13. Heating and cooling balance in the interstellar medium

13.1 Heating by shock waves

The gas between stars, commonly referred to as the interstellar medium, and the gas between galaxies, called the intergalactic medium, is subject to a number of heating processes, which must be balanced by cooling, otherwise the temperature of the medium of perpetually increase. Some heating processes operate continuously, like heating by absorption of radiation. If the absorption is done by free particles, like free electrons, all the energy of the absorbed photon is available as heat. If the absorption is doneby exciting or ionizing an atom, much of the photon energy is stored as potential energy in the atom. In case of ionization only the kinetic energy of the freed electron can be thermalized, so the photon energy minus the binding energy of the atomic electron is available as heat. Gas can also be collisionally heated by energetic particles called cosmic rays.

Other heating processes like shock heating operate intermittendly. Let us estimate the heating contributed by supernova remnant shocks. Measurements indicate that typically every $t_{\rm SN} = 50$ years a supernova explodes in the Galaxy and the typical explosion energy is $E = 10^{51}$ ergs. The Galaxy can for our purposes be approximated as a disk with radius 10.000 pc (parallax second=parsec, 1 pc = 3 Light-years) and thickness 500 pc, so its volume is $V_{\rm gal} \simeq 1.5 \cdot 10^{11}\ {\rm pc}^3$. From the jump conditions at strong ($M \to \infty$) hydrodynamical shocks we derived the post-shock temperature as a function of the shock velocity as

$$kT_2 = \frac{2\,(\gamma-1)}{(1+\gamma)^2}\, m\, V_s^2$$

$$\Rightarrow\ T_2 \simeq (3\cdot 10^5\ {\rm K}) \left(\frac{V_s}{100\ {\rm km/s}}\right)^2 \tag{13.1}$$

From the Taylor-Sedov blast-wave solution we know that the shock velocity and radius scale as

$$V_s(t) = \frac{dr_s}{dt} = \frac{2}{5}\, x_0 \left(\frac{E}{\rho_u\, t^3}\right)^{1/5} \qquad r_s(t) = x_0 \left(\frac{E\, t^2}{\rho_u}\right)^{1/5} \tag{13.2}$$

where x_0 marks the shock location in the self-similar coordinates. Let us for simplicity just use $x_0 = 1$. Let us also take the average value for the gas density in the interstellar medium.

$$\text{On average :} \qquad n \simeq 1\ {\rm atom/cm^3} \qquad \rho \simeq 2\cdot 10^{-24}\ {\rm g/cm^3} \tag{13.3}$$

We can now ask ourselves: how often is the interstellar medium heated to at least a million degrees temperature? According to Eq.13.1 this would require the region be overrun by a shock with at least the critical velocity $V_c \simeq 180$ km/s. The blastwave velocity is larger than this critical value as long as the blastwave radius is smaller than the critical value

$$r_c \simeq \left(\frac{2^2\, E}{\rho_u\, 5^2\, V_c^2}\right)^{1/3} \simeq 6\cdot 10^{19}\ {\rm cm} \simeq 20\ {\rm pc} \tag{13.4}$$

for our parameters. The volume occupied by the remnant then is

$$V(r_c) \simeq \frac{4\pi}{3}\, r_c^3 \simeq 3.4 \cdot 10^4 \ \mathrm{pc}^3 \tag{13.5}$$

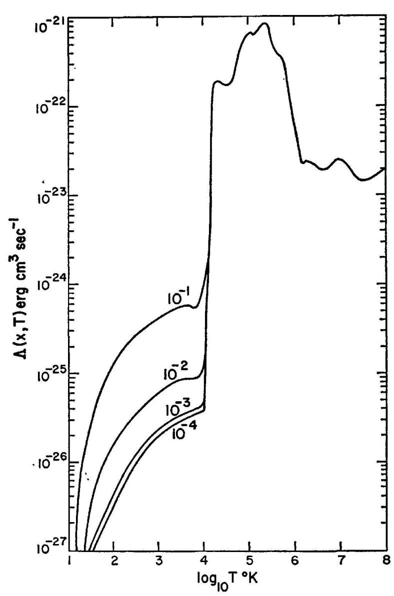
For each location the probability P to be overrun by the blastwave is identical to that being inside the volume $V(r_c)$ and given by the ratio of $V(r_c)$ and the total volume of the Galaxy, $V_{\rm gal}$. The average time between two encounters with shock waves that would heat to at least a million degrees then is

$$t_{rep} = t_{SN}\, \frac{V_{\rm gal}}{V(r_c)} \simeq (2 \cdot 10^8 \ \text{years}) \left(\frac{n}{\text{atoms/cm}^3}\right) \left(\frac{T}{10^6\ \mathrm{K}}\right) \tag{13.6}$$

where I have added the dependence on the gas density and the temperature, to which we gas is to be heated. Two hundred million years may seem a long time, but one has to compare this to the time it takes to cool the gas again.

13.2 The cooling of interstellar gas

Interstellar gas cools by radiating. Free electrons radiate efficiently on account of the acceleration in the Coulomb fields of ions, which we call bremsstrahlung. More efficient in many circumstances is line radiation from heavier atoms and ions, which includes so-called forbidden lines, which cannot be observed in the laboratory. These arise from states that have a very long lifetime with respect to radiative transitions. In the lab the atoms will all be collisionally de-excitated, but that doesn't work in space on account of the extremely low density, thus allowing the radiative transition to operate.



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

The cooling function Λ is based on the probability of all transitions. The real energy loss rate per atom depends in addition on the number of interaction partners, i.e. the density of gas. The rate of change in the thermal energy density of gas also depends on how many particles per volume element loose energy, i.e. in total it scale with the square of the density.

$$\frac{\partial\epsilon}{\partial t} + \ldots = -\frac{\rho^2}{m_p^2}\,\Lambda(T) \qquad \text{or} \qquad \frac{\partial T}{\partial t} = -\frac{\rho}{m}\,\frac{\gamma-1}{k}\,\Lambda(T) \tag{13.7}$$

At temperatures between 10^6 K and 10^8 K the cooling function is approximately constant and the rate of change of the temperature is

$$\frac{\partial T}{\partial t} \simeq -(2\cdot 10^{-7}\ \mathrm{K/s})\left(\frac{n}{\mathrm{atoms/cm^3}}\right) \tag{13.8}$$

The timescale on which gas cools significantly is then estimated as

$$\tau_{\mathrm{cool}} = \frac{T}{|\dot{T}|} \simeq (1.5\cdot 10^5\ \mathrm{years})\left(\frac{n}{\mathrm{atoms/cm^3}}\right)^{-1}\left(\frac{T}{10^6\ \mathrm{K}}\right) \tag{13.9}$$

Comparing Eq.13.6 and 13.9 we see that between two encounter with a SNR blastwave the gas will cool and likely reach an equilibrium state, unless the gas density is very low. That leaves us with the question: what are temperature equilibrium states for interstellar gas?

13.3 Temperature equilibria for gas

An equilibrium may exist between the continuous heating by energetic particles and radiation on one side and radiative cooling on the other side. Once out of equilibrium, gas has two ways of returning to equilibrium, (i) by an imbalance of heating versus cooling with the right sign and (ii) by expansion or compression. In the absence of large-scale expanding or compressing flows and under a hydrostatic equilibrium, what would be stable temperature equilibria? Are they possible at all temperatures?

An equilibrium is characterized by an exact balance of the heating and cooling terms.

$$\dot{T} = \frac{1}{n}\,(\mathcal{H}-\mathcal{C}) = \frac{\mathcal{H}}{n} - n\,\Lambda = 0 \tag{13.10}$$

The heating arises from interactions with external agents, energetic particles and radiation, and will depend on density (in the equation for ϵ) but not on temperature. The heating per atom ($\frac{\mathcal{H}}{n}$) is usually constant.

We now wish to see, whether or not the equilibrium is stable. If the system is subjected to a temperature perturbation, does it return to the equilibrium temperature or would it move away? Let us denote the equilibrium temperature as T_0. Then

$$\frac{\mathcal{H}}{n} = n\,\Lambda(T_0) \tag{13.11}$$

Suppose an infinitesimal perturbation of the temperature $T = T_0 + \delta T$. Then

$$\dot{T} = \frac{\mathcal{H}}{n} - n\,\Lambda(T_0 + \delta T) = n\,\Lambda(T_0) - n\,\Lambda(T_0 + \delta T) = -n\,\delta T\,\frac{\partial \Lambda}{\partial T}\Big|_{T_0} \tag{13.12}$$

So the heating/cooling imbalance imposed by a temperature perturbation is directed opposite to it, that is correcting the perturbation, if the cooling function is increasing with temperature. If the cooling function were falling off with temperature, the equilibrium would thus be unstable. The cooling function has a positive gradient for all temperature below 10^5 K, and steep gradients below 1000 K and around 10^4 K. This is why in the interstellar medium we find most of the gas at low temperatures, molecular hydrogen at about 40 K, atomic hydrogen between 50 K and a few hundred Kelvin, and ionized gas at 10^4 K where it is held by the strong radiation field of young massive stars (HII regions). The phases in which the interstellar gas is observed can thus be understood in terms of temperature equilibria. Dense gas tends to have lower temperature in equilibrium, where the cooling function is lower, because $\rho\,\Lambda$ must balance the heating. There is also a hot dilute gas, that doesn't have a characteristic temperature, because there is not stable temperature equilibrium. Typically the interstellar gas is in pressure equilibrium (Dense gas tends to have lower temperature!), so the different phases of the gas satisfy

$$n_{\mathrm{H}_2}\,T_{\mathrm{H}_2} \simeq n_{\mathrm{H}I}\,T_{\mathrm{H}I} \simeq n_{\mathrm{hot}}\,T_{\mathrm{hot}} \tag{13.13}$$

Gas at a few million degrees therefore tends to have a low density $n \approx 10^{-3} - 10^{-2}$ atoms/cm^3 and the cooling time (cf. Eq.13.9) is of the order of 10^8 years, so the gas is not in equilibrium.