Part IV: Cooling and Condensation of Interstellar Matter

On the Cooling of Interstellar Matter

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WE shall not discuss here in detail the problem of the temperature equilibrium of interstellar matter. Some improvement of our knowledge has been effected by Seaton's results[1] concerning the collisional cross sections of the ions C^+, Si^+, Fe^+, which are important for the temperature equilibrium of the HI regions, and by his results[2] concerning the excitation of the forbidden lines in gaseous nebulae.

In the case of HI regions, Seaton has calculated the loss of energy $\mathcal{L}_{ei}$ per second per hydrogen atom per electron due to inelastic collisions of electrons with ions. We have collected his results in Table I. In Table II, we give the energy gain $\mathcal{G}_{ei}$ per second per hydrogen atom per electron due to photoionization, calculated with the same assumptions concerning the chemical composition and with a color temperature of 2×10^4°K. The energy losses being greater than those found by Spitzer and by Spitzer and Savedoff,[3] the equilibrium temperature in an HI region will be lower (18°K in place of 21°K). Since the temperature of the hydrogen clouds as found from observations of the 21-cm line is in the neighborhood of 125°K, another source of energy has to be found. Seaton[1] has explored Kahn's assumption[4] that encounters between clouds are an important supplementary source of energy.

Rather than discuss the problem of the temperature equilibrium of interstellar matter, I consider the problem of the temperature changes in interstellar space, especially the question of how hot interstellar matter (for example, an HII region) can cool down to low temperatures and become, for example, a cold HI region.

In nonequilibrium conditions, the kinetic temperatures of the neutral and the charged particles may be quite different. The question has been considered by Spitzer, with reference to the following problems: (1) equipartition of energy between electrons, (2) equipartition of energy between protons, (3) equipartition of energy between protons and electrons, and (4) equipartition of energy between neutral hydrogen and electrons.

As is well known, the times of relaxation t_1, t_2, t_3, t_4 can be put in the order $t_1<t_2<t_3<t_4$. It should be noticed that the time of relaxation t_4 is much longer than the others. This is the reason why Spitzer and Savedoff[3] and Seaton[1] have considered in some detail the case when the temperature T_H of the neutral hydrogen atoms is different from the temperature T_e of the electrons.

Let us consider first the case of an HI region.

The rate of exchange of energy between electrons and hydrogen atoms may be written as $\gamma n_H n_e$, with

$$\gamma=8Q\frac{m_e}{m_H}\left(\frac{2kT}{\pi m_e}\right)^{\frac{1}{2}}k(T_H-T_e) \qquad (1)$$

(Spitzer and Savedoff[3]). Q is the elastic cross section. Seaton has given as best estimate $Q=6.3\times10^{-15}$ cm^2, from which we obtain

$$\gamma=1.16\times10^{-27}T_e^{\frac{1}{2}}(T_H-T_e). \qquad (2)$$

TABLE I.

		$\mathcal{L}_{ei}$ [ergs cm^3 sec^{-1}]			
T_e	$10^{24}\mathcal{L}_{ei}$	T_e	$10^{24}\mathcal{L}_{ei}$	T_e	$10^{24}\mathcal{L}_{ei}$
10	0.00018	40	0.092	300	1.18
12	0.00077	50	0.131	500	1.6
14	0.0021	60	0.167	1000	1.8
16	0.0046	80	0.237	1500	1.7
18	0.0082	100	0.32	2000	1.6
20	0.0129	150	0.56	3000	1.45
30	0.049	200	0.80	5000	1.2

TABLE II.

$\mathcal{G}_{ei}$ [ergs cm^3 sec^{-1}]	
T	$10^{24}\mathcal{G}_{ei}$
7.9	0.0123
15.8	0.0079
31.6	0.0051
79	0.0028
158	0.00175
316	0.00110

(for a color temperature $T_c=20\,000$°K)

[1] M. J. Seaton, Ann. Astrophys. **18**, 188 (1955).
[2] M. J. Seaton, Proc. Roy. Soc. (London) **A218**, 400 (1953).
[3] L. Spitzer, Jr., Astrophys. J. **120**, 1 (1954); L. Spitzer, Jr., and M. Savedoff, Astrophys. J. **111**, 593 (1950).
[4] F. D. Kahn, *Gas Dynamics of Cosmic Clouds*, edited by H. C. van de Hulst and J. M. Burgers (North-Holland Publishers, Amsterdam, the Netherlands, 1955), p. 60.

We can therefore write the rates of exchange of energy for the H atoms and for the electrons as follows:

$$\frac{d}{dt}(\tfrac{3}{2}n_{\mathrm{H}}kT_{\mathrm{H}})=-\gamma n_e n_{\mathrm{H}}, \tag{3}$$

$$\frac{d}{dt}(\tfrac{3}{2}n_e kT_e)=(\mathcal{G}_{ei}+\gamma-\mathcal{L}_{ei})n_e n_{\mathrm{H}}. \tag{4}$$

Since the hydrogen temperature changes very slowly, we can first suppose it to be constant. We then find that the electron temperature reaches its equilibrium value in a short time. Close to equilibrium $\gamma=0$, and for $n_{\mathrm{H}}=30$, $(\mathcal{G}_{ei}-\mathcal{L}_{ei})n_{\mathrm{H}}\sim 5\times 10^{-26}\delta T$, which leads to a time constant $t_e=1.3\times 10^2(30/n_{\mathrm{H}})$ years.

Hence T_e is always close to its equilibrium value, and we can write

$$\mathcal{G}_{ei}+\gamma-\mathcal{L}_{ei}=0. \tag{5}$$

In an HI region the number of free electrons is always small, and we can write for T_{H}:

$$\frac{d}{dt}(\tfrac{3}{2}kT_{\mathrm{H}})=-\gamma n_e, \tag{6}$$

from which we can derive the time of relaxation for the hydrogen temperature,

$$t_4=t_{\mathrm{H}}=\frac{1.8\times 10^{11}}{n_e T_e^{\frac{1}{2}}}. \tag{7}$$

With $n_e=2\cdot 10^{-4}n_{\mathrm{H}}$ we derive the following value of t_4 in years:

$$t_4=2.8\times 10^7 n_{\mathrm{H}}^{-1}T_e^{-\frac{1}{2}}\ \mathrm{yr}. \tag{8}$$

We therefore reach the following conclusion: In an HI region $\mathcal{G}_{ei}$ is always small. If the temperature of the electrons is high, it might be only because the hydrogen temperature is also high. This case, studied by Seaton, is the case when the main source of energy of the electrons is the heat content of neutral hydrogen. The neutral hydrogen cools slowly.[1]

The importance of the hydrogen molecules is not fully known.

Let us consider now the case of an HII region. The number of free electrons is much larger and close to the number of hydrogen atoms (ionized+neutral). We may suppose that hydrogen has been ionized and that before ionization the temperature T_{H} was low. We can estimate the time of relaxation t_4 by taking $T_e=5000$°K:

$$t_4\sim 80/n_e\ \mathrm{yr}.$$

We therefore reach the conclusion that in an HII region the temperature of the neutral hydrogen atoms is essentially the same as the temperature of the electrons and protons.

We shall now consider two problems: (1) the transformation of an HII region into an HI region; and (2) the condensation process considered by Zanstra.[5]

If an HII region is contracting, the temperature of the neutral hydrogen atoms formed during the contraction will be the temperature of the HII region, e.g., 5000°K. When the region has become neutral, we are left with an HI region with a small number of neutral hydrogen atoms at high temperature. The neutral hydrogen will cool slowly, according to Seaton's result.

Let us now consider Zanstra's process.

It should be noted that Zanstra's basic assumption is that the low-lying level which produces the cooling of interstellar matter belongs to the neutral atom. In other words, from the fundamental level of the neutral atom we may have two transitions,

$$\text{collisional excitation,}\quad A\rightarrow A^*,$$
$$\text{photoionization,}\quad A+h\nu\rightarrow A^+ +e.$$

In an HII region, ions such as 0+, with an excited level at 3.31 ev, form the cooling agent. The ionization potentials are O:13.61:35.15. Therefore, oxygen is singly ionized and not doubly ionized, unless the color temperature of radiation is exceedingly high.

In an HI region, C^+, with an excited level at 0.0079 ev, is the cooling agent. The ionization potentials are C:11.26:24.38.

Therefore, also, carbon is singly ionized and not doubly ionized. The same is true of silicon and iron, which are the efficient cooling agents at $T_e>125$°K.

Let us consider now if the contraction process imaged by Zanstra can exist even if the neutral and the ionized atom have a low-lying excited level.

In the form used by Zanstra, the equation of thermal equilibrium can be written

$$\tfrac{3}{2}Cn_A k[\bar{T}-\tfrac{2}{3}T_e]=\chi\beta n_A n_e+\chi'\beta' n_{A^+}n_e,$$

where C is a constant depending upon the incident radiation field and atomic parameters, and the β are of the form $f[T_e]\exp[-\chi/kT_e]$. The equation of ionization equilibrium may be written

$$Cn_A=C'n_{A^+}n_e.$$

From these two equations we obtain an expression for the electron density,

$$n_e=\frac{\tfrac{3}{2}Ck[\bar{T}-\tfrac{2}{3}T_e]-\chi'\beta'[C/C']}{\chi\beta};$$

and thus for the electron pressure, $p_e=n_e kT_e$, we have

$$p_e=\frac{\tfrac{3}{2}Ck}{\chi\beta}\left\{(\bar{T}-\tfrac{2}{3}T_e)-\frac{2\chi'\beta'}{3C'k}\right\}.$$

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[5] H. Zanstra, *Gas Dynamics of Cosmic Clouds*, edited by H. C. van de Hulst and J. M. Burgers (North-Holland Publishers, Amsterdam, the Netherlands, 1955), p. 70.

Noting the form of the temperature-dependence of the β, we see that the electron pressure has two extremals for sufficiently large $\bar{T}$, *viz.*, Zanstra's suggested separation into two phases of equal pressure. If we consider the existence of these extremals for large values of T_e, we readily show that we require

$$\bar{T} > \frac{2\chi'\beta'}{3C'k}.$$

With the expressions:

$$\beta' = 8.6 \times 10^{-6} \Omega(n,n') \varpi_n^{-1} \sim 10^{-5.3},$$

$$C' = \frac{8\pi\sigma k h^2 \nu_1^2}{\varpi_n c^2 [2\pi m_e k]^{\frac{3}{2}}} \sim 10^{-11.2},$$

we obtain the condition $\bar{T} > 10^{7.7}$°K, and thus conclude that the separation into two phases hypothesized by Zanstra can play no significant role in HI regions.