Interstellar Clouds

-The physical state of interstellar matter depends on its composition and the local temperature, pressure, and density

-The stability of the state depends on the relative rates of energy gain and loss

Typical diffuse cloud

T_K~50-100 K n_H~10^1-10^2 cm^{-3} & mostly HI; n_{e-}~10^{-4} n_H; M~400 $M_\odot$; R~5 pc

total thermal energy $E_{th} \sim 3MkT/2m_H \sim 10^{46}$ ergs

gravitational binding energy $|E_G| = 3M^2G/5R \sim 2\cdot10^{45}$ ergs

⇒ HI clouds not gravitationally bound

Thermal stability ⇔ Rate of heat transfer of gas ⇔ pressure equilibrium

1st law of thermodynamics ($\Delta E=Q-W$): $\rho d\varepsilon/dt = n d(3/2kT)/dt = nT ds/dt - P/n\, dn/dt = nT ds/dt - kT dn/dt$

$\rho=\mu m_H n$ μ=mean molecular weight s=entropy ε=internal energy per mass

For a monatomic gas

$$\Gamma-\Lambda = 3nk/2\, dT/dt$$

where Γ: heating rate (kinetic energy gained/volume/time)

Λ: cooling rate Γ,Λ complicated functions of T,ρ,Z

Cooling processes: A heated gas cools through the conversion of kinetic energy into luminosity by various processes. The efficiency of cooling is a sensitive function of composition and the gas must be optically thin to emitted photons.

⇒Mechanisms:

- free-free (bremsstrahlung)
- free-bound
- collisions with atomic H (more important for cooler regions)
- e^- impact excitation of fine structure levels of neutral and ionized components

Element	A.W.	n_x/n_H	n_x/n_H*AW	χ (eV)
Carbon	12	4 10^{-4}	0.0048	11.3
Nitrogen	14	10^{-4}	0.0014	14.5
Oxygen	16	8 10^{-4}	0.0128	13.6
Mg	24	3 10^{-5}	0.0007	7.8
Silicon	28	3 10^{-5}	0.0008	8.1
Sulfur	32	1.6 10^{-5}	0.0005	10.4
Iron	56	2.5 10^{-5}	0.0014	7.9
Neon	20	2.6 10^{-5}	0.0005	21.6

$\chi<13.6$ eV ⇒partly ionized in HI regions
⇒cooling due to impacts by electrons with C^+,S^+,Fe^+,Si^+

$\chi>13.6$ eV ⇒ionized in HII regions
⇒cooling due to impacts by electrons with N^+,O^+,O^{++}

Gas Cooling & Heating

In a typical HII region the cooling occurs almost entirely from e$^-$ excitation of ionized atoms of elements C,N,O,Ne since these have excited levels a few eV above the ground state; these levels are collisionally-populated at $T \sim 10^4$ K.

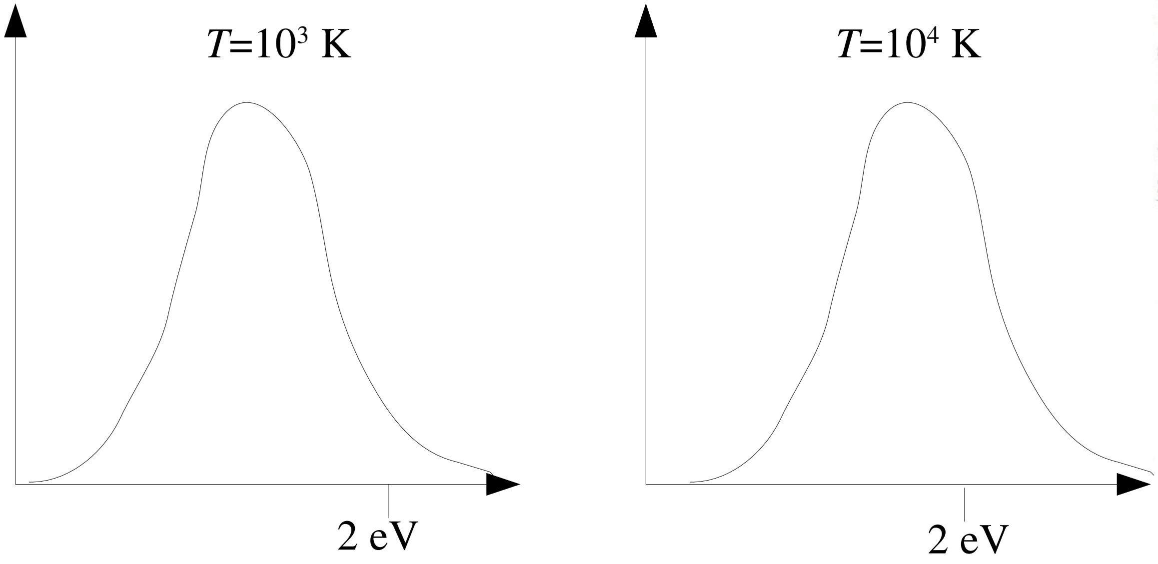
Collisional cross-sections are 10^5 times the radiative cross-sections.

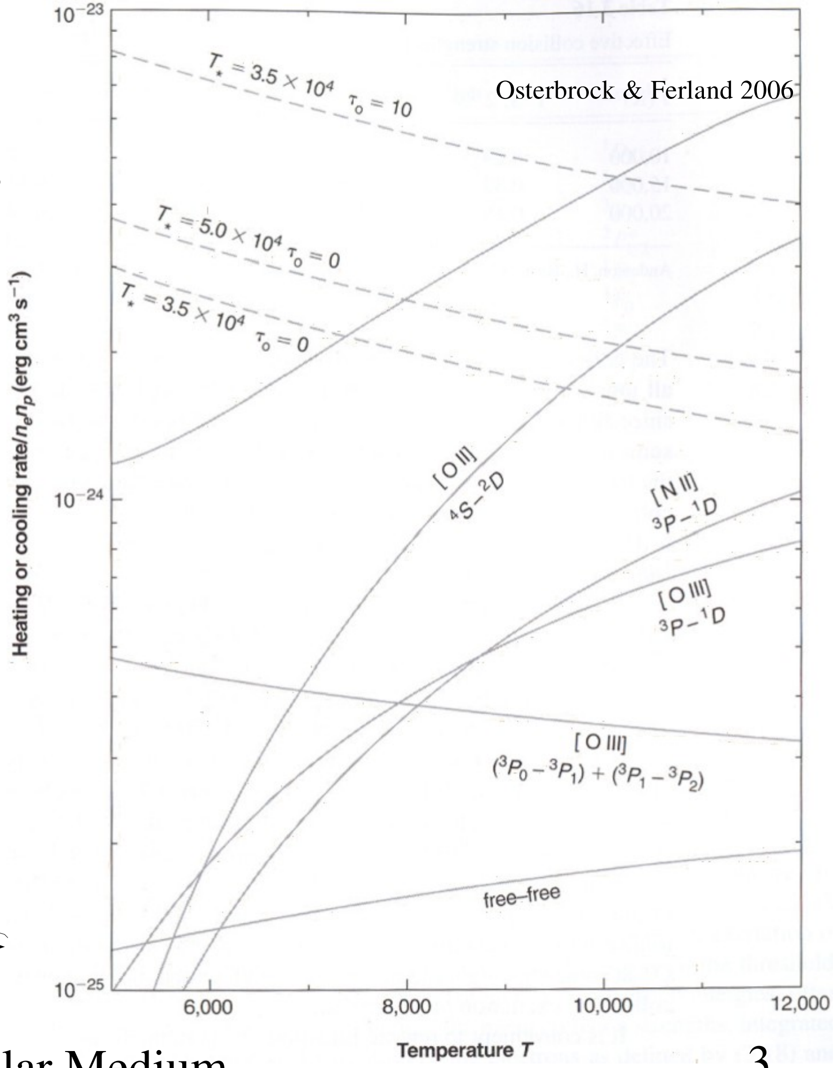
⇒ If not for the low abundance of these elements, there would be only cool HII regions!

In contrast, H at the $n=2$ level quickly becomes ionized, be it via $h\nu$ or e$^-$. And atomic H at $n=1$ has weak fine structure radiation.

Concept Question:
Does the cooling rate increase with T for HII regions?

e$^-$ kinetic energy distributions





Osterbrock & Ferland 2006

Interstellar Cooling Function

$$\Lambda(x,t) = \sum_i n(x_i)/n_H \, \{x L_{e-}(x_i/T) + (1-x) L_H(x_i/T)\}$$

where $x = n_{e-}/n_H$ fractional ionization

$L_{e-} =$ cooling efficiency by e^- impact excitation

$L_H =$ cooling efficiency by neutral hydrogen impact excitation

Impact? I thought we were talking about cooling, not heating.

Thermal Equilibrium $\Gamma = \Lambda$ at T_{eq}

Consider the rate of change in temperature when $T \neq T_{eq}$

$dT/dt = -(T - T_{eq})/t_{relax}$ t_{relax} = relaxation time

Equation of state for ideal gas $P = nkT$

$\Gamma - \Lambda = 3/2 nk dT/dt = -3/2\, P/T\, (T - T_{eq})/t_{relax}$

solve for relaxation time

$t_{relax} = -3/2\, P/T\, (T - T_{eq})/(\Gamma - \Lambda)$

$t_{relax} > 0$: if $T \neq T_{eq}$, the gas will tend to return to T_{eq} (thermal __________)

$t_{relax} < 0$: if $T \neq T_{eq}$, the difference $T - T_{eq}$ will continue to grow (thermal __________)

Some important cooling transitions in cool interstellar clouds (T~100 K)

Transition	Colliding Partners	ΔE/k
C^+ ($^2P_{½} \rightarrow {}^2P_{3/2}$)	H, e^-, H_2	91.3 K
Si^+ ($^2P_{½} \rightarrow {}^2P_{3/2}$)	e^-	413 K
O ($^3P_2 \rightarrow {}^2P_{1,0}$)	H, e^-	228 K, 326 K

Main Cooling Mechanisms at Different Temperatures for Neutral and Partially Ionized Gas

Temperature (K)	Main Coolant	~Cooling Rate (J m^{-3} s^{-1})
10	CO	$10^{-45}n^2$
100	H_2, C^+	$10^{-40}n^2$
1,000	Metastable ions	$10^{-38}n^2$
10,000	H, H^+, p^+, e^-	$10^{-35}n^2$

Gas Cooling & Heating

Heating Processes: conversion of energy originally stored in some background radiation field (including cosmic rays) into kinetic energy, which then is carried away by particles, especially electrons, thermalized in elastic collisions

Primary interaction $A + \{h\nu \text{ or } p^+\} \rightarrow A^+ + e^- + \{\text{nothing or altered } p^{+\prime}\}$

Heating occurs if kinetic E carried away by the liberated e- exceeds the mean kinetic E of the gas

i) Processes that continuously operate in space and time

1. starlight at λ<912Å
2. low energy cosmic rays (1-10 MeV)
3. soft X-rays (~0.1-0.3 keV)
4. cloud collisions
5. hydromagnetic waves
6. dissipation of turbulent energy of the ISM

What's special about 912Å?

ii) Processes that continuously operate in time, but localized in space

1. heating and ionization due to photons with λ<912Å in the vicinity of O,B *s
2. same, near UV *s (on way from red giant to white dwarf)
3. EUV photons from helium recombinations
4. photoelectric emission from grains
5. collisional de-excitation of vibrational levels of H_2
6. radiative dissociation of H_2

iii) Processes that are time-dependent and localized in space

e.g., supernovae (McKee and Ostriker model)

Gas Cooling & Heating

Models of the ISM:

1. Heating mechanisms
2. Thermal equilibrium $\Gamma=\Lambda$
3. Ionization balance ionizations = recombinations

$\Rightarrow n_{e-}/n_H = x(T)$ fractional ionization

$\Rightarrow \xi/n_H(T)$ primary hydrogen ionization rate per atom

If the gas is thermally stable, then $dT/dt=0$

and $\Gamma-\Lambda = 3nk/2\ dT/dt = 0$

Equilibrium temperature $\Lambda(\rho,T_{eq}) = \Gamma(\rho,T_{eq})$

where $\rho \approx m_H n_H$ for HI clouds ($n_H \gg n_{e-}$)

Example application: Milky Way coronal gas (10^6 K):

Spitzer 1956 ⇒ suggested possibility of Galactic corona

high T ($>10^6$ K) gas radiates inefficiently

rate of free-free cooling $\varepsilon_{ff} = 2^5 \pi e^6 Z^2 n_{e-} n_i/(3hm_{e-}c^3)\ (2\pi kT/(3m_{e-}))^{½} \Rightarrow t_{dissipate} =$

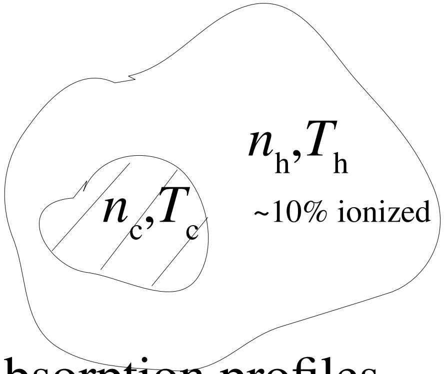
$\Rightarrow$ once gas is very hot, stays hot for $> 10^{10}$ yr

For $T < 10^6$ K, cooling occurs fairly quickly ($<10^8$ yr) via collisionally-induced line transitions

$\Rightarrow$ medium-hot gas must be continually heated to stay medium-hot

Gas Cooling & Heating

Field, Goldsmith, & Habing 1969 Two-phase model



Two-phase model: clouds $n_c \sim 10\ \mathrm{cm}^{-3}$, $T_c \sim 10^2$ K

intercloud medium $n_h \sim 10^{-1} \mathrm{cm}^{-3}$, $T_h \sim 10^4$ K

-original evidence that all the HI gas is not at $T \sim 125$ K:

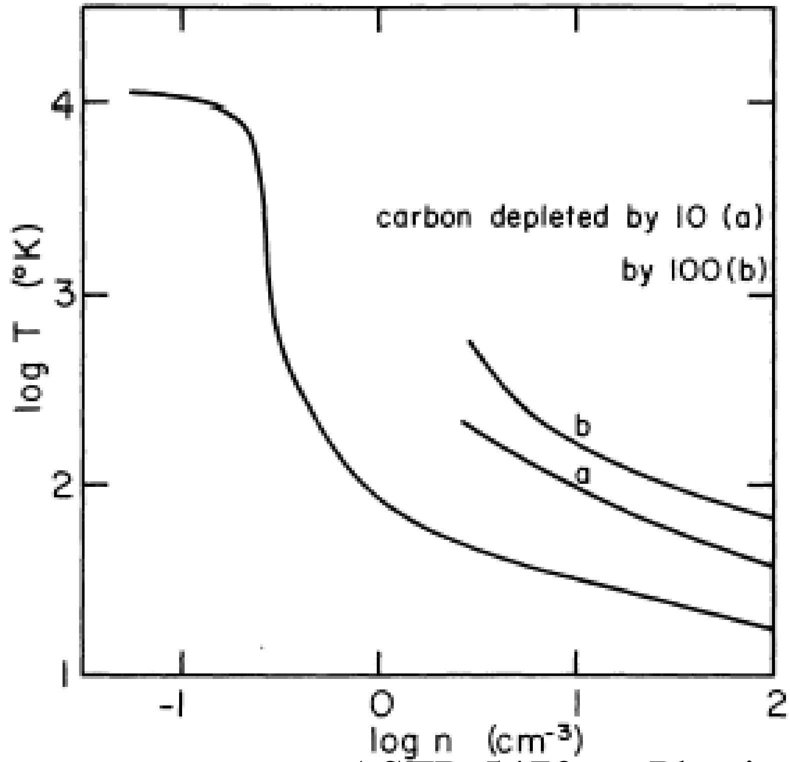
1. HI self-absorption seen in emission profiles
2. consistent difference seen in appearance between emission and absorption profiles
3. difficult to understand how gravitationally unbound clouds could hold together

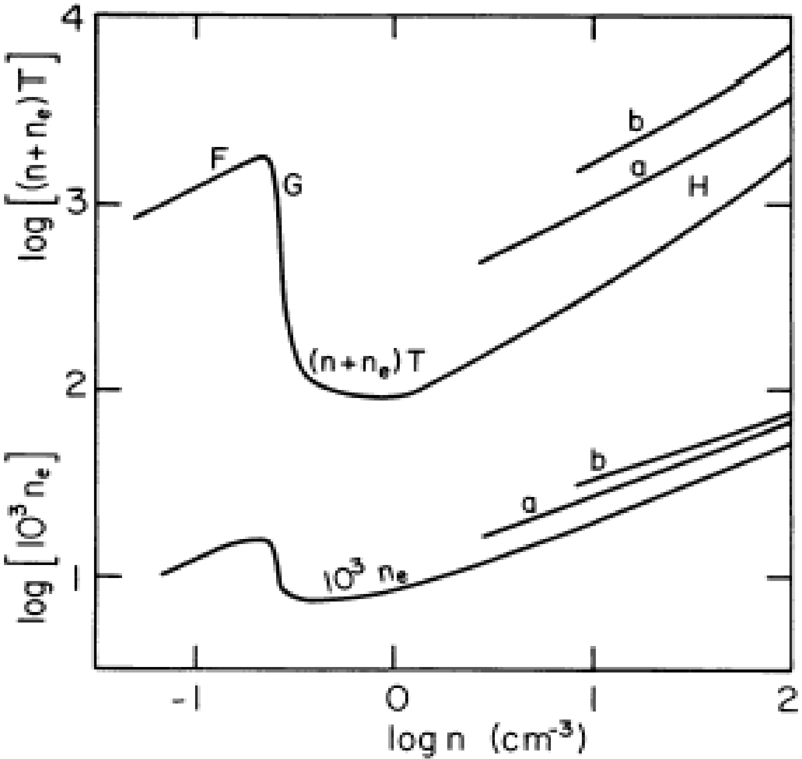
How could this help?

⇒ pressure confinement $P \sim (n_{e-}+n_H)kT$ $n_{cold}T_{cold} \sim n_{hot}T_{hot}$

-cosmic ray heating of hot ISM

-cooling due to collisional excitation of H, He at high T and C^+ (among others) at lower T





Field, Goldsmith, & Habing 1969 Two-phase model

Balance heating by cosmic rays against cooling by H at high *T* and C^+ at low *T*

(updated two phases: McKee 1995)

FGH 1969

Find three phases in pressure equilibrium; two are thermally stable ('F' and 'H')

A third stable phase should exist above 10^6 K, with bremsstrahlung cooling (Spitzer 1956?)

~75% of the gas in cool phase 'H' (HI + H_2?)

Heating (Γ) from cosmic rays (2 MeV from SN ejecta)

Assuming ξ_H=H ionization rate = $4 \cdot 10^{-16}$ sec^{-1} H^{-1}, get 8-20 eV per ionization

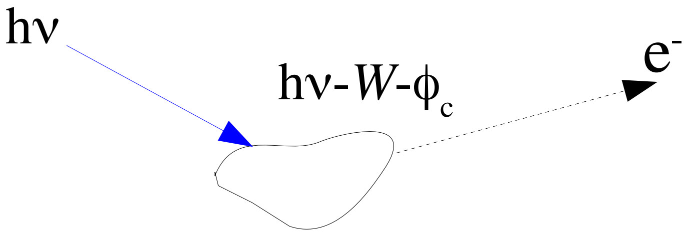
$$\Gamma_{CR} = n_H \xi_H \langle E \rangle = n_H \cdot 4\text{x}10^{-16} \cdot 10\text{eV} = 6.4 \cdot 10^{-27}\, n_H$$

Which are examples of a 'hot' ISM? A region of space where

a) locally, photons are more energetic than global average, e.g., mostly X-ray and ultraviolet.
b) locally, particles are moving much faster than global average.
c) locally, dust particles are much warmer than global average.
d) a and b
e) all of the above
f) b and c
g) a and c

In-depth analysis of one heating mechanism: the heating of neutral gas by photo-ejected electrons from small grains.

Early references: Watson 1972; Jura 1976
Review: Hollenbach & Tielens 1999, *Reviews of Modern Physics*



Efficiency of grain heating ($\varepsilon_{\rm grain}$) depends on probability Y that electrons escape times the fraction of the photon energy carried away as kinetic energy by the electron.

'The yield is a complex function of the grain size a, the collision lengthscale for low-energy electrons in solids l_e (~10Å), the far-ultraviolet absorption lengthscale inside a grain l_a (~100Å), and the photon energy hν. $Y \sim l_e/l_a \sim$ ____.

With typical FUV photon energy of 10eV and W~5eV, the maximum efficiency is only _____. Including positive charging, the efficiency will be much less.'

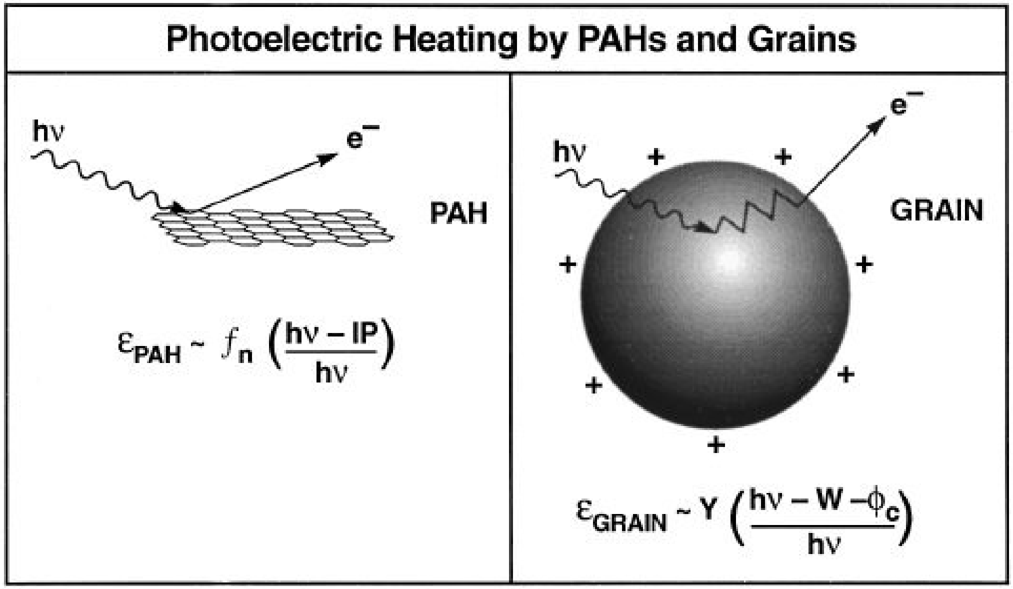


FIG. 13. A schematic of the photoelectric heating mechanism. A far-ultraviolet photon absorbed by a dust grain creates a photoelectron which diffuses through the grain until it loses all its excess energy due to collisions with the matrix or finds the surface and escapes. For PAHs, the diffusion plays no role. A simple expression for the heating efficiency ϵ is indicated. See text for details.

What is ϕ_c?

The heating of neutral gas by photo-ejected electrons from small grains.

It's much easier to eject electrons from very small grains and planar PAH molecules. For PAHs, the ionization potential is $IP = W + \phi_c = W + (Z + 0.5)e^2/C$, where the capacitance C for compact PAHs is ______. The limiting factor here is that IP can be greater than 13.6eV. Only a fraction f_n of PAHs can be ionized by FUV photons. So with photon energy of 10eV and IP of 7eV, and assuming that half of the incoming photon energy is converted to electronic excitations, the maximum efficiency is ______.

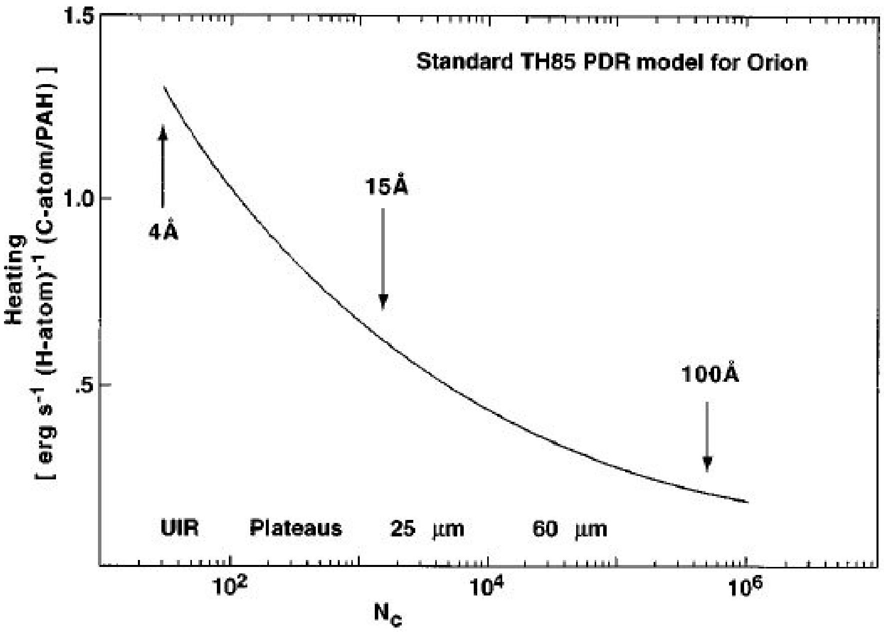
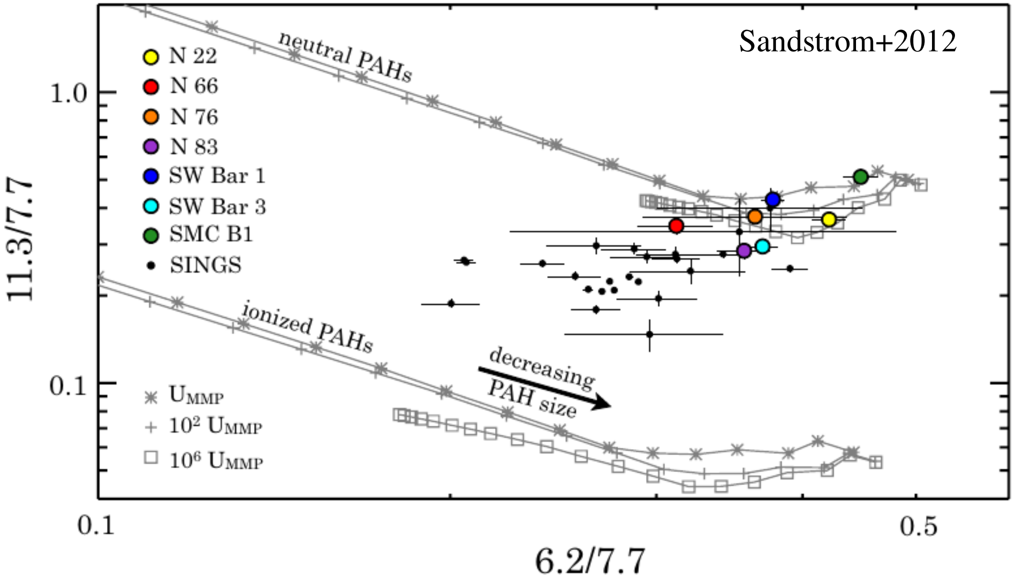


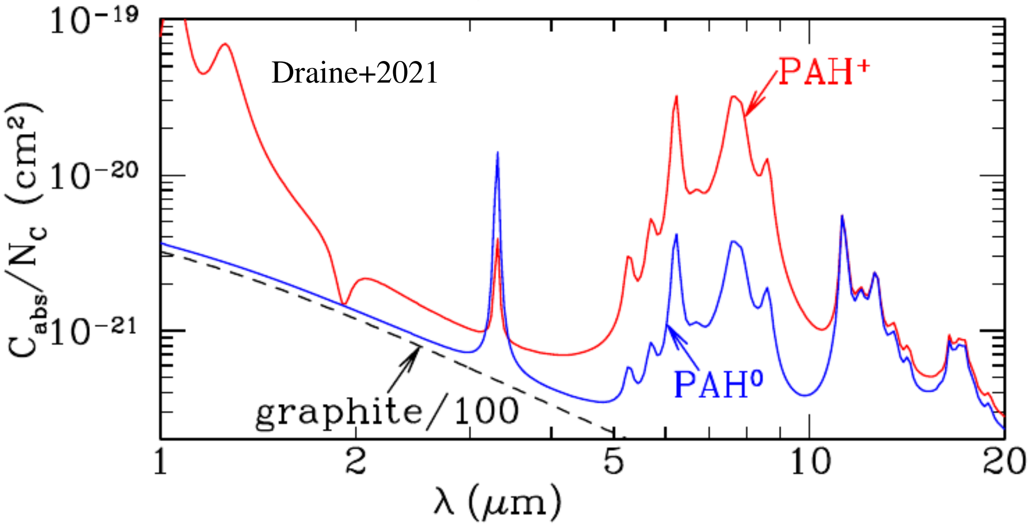
FIG. 14. The contribution to the photoelectric heating of interstellar gas by grains of different sizes (Bakes and Tielens, 1994). The results of these calculations are presented in such a way that equal areas under the curve correspond to equal contributions to the heating. Species with $\simeq 50$ C atoms are the carriers of the IR emission features at 3.3, 6.2, 7.7, and 11.3 µm. The plateaus underneath these features and the 12 µm cirrus are carried by somewhat larger species ($\simeq 200$ C atoms). The 25 and 60 µm cirrus correspond to species with 5×10^4 and 5×10^5 C atoms, respectively.

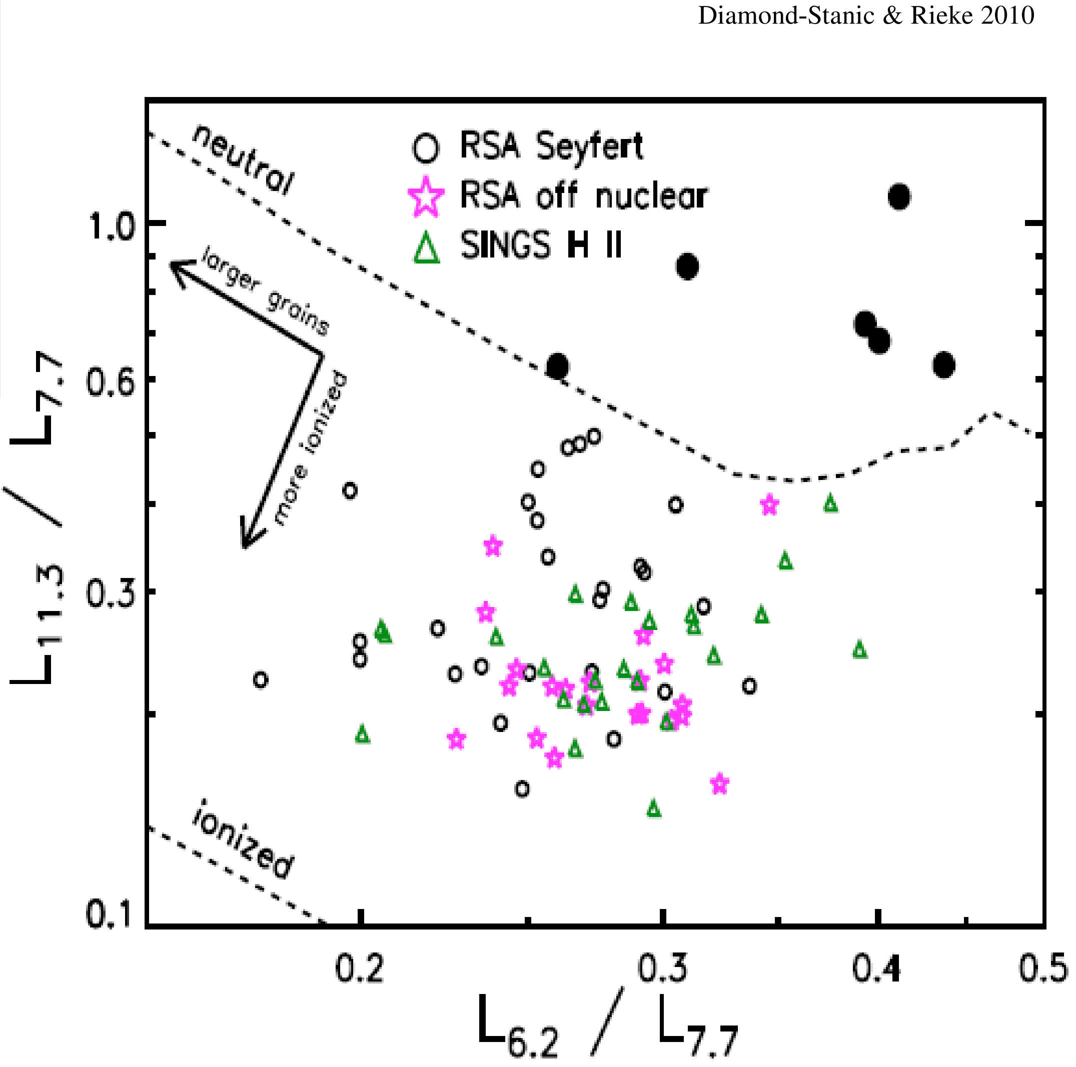
So about half of the photoelectric heating arises from grains with size less than 15Å, and the other half from grains between 15 and 100Å. Grains of size >100Å contribute negligibly to the heating.

The heating of neutral gas by photo-ejected electrons from small grains.

Theoretical models, buttressed by laboratory efforts, predict that the PAH emission features near 8 μm are more ionized than the features at 11 μm. Therefore, predict how the 8μm/11μm PAH ratio should vary as a function of the "hardness" of the radiation field ("harder" implies "bluer", with relatively more energetic photons).

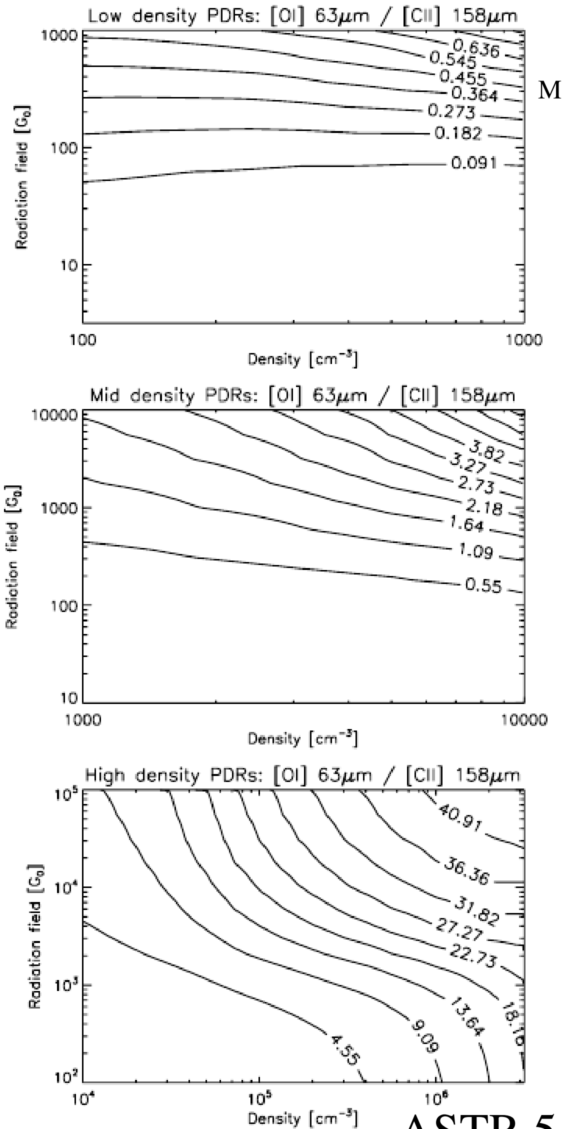

Sandstrom+2012


Draine+2021


Diamond-Stanic & Rieke 2010

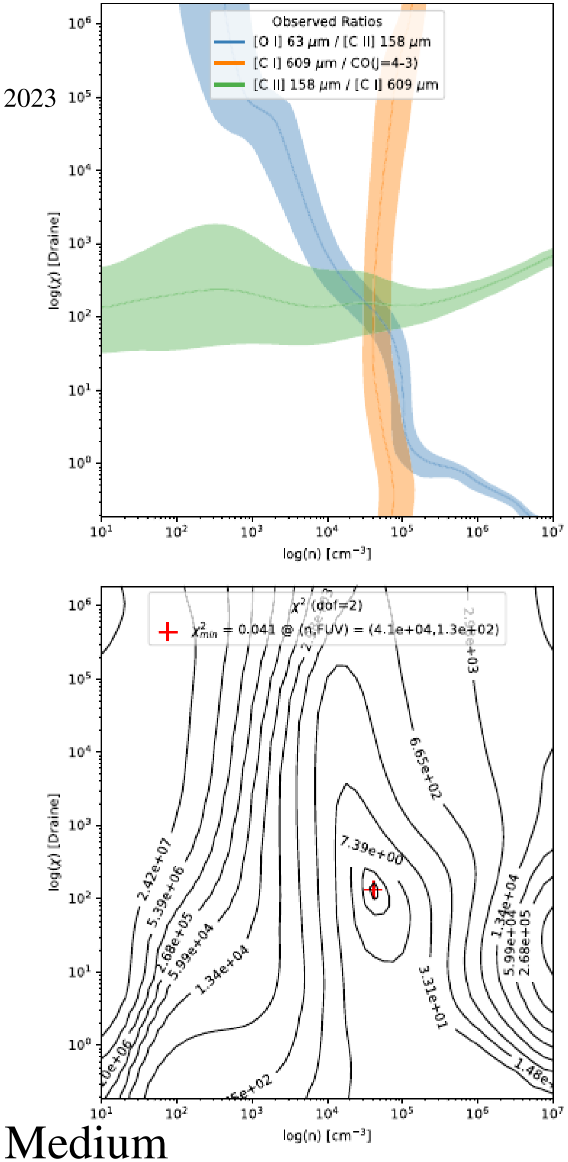
Gas Cooling & Heating

The energized and liberated electrons ultimately bump into atoms in the *neutral* ISM.
[CII]158μm and [OI]63μm dominate the resultant cooling of the *neutral* ISM.
https://www.youtube.com/watch?v=SoZjymOsvsE
These two transitions dominate because of their their abundances (see table on Slide 2) and low excitation energies: $\Delta E/k$ ~ ___ K for [CII]158μm and ___ K for [OI]63μm.



Meijerink+2007

Pound & Wolfire 2023



Gas Cooling & Heating

[CII]158μm is the most important coolant of the neutral ISM. It is the fourth most abundant element and has a lower ionization potential (11.26eV) than hydrogen, so that carbon will be in the form of C^+ in the neutral surface layers of far-UV illuminated neutral gas clouds. The depth of these C^+ zones is generally determined by dust extinction and often extends to A_V<4 mag. The 158μm line is also easy to excite ($\Delta E/k$~91 K or ΔE~8meV), so that C^+ can cool warm (30 K < T < 10^4 K) neutral gas whereas the two most abundant atoms H and He cannot (Malhotra et al. 2001).

[CII]/*FIR* is about 0.2-0.7% in normal and star-forming galaxies. This jibes with theoretical predictions of 0.1-1.0%. The efficiency here is defined as the energy input to the gas divided by the total energy of the FUV photons absorbed by dust grains. Although the gas receives 10^2-10^3 times less heating energy per unit volume than the dust, the gas attains higher equilibrium temperatures because _____________? (see also Slide 17)

Photodissociation Regions: FUV-illuminated (6eV<13.6eV) neutral ISM ⇒ majority of mass of ISM

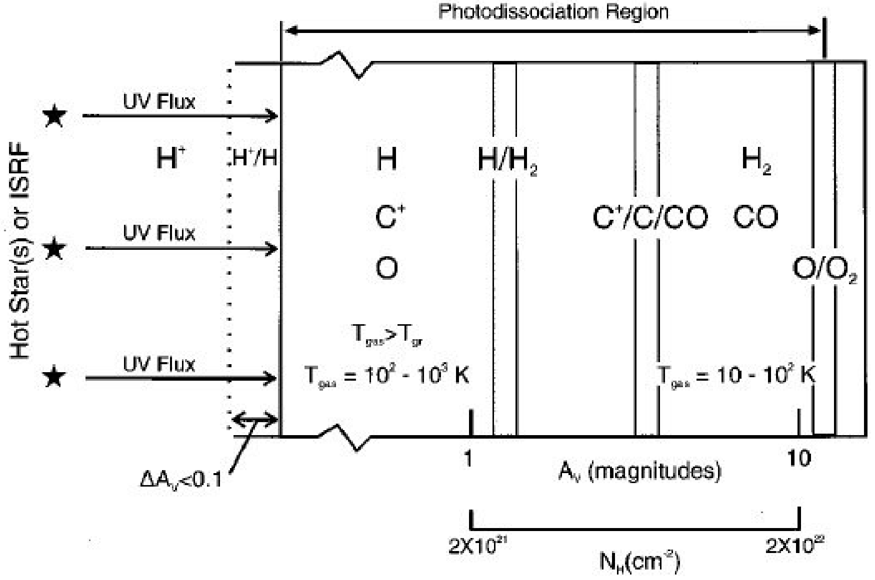


FIG. 3. A schematic diagram of a photodissociation region. The PDR is illuminated from the left and extends from the predominantly atomic surface region to the point where O_2 is not appreciably photodissociated ($A_V \simeq 10$). Hence the PDR includes gas whose hydrogen is mainly H_2 and whose carbon is mostly CO. Large columns of warm O, C, C^+, and CO, and vibrationally excited H_2 are produced in the PDR.

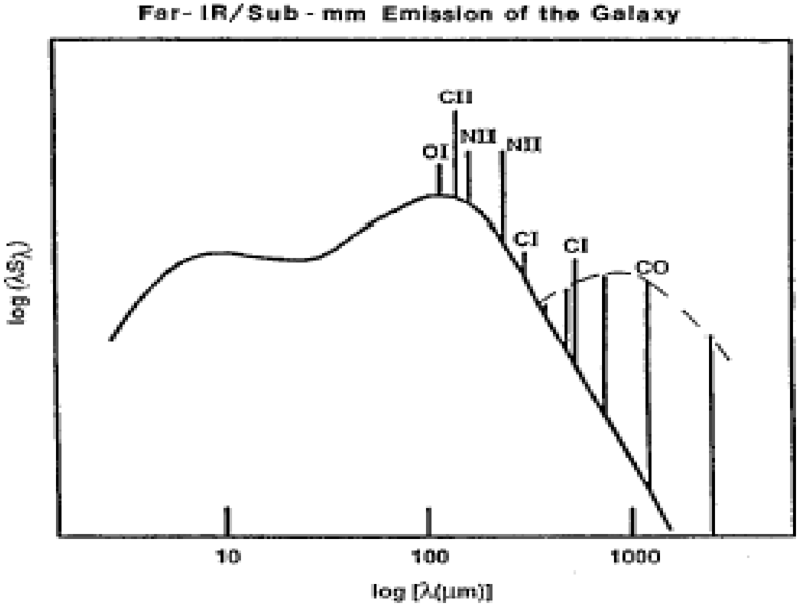


FIG. 4. The Cosmic Background Explorer (COBE) observation of the far-infrared spectrum of our Milky Way Galaxy (Wright *et al.*, 1991; figure from Genzel, 1991). With the exception of the [NII] emission and a controversial portion of the [CII] emission, the bulk of the emission is from PDRs. Note that there is no information from COBE on the line spectrum of the Milky Way at wavelengths less than the [OI] 145 μm line.

Gas Cooling & Heating

Since most of the heating in the neutral ISM derives from small grains, what happens to [CII]/TIR as the intensity and hardness of the interstellar radiation field (ISRF) increase?

Hint: [CII]158μm represents gas cooling, TIR is starlight reprocessed by dust grains into the infrared, and the neutral ISM is predominantly heated by photo-ejection from very small grains/PAHs.

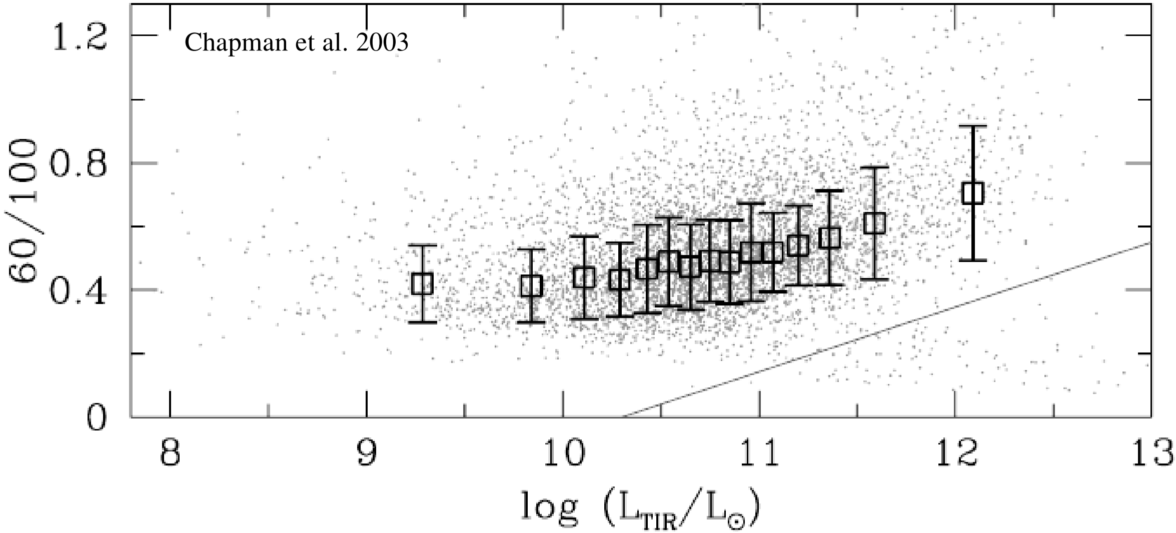
a) What happens to TIR as the ISRF increases?

b) What happens to photo-ejection heating from PAHs as the ISRF increases?

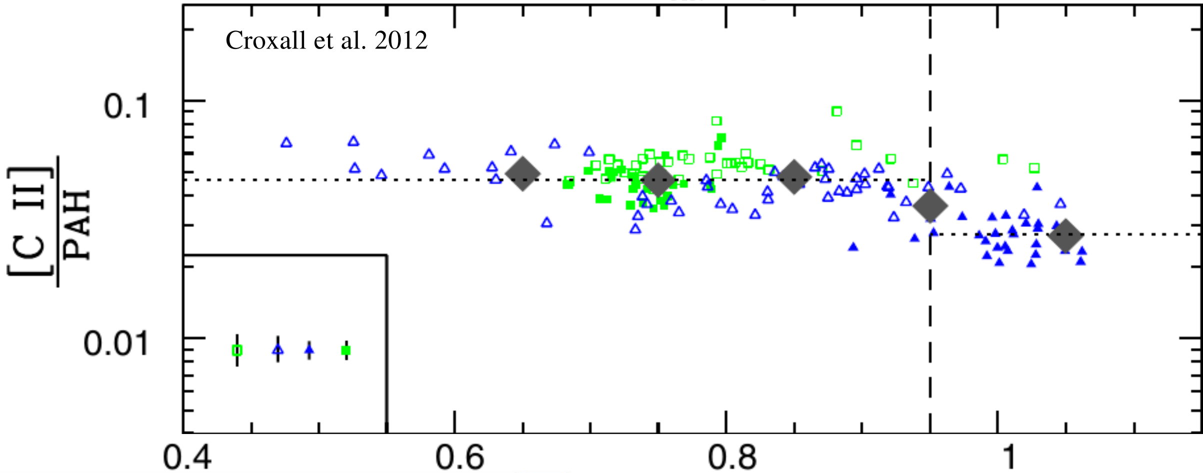
c) Take the above two results to make a predicted curve of [CII]/TIR vs ISRF.

Gas Cooling & Heating

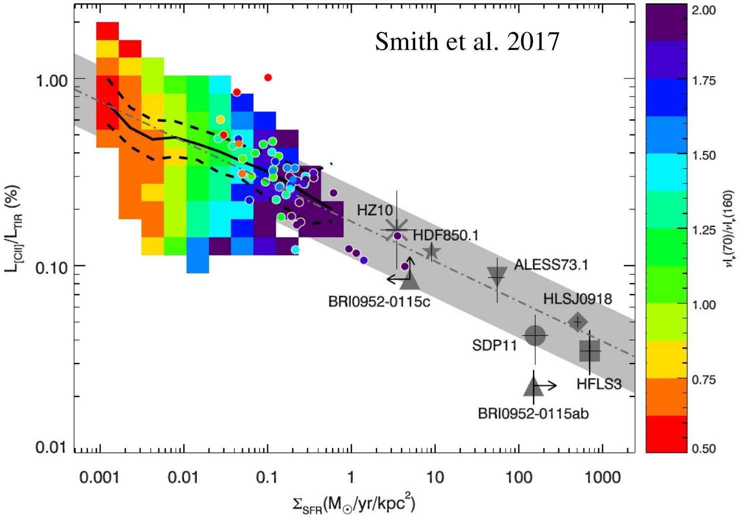
a) TIR increases with the heating as gauged by dust temperature, as expected.



[CII]/PAH does not drop with heating ⇒ direct evidence for coupling between heating by photo-ejection from PAHs and C^+ cooling!



c) [CII]/TIR drops with heating. The cooling by C^+ is not one-to-one with big dust grain emission.



Gas Cooling & Heating

Dust grains are heated by the interstellar radiation field. The large dust grains are in thermal equilibrium. Why then is the interstellar gas at such a higher temperature than the dust? Doesn't that seem strange? The gas is bathed in the same interstellar radiation field as the dust.

excerpted from Harwit 2006

Deep inside molecular clouds where little to no spectral line radiation escapes, the cooling is dominated by dust grain radiation. However, in order to cool, dust grains must be first heated. They are heated by _____________. They then re-radiate in the infrared, and thus provide the primary form of protostellar cooling that permits these clouds to contract to form stars.

The rate at which grains can cool the gas is only as fast as the molecules can transfer the energy to the grains. The rate of heat transfer is

$$\mathrm{d}Q_{\mathrm{gr}}/\mathrm{d}t = n_{\mathrm{H2}}\pi a^2(3\mathrm{k}T_{\mathrm{H2}}/m_{\mathrm{H2}})^{1/2}\,(T_{\mathrm{H2}}-T_{\mathrm{gr}})\alpha(c_{\mathrm{v}}T_{\mathrm{H2}}/N_{\mathrm{Avogadro}})$$

α is an efficiency factor for energy transfer via impacts by molecules

$c_{\mathrm{v}}T_{\mathrm{H2}}/N_{\mathrm{Avog}}$ is the energy the molecule could transfer (c_{v} heat capacity/mole)

The number density of grains is $n_{\mathrm{gr}} = n_{\mathrm{H2}}X_{\mathrm{gr}}m_{\mathrm{H2}}/\rho_{\mathrm{gr}}(4\pi a^3/3)$ X_{gr} is grain fraction by mass

Gas Cooling & Heating

The product of these two equations gives the amount of gas cooling (grain heating):

$$L_{\rm gr} = {\rm d}Q_{\rm gr}/{\rm d}t\; n_{\rm gr} = 10^{-22}\,(n_{\rm H2}/10^4\ {\rm cm}^{-3})^2\,(X_{\rm gr}/10^{-3})\,(\alpha/0.333)\,(2\ {\rm g\ cm}^{-3}/\rho_{\rm gr})\,(10^{-5}\ {\rm cm}/a)\,(c_{\rm v}/N_{A{\rm v}}/1.5)\,(T_{\rm H2}/50\ {\rm K})^{1.5}\,((T_{\rm H2}-T_{\rm gr})/30\ {\rm K})\ {\rm erg/cm^3/s}$$

This is how quickly the gas can transfer its heat energy to the grains. Compare this to the rate at which grains can shed this energy – the grain radiative cooling with efficiency $Q_{\rm em}$ is

$$L_{\rm rad} = 4\pi a^2 n_{\rm gr} \sigma T_{\rm gr}{}^4\, Q_{\rm em} =$$

$$= 4.4\ 10^{-21}\ (n_{\rm H2}/10^4\ {\rm cm}^{-3})\,(X_{\rm gr}/10^{-3})\,(Q_{\rm em}/10^{-4})\,(2\ {\rm g\ cm}^{-3}/\rho_{\rm gr})\,(10^{-5}\ {\rm cm}/a)\,(T_{\rm gr}/20\ {\rm K})^4\ {\rm erg/cm^3/s}$$

The numbers I've used are typical for a molecular cloud. In other words, the radiative cooling is sufficient to keep molecular clouds cool. As the clouds collapse, the density rises and thus $L_{\rm gr}$ rises more quickly than $L_{\rm rad}$.$^{\text{why?}}$ As the grains become hotter they begin emitting at shorter wavelengths where their efficiency $Q_{\rm em} \propto T_{\rm gr} \propto a/\lambda$. Thus $L_{\rm rad}$ rises in proportion to $T_{\rm gr}{}^5$.

Follow-up to Just-in-Time question:

Name two reasons why X-ray heating for the local ISM is substantially less than the photo-electric heating rate due to FUV photons.

→

For a pure hydrogen gas, what is the approximate ratio of X-ray absorption cross-sections for 0.1 keV X-rays and 1.0 keV X-rays?