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III-3-4. Energy Spectrum of Suprathermal Particles and Formation of Star Clusters in Interstellar Space

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The energy spectrum of suprathermal particles in interstellar space is examined in connection with the temperature ($\sim$100°K) of normal interstellar HI clouds and with the formation of star clusters. The omnidirectional intensity spectrum $j_0(E)dE$ (E in keV) of suprathermal particles may be represented, for example, by $(2\times10^{-2}\,E)dE$ cm^{-2} sec^{-1} for $E<10^3$ keV and $(2\times10^4/E)dE$ cm^{-2} sec^{-1} for $E>10^3$ keV. Interstellar clouds with masses M less than $10^3\,M_{\odot}$ are stable against contraction, while a proto-galactic-cluster with $M\sim10^2\,M_{\odot}$ and radius $R\sim10^{19}$ cm can be originated from a cold core of a cloud of $M\sim10^3\,M_{\odot}$ owing to the gravitational instability, in agreement with observed astronomical evidences.

The cosmic radiation has been tacitly defined as the entity consisting mainly of particles with relativistic energies. These particles must have had thermal or epithermal energies before they have got accelerated. In the recent development of space observations and ionospheric measurements have been found a considerable amount of non-relativistic particles trapped in the geomagnetic field or associated with solar disturbances. Since particles have to pass through such a suprathermal but non-relativistic energy region before they are accelerated to relativistic energies, studies of such sub-cosmic ray particles are considered as important in understanding the acceleration mechanism. On the other hand, it has been pointed out[1] that sub-cosmic rays may play an appreciable role in the energy balance in the Galaxy. Namely, the temperature of interstellar clouds is possibly maintained owing to the heating by slow protons and α-particles, which is balanced with the cooling due to the excitation of low lying levels of some metallic ions and molecules by thermal electrons[2] followed by forbidden emission. In order to explain the observed temperature of HI clouds, about 100°K, we estimated[3]

$$<jQ>_0=\int j(E)\,Q(E)\,dE\simeq10^{-15}\ \mathrm{sec}^{-1}\,, \quad (1)$$

where $j(E)dE$ is the omnidirectional flux intensities of slow particles with kinetic energies between E and $E+dE$ and $Q(E)$ the cross sections effective for energy transfer, provided that the hydrogen density in the cloud is $n(\mathrm{H})\simeq10\ \mathrm{cm}^{-3}$.

The heating by the slow particles may have further astrophysical bearing in the following two respects. Firstly, the slow particles excite hydrogen and helium atoms in interstellar clouds, so that the radiations such as L_α, H_α, P_α and $2\,h\nu$, the last being as due to the 2s-1s transition, could be observed from active clouds, in which the acceleration is much more effective than in average clouds.[3][4]

Secondly, the heating takes part in the instability of an interstellar cloud and, consequently, in the condensation which leads to the formation of stars.[5] Since the particles lose energy as they penetrate into a cloud, the heating is not always uniform over the cloud. If the energy spectrum of the particles is so steep that they are mostly of low energies, only a rather thin layer near the surface of a cloud is heated but its inner part cools down. Consequently, the instability of a short wave length can take place in the inner part, thus resulting in a galactic cluster of small total mass. If, on the other hand, the whole volume of a cloud is uniformly heated due to the high average energy of the particles, the total mass of a cluster may be large. If there takes place acceleration of particles associated with the instability, the situation would be more com-

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plicated. In this way the information about interstellar clouds and galactic clusters will give us some clues on the energy spectrum of sub-cosmic rays.

In the present paper we are mainly concerned with the latter problem and try to find a relation between the stellar formation and the suprathermal particles. In contrast to our previous work,[5] electrons are here assumed to be produced by the ionization process of suprathermal particles on the basis of our recent investigation.[3]

According to reference 3, the thermal equilibrium per unit volume is represented as

$$n(\mathrm{H}) < j\,Q > \bar{w} = f(T)\, n(\mathrm{H})\, n(e)\,, \qquad (2)$$

where $\bar{w} \simeq 10\,\mathrm{eV}$ is the mean energy gain per ionizing collision, and the cooling function $f(T)$ is shown in Fig. 1

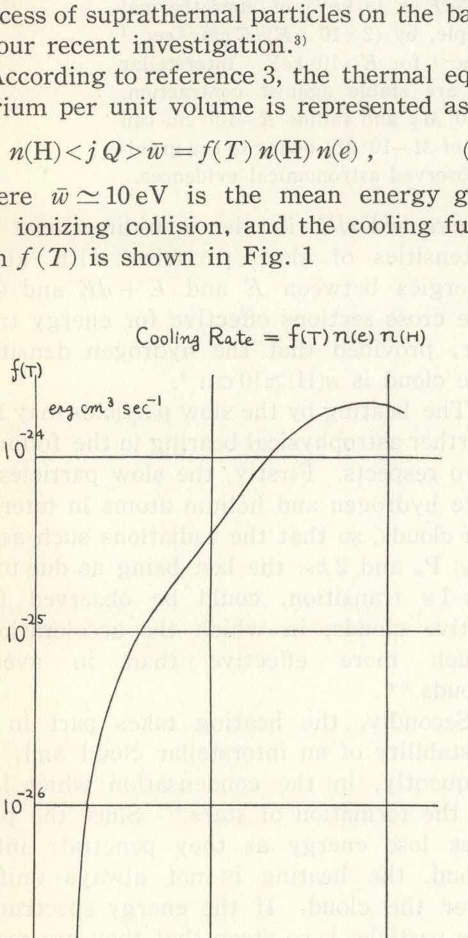

Fig. 1. Cooling function (*cf.* Ref. 2).

The right hand side in Eq.(2) represents the energy loss due to the excitation of low lying levels of C^+, Si^+, and Fe^+, whose density is proportional to the density of hydrogen atoms, $n(\mathrm{H})$. The electron density $n(e)$ is essentially determined by the equilibrium between the ionization by suprathermal particles and the recombination with hydrogen ions, so that

$$n(\mathrm{H}) < j\,Q > = \alpha(T)\, n(e)\, n(\mathrm{H}^+)\,. \qquad (3)$$

We have assumed that Q is essentially the ionization cross section. Since electrons are chiefly supplied from hydrogen atoms under ordinary conditions of interstellar clouds[3], unless the value of $< j\,Q >$ is less than 10^{-3} times the value given by Eq. (1), we may put $n(e) \simeq n(\mathrm{H}^+)$ and consequently

$$n(e) \simeq \sqrt{n(\mathrm{H}) < j\,Q > / \alpha(T)}\,. \qquad (4)$$

Now we consider a spherical cloud of radius R and mass M; these two are connected by

$$M = (4\pi/3)\,(\mu\, m_{\mathrm{H}})\, n(\mathrm{H})\, R^3\,, \qquad (5)$$

where m_{H} is the mass of a hydrogen atom and μ the mean molecular weight ($\simeq 1.5$). The equilibrium condition (2), combined with Eqs. (4) and (5), results in

$$f(T)^2/\alpha(T) = (4\pi/3)(\mu\, m_{\mathrm{H}})\bar{w}^2 < j\,Q > (R^3/M)\,. \qquad (6)$$

Fig. 2 shows the numerical result of Eq. (6), from which the value of $< j\,Q >_0$ in Eq. (1) has been estimated.

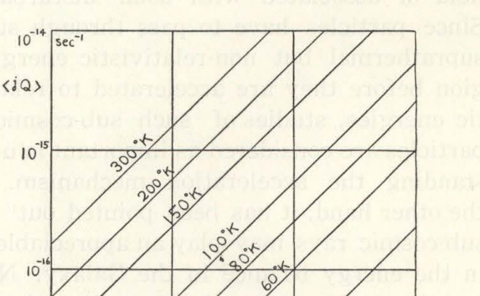

Fig. 2. Dependence of temperature on density and heating rate.

The condition (6) does not always hold everywhere in a cloud, because the suprathermal particles may be absorbed therein, so that they cannot reach its inner region. Then we have to distinguish the value of $< j\,Q >$ averaged over the whole cloud from that in the interstellar space $< j\,Q >_0$ as

$$< j\,Q > = q < j\,Q >_0\,. \qquad (7)$$

Here q depends on the ratio of the penetrat-

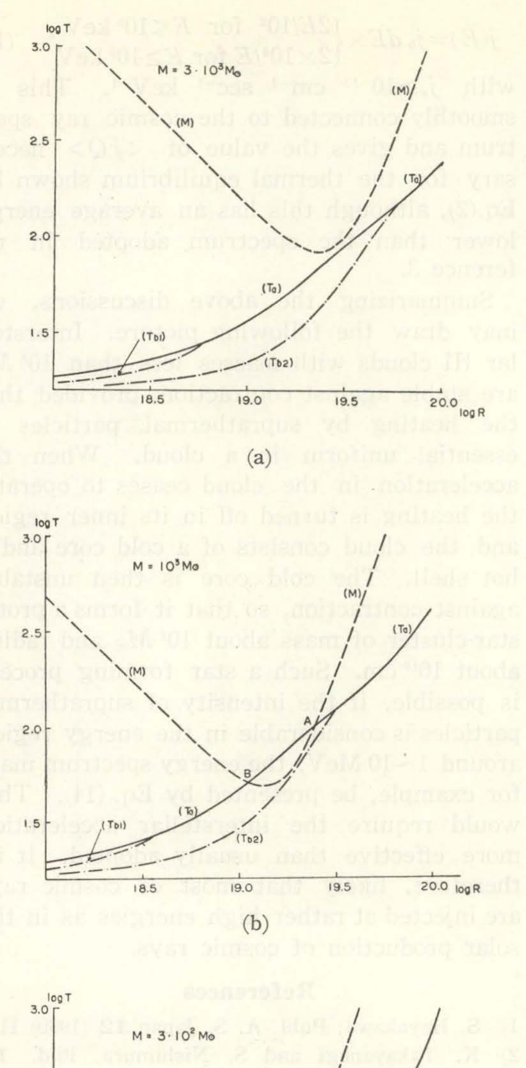

Fig. 3. Mechanical equilibrium (dashed curves) and thermal equilibrium for three different masses. Solid line shows thermal equilibrium for the case that the spectrum of heating particles is unmodified; while, chain lines show the effect of the modification within the cloud, (b1 for higher average energy, b2 for lower average energy).

ing depth, D, of the particles and R, and also on the possible hydromagnetic activity which may be responsible for the acceleration of particles in the cloud. According as whether (a) $D \simeq R$ and/or the acceleration is operative or (b) $D < R$ and the acceleration is ineffective, the value of q is given qualitatively by

$$q \simeq \begin{cases} 1 \text{ in case (a)}, & (8a) \\ D/R \text{ in case}, & (8b) \end{cases}$$

The penetration depth is related to the range $\tau/n(\mathrm{H})$ as

$$D = \tau/n(\mathrm{H})\nu\,, \qquad (9)$$

where ν is to allow for the helical motion of the particle in a magnetic field and for the scattering by magnetic irregularities. The range is given for $E \gtrsim 300$ keV approximately by

$$\tau = 3.8\times10^{15}\, E^{1.71}\ \mathrm{cm}^{-2}\ (E \text{ in keV})\,. \qquad (10)$$

The formula (8b) then reduces to

$$q \simeq 3.8\times10^{15}(4\pi/3)(\mu m_{\mathrm{H}})(E^{1.71}/\nu)(R^2/M)\,. \qquad (8b')$$

Here and in the following E should be considered as an effective mean energy of the incident protons.

Combining Eqs. (6), (7) and (8), we have

$$\frac{f^2(T)}{\alpha(T)} = \begin{cases} 1.1\times10^{-60}(R^3/M) \text{ in case (a)}. & (11a) \\ 4.0\times10^{-68}(E^{1.71}/\nu)(R^5/M^2) \text{ in case (b)}. & (11b) \end{cases}$$

Solid curves (T_a) in Figs. 3a–c show the thermal equilibrium given by Eq.(11a), while dott-dashed curves, T_{b1} and T_{b2} show the T-R relations according to Eq. (11b) for assigned values of M, in which the values of $E^{1.71}/\nu$ are taken as 5×10^6 and 5×10^4 respectively. The latter corresponds to $E = 1$ MeV for $\nu = 10$.

These thermal curves should be combined with curves of the mechanical equilibrium, shown by dashed M-curves in Figs. 3, following the virial relation

$$3\,M(\mathscr{R}/\mu)T - 4\,\pi p R^3 - AGM^2/R = 0\,. \qquad (12)$$

Here $\mathscr{R}$ and G respectively denote the gas and the gravitation constants, p the external interstellar pressure ($\sim 1.4\times10^{-13}$ dyne cm^{-2}) and A a constant (~ 0.6) representing the degree of central condensation.

For the cloud mass greater than 3000 $M_\odot$ no equilibrium configuration is found to exist, as shown in Fig. 3a. Such a massive cloud is dynamically unstable, so that it will split into fragments due possibly to turbulent disturbances. We are, therefore, interested in clouds of masses around 1000 $M_{\odot}$ and smaller. For such clouds two equilibrium configurations are found to exist at A and B in Figs. 3 b, c; only the one of smaller density (A) is evolutionally interesting.

For $M \simeq 1000\, M_{\odot}$ there holds case (b) if $E^{1.71}/\nu \lesssim 5\times10^4$ when the acceleration in the cloud ceases to operate. Then the cloud which has been stable in case (a) becomes unstable for contraction, because the temperature in the inner region decreases to about 20°K due to the cooling mechanism discussed in reference 2. Putting the representative pressure p' inside the cloud ($p' \simeq 1.5\,p$) in place of p in Eq. (12) and keeping $T=20$°K, we have from Fq. (12)

$$M_c \simeq 150\, M_{\odot}\,, \quad R_c \simeq 10^{19}\,\mathrm{cm} \tag{13}$$

as the critical mass and radius for instability. It is noted here that these values of mass and radius can be attained for the cold core inside the cloud of $M=10^3\, M_{\odot}$ at $R=2\cdot10^{19}$ cm (*cf*. Fig. 3*b*), provided that $\nu \simeq 10$ in Eq. (9). The part within the critical radius thus turns into a proto-star-cluster. Its mass of about $10^2\, M_{\odot}$ is in fair agreement with the observed for galactic clusters.

The above argument implies that the average energy of suprathermal particles is so low that they can hardly reach the inner region. On the other hand, if $E^{1.71}/\nu \ll 5\times10^4$, practically the whole cloud is cooled down, so that, a cluster of $10^3\, M_{\odot}$ would be materialized. The energy spectrum of suprathermal particles consistent with this penetration depth may be expressed rather arbitrarily at present as

$$j(E)=j_0\, dE \times \begin{cases} 2E/10^2 & \text{for } E \leq 10^3\,\mathrm{keV}\,, \\ 2\times10^4/E & \text{for } E \geq 10^3\,\mathrm{keV} \end{cases} \tag{14}$$

with $j_0 \simeq 10^{-13}$ cm^{-2} sec^{-1} keV^{-1}. This is smoothly connected to the cosmic ray spectrum and gives the value of $<jQ>$ necessary for the thermal equilibrium shown by Eq.(2), although this has an average energy lower than the spectrum adopted in reference 3.

Summarizing the above discussions, we may draw the following picture. Interstellar HI clouds with masses less than $10^3\, M_{\odot}$ are stable against contraction, provided that the heating by suprathermal particles is essential uniform in a cloud. When the acceleration in the cloud ceases to operate, the heating is turned off in its inner region and the cloud consists of a cold core and a hot shell. The cold core is then unstable against contraction, so that it forms a proto-star-cluster of mass about $10^2\, M_{\odot}$ and radius about 10^{19} cm. Such a star forming process is possible, if the intensity of suprathermal particles is considerable in the energy region around 1~10 MeV; the energy spectrum may, for example, be presented by Eq. (14). This would require the interstellar acceleration more effective than usually adopted. It is, therefore, likely that most of cosmic rays are injected at rather high energies as in the solar production of cosmic rays.

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