MULTICOMPONENT, INHOMOGENEOUS AND EXPANDING PLASMAS BASED ON GRAVITATIONAL AND "DARK ENERGY DENSITY" INTERACTIONS †

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Abstract. Plasmas involving gravitational and "dark energy density" interactions and featuring inhomogeneous expansion rates and mass densities are introduced, referring to recent observations of the "closer" Universe.These (cosmological) plasmas are envisioned as composed of four populations: the Field Galaxies, featuring the highest mass densities, the Loaded Galaxy Clusters, the Diffuse Intergalactic Medium and the Pervading Dark Matter in which the visible populations are immersed. The Loaded Galaxy Clusters include the optically observed clusters of galaxies, the associated electromagnetic radiation (X-rays) emitting plasmas and the dark matter that contains them.

Characteristic "Population Mixing Modes" are identified that can be sustained by factors that include the source of momentum for the visible populations. A dark energy density transport equation is proposed, involving a diffusion process combined with an outflow of dark energy density, that is analogous to transport equations introduced for laboratory and space plasmas near (but not in) thermal equilibrium.

1. Introduction

The series of observations by the Dark Energy Spectroscopy Instrument, beginning with those reported in Ref.[1], and their interpretation [1, 17] combined with the expected results of other relevant undertakings have been a stimulus to formulate a multi-component "cosmological plasma" (CP) model that involves both gravitational and dark energy density interactions.

This inhomogeneous expanding plasma [10] is considered to be composed of four populations, three of them "visible", and is characterized by an intrinsic coupling of gravitational and dark energy density interactions.

The four basic populations are:

a) Field Galaxies ("light", visible component)
b) Loaded Galaxy Clusters ("heavy", visible component)
c) Diffuse Intergalactic Medium
d) Pervading Dark Matter in which the visible components are immersed.

Loaded galaxy clusters include the optically observed galaxies, the high energy electromagnetic plasmas, observed by their X-rays emission and whose total mass can exceed that of the galaxies (in a cluster), and the containing dark matter. The pervading Dark Matter (DM) population includes the two recognized [14] components of it, Self-Interacting DM and Cold DM.

A significant process for the dynamics of this kind of plasma is the excitation of "Population Mixing Modes", involving all populations, that are sustained by the gradient of their expansion velocity. The theory of these modes is analogous to that of "impurity modes" [8] of magnetically confined plasmas and, in a special case, may be reminiscent of that of ion-acoustic modes [7] found when the electron temperature is well in excess of that of the nuclei component.

Since the excitation of these modes is associated with a significant expansion velocity, the issue that arises is that of the expansion energy density that the plasma needs to acquire locally. Therefore, referring to a spherically symmetric configuration, a transport equation rather than an equation of state [1, 17] is introduced, that involves an inward diffusion and an outward flow ("dark wind") of dark energy density associated with the gradient of the expansion velocity.

2. Characteristics and Limits of the Adopted Theory

Referring to spherical coordinates, the following analysis is limited to be concerned with two-dimensional processes for radial distances (e.g. $\lesssim$ 1 Gpc), corresponding to a "Closer Universe" for which the classical Poisson's equation can be adopted, dealing with non uniform mass density distributions, and where the mean expansion velocity of the visible components is significantly smaller than c, the light velocity.

The adopted equations include gravitational and "dark energy density" interactions that are not included in Einstein's equation. The inhomogeneous distributed mass of the cosmological plasma is indicated by the mass density $\rho_{cp} = \rho_l + \rho_h + \rho_{dm} + \rho_{im}$ Here ρ_l refers to the field galaxy population, ρ_h to the loaded galaxy clusters, ρ_{dm} to the pervading dark matter and ρ_{im} to the intergalactic medium.

On the basis of existing estimates, ρ_l is taken to be considerably larger than the loaded galaxy clusters mass density, ρ_h. Thus we refer to the latter as a minority population. The density ρ_{im} is regarded as negligible relative to ρ_h.

As a first approach, we describe the dynamics of the visible populations by fluid equations. If we assume that the "pressure" of the field galaxy population (the l-population), that is prevalent, is a scalar, the relevant "temperature" can be indicated as $W_l = \frac{p_l}{\rho_l}$.

In view of dealing with "mode-population" resonant interactions [9] that will be mentioned later and of extending the presented analysis, we may refer to the mass density distribution in phase space $f_m(\mathbf{x}, \mathbf{v}, t)$, $m = l, h$, for each of the visible populations when the considered velocities are limited to be non relativistic.

In particular, noting that the masses of the individual constituents of the visible populations are not all equal nor constant, the mass density of these populations is related to f_m by

$$\rho_m = \int d^3\mathbf{v} f_m(\mathbf{x}, \mathbf{v}, t), \tag{1}$$

and the mass flow by

$$\mathbf{\Gamma}_m = \int d^3\mathbf{v}\,\mathbf{v}\, f_m(\mathbf{x}, \mathbf{v}, t). \tag{2}$$

The evolution of f_m can be described by a collisionless Boltzmann equation [2] with an effective source S_f, that is

$$\frac{\partial f_m}{\partial t} + \mathbf{v} \cdot \nabla_x f_m - \nabla \Phi_G \cdot \nabla_v f_m = S_f, \tag{3}$$

where

$$\nabla^2 \Phi_G = 4\pi G \rho_{cp}. \tag{4}$$

The dark matter component is limited to be characterised by its mass density only.

In the following, processes that are two-dimensional are investigated. When referring to the case of a plasma with constant (uniform) density, that will be mentioned later, the well known relevant theory [16] is based on the metric

$$ds^2 = -(cdt)^2 + a(t)^2 d\mathbf{x}^2, \tag{5}$$

where $a(t)$ is the characteristic scale factor. In the case of spherical symmetry with an observer at $r = 0$, the specific metric is $ds^2 = -(cdt)^2 + a(t)^2(dr^2 + r^2 d\mathbf{\Omega}^2)$, where $d\mathbf{\Omega}^2 = d\theta^2 + \sin^2\theta d\phi^2$.

The analysis that follows implies that the scale distances associated with concentrated masses, such as massive black holes, are negligible. These distances may be represented by a Schwarzschild radius for a point mass $M_\star$, $r_S \equiv 2GM_\star/c^2$. In this case a local gravitational potential, such as the Paczyński-Wiita potential [15], can be considered.

Likewise, we shall consider timescales for the analysed collective modes that are significantly shorter than those, such as that implied by Eq. (5), of the evolving state from which the modes can emerge.

3. "Unperturbed" State

In the presence of an inhomogeneous expansion velocity, $\mathbf{u}_0 = u_0(r)\mathbf{e}_r$, with $u_0 > 0$ and $du_0/dr > 0$, that is the prevalent component of the l-population radial velocity $u_r|_l$, the considered visible populations can be subject to "mixing" modes of the kind inspired by the theory of "impurity modes" [8] found for electromagnetic plasmas. These can mix a population (impurity) whose elements are more massive than those of the majority (light) population. In fact, the evolution of the particle density profiles of the involved populations has been found, by an extensive series of experiments on laboratory plasmas, to be consistent with the predicted effects of the excitation of these modes.

In the present theory, galaxy clusters are viewed as "impurities" immersed in the field galaxy population. To start with, we consider the "unperturbed" state of the plasma from which mixing modes can emerge. This state, where all quantities are assumed to be independent of θ and ϕ, is envisioned to evolve on a longer time scale than the characteristic time scales of the analysed mixing modes.

Thus the mass balance equation for two of the visible (l and h) populations can be written as

$$\frac{\partial \rho_l}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(\rho_l u_r|_l\right)\right] = S_l \tag{6}$$

and

$$\frac{\partial \rho_h}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(\rho_h u_r|_l\right)\right] = S_h \tag{7}$$

where $S_l(r,t)$ and $S_h(r,t)$ are the relevant mass sources.

The corresponding momentum conservation equations are

$$\rho_l \frac{\partial}{\partial t} u_r|_l \simeq -\rho_l \left[\frac{\partial}{\partial r}\left(\Phi_G + \frac{1}{2}u_r|_l^2\right) - S_{pl}\right] - \left(\nabla \cdot \mathbb{P}\right)_r|_l \tag{8}$$

where $S_{pl}\rho_l$ indicates the momentum acquisition rate by the l-population, $u_r|_l^2 \simeq u_0^2 \equiv 2W_0$ as $|\left(\nabla \cdot \mathbb{P}\right)_r|_l| \ll \rho_l W_0$, and

$$\frac{\partial}{\partial t} u_r|_h \simeq -\frac{\partial}{\partial r}\left(\Phi_G + \frac{1}{2}u_r|_h^2\right) + S_{ph} - \left(\nabla \cdot \mathbb{P}\right)_r|_h \frac{1}{\rho_h}. \tag{9}$$

For the sake of simplicity, we consider the tensors $\mathbb{P}|_l$ and $\mathbb{P}|_h$ to have only diagonal components, an assumption that remains to be justified.

Clearly, Eqs. (8) and (9) imply that

$$\frac{\partial}{\partial t} u_r|_h - S_{ph} + \frac{1}{2}\frac{\partial}{\partial r} u_r|_h^2 = \frac{\partial}{\partial t} u_r|_l - S_{pl} + \frac{1}{2}\frac{\partial}{\partial r} u_r|_l^2. \tag{10}$$

The gravitational potential is related to ρ_{cp} by the Poisson's equation

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \Phi_G}{\partial r}\right) = 4\pi G\rho_{cp}. \tag{11}$$

requiring that

$$\frac{\partial^2}{\partial r^2}\Phi_G + \frac{2}{r}\frac{\partial \Phi_G}{\partial r} \simeq \frac{\partial^2}{\partial r^2}\Phi_G - \frac{1}{r}\frac{\partial}{\partial r}u_r|_l^2 + \frac{2}{r}\left(S_{pl} - \frac{\partial}{\partial t}u_r|_l\right) > 0. \tag{12}$$

Considering that dW_0/dr is assumed to be positive, it is evident that the "source" term $S_{pl} - \frac{\partial}{\partial t}u_r|_l$ has an important role to envision a plausible profile for Φ_G.

Moreover, it is assumed that a Jeans instability involving large scale distances is not affecting the unperturbed state. In fact, we note that, in a single component homogeneous plasma, linearised density perturbations with wave number k are governed ([16]) by the differential equation

$$\ddot{\hat{\rho}} + 2H\dot{\hat{\rho}} = (4\pi G\rho - \frac{k^2c_s^2}{a^2})\hat{\rho}. \tag{13}$$

Here $H = \dot{a}/a$ represents the Hubble-Lemaître expansion rate and a is the cosmological expansion parameter [see Eq.(5)].The standard Jeans dispersion relation is recovered by setting $H = 0$ and $a = 1$.

4. Population Mixing modes

Referring to the perturbed state, the modes of interest are considered to oscillate and evolve over time scales that are much shorter than those associated with the unperturbed state treated in Section 3. These modes can, then, be represented by two-dimensional perturbations

$$\hat{\Phi}_G \simeq \tilde{\Phi}_G(r_0)\exp\{-i\omega t + i[m^0(\theta-\theta_0)+k(r-r_0)]\} \tag{14}$$

that are radially localised around the surface $r = r_0$ and around the angle $\theta_0 \neq 0$ over an interval $\Delta\theta \ll \theta_0$. Here m^0 is an integer, $(m^0\Delta\theta) \gg 1$, $|ku_0/(du_0/dr)| \gg 1$ and $(kr_0/m_0)^2 \ll 1$. Thus

$$\nabla\hat{\Phi}_G = i\left\{\frac{m^0}{r_0}\,\mathbf{e}_\theta + k\mathbf{e}_r\right\}\tilde{\Phi}_G. \tag{15}$$

Considering at first the l-population, the perturbed linearised mass conservation equation, if the perturbation of S_l is neglected, can be written as

$$\frac{\partial\hat{\rho}_l}{dt} + \mathbf{u}_l\cdot\nabla\hat{\rho}_l + \hat{\mathbf{u}}_l\cdot\nabla\rho_l + \rho_l\nabla\cdot\hat{\mathbf{u}}_l + \hat{\rho}_l\nabla\cdot\mathbf{u}_l = 0. \tag{16}$$

Then

$$-i\left(\bar{\omega} + iu_0'\right)\hat{\rho}_l + \rho_l\left(\nabla\cdot\hat{\mathbf{u}}_l\right) \simeq 0 \tag{17}$$

where $\bar{\omega} \equiv \omega - ku_0$, $u_0' = (du_0/dr)_{r=r_0} \gg u_0/r_0$ and $|d\rho_l/dr| \ll |k\rho_l|$.

When the perturbation of S_{pl} is neglected, the relevant momentum conservation equation can be written as

$$\hat{\rho}_l\left(\frac{d\mathbf{u}_l}{dt} - S_l\mathbf{e}_r\right) + \rho_l\left(\frac{d\hat{\mathbf{u}}_l}{dt} + \hat{\mathbf{u}}_l\cdot\nabla\mathbf{u}_l\right) = -\nabla\hat{p}_l - \hat{\rho}_l\nabla\Phi_G - \rho_l\nabla\hat{\Phi}_G \tag{18}$$

where $\hat{p}_l = \hat{\rho}_l W_l + \rho_l\hat{W}_l$, assuming that the relevant pressure tensor is isotropic.

In particular, the l.h.s. of Eq.(18) becomes, approximately,

$$\hat{\rho}_l\left(u_0u_0'\right)\mathbf{e}_r + \rho_l\left[-i\omega\hat{\mathbf{u}}_l + \mathbf{u}_0\cdot\nabla\hat{\mathbf{u}}_l + \hat{\mathbf{u}}_l\cdot\nabla\mathbf{u}_0\right] \simeq \hat{\rho}_l\left(u_0u_0'\right)\mathbf{e}_r + \rho_l\left(\hat{u}_r|_l u_0'\right)\mathbf{e}_r + \rho_l\left(-i\bar{\omega}\right)\hat{\mathbf{u}}_l \tag{19}$$

and, if the operator $\nabla\cdot$ is applied, this becomes approximately

$$\begin{aligned} -i\bar{\omega}\rho_l\nabla\cdot\hat{\mathbf{u}}_l + ik\left(\hat{\rho}_l u_0 + \rho_l\hat{u}_r|_l\right)u_0' &\simeq \\ \bar{\omega}\left(\bar{\omega} + iu_0'\right)\hat{\rho}_l + ik\left(\hat{\rho}_l u_0 + \rho_l\hat{u}_r|_l\right)u_0' & \end{aligned} \tag{20}$$

Applying the same operator to the r.h.s. of Eq.(18), the result is

$$-\nabla^2\hat{p}_l - \hat{\rho}_l\nabla^2\Phi_G - \nabla\hat{\rho}_l\cdot\nabla\Phi_G - \nabla\rho_l\cdot\nabla\hat{\Phi}_G - \rho_l\nabla^2\hat{\Phi}_G \simeq \tag{21}$$

$$k_\theta^2(\hat{p}_l + \rho_l \hat{\Phi}_G) + ik\left[\hat{\rho}_l \left(u_0 u_0^{'} - S_{pl}\right)\right],$$

where $k_\theta = m^0/r_0$, $|\nabla\rho_l \cdot \nabla\hat{\Phi}_G| \ll \rho_l k_\theta^2 |\hat{\Phi}_G|$, $|\nabla^2\Phi_G| \ll |ku_0 u_0^{'}|$ and the $\partial u_r|_l/\partial t$ term is neglected relative to S_{pl}.

Then we obtain

$$\bar{\omega}\left(\bar{\omega} + iu_0^{'}\right) + ikS_{pl} - k_\theta^2 W_l \simeq \frac{\rho_l}{\hat{\rho}_l}\left\{k_\theta^2\left(\hat{\Phi}_G + \hat{W}_l\right) - iku_0^{'}\hat{u}_r|_l\right\} \tag{22}$$

and for the h-population

$$\bar{\omega}\left(\bar{\omega} + iu_0^{'}\right) + ikS_{ph} - k_\theta^2 W_h \simeq \frac{\rho_h}{\hat{\rho}_h}\left\{k_\theta^2\left(\hat{\Phi}_G + \hat{W}_h\right) - iku_0^{'}\hat{u}_r|_h\right\}. \tag{23}$$

Subtracting the two equations

$$-\left(W_l - W_h\right) \simeq \left[\left(1 - \Sigma_0\right)\hat{\Phi}_G + \left(\hat{W}_l - \Sigma_0 \hat{W}_h\right) - \frac{iku_0^{'}}{k_\theta^2}\left(\hat{u}_r|_l - \Sigma_0 \hat{u}_r|_h\right)\right]\frac{1}{\hat{\epsilon}_l} - \frac{ik}{k_\theta^2}\left(S_{pl} - S_{ph}\right), \tag{24}$$

where $\hat{\epsilon}_l \equiv \hat{\rho}_l/\rho_l$ and $\Sigma_0 \equiv \hat{\epsilon}_l\left(\rho_h/\hat{\rho}_h\right)$. If we define

$$\hat{\Phi}_G^0 \simeq \hat{\Phi}_G(\Sigma_0 - 1) - \hat{\epsilon}_l \frac{ik}{k_\theta^2}\left(S_{pl} - S_{ph}\right), \tag{25}$$

with $\Sigma_0 \neq 1$, where

$$\frac{\hat{\Phi}_G^0}{\hat{\epsilon}_l} \equiv \left(W_l + \frac{\hat{W}_l}{\hat{\epsilon}_l}\right) - \left(W_h + \Sigma_0\frac{\hat{W}_h}{\hat{\epsilon}_l}\right) - \frac{iku_0^{'}\left(\hat{u}_r|_l - \hat{u}_r|_h\right)}{k_\theta^2 \hat{\epsilon}_l}, \tag{26}$$

observing that $\hat{\Phi}_G$ diverges for $\Sigma_0 \to 1$, if Σ_0 is real, we derive

$$\bar{\omega}\left(\bar{\omega} + iu_0^{'}\right) + ik\left(\frac{S_{pl}\Sigma_0 - S_{ph}}{\Sigma_0 - 1}\right) \simeq k_\theta^2\left(W_l + \frac{\hat{W}_l}{\hat{\epsilon}_l}\right) + \frac{1}{\Sigma_0 - 1}\left(\frac{\hat{\Phi}_G^0}{\hat{\epsilon}_l}\right)k_\theta^2. \tag{27}$$

This can be considered the mode dispersion relation once all quantities involving ratios of perturbed amplitudes are evaluated. In particula, for $\hat{W}_l/\hat{\rho}_l$ and $\hat{W}_h/\hat{\rho}_h$ we may use at first an adiabatic equation of state showing that they are positive quantities, but the phase space approach outlined in Section 2 is worth pursuing in this context. In any case it is clear that, according to Eq. (27), the considered modes can acquire meaningful growth rates.

For this, the marginal stability condition corresponding to $\Im\bar{\omega} = 0$ is particularly important and, assuming that Σ_0 and the r.h.s. of Eq.(27)

are real, it reduces to

$$u_0^{'} = -\frac{k}{\bar{\omega}}\left(\frac{S_{pl}\Sigma_0 - S_{ph}}{\Sigma_0 - 1}\right). \tag{28}$$

Since $u_0^{'} > 0$ can be considered a mode damping factor, it can represent the rate [9] at which the involved mode sustains it. Conversely, the r.h.s of Eq(28) can be considered as a growth factor representing the rate at which the exited mode gains energy from the affected populations (see Section 5).

Finally, the relevant form of the perturbed Poisson's equation is

$$-\left(\frac{m^0}{r_0}\right)^2 \hat{\Phi}_G \simeq 4\pi G\left[\hat{\rho}_{dm} + \hat{\rho}_l + \hat{\rho}_h\right] \tag{29}$$

that is

$$-\left(\frac{m^0}{r_0}\right)^2 \hat{\Phi}_G \simeq \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\Phi_G}{dr}\right)\frac{1}{\rho_{cp}}\left\{\hat{\rho}_{dm} + \hat{\rho}_l\left[1 + \frac{\rho_h}{\rho_l}\frac{1}{\Sigma_0}\right]\right\}, \tag{30}$$

indicating that $\hat{\rho}_{dm}$ has an important role in Eq.(30). Moreover, since

$$\frac{|\hat{\rho}_{dm}|}{\rho_{dm}} \simeq \frac{|\hat{\rho}_{dm}|}{\rho_{cp}} \simeq (\frac{m^0}{r_0})^2\left|\hat{\Phi}_G\Big/\frac{d^2\Phi_G}{dr^2}\right|, \tag{31}$$

where $\Phi_G \sim W_0$ and $|\hat{\Phi}_G|$ is given by Eq.(25). It is clear that $|\hat{\rho}_{dm}/\rho_{dm}| < 1$, as implied by the presented analysis, is consistent with the plausible magnitude of all the factors included in Eq.(25).

5. Ad hoc Transport Equation

Referring to well confined laboratory plasmas, theory based transport equations have been introduced and shown to reproduce the observed transport properties both of particles [4] and angular momentum [5]. In these equations, an effective diffusion coefficient $D_\star$ and a "counter diffusion" flow velocity U_{CD} have a primary role. Thus, we may adopt an equation of the same kind [10] in order to describe how the energy density $(\rho_l + \rho_h)W_0 = (\rho_l + \rho_h)u_0^2/2$ can reach and be maintained on a spherical surface with radius r.

In particular we may adopt the following expression for the W_0 transport velocity

$$(V_\star)_r \simeq -D_\star \frac{\partial W_0}{\partial r} - U_{CD} W_{*S}, \tag{32}$$

and consider the consequent "W_0-energy" balance equation, under stationary conditions,

$$\nabla \cdot \left[\mathbf{e}_r \left(V_\star\right)_r\right] = S_w \tag{33}$$

where S_w is the relevant source. This equation has to be compatible with the momentum conservation equation (8) and Poisson's equation (11). .

Moreover, considering the existing indications on the expansion rate at very large distances, we may take

$$U_{CD} \simeq (r_M - r)\Omega_{CD} > 0. \tag{34}$$

As in the case of laboratory plasmas, the diffusion term included in Eq.(32) as well as U_{CD} can be attributed to fine grain modes [4] excited within the l-population. To the extent that $\left|\nabla \cdot \left[\mathbf{e}_r \frac{dW_0}{dr}\right]\right| \gg |S_w|$, the relevant transport equation is represented by

$$D_\star \frac{\partial W_0}{\partial r} - (r_M - r)\Omega_{CD} W_{*S} \simeq 0, \tag{35}$$

and refer to $U_{CD}W_{*S}$ as a "Dark Wind". For $W_{*S} = W_0$ a relevant solution can be easily found as a function of $\Omega_{CD}/D_\star$ and r_M. Accordingly, the "Closer Universe" region would correspond to $r < r_M$, where $dW_0/dr > 0$.

We point out that the Dark Energy equation of state adopted in Refs.[17] and [1], that is

$$\bar{\bar{w}} = (\bar{\bar{w}}_0 + \bar{\bar{w}}_a) - a\bar{\bar{w}}_a, \tag{36}$$

involves $\bar{\bar{w}}(a) < 0$, $\bar{\bar{w}}_0/\bar{\bar{w}}_a > 0$ and deals with negative pressures, a concept that is not associated with the physics of the multicomponent plasma introduced earlier.

6. Relevant Considerations

Clearly, the presented analysis is in need of a proper reformulation that would involve relevant General Relativity corrections and a numerical effort directed at verifying and extending it. In fact, the described theory of the "Population Mixing Modes" is limited to distances (i.e. $\lesssim$ 1 Gpc) of the Closer Universe where the expansion velocity is well below the speed of light and the classical Poisson's equation can be used to deal with non-homogeneous mass distributions.

Further developments will have to refer to ongoing observations of (spatial) distributions of the cosmological plasma components in the Closer Universe and to the results of relevant analyses such as those reported lately by DESI [13].

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