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Abstract

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ASTRONOMY

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THE ELECTRON TEMPERATURE OF A MEDIUM UNDER SYNCHROTRON RADIATION

(Presented by Academician V. A. Ambartsumian, 11 IX 1959)

Let there be, in the atmosphere or in a limited volume of a stellar atmosphere, an emission of synchrotron radiation (bremsstrahlung radiation of relativistic electrons in a magnetic field). Let us further assume that the density of the synchrotron radiation in the region of short wavelengths, shorter than 912 Å (L_c-radiation), is considerably greater than the density obtained from Planck's formula at the stellar temperature T_*. Then it may be considered that the ionization of hydrogen atoms in the medium is entirely due to the density of the synchrotron L_c-radiation. The electron temperature of this medium, since the occurrence of forbidden lines in it is excluded, will obviously be determined by the residual energy of the electrons torn away in the photoionization of hydrogen atoms under the influence of the synchrotron L_c-radiation.

In the present article the problem of determining the electron temperature of the medium is considered under the following assumptions: a) free electrons are formed by the photoionization of hydrogen atoms under the influence of synchrotron short-wavelength radiation generated in the volume of the stellar atmosphere under consideration; b) the electrons lose their energy by recombination processes connected with hydrogen; c) a Maxwellian velocity distribution is established among the electrons.

The starting point in solving the posed problem is the following two equilibrium conditions: a) the stationarity condition—the number of atoms entering the continuum through photoionization per unit time must be equal to the number of atoms leaving the continuum; b) the condition of radiative equilibrium—the amount of energy expended on the photoionization of hydrogen atoms must be equal to the amount of energy emitted in recombination.

We shall assume in what follows that photoionization occurs only from the ground state; this assumption may be considered acceptable if one bears in mind the extremely small degree of excitation of hydrogen atoms under the conditions of stellar atmospheres. Recombination of free electrons occurs to all levels, and we shall take them into account. The role of free-free transitions is insignificant; therefore we shall neglect them.

If the energy spectrum of relativistic electrons is continuous and has the form $N_e = KE^{-\gamma}$, then the density of radiation at frequency ν, generated by these electrons when they are braked in a magnetic field, may be represented in the following form:

$$\rho_\nu = \text{const} \cdot \nu^{(1-\gamma)/2}. \tag{1}$$

Denoting by n_1 the number of hydrogen atoms in the ground state per unit volume and by $k_{1\nu}$ the coefficient of continuous absorption, calculated per atom, we shall have for the number of ionization acts per unit—

the expression per unit time

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu} \frac{\rho_\nu c}{h\nu} \, d\nu, \tag{2}$$

where ν_0 is the ionization frequency.

For the number of recombinations to all levels we have (see, for example, (1))

$$4\pi n^+ n_e \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) e^{-m_e v^2/2kT_e} v^3 \, dv, \tag{3}$$

where n^+ and n_e are the numbers of hydrogen ions and free electrons per unit volume; T_e is the electron temperature of the medium; $\beta_i(T_e)$ is the effective recombination cross section.

Application of the stationarity condition gives

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu} \frac{\rho_\nu c}{h\nu} \, d\nu = 4\pi n^+ n_e \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) e^{-m_e v^2/2kT_e} v^3 \, dv. \tag{4}$$

In order to write the condition of radiative equilibrium, one must calculate the energy absorbed in photoionization and the energy emitted in recombination, and set them equal. We obtain

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu} \rho_\nu c \, d\nu = 4\pi n^+ n_e \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) h\nu e^{-m_e v^2/2kT_e} v^3 \, dv. \tag{5}$$

The function $\beta_i(T_e)$, appearing in (4) and (5), has the form

$$\beta_i(T_e) \sim k_{i\nu} \frac{i^2 \nu^2}{v^2}. \tag{6}$$

In writing the expressions for the absorption coefficients $k_{1\nu}$ and $k_{i\nu}$, we shall also take into account the influence of negative absorption; we obtain

$$k_{1\nu} \sim \frac{1}{\nu^3} \left(1 - e^{-h\nu/kT_e}\right); \qquad k_{i\nu} \sim \frac{1}{\nu^3 i^5} \left(1 - e^{-h\nu/kT_e}\right). \tag{7}$$

Taking into account (1), (6), and (7), we find from (4) and (5), introducing into them also, instead of $m_e v^2/2$, the quantity $h\nu - h\nu_i$:

$$\frac{\displaystyle\int_{x_0}^{\infty} x^{-(7+\gamma)/2} (1 - e^{-x})\, dx}{\displaystyle\int_{x_0}^{\infty} x^{-(5+\gamma)/2} (1 - e^{-x})\, dx} = \frac{\displaystyle\sum_{i=1}^{\infty} \frac{e^{x_i}}{i^3} \left[\int_{x_i}^{\infty} \frac{e^{-x}}{x}\, dx - \int_{2x_i}^{\infty} \frac{e^{-x}}{x}\, dx \right]}{\displaystyle\sum_{i=1}^{\infty} \frac{1}{i^3} \left(1 - \frac{1}{2} e^{-x_i}\right)}, \tag{8}$$

where $x_0 = h\nu_0/kT_e$, $x_i = h\nu_i/kT_e$; ν_i is the ionization frequency from the i-th state.

In relation (8) the only unknown is the electron temperature T_e, which is determined uniquely. For this purpose, first x_0 is determined from (8) for a given value of γ, and then T_e from the relation

$$T_e = \frac{h\nu_0}{kx_0}. \tag{9}$$

Analysis of the formulas written above shows that the electron temperature of the medium under synchrotron radiation depends only weakly on the spectrum of the relativistic electrons γ; therefore it is determined entirely by the very mechanism of emission of the medium.

The calculations gave $T_e = 110\,000^\circ$ for $\gamma = 3$; $T_e = 100\,000^\circ$ for $\gamma = 5$. Thus, the theoretical electron temperature of the atmosphere (or of part of the atmosphere) of a star in which synchrotron radiation is generated is very high and exceeds by an order of magnitude the electron temperature of gaseous nebulae. It is interesting to note that if the radiation of the photospheric layers of the star is represented by Planck' s law, then the temperature of this star, under the assumptions made above, must be of the order of $200\,000^\circ$ in order that the electron temperature in its atmosphere be of the order of $100\,000^\circ$.

Since the residual energy of the electron after photoionization of hydrogen is fairly high, it may in part be expended on the excitation and ionization of hydrogen atoms in the ground state by means of inelastic collisions. This factor in the loss of electron energy may lead to a "cooling" of the medium and, consequently, to some lowering of its electron temperature. However, in order to achieve a noticeable "cooling" effect, the concentration of neutral hydrogen atoms must be sufficiently large. But even in this case the residual energy of the free electrons will nevertheless correspond to a fairly high electron temperature of the medium, because the excitation and ionization potentials of hydrogen have comparatively high values.

Along with this, a case is possible in which the degree of ionization of hydrogen in the medium is so high that the actual concentration of neutral hydrogen atoms is insufficient to absorb the greater part of the residual energy of the free electrons. In this case the "cooling" effect due to neutral hydrogen will practically not affect the high value of the electron temperature of the medium obtained above.

One may try to find evidence for the theoretical conclusions made above, for example, in some non-stationary stars. If the phenomenon of a flare-up or a short-lived increase in brightness in them is caused by the emission of synchrotron radiation in some part of their atmosphere, then the widths of the spectral lines, for which there is reason to suppose that they arose precisely in that volume of the medium where the generation of synchrotron radiation occurs, must be sufficiently large, corresponding to the high value of the electron temperature.

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Note: Figure translations are in progress. See original paper for figures.