ISM heating and cooling

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Outline

- Overview and Motivation
- Heating and Cooling of Ionized Regions
- Heating and Cooling of Diffuse (A_V<1) ISM clouds
- Heating and Cooling of Dense molecular clouds

Literature

- Draine "Physics of the interstellar and intergalactic medium"
- Van Dishoeck "ISM Lecture Notes" at Leiden
- Spitzer "Diffuse Matter"
- Bovino summary at earlier KROME school
- Neufeld et al.(95) for Molecular Cloud Cooling
- Flower and Pineau des Forets (Primordial Gas)

Importance of understanding thermal equilibrium

- ISM temperature determines properties such as the Jeans length and the sound speed
- Thermal pressure often dominates both magnetic and turbulent pressure
- Understanding the cooling processes often allows useful diagnostics

Temperature of ISM phases

- Ionized Regions (HII Regions) are typically 10000 K (thermostat reflects excitation energy of cooling transitions)
- Diffuse HI (neutral atomic H) regions have a dense phase (T 50-200 K) and a warm phase (order 5000 K)
- Molecular Clouds tend to have T of order 10-30 K

Thermal Equilibrium in HII Regions

- Via the excess energy of photelectrons
- $E_{heat} = h\nu - I.P$
- Heating Rate is product of Ionization rate and E_{heat}
- Time Scale $1/(\beta n(e))$ or $10^5/n(e)$ yrs with n(e) in cm^{-3} . Steady state usually valid (cf sound crossing time)

Ionization Equilibrium from Van Dishoeck

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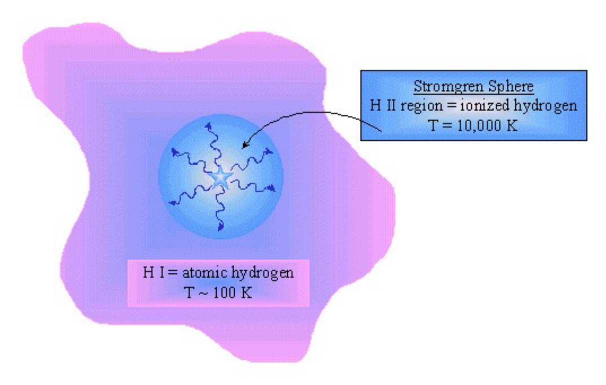
2.5 Photoionization of pure H nebula

- Q: how many hydrogen atoms can be ionized by UV photons from star?
- Statistical equilibrium: photoionization = recombination



$$n(\mathrm{H})\Gamma_{pi}(\mathrm{H}) = n(e)n(\mathrm{H}^+)\alpha_H$$

Model Atmosphere SEDs

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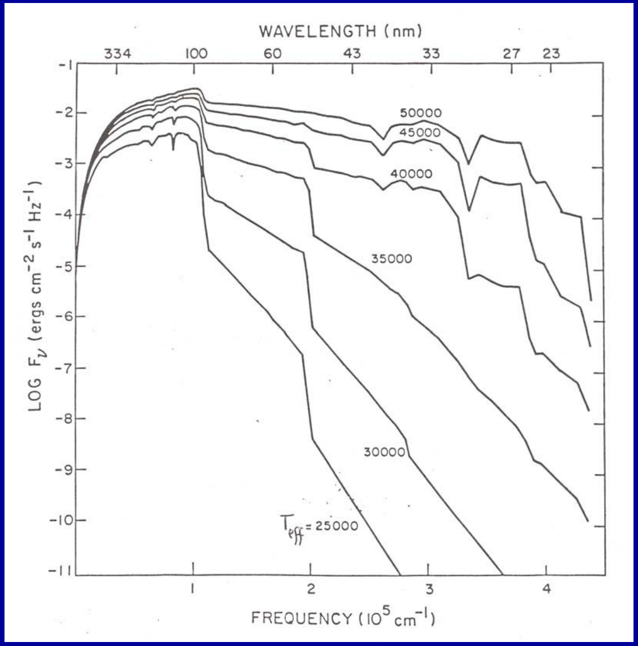
Stellar fluxes



The ionization rate in an HII region is a convolution of the cross section σ_{ph} and the mean intensity J(v). Note that most of the contribution comes from close to threshhold v_H (13.6 eV)

$$\beta_{ph} = \int_{\nu_H}^{\infty} \sigma_{ph}(\nu) \frac{J(\nu)}{\mathrm{h}\nu} d\nu$$

The recombination rate to level n is an average over a Maxwellian velocity distribution for the recombining electrons folded with the cross section $\sigma_{rr,n}$.

$$\alpha_n = \frac{4}{\sqrt{\pi}} (\frac{m_e}{2kT})^{1.5} \int u^3 \sigma_{rr,n}(u) \exp -(\frac{m_e u^2}{2kT}) du \qquad (2)$$

The condition of ionization equilibrium is now obtained by summing over all α_n with $n \geq 2$. Then :

$$\beta_{ph} n(HI) = N_e N(H^+) \sum_2^{\infty} \alpha_n \qquad (3)$$

Recombinations to n=1 produce a Ly Continuum Photon which normally (Case B) reionises H on the spot

We think that the K.E. of the electrons ejected during photoionization of H is the main heating process. How much energy is injected per photoionization. This will be something like :

$$\beta_{ph}\bar{E}_{PE} = \int_{\nu_H}^{\infty} \sigma_{ph}(\nu)\frac{J(\nu)}{\mathrm{h}\nu}(\mathrm{h}\nu - I_H)d\nu \qquad (1)$$

and the heating rate (erg cm^{-3} s^{-1}) is :

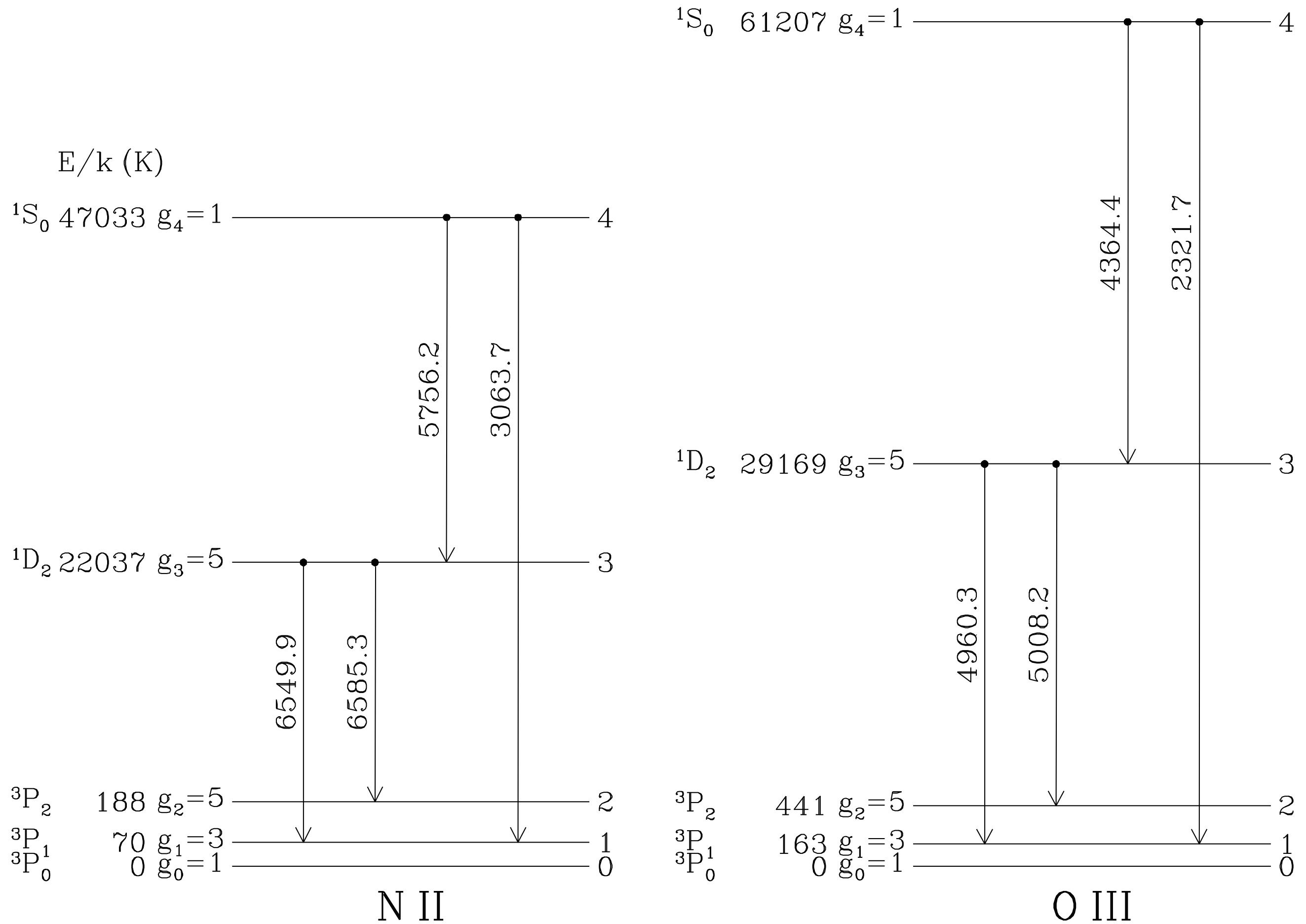
$$\Gamma_H = \beta_{ph} n(HI)\bar{E}_{PE} = \beta_{rec} N_e^2 \bar{E}_{PE} \qquad (2)$$

The heating rate depends on the recombination rate and thus is proportional to the square of Ne as (roughly) is the cooling rate

Cooling Ionized Gas

- Mainly via forbidden nebular lines such as OIII 5007 Angstrom
- These are excited by electron collisions with the different ions
- The cooling therefore depends on metallicity (abundances) and ionization equilibrium

ENERGY LEVELS FOR OIII and NII



Forbidden Line Cooling

- Solve for level populations including collisional and radiative processes
- Then sum over cooling from each level and species

This tends to behave as an exponential exp(-T0/T) where T0 (roughly 30000K) Is upper level excitation

Solve for level populations

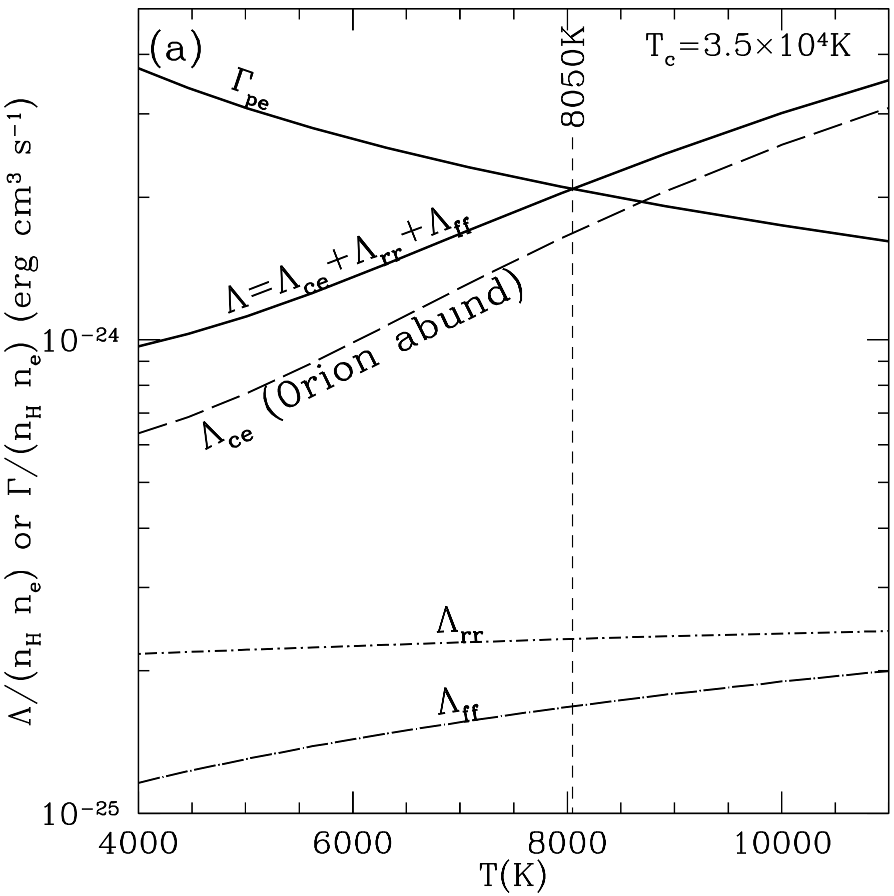
$n_i\ (\Sigma A_{ij} + C_{ij} n(e)\ = \Sigma n_j (A_{ji} + C_{ji} n(e))$

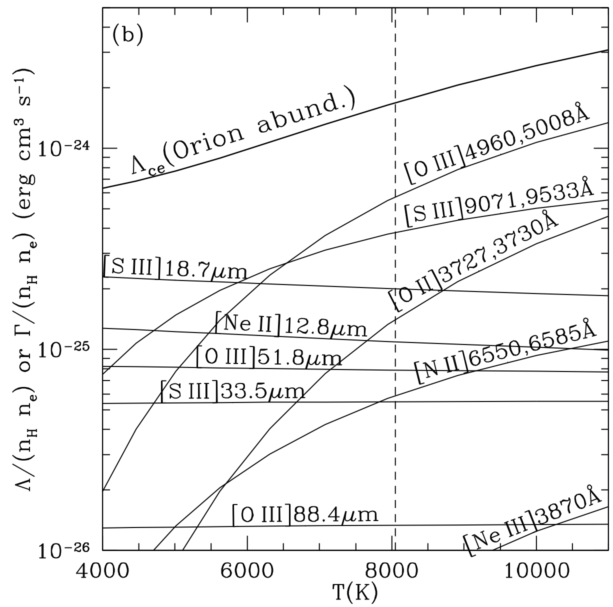
where $n(e)$ is electron density, A_{ij} is spontaneous transition probability C_{ij} is collisional rate .
Add conservation equation for sum over n_i

$$C.Rate = \Sigma\ \Sigma\ n(X,i)\ \Sigma\ A_{ij}\ (E_i - E_j)$$

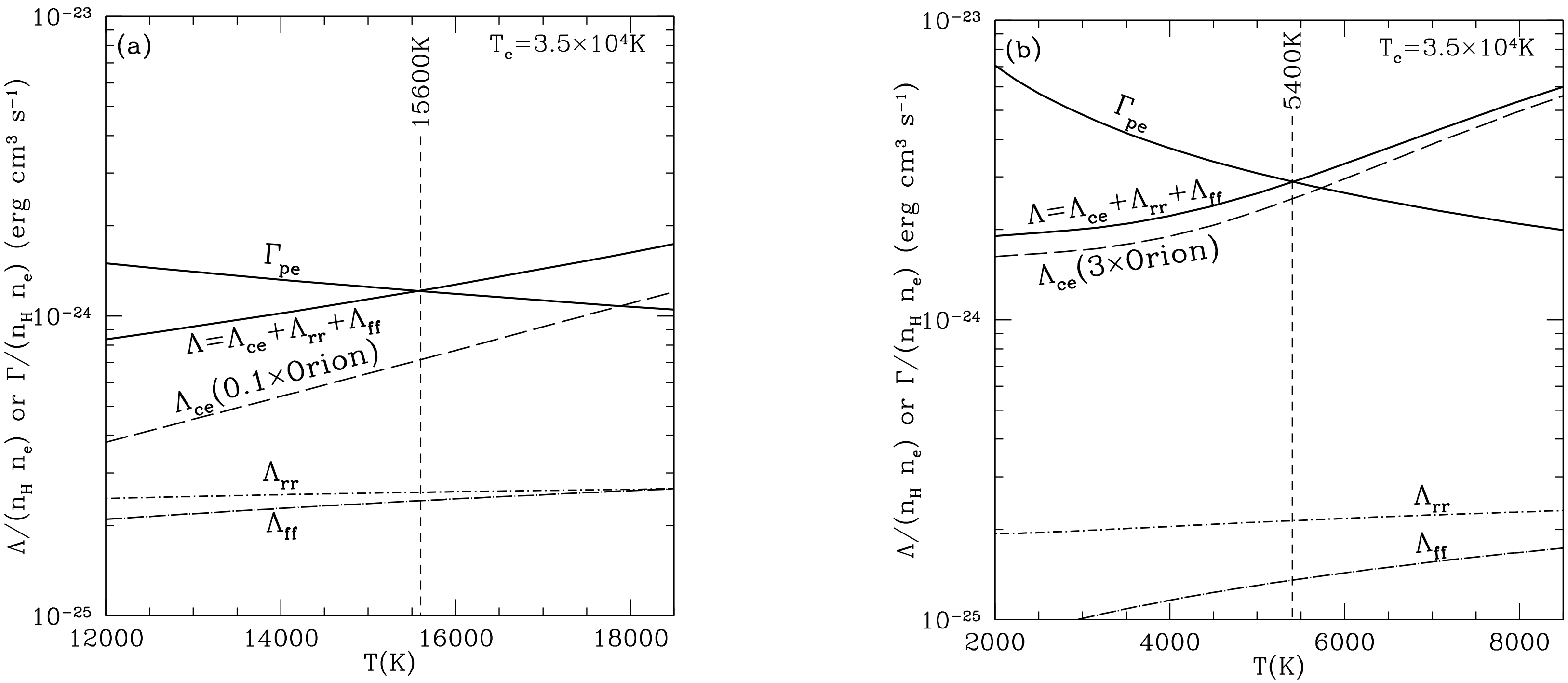
Equilibrium between heating and cooling in HII region for “Orion abundances” and Equilibrium T 8050 K

Heating from star of T_{eff} 35000 K





Abundance changes can greatly affect the equilibrium T (15600 K for 0.1*Orion to 5400 K for 3*Orion



Atomic H (HI) regions

- Optically thick in the Lyman continuum
- Elements with Ion.Potenial less than 13.6 eV (C,Si,S) are ionized
- Cold clouds seen in HI absorption (CNM) but warmer intercloud HI only emission
- Optical (UV) measurements imply thermal pressure n(HI)T 3000 cm^{-3}K

Heating HI clouds

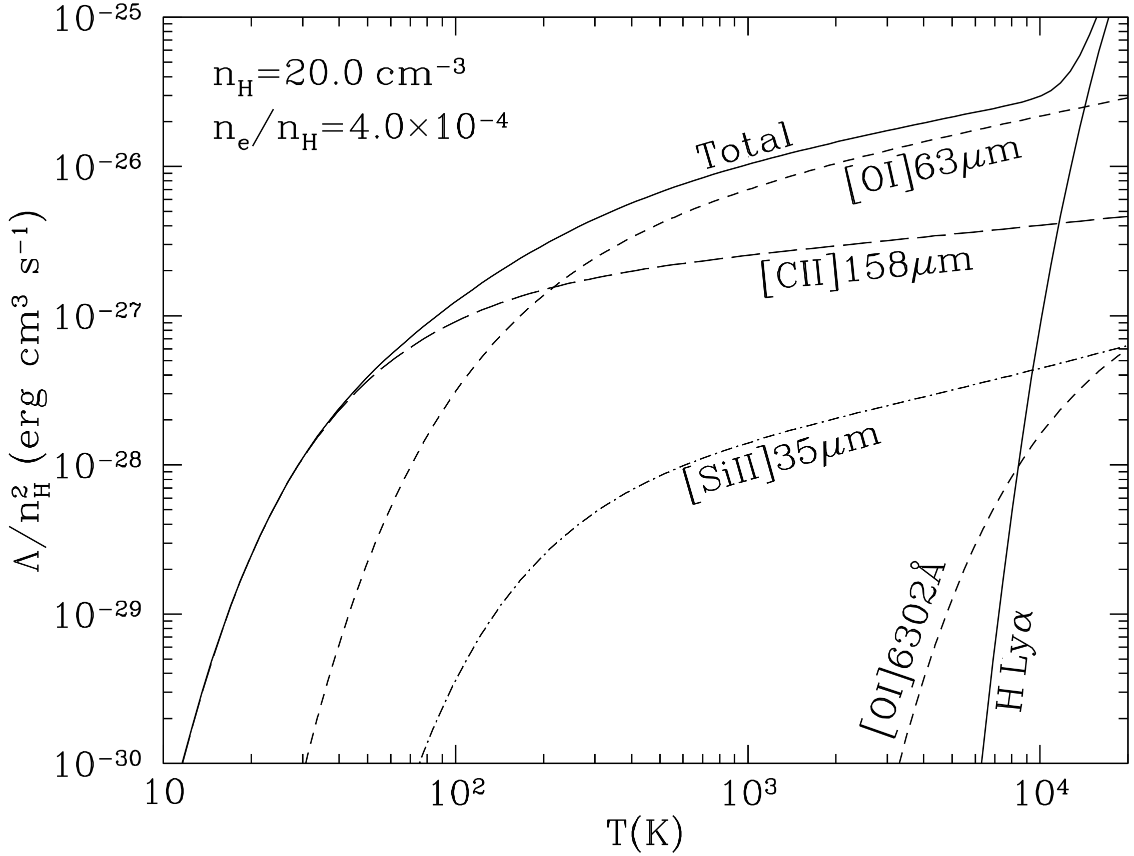
- Cosmic Ray (X-ray) ionization (secondary (35eV)electrons interact with background plasma
- Photoelectrons from FUV interacting with small grains and PAHs (usually dominant)
- MHD dissipation

Photoheating of grains proportional to density
And dependent on photoelectric yield

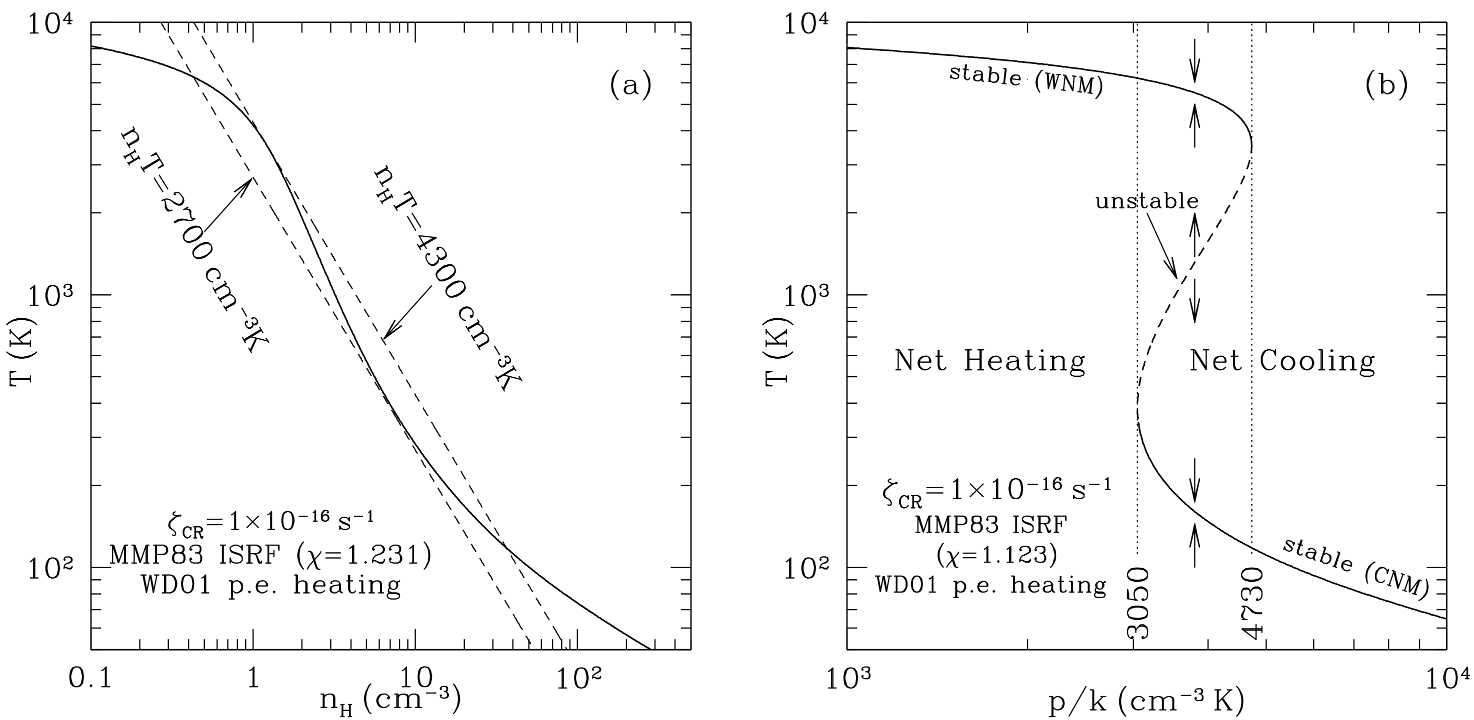
Cooling HI through fine structure lines

- CII 157 micron 2p(3/2)-2p(1/2) transition with critical density 3000 cm-3 mostly dominant (rate as exp(-92/T)). Note that both electron and atomic H collisions need to be considered
- OI 63 micron 227 K above ground
- At very low metallicity however H2 (HD?) may dominate (and this dominates in early universe)

Cooling rate for typical ISM cloud as fn of temperature. Note dominance of fine structure Lines till 10000 K. Solar metallicity



Plot of temperature versus densityand temperature versus pressure for typical ISM UV radiation field, grain properties, CR ionization. Note the 2 phase character in small range of pressure



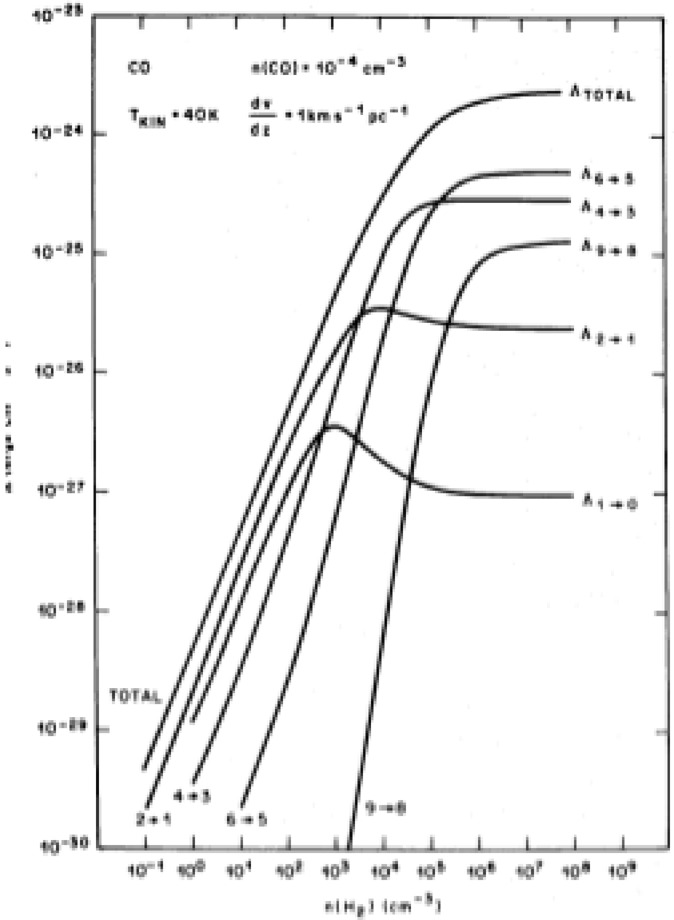
Heating molecular gas

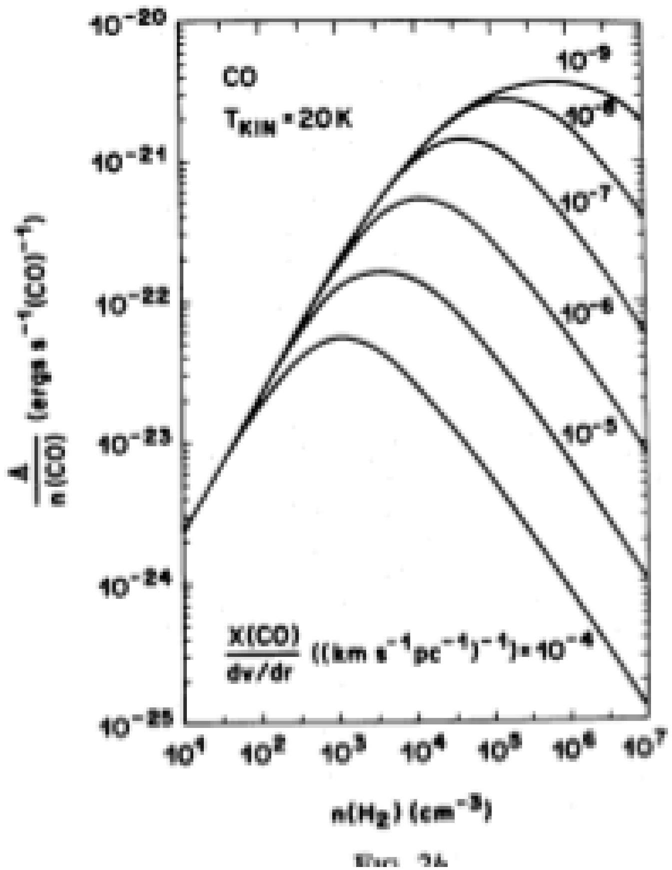
- Molecular (hence high extinction clouds) exclude UV!
- Cosmic Rays (Ion. Rate of order 10^{-17} s -1) are one possibility
- Compression and Ambipolar Diffusion (Wide lines in Gal.center and extrag. Clouds)
- Interaction with heated dust grains (involves the uncertainty about the “accomodation coefficient”)
- H2 formation heating?

Cooling molecular gas

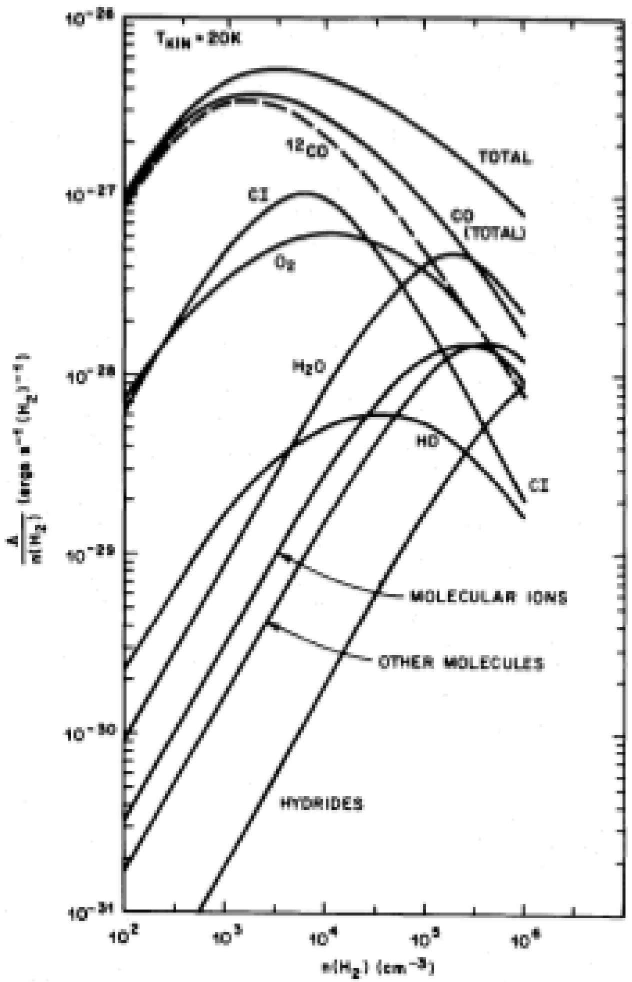
- At solar metallicity, CO (and 13CO) lines likely dominate.
- This implies dealing with cooling due to optically thick transitions (local rad.transport OK?)
- One has to consider escape probabilities dependent on geometry and vel. field
- Goldsmith Langer (1978) and Neufeld Lepp Melnick(95) !

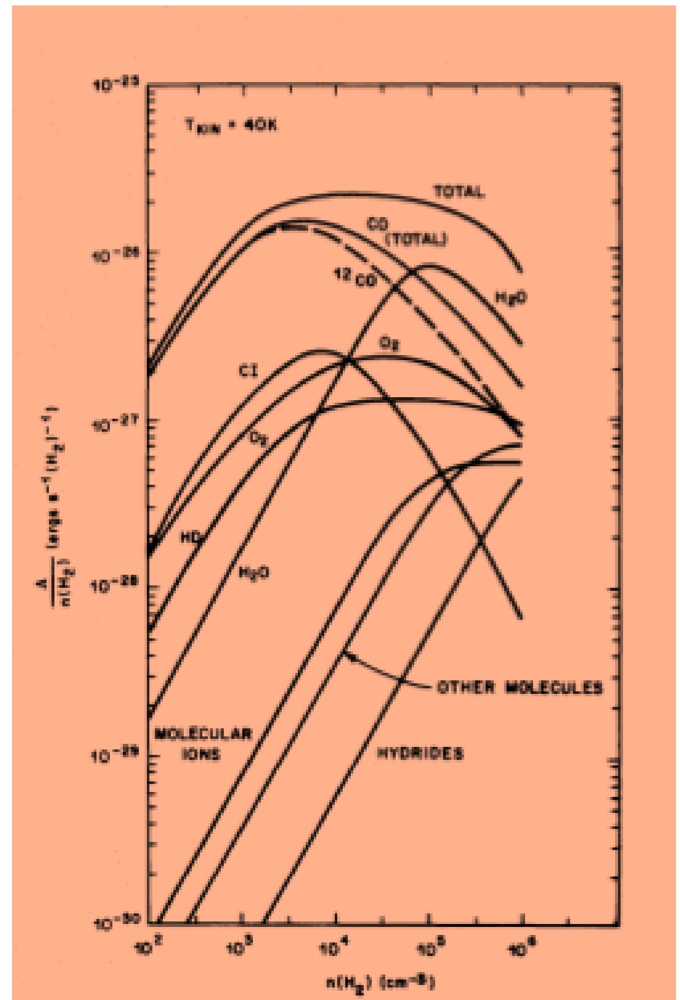
On left contribution of different CO transitions in optically thin limit as fn of n. On right, CO cooling for different abundances (Cooling from rare CO isotopomers becomes important at high n



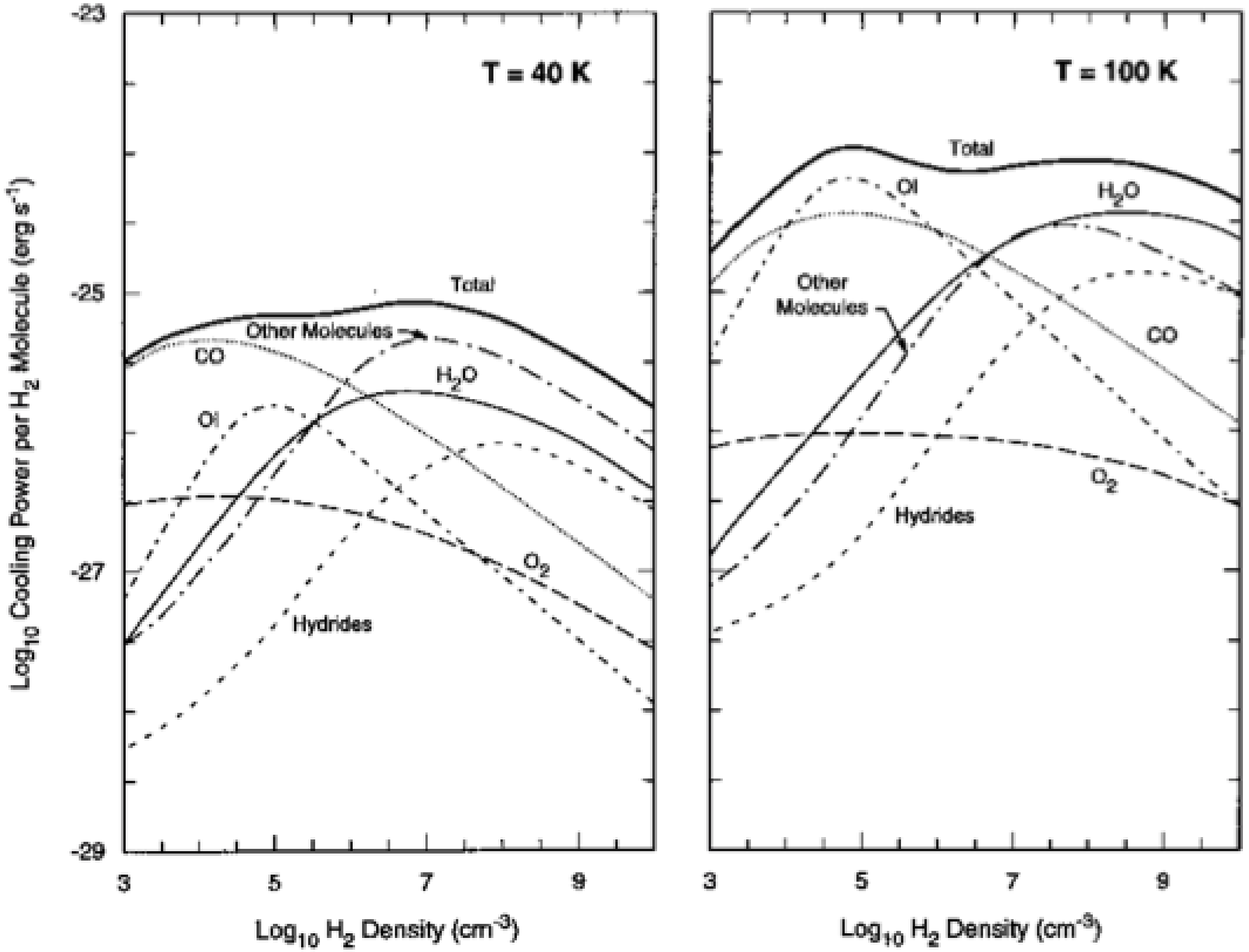


Contribution of different species to cooling at 20 and 40K (Goldsmith Langer). Note that Abundances are uncertain

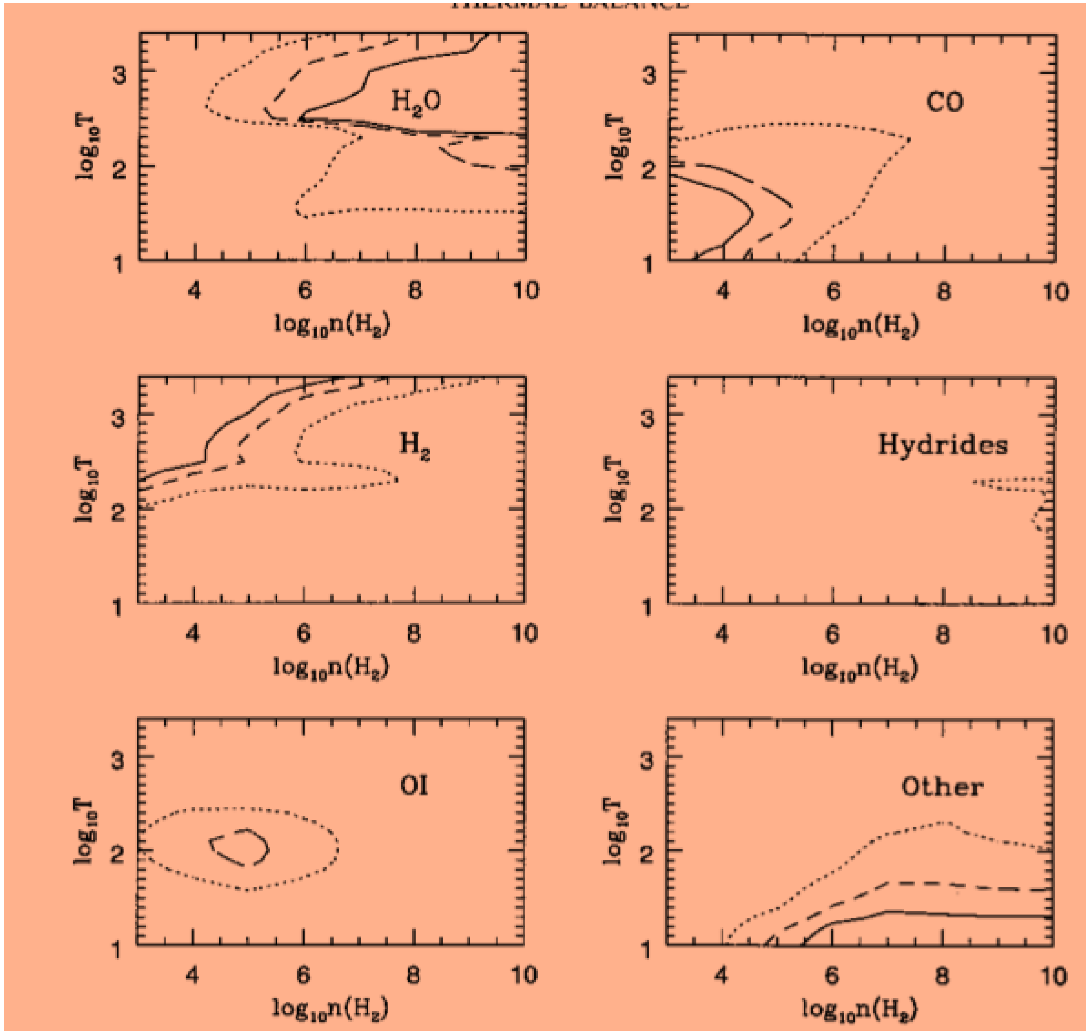




High T Cooling Function from Neufeld et al 95



Fraction of Cooling (70 percent , solid from different species, Neufeld et al)



Comments on molecular cloud heating cooling

- Much depends on vel.field and geometry which affect escape probability
- External radiation field (dust emission) can be very important
- Sensitive to chemistry(particularly H2O)
- How to deal with HD or MHD heating is a challenge (interplay of low Mach No shocks with the medium?)
- Work on turbulent dissipation by Pons et al., Spaans Meijerink

Conclusions in general

- The easy problems have been solved
- Buona Fortuna!!

PDRs or Photon Dominated Regions

- Essentially all regions not shielded from UV
- In dense clouds close to hot stars, transition zone between molecular gas and atomic/ionized regions
- Large gradients in temperature, ionization degree, chemical make up

Schematic representation of PDR at interface between HII region and molecular cloud