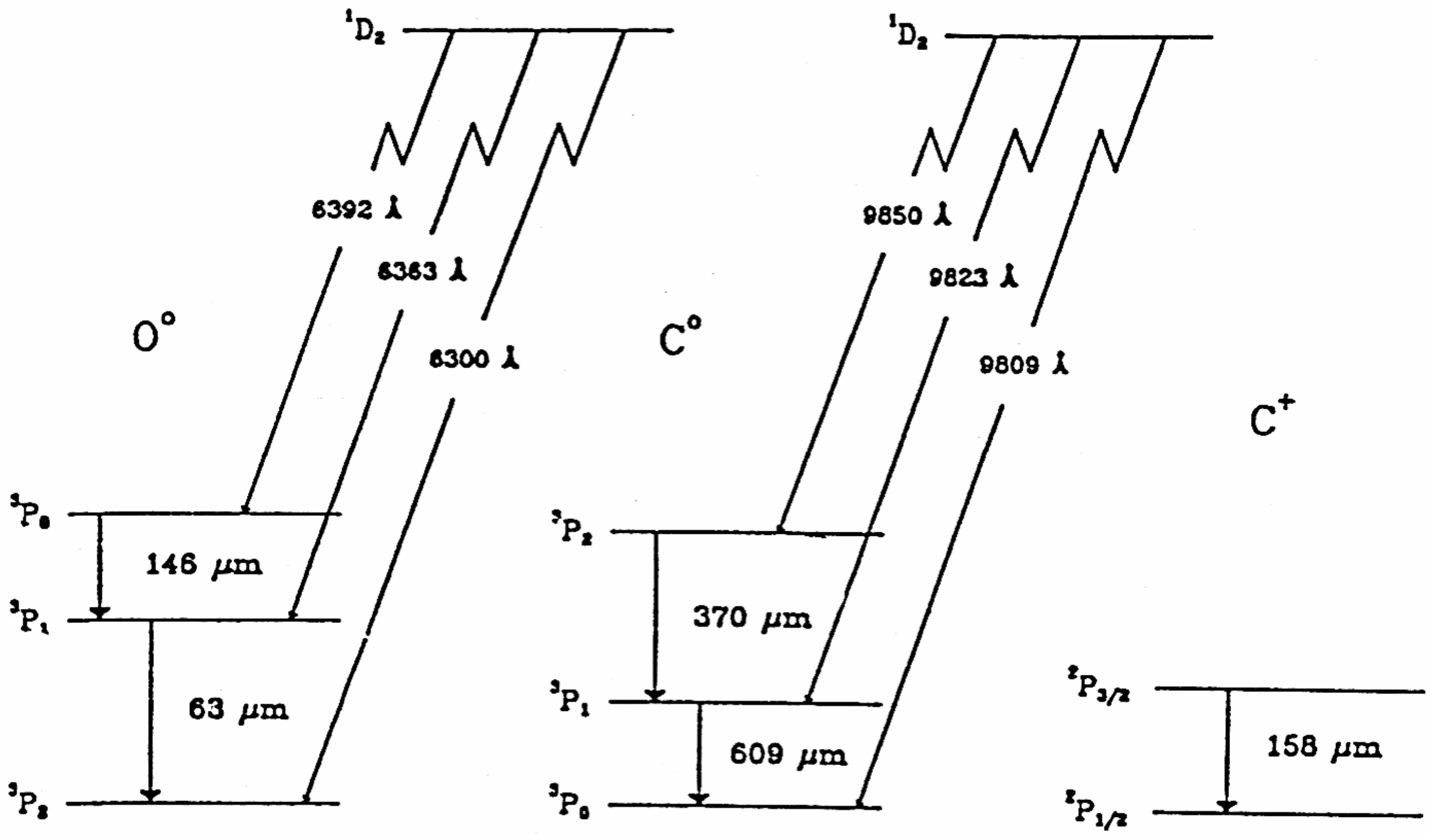


**Fig. 2.** Lowest energy levels and fine structure transitions of $O^0$, $C^0$ and $C^+$

Genzel, Saas-Fee Advanced Course 21

# Cooling of neutral gas

- Almost all carbon in the gas phase is present in form of CII while almost all oxygen is in OI
- SiII, SII and FeII are abundant but their fine structure transitions can be only excited by collisions with electrons and neutrals at high temperatures
- At low temperatures only the upper fine-structure level of CII at 91.2 K is excited
- The line intensity at 157.7µm is

$$I_{ul} = \frac{n_u A_{ul} h\nu}{4\pi} \,\mathrm{erg\,s^{-1}cm^{-3}str^{-1}}$$

- The OI first fine-structure level is at 228 K, warm neutral gas



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# Cooling of neutral gas

- The cooling rate per unit volume is

$$\Lambda_{e,CII} = n_C C_{lu} h\nu = n_C n_e \frac{8.63 \cdot 10^{-6} \Omega_{ul}}{g_l \sqrt{T}} e^{-\frac{h\nu}{kT}} h\nu$$

$$\Lambda_{e,CII} \cong 1.23 \cdot 10^{-27} n_H^2 d_C^2 e^{-\frac{91.2K}{T}} \left( \frac{T}{100K} \right)^{-\frac{1}{2}} \mathrm{erg\ s^{-1} cm^{-3}}$$

$$\Lambda_{H,CII} \cong 7.9 \cdot 10^{-27} n_H^2 d_C e^{-\frac{91.2K}{T}} \mathrm{erg\ s^{-1} cm^{-3}}$$

- $d_C$ denotes the depletion fraction of carbon
- The excitation by collisions with hydrogen atoms excite the carbon fine structure level on a higher degree, as long as the ionization fraction of the gas is low

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# Cooling of ionized gas

- Excitation by electron collisions with ions is the dominant process in ionized gas, Lyα dominates
- The cooling line intensity can be calculated -as in case of carbon- but de-excitation processes have to be considered
- The full radiation transfer and excitation conditions have to be considered in model calculations
- Only the free-free continuum radiation is important, while the free-bound and 2-photon continuum can be safely neglected

$$\Lambda_{ff} = 1.42 \cdot 10^{-27} \sqrt{T} n_e \left( n_{H^+} + n_{He^+} + n_{He^{++}} \right) \mathrm{erg\,s^{-1}cm^{-3}}$$

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# Cooling of ionized gas

HEATING AND IONIZATION OF HI REGIONS 383

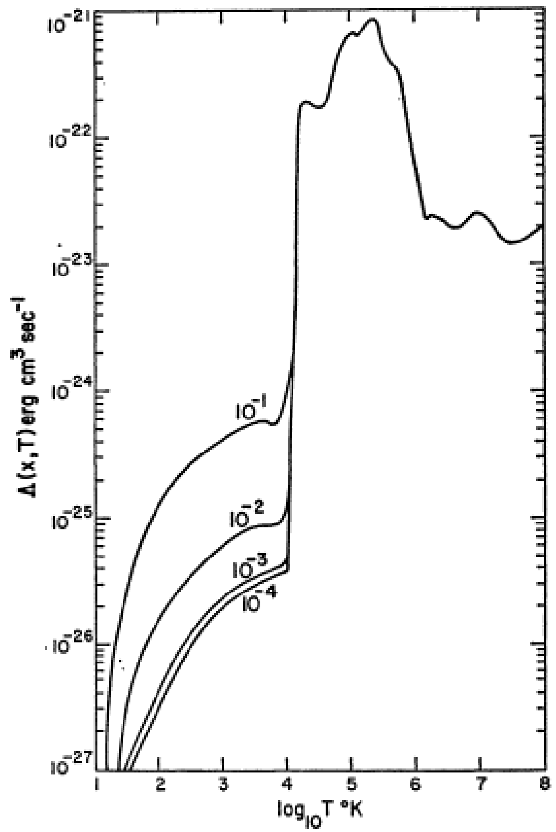


FIGURE 2. The interstellar cooling function $\Lambda(x, T)$ for various values of the fractional ionization $x$. The labels refer to the values of $x$.

Dalgarne & McCray 1972

U. Klein/J.Kerp
ISM 2009

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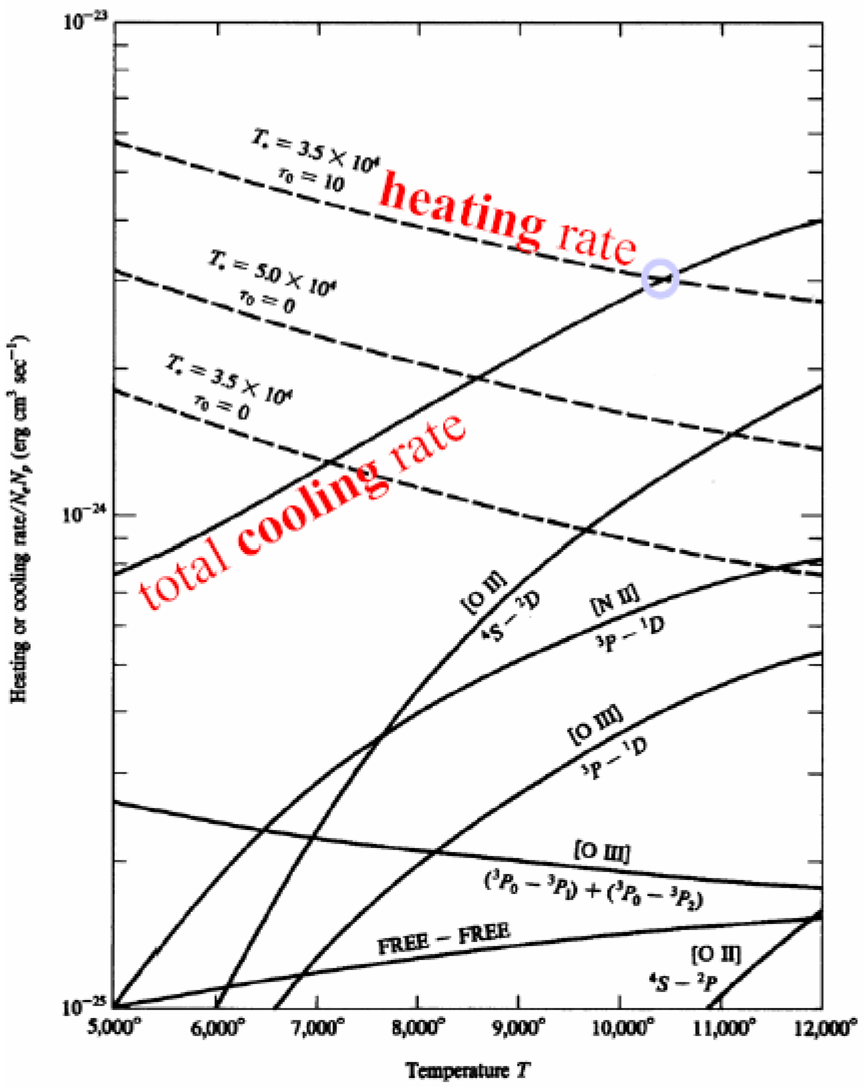
# Cooling of ionized gas




E. van Dishoeck, 2006 lecture 4



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# Cooling of molecular gas

- The most important coolant are the rotational emission lines of CO
- The emission line of the CI fine-structure line 23.4 K above the ground level is also important
- On large scales the cooling by CO and CI are of the same importance
- The calculation of the energy released by the CO transition is not easy, because all thermally populated energy levels are optically thick

$$\Lambda_{CO} \approx 4\pi \sum_{l}^{J_m} B\left(\nu_{J,J-1}, T\right)\beta_{J,J-1}$$

- With B for the black body spectrum and β as escape probability

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# Cooling of molecular gas

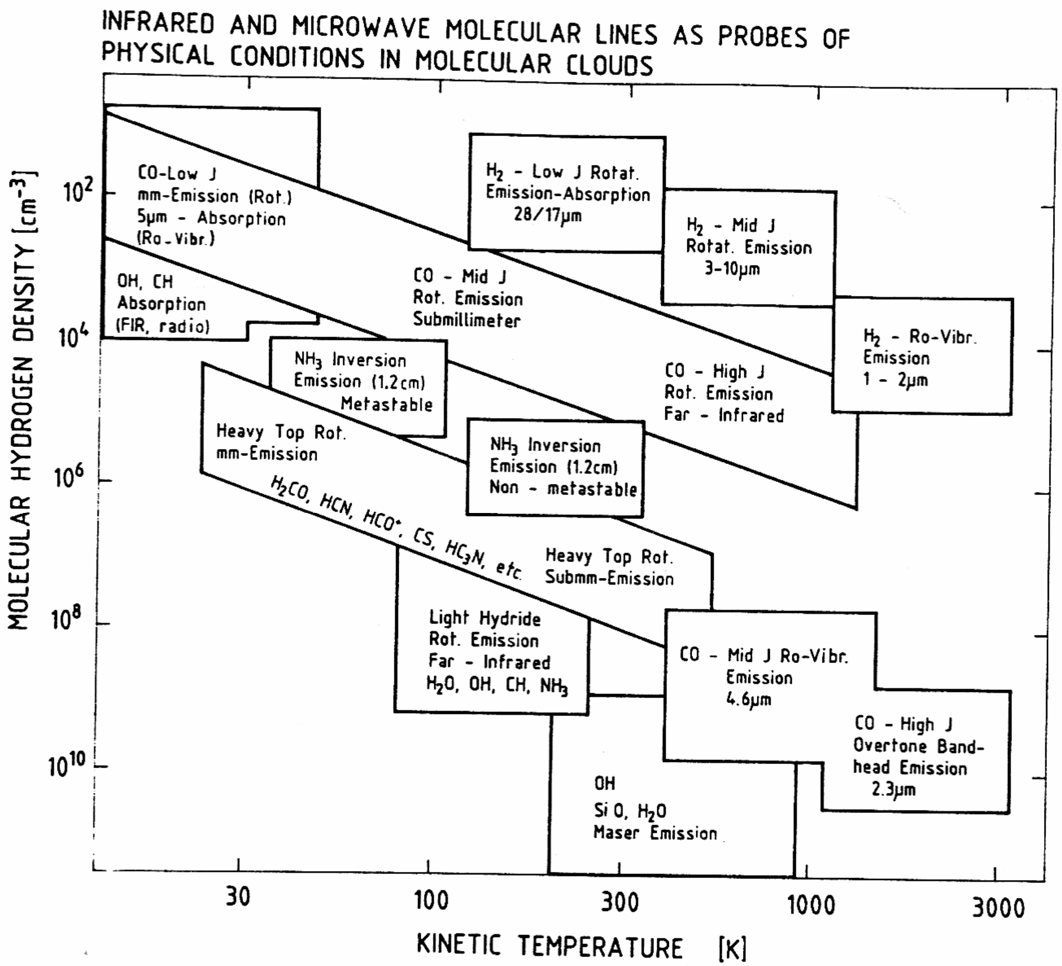


**Fig. 8.** Molecular lines as probes of physical conditions in interstellar clouds

Genzel, Saas-Fee Advanced Course 21



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# Cooling of molecular gas



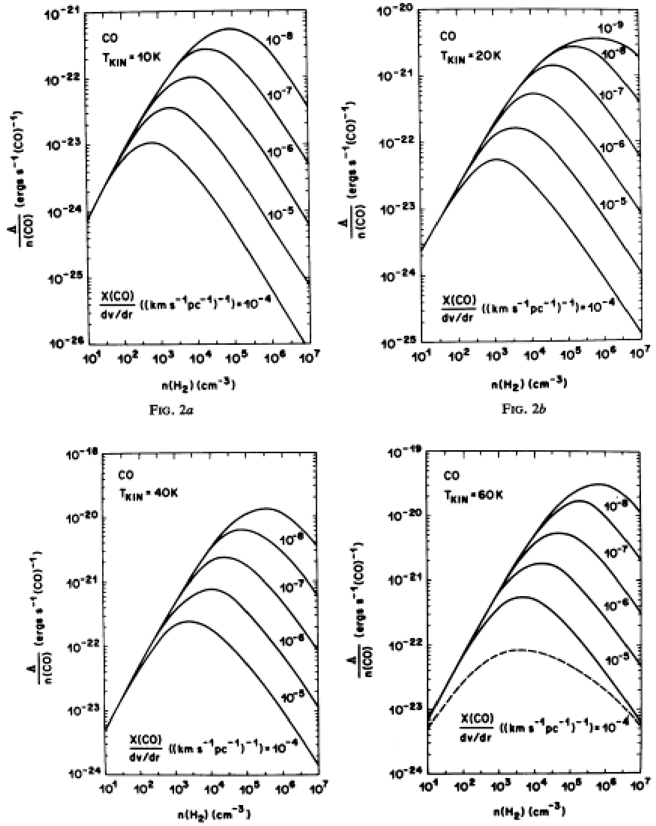


FIG. 2a FIG. 2b FIG. 2c FIG. 2d

FIGS. 2(*a*)–2(*d*).—Cooling per CO molecule as a function of $n(H_2)$ and CO fractional abundance for kinetic temperatures 10 K, 20 K, 40 K, and 60 K. The broken line in Fig. 2*d* indicates the cooling for $X(\mathrm{CO})/(dv/dr) = 10^{-4}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$ if the effect of trapping on the escape probabilities but not on the level populations is taken into account. The trapping reduces the population of levels $J \leq 3$ and increases the population of levels $J \geq 4$.

Goldsmith & Langer 1978



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# Requirements for cooling

- **High frequency of collisions** (depends on the chemical composition of the gas)
- The amount of **exchanged energy is less than the thermal (kinetic) energy of the gas**
- High probability of energy exchange (depends on the chemical composition of the gas)
- The **excitation energy is transported via photons**
- The photons are emitted by the excited atom/ion before the next particle collision happens
- The photons leave the gas distribution without any photoelectric absorption event along the path

# Thermal equilibrium and stability

- We studied up to now all heating and cooling mechanisms of the different gaseous phases, however these phases are coupled in the Milky Way in a form that can be approximated by an equilibrium
- The term equilibrium denotes the fact that several phases co-exist within the Milky Way Galaxy at the same time but does not imply that this situation will last forever
- Stability considerations accordingly will help to estimate the relevant time scale for a quasi equilibrium situation

# The atomic medium

- Heating
  - Photoelectric heating by dust grains $\Gamma_{pe}$
  - Heating by soft X-rays $\Gamma_X$
- Cooling
  - Fine-structure line of CII at 158µm $\Lambda_{e,CII} + \Lambda_{H,CI}$
- Combining heating and cooling, we find

$$10^3 \varepsilon\chi = n_H d_C e^{\frac{91.2}{T}} \left[ 1.23 d_C \sqrt{\frac{T}{[100K]}} + 7.9 \right]$$

- Inserting n=25 cm$^{-3}$, T= 100 K, $n_e = n_{CII}$ we find $\Lambda/n_H$ and $\Gamma/n_H$ equal with $3 \cdot 10^{-26}$ erg s$^{-1}$ H$^{-1}$



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# The atomic medium

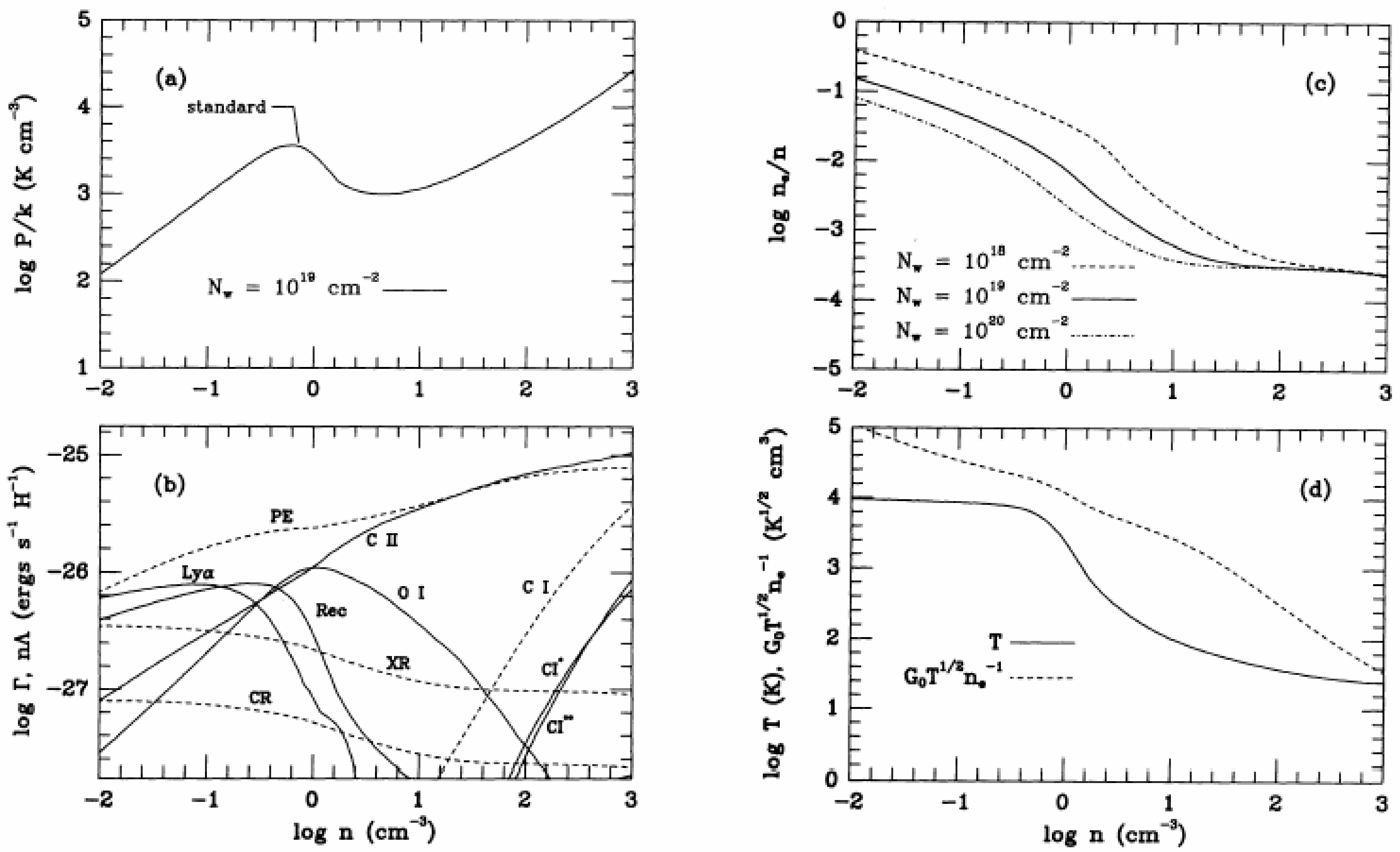


FIG. 3.—(*a*) Thermal pressure $P/k$ vs. hydrogen density $n$ for standard model (see § 3.1). Gas is thermally stable for $d(\log P)/d(\log n) > 0$. (*b*) Heating and cooling rates per hydrogen nucleus vs. density $n$ for pressure curve of panel *a*. Heating rates (*dash*); Photoelectric heating from small grains and PAHs (PE); X-ray (XR); Cosmic ray (CR); photoionization of C (C I). Cooling rates (*solid*); C II fine-structure (C II); O I fine-structure (O I); Recombination onto small grains and PAHs (Rec); Lyα plus metastable transitions (Lyα); C I fine-structure 609 μm (C I*); C I fine-structure 370 μm (C I**). (*c*) Electron fraction $n_e/n$ as a function of hydrogen density $n$ for the pressure curve of panel *a* (*solid*). Also shown are curves for $N_w = 10^{18}$ cm$^{-2}$ (*dash*), and $N_w = 10^{20}$ cm$^{-2}$ (*dash-dot*). (*d*) Gas temperature $T$ (*solid*) and ionization parameter $G_0 T^{1/2}/n_e$ (*dash*) as a function of hydrogen density $n$ for the pressure curve of panel *a*.

Wolfire et al. 1995, ApJ 443, 152



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# The end