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RADIATION INSTABILITY OF A BOUNDED PLASMA

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As is known, in a thermodynamically nonequilibrium plasma the formation of instabilities is possible. Usually kinetic and magnetohydrodynamic instabilities are considered. It is of interest to draw attention to the case when an instability arises because of nonequilibrium radiation, i.e., when the volume radiation density is less than the Planck density.

Let us imagine that, in a homogeneous plasma, for some reason (fluctuations, etc.) there has arisen a region with a somewhat higher density. Since the radiation power of an optically transparent plasma is proportional to the square of the density, while its dependence on temperature is no stronger than $T^{\pm 1/2}$ (for example, for hydrogen this is true at $T > 2$ eV), an increase in density will lead to cooling of the plasma region in comparison with the surrounding unperturbed plasma, and this will cause a flow of plasma into the given region. As a result the density will increase still more, and so on. In this way a clot of relatively dense and cold plasma will be formed, whose final parameters are determined by competing processes: absorption of radiation, thermal conductivity, etc.

If there is a bounded volume of plasma with temperature T, concentration of charged particles n, and characteristic size Λ, then over a wide range of values of T, n, Λ the radiation is not trapped. This can be estimated from the transparency condition for radiation

$$\Lambda \ll \sigma T^4 / \left(a_1 n^2 T^{1/2} + a_2 n^2 T^{-1/2}\right); \quad (1)$$

a_1 and a_2 are the coefficients of bremsstrahlung and recombination radiation, respectively, and σ is the Stefan-Boltzmann constant. Inequality (1) is valid when line radiation is neglected, i.e., for sufficiently high temperatures.

In what follows, for simplicity, we shall consider hydrogen plasma bounded by immobile walls, and shall regard thermal conductivity as negligible. The equation of energy balance for the entire plasma volume in the case where bremsstrahlung radiation dominates is:

$$\frac{3}{2}\frac{dp}{dt} = -\frac{a_1}{\sqrt{2}}n^{3/2}p^{1/2}, \qquad p = 2nT, \tag{2}$$

which gives

$$T = T_0(1 - t/\tau_0)^2, \tag{3}$$

where $\tau_0 = 6T_0^{1/2}/a_1 n_0$ is the time of complete radiative cooling of the plasma.

Suppose that in some region v ($v \ll \Lambda^3$) the concentration n_1 is somewhat greater than n_0. The energy equation for this volume is:

$$\frac{3}{2}\frac{dp}{dt} - \frac{5}{2}\frac{p}{n_1}\frac{dn_1}{dt} = -\frac{a_1}{\sqrt{2}}n_1^{3/2}p^{1/2}. \tag{4}$$

We substitute p from equation (2), assuming that throughout the whole volume $p = \text{const}$. This is valid if the time of sound propagation in the selected volume is substantially less than the cooling time

$$\Lambda_{\text{cr}}/\sqrt{5T/3m_i} < \tau_0. \tag{5}$$

Integrating equation (4), we obtain

$$\frac{n_1}{n_0} = \left[1 + \frac{1 - (n_{10}/n_0)^{3/2}}{(1 - t/\tau_0)^{3/5}}\right]^{-2/3}; \tag{6}$$

here n_{10} is the initial density in the selected volume. As can be seen, the time for the formation of the condensation is approximately equal to the cooling time.

In the case when recombination radiation dominates, we obtain the decay formula

$$T = T_0(1 - t/\tau_0)^{2/3}, \tag{3a}$$

the cooling time $\tau_0 = 2T_0^{3/2}/a_2 n_0$, and the dependence of the growth of the concentration in the condensation

$$\frac{n_1}{n_0} = \left[1 + \frac{1 - (n_{10}/n_0)^{5/2}}{1 - t/\tau_0}\right]^{-2/5}. \tag{6a}$$

The formation of a cooled condensation is hindered by the process of temperature equalization caused by thermal conductivity. The minimum critical size of

Fig. 1

Figure 1: Fig. 1

a condensation is determined from the condition that the cooling time and the temperature relaxation time be equal, i.e.,

$$\lambda_{\min} = \tau_0 \chi / 1.5nk; \tag{7}$$

χ is the coefficient of thermal conductivity of the plasma.

Thus, the region of instability proves to be bounded by conditions (1) and (7). For example, for a temperature of 100 eV this region is shown in Fig. 1. Condition (5) imposes an upper limit on the critical size of the condensation (in Fig. 1—the dashed line). Undoubtedly, the presence of a magnetic field should have a substantial effect on the processes. In any case, by reducing thermal conductivity, the magnetic field expands the region of instability toward smaller characteristic sizes.

Fig. 1

We have considered a plasma bounded by walls. However, it is not difficult to see that if $\Lambda \gg \lambda_{\text{cr}}$ (formula (5)), then the expansion time is substantially greater than the cooling time, and all the arguments presented are applicable to an expanding plasma. Thus, radiation instability can form in astrophysical objects, in the expanding plasma of an explosion. On laboratory scales this phenomenon may appear at lower temperatures. For hydrogen, $\lambda_{\min} \sim 1$ cm at $T = 10$ eV and $n = 10^{18}$ cm^{-3}.

For a plasma with Z and $A > 1$, the instability region and the characteristic times change accordingly. In connection with this circumstance, let us note one possibility. The formation of a condensation may be caused not only by a local increase in concentration, but also by an increase in the effective charge of the plasma ions, for example the concentration of impurity ions. In this case an interesting effect is possible: the displacement of "dirty" plasma by purer plasma.

The restriction we have adopted to a decaying plasma is not obligatory. It is only necessary that the determining mechanism for energy loss be untrapped radiation. In this sense, the phenomenon described can also manifest itself in high-temperature arcs of sufficiently large density and sufficiently large dimensions.

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