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Cosmic Matter Creation from Viscous Energy Dissipation: A Resurrection of Fred Hoyle's Dream

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Abstract

Fred Hoyle is known as creator of the so-called "steady state universe" which latter, although permanently expanding, does not change its state of matter, especially keeping its density constant. To achieve this virtue Hoyle introduced into the energy-momentum tensor of the GRT field equations a term derived from a so-called ad-hoc creation field astonishingly leading to field equations very similar to the ones already developed by Tolman when introducing energy sources connected with viscous dissipation forces acting upon dust-like cosmic matter [1]. In this article here we shall again study the action of viscous forces in cosmic baryonic matter and shall boil it down to volume viscosity contributions to the viscous stress tensor in a universe with a compressible Hubble flow. Assuming that by collisions of any kind the energy of the differential Hubble drift between two collision points of cosmic matter particles, seen in the non-inertial rest frames of moving particles, is randomized and converted into thermal energy, one can then show with the help of a kinetic transport equation that during the cosmic expansion permanently thermal energy is generated leading to the result that the matter temperature, instead of falling-off, is linearly increasing with the scale of the universe. This not only questions the standard use of the model of pressure-free, dust-like matter in the universe, but furthermore indicates the possibility of an asymptotic cosmic-ray-like matter state including the possibility of matter creation by pair production.

Introduction

At several places in the scientific literature it has been discussed whether or not the effects of viscous forces operating in the cosmologically expanding cosmic matter or cosmic radiation might play a non-negligible role for the expansion fate and the evolution of the thermal state of the material universe. Many different aspects of this problem were already discussed much earlier by e.g. Weinberg [2], Treciokas and Ellis [3], Nightingale [4], Klimek [5], Heller et al. [6], Heller and Klimek [7]. Interestingly enough it also has been recognized that under specific forms of a volume (bulk) viscosity the resulting terms in the energy-momentum tensor of the Einsteinian field equations become formally identical to Hoyle's creation terms in the frame of his steady-state model of the universe [8]. That means the energy creation, connected with the operation of viscous energy dissipation, can act, at least mathematically and in principle, equivalently to a matter creation term analogous to the one developed by Hoyle in the form of Hoyle's creation field C(sub) ij and allowing as a solution the so-called and often criticized "steady state" universe. In order, however, to decide whether or not this kind of viscous energy dissipation could explain a mechnism like Hoyle's matter creation, it is not of prime importance to discuss the mathematical equivalence of the dissipation and the creation terms, but more it is of eminent importance to study whether on physical grounds a cosmic viscous dissipation term can be imagined which could have enough efficiency to explain a phenomenon like cosmic matter creation. Alternative ideas on cosmic matter creation have already in the past been discussed at several places in the literature as e.g. by Mach [9], Dehnen and Honl [10], Hoyle [11, 12], Hoyle, Burbidge and Narlikar [13], Fahr [14], Fahr and Zoennchen [15], Fahr and Heyl [16, 17], Fahr and Sokaliwska [18, 19]. In the following part of the paper we shall, however, now study in more detail how much matter creation can especially be expected to originate from the process of viscous energy dissipation in thermal matter of a cosmic Hubble flow.

Recalculation of the cosmological viscosity term

The full energy-momentum tensor for viscous hydrodynamics is given by

$$\Pi_{\alpha\beta} = P\delta_{\alpha\beta} + \rho V_\alpha V_\beta - \sigma_{\alpha\beta} \quad (1)$$

With P denoting the scalar pressure of matter, ρ the matter density, and V_α representing the components of the 4-vector bulk velocity of the fluid. Furthermore here in the upper expression the viscous stress tensor elements are included which are given in the standard form by

$$\sigma_{\alpha\beta} = 2\eta(V_{\alpha\beta} - \frac{1}{3}\delta_{\alpha\beta}\mathrm{div}\vec{V}) + \zeta\delta_{\alpha\beta}\mathrm{div}\vec{V} \quad (2)$$

With η and ζ denoting the coefficients of shear viscosity and of volume viscosity, respectively, and $\delta_{\alpha\beta}$ being the Kronecker delta. Furthermore, here the expression $V_{\alpha\beta}$ is defined by

$$V_{\alpha\beta} = \frac{1}{2}(\frac{\partial V_\alpha}{\partial x_\beta} + \frac{\partial V_\beta}{\partial x_\alpha}) \quad (3)$$

and in addition div $\vec{V}$ is defined by

$$\text{div}\vec{V} = \sum_\alpha \frac{\partial V_\alpha}{\partial x_\alpha} \quad (4)$$

The interesting point at applications of this hydrodynamic stress tensor in cosmology now is that, due to the cosmological principle which in any case should be respected and fulfilled, no in homogeneities in space are allowed and hence all traditional shear viscosity terms, connected with α unequal β, automatically due to homogeneity requirements have to disappear, i.e. such terms should not appear in Robertson-Walker cosmologies. On the other hand, if the matter flow were characterized by incompressibility, then it naturally turned out that div $\vec{V}$ had to vanish, and thus all terms connected with the volume viscosity ζ would consequently also vanish.

However, under the given fact of a compressible homologous, cosmic Hubble flow in cosmology (see next section for a proof), when in addition reminding that the first term on the right hand side of Equation (2) vanishes, i.e. $V_{\alpha\alpha} - (1/3)$ div $\vec{V} = 0$, one then would be left only with the following main axis stress tensor elements for $\alpha = \beta$

$$\sigma_{\alpha\alpha} = \zeta\delta_{\alpha\alpha}\text{div}\vec{V} = \zeta\text{div}\vec{V} \quad (5)$$

Here it is interesting to note, as evident from the above, that only the effects connected with volume viscosity ζ, in view of the "cosmological principle" (i.e. perfect spatial symmetry) are of relevance in cosmology and, dependent on the sign of the term div $\vec{V}$, can either cause positive or negative energy contributions. Concerning the magnitude of the viscosity effect, it becomes evident that it is important to decide which basic processes are involved in cosmic volume viscosity, that means which microscopic interaction processes (i.e. collision types in the concept of Landau-Lifshitz) might be responsible for cosmic matter viscosity. Evidently most effective would of course be matter annihilation processes or particle production processes in the early, hot phase of the universe, before cosmic temperatures have dropped down to levels of $KT < 2mc^2$ and matter annihilation is completed. But we shall look again into this problem further down in this paper.

Calculation of the compressibility of the Hubble flow

One should be aware of the fact that, even though no spatial inhomogeneities are cosmologically admitted, one nevertheless in a homologously expanding universe should be aware that a relative velocity v of each space point origin exists with respect to any other space point at a distance r from origin. This velocity v which is given by

$$v(r) = H \cdot r \quad (6)$$

with the Hubble parameter defined as $H = \dot{R}/R$ and R denoting the scale of the universe. Hence, just this shows that the Hubble fluid does not behave as an incompressible fluid, since it has the following non-vanishing 3D divergence given by

$$div\vec{v} = \frac{\oint (H \cdot \vec{r}) \cdot d\vec{O}_r}{d\tau_r} = \frac{4\pi r^3 H}{(4\pi/3)r^3} = 3H \quad (7)$$

Thus, one must conclude that the Hubble fluid does not behave incompressibly and consequently should induce viscosity forces connected with the volume viscosity parameter ζ for $\alpha = \beta = 1, 2, 3$ through the terms

$$\sigma_{\alpha\alpha} = 3H \cdot \zeta\delta_{\alpha\alpha} \quad (8)$$

and the term $\sigma_{00} = dc/dt = 0$. It also should already be noted here that, since $H = \dot{R}/R$, the remaining stress tensor elements all are changing signs with the sign of $\dot{R}$, i.e. for expanding universes they are positive, while for collapsing universes they are negative. Now it very much depends on the magnitude of the viscosity parameter ζ, whether or not cosmic viscosity at the expansion by its dissipative energy generation could influence the evolution of the cosmic scale parameter $R = R(t)$.

An Easy-Minded Approach towards Viscous Dissipation

We start from kinetic considerations developed in Fahr and Dutta-Roy (2018) where cosmic material particles are described as freely moving particles by a cosmic kinetic distribution function according to $f(v,t) = n(t) \cdot \bar{f}(v, t)$ where $n(t)$ is the locally established particle density and f is a normalized distribution function with the property: $1 = 4\pi \int^3 \bar{f}(v,t) v^2 dv$. By use of the Liouville theorem, applied to the case of freely moving particles in an expanding Hubble universe, it has been shown by these authors that the evolution of the distribution function f(v, t) in time and velocity space under free propagation of particles (i.e. motion in a non-inertial rest frame with $v \neq 0$ and without particle collisions or wave-particle interactions) is described by the following partial differential equation

$$\frac{\partial f}{\partial t} = vH\frac{\partial f}{\partial v} - H \cdot f \quad (9)$$

Starting here again from this context, but in addition also considering now collision processes occuring between these cosmic particles when moving through cosmic space, may indicate the following procedure:

Facing an individual particle with a velocity v at its local place in space, then this particle at its motion generally covers a mean free path $\lambda(v)$, before it undergoes a collision, and is moving in a non-inertial rest frame (the inertial rest frame is defined by the bulk flow or that particle with $v = 0$ in the bulk frame). But now it is important that at the place of the next collision this particle has entered a new Hubble-induced particle milieu (i.e. a new kinetic regime of a new cosmic rest frame) with respect to which its velocity has changed by the respective Hubble-induced drift amounting to $dv = -\lambda(v) \cdot H$. Expressing this in terms of the Hubble-induced deceleration dv/dt per mean free path one finds, with μ being the mean collision frequency, the following expression:

$$\frac{dv}{dt} = \mu \cdot \lambda(v) \cdot H = \frac{\lambda(v) \cdot H}{\frac{\lambda(v)}{v}} = -v \cdot H \quad (10)$$

From this result one can also derive the mean kinetic energy lost up to the occurence of such a collision and finds

$$\frac{d}{dt}(\frac{1}{2}mv^2) = \frac{d}{dt}E_{kin}(v) = -mv \cdot (v \cdot H) = -2E_{kin}(v)H \quad (11)$$

which interestingly enough states that the Hubble-induced decrease of the kinetic particle energy per cosmic time does not depend on the actual local mean free path for collisions, but solely on the Hubble parameter. Here, the restriction is made that $\lambda(v)$ should always be smaller than the scale R of the universe.

Assuming now that collisions between cosmic particles randomly redistribute the mean-free-path accumulated, differential Hubble drift energy $E_{kin}(v)H$, converting it into randomized local thermal energy by viscous dissipation (collisional redistribution), permits to estimate the kinetic average of the local temperature change per time of the whole particle population due to collisional dissipation by

$$\left|\frac{d}{dt}\right|_{dis}(\frac{3}{2}nkT) = \left|-m\int^{3} v^2 Hf(v,t)d^3v\right| = \left|4\pi mn(t)H\int v^4\bar{f}(v,t)dv\right| = 3\,|H|\cdot P \quad (12)$$

Introducing this term into the moment transport equation which is obtained from the kinetic transport equation Eq. (9) by multiplying the whole equation with $(4\pi/3)mv^4$ dv and integrating this expression over the velocity space (see Fahr and Dutta-Roy, 2018) will then lead to the following moment equation for the particle pressure P(t)

$$\frac{\partial P}{\partial t} = \int_0^\infty (4\pi/3)mv^4 vH\frac{\partial f}{\partial v}dv - H\cdot P + 3H\cdot P \quad (13)$$

leading to the following more developed differential equation

$$\frac{\partial P}{\partial t} = -5H\cdot P + 2H\cdot P = -3H\cdot P \quad (14)$$

with the following solution for $P = P(t)$:

$$P(t) = P(t_0)\exp[-3\int_{t_0}^t H(t)dt] \quad (15)$$

As one can see the pressure drop-off with cosmic time in this case here goes with a factor 3 in the exponential function, instead of with a factor 4 as in case of no dissipation (see Fahr and Dutta-Roy, 2018). This is due to the fact that, in the present case, energy, originating from the thermalized differential Hubble drift, under elastic collisions is converted into randomized thermal energy, while in the earlier case no additional thermal energy was generated and taken into account.

First assuming here that the Hubble drift energy dissipation does not change the particle numbers (i.e. no particles are annihilated or generated, respectively), we can derive again from the kinetic transport equation (Eq. 9) the relation for the density moment thus given, as already earlier by Fahr and Dutta-Roy (2018), in the form

$$n(t) = n(t_0)\exp[-4\int_{t_0}^t H(t)dt] \quad (16)$$

This together with Eq. (9) then leads to

$$KT(t) = \frac{P(t)}{n(t)} = \frac{P(t_0)\exp[-3\int_{t_0}^t H(t)dt]}{n(t_0)\exp[-4\int_{t_0}^t H(t)dt]} = KT_0\exp[+\int_{t_0}^t H(t)dt] \quad (17)$$

expressing the fact that under such conditions - astonishingly enough and not taken into account elsewhere - the temperature $T(t)$ of the particles, instead of decreasing with the expansion, should increase with the expansion of the universe according to the relation:

$$T(t) = T(t_0)\exp[+\int_{t_0}^t H(t)dt].$$

This is physically explained by the permanent production of thermal energy in connection with the strong decrease of the particle density, i.e. a strong increase of thermal energy per particle.

Particle creation

Now we start again from the kinetic transport equation (Eq. 9), but this time we especially look for the transport equation of the density moment $n = n(t)$ by multiplying the kinetic equation with $4\pi v^2 dv$ and integrating it over the whole velocity space, however, now including a term $|\frac{\partial n}{\partial t}|_{dis}$ for particle creation from viscous energy generation. This then yields the following moment equation

$$\frac{\partial n}{\partial t} = \int(4\pi v^2 dv)vH\frac{\partial f}{\partial v} - H\cdot n + \left|\frac{\partial n}{\partial t}\right|_{dis} \quad (18)$$

where the term $|\frac{\partial n}{\partial t}|_{dis}$ is thought to represent a possible particle production per unit volume and time due to matter creation from the energy going into pair-production collision processes. This latter term thus might be extracted from the energy dissipation term assuming that, as a maximum, the following particle creation rate could be expected to result from it

$$\left|\frac{\partial n}{\partial t}\right|_{dis} \leq \frac{1}{mc^2}\left|\frac{d}{dt}\right|_{dis}(\frac{3}{2}nkT) = \frac{3H\cdot P}{mc^2} \quad (19)$$

and thus leads to the following revised density moment equation

$$\frac{\partial n}{\partial t} \leq -3H\cdot n - H\cdot n + \frac{3H\cdot P}{mc^2} \quad (20)$$

which expresses the fact that the particle production term will only become non-negligible, if thermal energies are growing up to the order of the rest mass energy of the particles, i.e. of the order of $E_0 = 2mc^2$. Therefore we now write the pressure in the form $P = n(E - E_0) = nm(\bar{\gamma} - 1)mc^2$ with $\bar{\gamma} = \gamma(T)$ being the mean thermal average of the relativistic γ-factor of the actually present cosmic matter (see e.g. Goenner, 1996, French, 1971). Then we can write

$$\frac{\partial n}{\partial t} \leq -4H\cdot n + 3H(\bar{\gamma} - 1)n = Hn[3(\bar{\gamma} - 1) - 4] \quad (21)$$

and can see that already for mildly relativistic matter with values $\gamma \geq 2$ the particle creation term becomes of influence. In view of the fact that viscous energy dissipation leads as shown above to a linear temperature increase according to the relation $T(t) = T(t_0) \cdot (R(t)/R(t_0))$, this seems unavoidably to be happening. However, to tell the truth here, under such conditions of weakly relativistic cosmic matter particles we also have to realize that we would need to modify the Liouville theorem and the kinetic transport equation for relavistic particle velocities. Before this has not been done we can thus not draw finite conclusions.

Present Conclusions

As we feel, the most important thing of this study is that the dissipation of viscous energies in an expanding universe leads to an absolutely unexpected reaction to the particle temperature of the cosmic matter particles (normal baryonic matter). While in all other cosmologic scenarios baryonic matter is cooling off in the course of the expansion of the universe, we have shown here that under the effect of viscous energy dissipation due to elastic particle collisions the energy gain per expansion step is such that the temperature of the baryons, instead of falling off, will in fact increase. This clearly shows that model cosmologies working with dust-like cold baryonic matter ($KT << mc^2$) under the inclusion of viscous energy dissipation are not anymore viable. On the contrary, now it has furtheron to be considered that the baryonic matter in the course of the expansion of the universe will become more and more pressurized and its gravitational action on the cosmic expansion will thus become stronger and stronger. This may guide the view from the earlier dustlike, cold baryonic matter, traditionally treated in all cosmologic papers up to now, changes towards a form of a ”cosmic-ray”-like matter which more or less characterizes the main matter content of the later universe. Perhaps the extragalactic cosmic ray particles could under these views represent nothing else but the normal cosmic baryonic matter heated up by permanent viscous energy dissipations.

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