Equilibrium of Intergalactic Currents

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***Abstract*—The plasma universe approach to the structure of the universe considers space to be filled with a network of currents which can undergo pinch compression. The equilibrium structures of such currents are treated in the same way as the structure in laboratory pinches. The difference, for the galactic case, is that gravitational interaction forces between the particles must be included in the analysis. This paper illustrates a simple and straightforward way of achieving this.**

I. Introduction

The plasma universe approach to the structure of the universe considers space to be filled with a network of currents. The reason these currents exist is that, regardless of size, plasmas in relative motion are coupled via currents that they drive through each other. Since our observable universe consists almost entirely of matter in its plasma state (99.999% volumewise), which is delineated by transition regions (e.g., thin regions separating plasmas having different densities, temperatures, magnetization, and chemical composition), intergalactic currents are expected.

According to plasma cosmology, the universe on the large scale should exhibit the same structure as energetic plasmas on the small scale: a cellular morphology (because of the transition regions) with filamentary structure (because of the driven currents). Physical evidence that the universe does exhibit a cellular and filamentary structure on the large-scale (at distances approaching the Hubble dimension, 10^{26} m) has only recently been discovered [1]. Additional manifestation of electric currents in space include the filamentary structure of molecular clouds [2], [3].

Individually, it is well known that currents in laboratory plasma can pinch the plasma locally into a denser state (the Bennett pinch), with the possibility of a balance between the electromagnetic pinch ($\boldsymbol{j} \times \boldsymbol{B}$) force and the gradient of the plasma thermokinetic pressure. The only difference between a laboratory pinch and a galactic-dimensioned pinch is that the gravitational interaction between the particles must be accounted for. Earlier analyses of cosmic charged particle beams have also considered the effect of gravitation. Witalis [4], in a complete and lengthy investigation, derived a generalized Bennett relation that included the effects of beam inertia and beam self-fields. Carlvist [5] derived a relation applicable to steady-state beams which he then applied to several cosmic plasma situations.

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In this paper we illustrate how the gravitational interaction forces can be included in an intergalactic current in a simple and straightforward way.

II. Formulation

Consider the equilibrium structure of intergalactic electron–ion beams with gravitational interactions of particles included and the electromagnetic interaction caused by the moving charges. The gravitational potential, ψ, satisfies the equation

$$\Delta\psi = 4\pi G \sum_{\alpha} n_\alpha m_\alpha. \tag{1}$$

Here, G is the gravitational constant, n_α are the densities of particles of type $\alpha = i, e$, for ions and electrons, respectively, and m_α are the masses of the charges. The scalar and vector potentials of the electromagnetic field, ϕ and $\boldsymbol{A}$ satisfy the equations [6]–[8]

$$\Delta\phi = -4\pi \sum_{\alpha} n_\alpha e_\alpha \tag{2}$$

$$\Delta A = -\frac{4\pi}{c} \sum_{\alpha} e_\alpha n_\alpha v_\alpha. \tag{3}$$

The densities of the charges n_α are expressed via the potentials $\psi, \phi,$ and A as follows:

$$n_\alpha = \frac{N_\alpha}{2\pi\nu_\alpha} \exp\left\{-\frac{U_\alpha}{T_\alpha}\right\} \tag{4}$$

$$U_\alpha = e_\alpha\phi + m_\alpha\psi - e_\alpha\beta_\alpha A, \tag{5}$$

where T_α are the temperatures of the charges, N_α are the number of particles per unit length of the current channel, and ν_α are the normalization intergrals, for type-α particles:

$$\nu_\alpha = \int_0^\infty r\, dr \exp\left\{-\frac{U_\alpha(r)}{T_\alpha}\right\}. \tag{6}$$

In using (4), we have in mind that the charges are in equilibrium. This means that either a mean free path is much smaller than the radius of the current channel or the collision frequency of the charges is large compared with the characteristic time of evolution of the current. The characteristic time for a 350 Mpc long galactic current evolving with a velocity around 1000 km/s is of the order of 10^{19} s.

The stream as a whole in state of equilibrium is described by six parameters: $N_\alpha, T_\alpha,$ and $v_\alpha; \alpha = i, e$. With the proper choice of a frame of reference (moving with the ion subsystem), this number can be reduced to five, since $v_i = 0$.

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Introducing the dimensionless potentials

$$\Psi_\alpha = U_\alpha/T_\alpha, \tag{7}$$

the system of equations determining an equilibrium configuration can be written in the form [7]

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\Psi_i}{dr}\right) = \frac{2K_{ie}}{\nu_e}\exp(-\Psi_e) + \frac{2K_{ii}}{\nu_i}\exp(-\Psi_i) \tag{8}$$

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\Psi_e}{dr}\right) = \frac{2K_{ei}}{\nu_i}\exp(-\Psi_i) + \frac{2K_{ee}}{\nu_e}\exp(-\Psi_e), \tag{9}$$

where

$$K_{\alpha\beta} = -\frac{N_\beta}{T_\alpha}\left[e_\alpha e_\beta(1-\beta_\alpha\beta_\alpha) - Gm_\alpha m_\beta\right]. \tag{10}$$

The only difference between this system and one investigated previously [7] is the appearance of the gravitational term $Gm_\alpha m_\beta$ in (10). An analysis of this type of system of equations shows that an equilibrium configuration exists if the parameters $K_{\alpha\beta}$ obey the identity [7]

$$K_{ei}(K_{ii}+K_{ie}-2) + K_{ie}(K_{ee}+K_{ei}-2) = 0. \tag{11}$$

Expressing $K_{\alpha\beta}$ through N_α, T_α, and β_α, we get the sought-for energy balance equation:

$$\frac{1}{2}e_e^2N_e^2\beta^2 + \frac{1}{2}G(m_iN_i + m_eN_e)^2 = \frac{1}{2}(e_iN_i - e_eN_e)^2 + N_iT_i + N_eT_e, \tag{12}$$

valid for a cylindrically symmetric geometry.

III. Discussion

In equilibrium the energy of magnetic compression and gravitational compression (left-hand side of (12)) must be exactly compensated by the energies of electrostatic repulsion and kinetic energies of the charges (right-hand side of (12)). If the gravitational energy is much smaller than the magnetic energy, (12) yields, for usual pinch systems,

$$\frac{1}{2}e_e^2N_e^2\beta^2 = \frac{1}{2}(e_iN_i - e_eN_e)^2 + N_iT_i + N_eT_e. \tag{13}$$

The relativistic velocity, β, is related to the current, I, by $I = eN_ec\beta$. In the nonrelativistic limit, $\beta << 1$, the energy of the space charge is negligible, and we recover the Bennett relation

$$\frac{I^2}{2c^2} = N_iT_i + N_eT_e. \tag{14}$$

IV. Conclusion

The plasma universe approach to the structure of the universe considers space to be filled with a network of currents which can undergo pinch compression. The equilibrium structure of such currents can be considered in the same way as the structure of laboratory pinches. The difference is that in addition to electromagnetic forces one has to take into account the gravitational interaction of the particles. This is simply done in a straightforward way by including the gravitational and scalar and vector electromagnetic potentials in the formulation. This approach yields a Bennett relation modified by the presence of a compressional gravitational energy term.

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Anthony L. Peratt (SM'85) for a photograph and biography, please see the Guest Editorial in this issue.