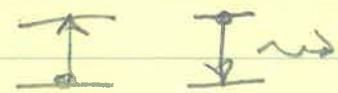
COOLING

At low density, gas cools primarily by 2-body collisional processes

$$X + e \rightarrow X^* + e$$



$$X^* \rightarrow X + \gamma$$

⇒ Cooling rate

$$\frac{\text{energy}}{\text{time vol}} = n^2 \Lambda$$

Λ ↑ cooling function

n^2 ↑ because 2-body. Commonly, $n = n_H$. (n_H: total H, including p, H_2, ...)

Possibilities:

(1) Cooling balances heating e.g. in photoionized nebulae.

(2) Gas heated somehow, and cooling time is long compared to age, e.g hot x-ray emitting gas in
- clusters of galaxies,
- supernova remnants.

Cooling function Λ

Depends on what are the dominant ion/atomic/molecular species.

A prototypical example is $\Lambda(T)$ for gas in collisional ionization equilibrium at temperature T.

– see eg Maio et al (2007) MNRAS 379, 963.

Features of cooling function:

(i) Rapid increase in cooling at $T \approx 10^4 K$ from coll. excitation of Ly α.

(ii) Rapid decrease in Lyα cooling at $T \approx 2 \times 10^4 K$ as H becomes fully ionized.

(iii) Various peaks in Λ at $T \sim 10^4 - 10^7 K$ as abundant species He, C, O, Si, Fe get excited, then become fully ionized.

(iv) A minimum in Λ near $T \sim 10^7 K$, then upturn to $\Lambda \propto T^{1/2}$ from free-free (bremsstrahlung)

$$p + e \rightarrow p + e + \gamma$$

(v) At $T < 10^4 K$, cooling dominated by forbidden lines of abundant species [CI], [CII], [OI], [SiII], [FeII]

(vi) At $T \lesssim 10^2 K$, molecular cooling dominates:

H_2, HD in metal-free primordial gas

CO in metal-polluted gas.

15.3

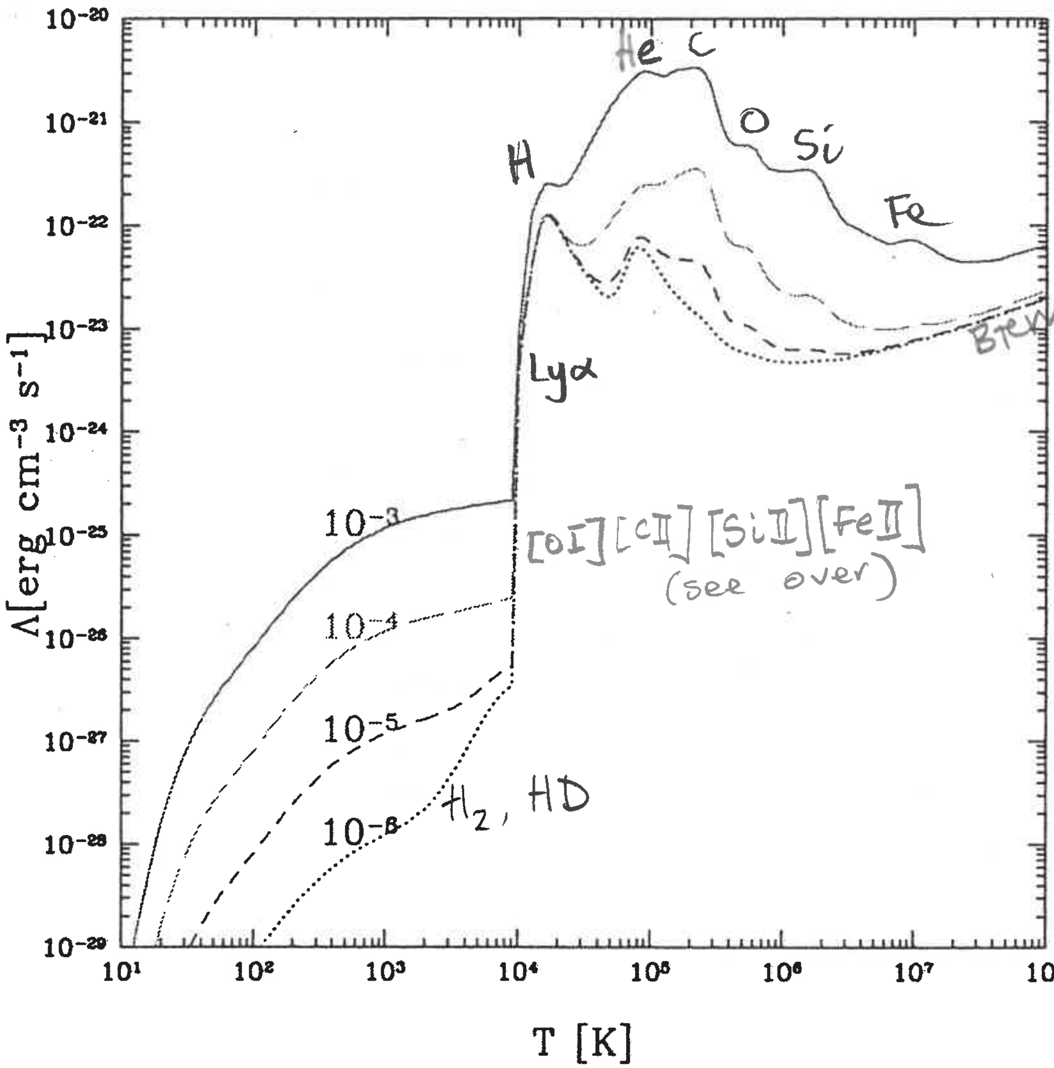


Figure 4. Total cooling due to hydrogen, helium, metals, H_2 and HD molecules as function of temperature, for gas having a hydrogen number density of 1 cm^{-3}. The fraction of H_2 and HD are fixed to 10^{-5} and 10^{-8}, respectively. The labels in the plot refer to different amount of metals, for individual metal number fractions of 10^{-3} (solid line), 10^{-4} (long-dashed line), 10^{-5} (short-dashed line) and 10^{-6} (dotted line).

for OI we will have a double phase of saturation: the first one at $\sim 10^5$ cm^{-3} involving the lower three states and the second one at $\sim 10^{11}$ cm^{-3} involving the higher two states.

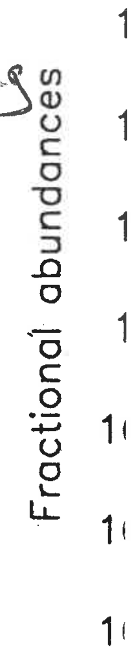


Figure 5. ... abundance ... $\Omega_{0m} = 1$ ... in a ΛCD... $\Omega_{0b} = 0.$ ...

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Dominant T ≲ 10⁴ K metal cooling lines, all forbidden.

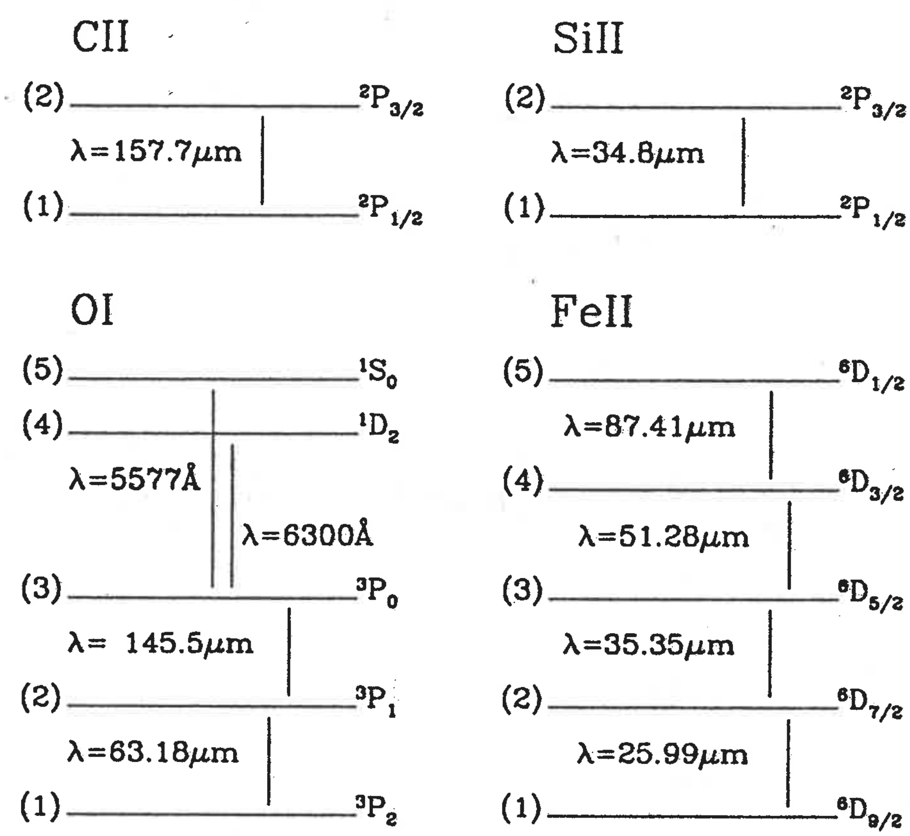

Figure B1. Scheme of the level models adopted for the different atoms with respective line transition data.

$$\gamma^e_{42} = 10^{-5}T^{-0.5} \quad \mathrm{cm^3\,s^{-1}};$$
$$\gamma^e_{52} = 10^{-5}T^{-0.5} \quad \mathrm{cm^3\,s^{-1}};$$
$$\gamma^e_{53} = 10^{-5}T^{-0.5} \quad \mathrm{cm^3\,s^{-1}};$$

we assume a fiducial normalization of 10^{-5} for missing data on e-impact rates. We have checked that the level populations are almost insensitive to the adopted values.

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Cooling instability

Suppose gas is heated somehow.
After a cooling timescale $t_{cool} = \frac{E}{\dot{E}}$

the gas starts to cool.
If the cooling rate increases as
T falls, then gas cools catastropically.
This is especially true at $10^5 K \lesssim T \lesssim 10^7 K$
where $\Lambda \uparrow$ as $T \downarrow$.
When gas cools, density usually also
increases (eg if pressure is constant,
so $p = nkT = const$, ie $n \propto T^{-1}$).
This enhances cooling catastrophe.