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Diffusion-generated electromotive force and seed magnetic field problem

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Abstract. Mechanisms of the Biermann type for magnetic field generation are discussed. Diffusion currents of electrons are responsible for these processes. They appear in the interstellar medium wherever electronic temperature and density gradient vectors are not parallel. An example of such currents at the border area between hot interstellar gas and atomic condensation is discussed, and a few other examples are also mentioned. Magnetic fields generated in this way can serve as seed magnetic fields for further dynamo amplification. The processes discussed are also essential for a better understanding of early stages of the galaxy evolution.

Key words: interstellar medium – magnetic fields – evolution of galaxy – formation of stars

1. Introduction

Cosmic magnetic fields are an essential part of interstellar matter. They influence diffusion processes, formation of stars, etc.

An initial very weak field can be amplified considerably by dynamo action on the Galactic scale (Moffatt 1978, Parker 1979, Krause *et al.* 1980), but for the dynamo to take place some weak field must already exist.

Several mechanisms have been presented for solving the problem. But unfortunately they cannot generate sufficiently large seed magnetic field without challenging our current understanding of the early stages of Galactic evolution (Rees 1987). The $\alpha - w$ dynamo exponentially amplifies the initial magnetic field $B_\circ$ to the present B value ($\sim 10^{-6}$G) in a time t: $B = B_\circ \exp(t/\tau)$, where τ is a characteristic growth time, which should be at least greater than the rotation period of galaxy $\sim 3 \times 10^8$ years. This gives a lower limit on the initial magnetic field: $B_\circ > 10^{-21}$G. It is also important at what stage of galactic evolution the magnetic fields emerge. If the interstellar magnetic fields originate only as a result of ejections from the first generation of stars (Ruzmaikin *et al.* 1988, p. 255) [1], the earlier stage of the galactic evolution would be quite different. This includes dynamics of supernova explosions, the formation of the first generation of stars and other problems (Rees 1987).

We claim that in the interstellar medium there exist mechanisms for generations the seed magnetic field. The mechanisms discussed can be considered to be of the Biermann type, because they appear wherever electronic temperature and density gradients are not parallel, similar to the condition required for the original Biermann mechanism to operate. Thermal energy is transformed into electrical energy and a temperature difference is essential for the electromotive force (*e.m.f.*) to appear, thus the *e.m.f.* can be called thermally generated. But we will call them *diffusion e.m.f.*s to emphasise the role of diffusion processes in their generation. These mechanisms are effective enough to seed the interstellar medium with magnetic field. The magnetic fields can then be amplified by a turbulent dynamo to the level which will influence star formation processes and further evolution of the first generation of stars. The seed fields generated by the mechanism discussed can also influence the process of dynamo amplification on the galactic scale.

The *e.m.f.*s emerge due to the existence of non-parallel gradient vectors of temperature and of electronic concentration. Unlike the original Biermann process (Biermann 1950) and other weaker or less probable battery processes (Catani and Sacchi 1966, Browne 1968, Harrison 1970, Lesch *et al.* 1989, Chakrabarti 1991) the mechanisms discussed do not require rotation of the medium under consideration and are more effective in interstellar conditions. They can also account for emergence of magnetic fields at the stage of early star formation and galaxy evolution, modifying our understanding of these periods of galactic history. We consider the interstellar medium nonuniform, multiphase, clumpy (see Myers 1987, Shull 1987, Lazarian 1992) and these conditions are very important for the diffusion *e.m.f.* to appear. This distinguishes our approach from many other works where it was implicitly assumed that interstellar characteristics were uniform.

Although the interstellar medium can be in equilibrium, electron fluxes can exist due to gradients of temperature and electronic density. They result in the appearance of the electric field. We will consider the situations when this electric field results in the *e.m.f.* build up in Sect. 2 and the astrophysical consequences of the resulting magnetic fields in Sects 3, 4 and 5.

2. Diffusion generated electromotive force

Consider a gas with an impurity of ions and electrons. Diffusion of electrons, the density and the mean thermal velocity of which are $n(x)$, $v(x)$ will be discussed. Ions will be considered at rest due

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[1] In stars the magnetic fields could originate due to the existence of the Biermann mechanism (Biermann 1950, Mestel *et al.* 1983)

to their greater mass. The diffusion flux of the electrons along the x-axis (see Fig. 1) is (Kittel *et al.* 1980):

$$Q(x) = \frac{1}{4}n_e(x-\lambda)v(x-\lambda) - \frac{1}{4}n_e(x+\lambda)v(x+\lambda) \simeq -\frac{\lambda(x)}{2}\frac{\partial\{n_e(x)v(x)\}}{\partial x} \tag{1}$$

where λ is the mean free path of the electrons.

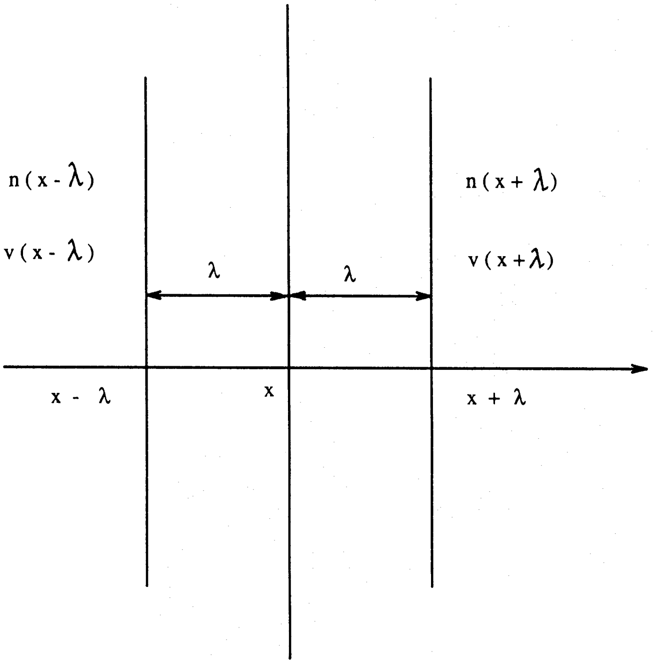

Fig. 1. Diffusion of electrons along the x-axis. The diffusion flux $Q(x)$ at x is the difference between the flux at $x-\lambda$ and the flux at $x+\lambda$ planes.

Taking into account that the mean thermal velocity $v(x) = \sqrt{\frac{8kT_e(x)}{\pi m_e}}$, where m_e is the electron mass and $T_e(x)$ is the electron temperature, and k is the Boltzmann constant, one can write

$$Q(x) = \sqrt{\frac{k}{2\pi m_e T_e(x)}}\,\lambda(x)\left\{2T_e(x)\frac{\partial n_e(x)}{\partial x} + n_e(x)\frac{\partial T_e(x)}{\partial x}\right\} \tag{2}$$

Assuming that collisions with neutrals are dominant (the electron liquid approximation is not valid and the electrons are small impurity), this flux results in the appearance of an electric field $E(x)$, and an associated conductivity flux (Mitchner *et al.* 1973):

$$Q_c(x) = -\frac{\sqrt{\pi}en_e(x)E(x)\lambda(x)}{\sqrt{8km_e T_e(x)}} \tag{3}$$

In equilibrium, these two fluxes must compensate each other, *i.e.* $Q(x) = -Q_c(x)$. Hence:

$$E(x) = -\frac{2k}{\pi e}\left\{\frac{\partial T_e(x)}{\partial x} + \frac{2T_e(x)}{n_e(x)}\frac{\partial n_e(x)}{\partial x}\right\} \tag{4}$$

In the three dimensional case, Eq. (4) becomes:

$$\boldsymbol{E}(\boldsymbol{x}) = -\frac{2k}{\pi e}\left\{\nabla T_e(\boldsymbol{x}) + \frac{2T_e(\boldsymbol{x})}{n_e(\boldsymbol{x})}\nabla n(\boldsymbol{x})\right\} \tag{5}$$

What we are actually interested in is curl$\boldsymbol{E}$. It is easy to see that

$$\nabla\times\boldsymbol{E} = -\frac{4k}{\pi e}\nabla\left\{\frac{T_e(\boldsymbol{x})}{n_e(\boldsymbol{x})}\right\}\times\nabla n_e(\boldsymbol{x}) = -\frac{4k}{\pi e n_e(\boldsymbol{x})}\nabla T_e(\boldsymbol{x})\times\nabla n_e(\boldsymbol{x}) \tag{6}$$

If, on the other hand, the electron fluid approximation is applicable, diffusion will result in hydrodynamic electron flux to compensate for the change of pressure in the electronic fluid. In this case a generalised Ohm's law (Alfvén *et al.* 1963, p. 178) is applicable:

$$\boldsymbol{E}(\boldsymbol{x}) = -\frac{1}{n_e(\boldsymbol{x})e}\nabla p_e(\boldsymbol{x}) \tag{7}$$

Applying the curl operation to both sides of Eq. (7) and considering $p_e(\boldsymbol{x}) = kn_e(\boldsymbol{x})T_e(\boldsymbol{x})$ (k is the Boltzmann constant) one easily comes to Eq. (6) ignoring the difference ($\frac{4}{\pi}\sim 1$) in the coefficients. However, the polarization in this case will be different:

$$\boldsymbol{E}(\boldsymbol{x}) = -k\left\{\nabla T_e(\boldsymbol{x}) + \frac{T_e(\boldsymbol{x})}{n_e(\boldsymbol{x})}\nabla n(\boldsymbol{x})\right\} \tag{8}$$

It is important for further discussion that both approaches give the same result for the diffusion generated *e.m.f.*

Several cases are of importance. They include *partially ionised gas* in the galactic disc and *pure plasma* which fills galactic halo, supernova cavities and the galactic centre, to mention just a few examples (see also Norman *et al.* 1989).

Pure plasma. It is obvious that in the case when the pressure is constant throughout the volume and the temperatures of the electrons and ions are equal, curl$\boldsymbol{E} = 0$.

Consider now the case where ions and electrons have different temperatures (T_i and T_e respectively). This can happen in astrophysical conditions due to the low efficiency of energy transfer from electrons to protons ($\frac{m_e}{m_i} \ll 1$) (Frank *et al.* 1985). In this case

$$kn_e(\boldsymbol{x})T_e(\boldsymbol{x}) + kn_i(\boldsymbol{x})T_i(\boldsymbol{x}) = p_\circ = \text{const} \tag{9}$$

According to Eq. (9) electronic pressure $p_e(\boldsymbol{x}) = kn_e(\boldsymbol{x})T_e(\boldsymbol{x})$ can vary while the total pressure p_0 is constant. The degree of charge separation given by $\frac{1}{4\pi}$div$E$ is so small that $n_e(\boldsymbol{x})$ is very nearly $n_i(\boldsymbol{x})$. Expressing $T_e(\boldsymbol{x})$ from Eq. (7) and using Eq. (6), one can find:

$$\nabla\times\boldsymbol{E} = \frac{4k}{\pi e n_e(\boldsymbol{x})}\nabla T_i(\boldsymbol{x})\times\nabla n_e(\boldsymbol{x}) \tag{10}$$

Wherever conditions for different electron and ion heating are valid one can hope to find an *e.m.f.* of the type discussed above.

The other possibility is a non-uniform pressure distribution (we consider for simplicity all the ions to have charge $+e$):

$$2kn_e(\boldsymbol{x})T(\boldsymbol{x}) = p(\boldsymbol{x}) \tag{11}$$

Combining this with Eq. (6) it is easy to obtain:

$$\nabla\times\boldsymbol{E} = -\frac{2}{\pi e n_e^2(\boldsymbol{x})}\nabla p(\boldsymbol{x})\times\nabla n_e(\boldsymbol{x}) \tag{12}$$

Plasma cannot generally be at rest when a pressure gradient is applied to it. One specific case when we do not observe jets and other violent phenomena caused by a pressure gradient is when the pressure gradients are due to the joint action of gravitational and centrifugal forces or gravitational forces alone. Ignoring the electron mass in comparison with the ion mass one can write:

$$\nabla p(\boldsymbol{x}) = \sum_j n_j(\boldsymbol{x}) m_j \boldsymbol{g}'(\boldsymbol{x}) \tag{13}$$

where $n_j(\boldsymbol{x})$ is the concentration of ions of mass m_j and $\boldsymbol{g}'(\boldsymbol{x})$ is the effective acceleration: $\boldsymbol{g}'(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{x}) - \omega^2(\boldsymbol{x})\boldsymbol{R}$ ($\boldsymbol{R}$ is a vector along the radius of the cylindric coordinate system, where the z-axis coincides with the axis of rotation; ω is the angular velocity). In the case of all masses equal to a proton mass m_p and ω dependent on the z coordinate we arrive at the well known Biermann result (1950):

$$\nabla \times \boldsymbol{E} = -\frac{2}{\pi e} m_p \nabla \times (\omega^2 \boldsymbol{R}) \tag{14}$$

The difference between the coefficients $\frac{2}{\pi}$ found here and $\frac{1}{2}$ in the Biermann (1950) work should not be considered very important due to the simplifications which were made here.

In the case of $\omega = \text{const}$ (including $\omega = 0$) there also can be *e.m.f.* generation if there is a non-symmetric distribution of ions with different masses (compare results of Mestel *et al.* 1962, Dolginov 1977, Mestel *et al.* 1983). Note that this particular battery process was found as just one example of much more general diffusion processes (compare Layzer *et al.* 1979).

Partially ionised gas. This case is richer in consequences because there are more parameters to vary. Consider the case of a medium in pressure equilibrium consisting of electrons, ions and atoms (molecules) with concentrations $n_e(\boldsymbol{x})$, $n_i(\boldsymbol{x})$, $n_a(\boldsymbol{x})$ respectively

$$kT(\boldsymbol{x})n_e(\boldsymbol{x}) + kT(\boldsymbol{x})n_i(\boldsymbol{x}) + kT(\boldsymbol{x})n_a(\boldsymbol{x}) = p_\circ = \text{const}, \tag{15}$$

where temperatures of all the components are equal. Again electronic pressure $p_e(\boldsymbol{x})$ can vary while p =const. The degree of charge separation given by $\frac{1}{4\pi}\text{div}E$ is so small that $n_e(\boldsymbol{x})$ is very nearly $n_i(\boldsymbol{x})$. It is possible to express the temperature from the previous expression:

$$T_e(\boldsymbol{x}) = \frac{p_\circ}{k(2n_e(\boldsymbol{x}) + n_a(\boldsymbol{x}))}. \tag{16}$$

According to Eq. (6)

$$\nabla \times \boldsymbol{E} = \frac{4p_\circ}{\pi e n_e(\boldsymbol{x})(2n_e(\boldsymbol{x}) + n_a(\boldsymbol{x}))^2} \nabla n_a(\boldsymbol{x}) \times \nabla n_e(\boldsymbol{x}) \tag{17}$$

In the case of a small neutral impurity in plasma ($n_a \ll n_e$)

$$\nabla \times \boldsymbol{E} \approx \frac{p_\circ}{\pi e n_e^3(\boldsymbol{x})} \nabla n_a(\boldsymbol{x}) \times \nabla n_e(\boldsymbol{x}) \tag{18}$$

While in the opposite case ($n_e \ll n_a$):

$$\nabla \times \boldsymbol{E} \approx \frac{4p_\circ}{\pi e n_e(\boldsymbol{x}) n_a^2(\boldsymbol{x})} \nabla n_a(\boldsymbol{x}) \times \nabla n_e(\boldsymbol{x}) \tag{19}$$

The gradients in the ionisation can emerge due to shocks, or different ionisation sources in the interstellar medium. It is well known that the concentration of ions and electrons is different in the hot, warm and cold phases of the interstellar medium (see Shull 1987). Even allowing for different sources of the atom and electron gradients they should not generally coincide. A relatively small impurity of atoms in plasma, and vice versa, can result in the appearance of *e.m.f.*

All the cases discussed above in connection with plasma are applicable to the partially ionised gas as well. There can be situations when the temperature of electrons is not equal to the temperature of ions and atoms. The result of this will be the appearance of a term similar to the right side of Eq. (10) in the right side of Eq. (17) (in addition to its original form). One can also consider a situation when the pressure of the medium is non-uniform. This situation results in adding a term similar to right side of Eq. (12) to the right side of Eq. (17), while the pressure gradient can be found according to Eq. (13) provided that m_j denote masses of different ions and atoms as well. As in the case with pure plasma there can be a non-vanishing contribution from the pressure term if there is some peculiar feature like dependence of either the rotating velocity field or the distribution of He ions and neutrals on cylindrical coordinates θ and z. As in the case discussed by Roxburgh (1966) it is possible to include a meridional circulation. A more careful analysis will be given elsewhere for such a possibility of seed field generation.

Not only the magnitude but also the structure of the seed magnetic field can be important.

3. An example of diffusion *e.m.f.*

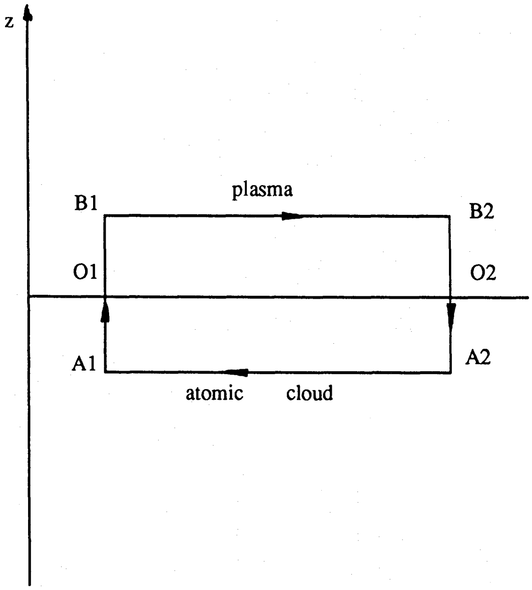

Fig. 2. Contour $A_1B_1B_2A_2$ has non-vanishing *e.m.f.* at the border of the atomic cloud and the plasma ($T_2 > T_1$).

Consider *e.m.f.* generation in a 'contour' shown on Fig. 2. The part A_1A_2 of the contour is situated deep inside the atomic cloud with temperature $T_\circ$. The part B_1B_2 is placed in the plasma where the temperature is varying between T_1 and T_2 over the region. Points O_1 and O_2 correspond to the contour crossing the plasma-atomic cloud border. In the vicinity of these points the temperature changes from $T_\circ$ below the atomic cloud surface to T_1 and T_2. To calculate the *e.m.f.* one can integrate Eq. (5) and Eq. (8) around the contour $A_1B_1B_2A_2$. It is easy to see, considering plasma in equilibrium (e.g. $n_e(\boldsymbol{x})T(\boldsymbol{x}) = \text{const}$), that

$$\int_{A_1B_1B_2A_2} \boldsymbol{E}(\boldsymbol{l})\,\mathrm{d}\boldsymbol{l} = æ \int_{z_O}^{z_A} \left\{ \frac{T_1(z)}{n_1(z)} \frac{\partial n_1}{\partial z} - \frac{T_2(z)}{n_2(z)} \frac{\partial n_2}{\partial z} \right\} \mathrm{d}z \tag{20}$$

where $æ = \frac{4k}{\pi e}$, subscripts “1” and “2” correspond to functions of temperature and density in the vicinity of points O_1 and O_2 respectively.[2] If ions and electrons are only a small impurity, whose contribution to the total pressure of the atomic cloud can be neglected, we can consider arbitrary distributions of these impurities. Assuming, for example, linear growth of temperature from $T_\circ$ inside the cloud to T_i $(i = 1, 2)$ at the border and exponential growth of electron (and ion) concentration towards the border (due to the presence of ionisation sources outside the cloud) [3], one comes to an estimate of the *e.m.f.*, $\varepsilon \sim \frac{k}{e}(T_2 - T_1)$. Different processes which can influence the temperature and ionisation rate will be discussed elsewhere. But for the moment we will be satisfied with a rough estimate that the *e.m.f.* is proportional to $\frac{k}{e}\triangle T$, where $\triangle T$ is a temperature difference. Thus generation of magnetic field is directed perpendicular to the contour and is concentrated mainly in the border area. It is easy to see that an *e.m.f.* generated along the border of separate atomic clumps embedded in plasma with a temperature gradient will sum up along a gradient. Formation of the large scale seed magnetic field from the magnetic fields by individual clumps depends on the effectiveness of the reconnection process. The latter is more effective when the clumps are closer to each other. As soon as a large scale magnetic field is formed, random motions of the individual clumps cannot destroy it, but only generate additional chaotic field by turbulent dynamo (Ruzmaikin *et al.* 1988, p. 250). That is why the *e.m.f.* generation of the magnetic field can be effective in the clumpy interstellar medium.

In the analysis we have ignored a possible influence of the magnetic field on the electronic diffusion, as it is the seed magnetic field generation we are interested here. This influence on the diffusion *e.m.f.* will be discussed elsewhere in detail.

4. Magnetic field generation by diffusion *e.m.f.*

As we seen in a previous section gradients of the electronic concentration ∇n naturally arise at the border areas of atomic clouds. Provided that a large scale temperature gradient is applied, this results in seed magnetic field generation on a large scale.

Since the interstellar medium has a high conductivity, the induction impedance plays a major role. That is why one can estimate the magnetic field increment $\triangle B$ through the surface S over the time $\triangle t$ as $\triangle B \sim \frac{c\varepsilon}{S}\triangle t$, where c is the speed of light. Measuring $\triangle t$ in years and S in $(\text{pc})^2$ one finds $\triangle B \sim 3 \cdot 10^{-26} \frac{\triangle T \triangle t}{S} (G)$. Assuming a temperature difference between the centre of the Galaxy and its edge of $\sim 10^6$K, one concludes that a field of the order of $\sim 3 \cdot 10^{-17}$G can be created in $\triangle t \sim 10^9$ years on the galactic scale. (We considered $S \sim h \times R$ where h is a half thickness of the atomic layer $\sim$ 100pc, R is the galactic radii $\sim 10^4$pc.) [4] The field consists of closed circular loops in the galactic plane, but the rise of warm gas elements, which is essential for $\alpha - w$ dynamo on the galactic scale, will result in the formation of dipole and further quadrupole configurations through twisting of the magnetic field lines and a reconnection process. Indeed, consider magnetic field loops inflated over the galactic disc. Due to the Coriolis forces the plane of each loop is being turned (Ruzmaikin *et al.* 1988, p. 120) Initially the pairs of loops at the opposite surfaces of the galactic disc have dipole symmetry. It is easy to see that, for example, a reconnection process of the adjacent loops will result in the formation of pairs of magnetic loops with quadrupole symmetry. Magnetic field of quadrupole configuration can be amplified by $\alpha - \omega$ dynamo (Parker 1979, p. 676).

According to Rees (1987), even a field of 10^{-18}G could suffice as a seed field on a galactic scale with the process being more efficient on smaller scales. If there is a similar temperature difference in the central galactic region, the field can reach $\sim 3 \cdot 10^{-16}$G. Compressed by the flow it can serve as a seed field for the centres of some galaxies, for example M82 (compare Lesch *et al.* 1989).

Observations show more active dynamo generation of magnetic fields due possibly to a stronger seed field B_0 in the spiral arm.

The mechanisms discussed here can serve for seed magnetic field generation not only in spiral galaxies, but also in elliptical galaxies, where there are indications of rather strong magnetic fields (Lesch *et al.* 1990 and references therein).

The seed magnetic field of the origin discussed can be amplified by dynamo action and influence the formation of the first generation of stars. At the border areas of the atomic clouds the magnetic field generated by diffusion *e.m.f.* can reach values more than 10^{-15} G, influencing thermal conductivity and thus inhibiting evaporation of the atomic clouds.

5. Discussion

As was pointed out by Rees (1987) early star formation and galactic evolution should be greatly influenced by environmental differences of a hydromagnetic kind. In this paper we have shown that magnetic fields could emerge in the stages prior to the formation of the first stars and that is why their existence should be considered by theorists concerned with the topics mentioned above. No one will claim that the evolution of the first generation galaxy population is similar to the present day evolution. The first supernova expansions, for example, happened into a medium which should have (as was shown in this paper) some magnetic field. But this field was much weaker than at present and mostly random. There are still many unclear points concerning the early stages of galaxy evolution, but the abundance of different mechanisms makes the emergence of magnetic field in the earliest stages more plausible. This point, apart from the fact that the introduced mechanisms can account for the existence of the large scale magnetic seed field, makes the diffusion generated *e.m.f.*s worth discussing in detail (Lazarian, in preparation).

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[2] Note that in the case of equal temperatures the integral Eq. (20) is zero.

[3] Ultraviolet and X ray bremsstrahlung can serve as an example of ionisation sources for the inner parts of the atomic condensation during the early stages of galaxy evolution, while discrete sources of ionisation and cosmic rays (Ginsburg et al. 1964) are likely to play their role at a later stage.

[4] The problems concerning the configuration of this field will be discussed in a separate paper which is under preparation.

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