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THE EVOLUTION OF STRUCTURE IN THE UNIVERSE FROM AXIONS

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Abstract:

We consider a cosmological scenario where axions provide the dark matter in the universe. Fluctuations in the axion field energy density produced by domain walls and strings cause the appearance of 'axion clumps' of masses of order $10^6\ M_\odot$ which most likely collapse to black holes by or at the time the universe becomes axion dominated at $T \sim 10$ eV. These objects form the building blocks for the clustering hierarchy theory of galaxy and supercluster formation on scales up to ~ 10 Mpc and $10^{15}\ M_\odot$.

It is well established that strong interactions do not violate CP invariance strongly as evidenced by the present upper limit on the electric dipole moment of the neutron. In order to explain this fact, Peccei and Quinn[1] proposed the inclusion into the theory of a global axial $U(1)_{PQ}$ symmetry which is spontaneously violated at an energy scale f_a implying the existence of a pseudo-Goldstone boson[2], the axion, which acquires a small mass from QCD instanton effects. The fact that these axions remain presently "hidden" from accelerator experiments and astrophysical effects implies that the axions must be very light and very weakly interacting so that f_a must be much larger than the weak scale, $G_F^{-1/2} \simeq 300$ GeV. The astrophysical limits[3] give $f_a > 10^9$ GeV.

Other recent work[4] has centered on the production and evolution of axions in the hot big-bang (Friedmann-Gamov) cosmology. This work indicates that the gravitational effects of a primordial axion mass density would be too large to be consistent with bounds on the galaxy deceleration parameter unless $f_a \lesssim 10^{12}$ GeV. In this paper we will concentrate on the possible effects of primordial axions on the development of structure in the universe.

The macroscopic physics of primordial axions in bulk is unique. The axions acquire a mass (10^{-5}eV $\lesssim m_a \lesssim 10^{-2}$ eV) from QCD instanton effects when the universe is at a temperature $T \sim \Lambda \sim 0.1$ GeV. The zero-momentum mode of the axion field constitutes a coherent state of axions at rest whose energy density $\rho_a \propto T^3$. In addition, the axions are also decoupled from the radiation field whose energy density $\rho_\gamma \propto T^4$. The coherent axion field behaves like a truly pressureless non-interacting gas. In addition, being bosons, the axions have no Fermi pressure either. Thus, the unique feature of a cosmic axion field, as opposed to photons, baryons, neutrinos and other "inos" is that its Jeans mass is zero, i.e., it is unstable to gravitational perturbations on all scales. This is easy to see when we recall that the Jeans length

$$\lambda_J = \frac{c_s}{(G\rho)^{1/2}} \tag{1}$$

is proportional to the velocity of sound in the fluid. In a fluid coupled to the radiation field $c_s \simeq c/\sqrt{3}$ and therefore $\lambda_J \simeq \lambda_H \sim ct$, the horizon scale. In a gas which is uncoupled, $c_s \simeq v$, the rms velocity of the gas particles. In this case we have $v \simeq 0$, therefore $\lambda_J \simeq 0$.

The fraction of the closure density of the universe in axion energy density is approximately given by[4] $\Omega_a h^2 \simeq 10^{-12} f_a$ (GeV) ($h = H_0/100$ km/s/Mpc). A model can be constructed where $f_a \sim 10^{12}$ GeV and $\Omega_a \simeq 1$ which can account for the missing mass in the universe[5]. Let us consider the case (henceforth assuming $h = 1$) where $\Omega_a \sim 1$, and baryon to axion energy density ratio $\rho_b/\rho_a \simeq 10^{-2}$, and let us further assume that the total Ω_{ino} (for neutrinos, gravitinos, photons, and other "inos") is much less than 1 so that the axion field energy dominates the mass of the universe. (Various considerations[6] give a total gravitational mass density in the universe $\Omega_{gr} = O(1)$. The value $\Omega_{tot} \simeq 1$ will be adequate for our purposes.) It then follows, since $\rho_a \propto T^3$ and $\rho_\gamma \propto T^4$, that there is a temperature $T_{eq} \simeq 10$ eV corresponding to a time $t_{eq} \simeq 1000$ yr after the big-bang such that $\rho_a(t_{eq}) = \rho_\gamma(t_{eq})$. At earlier times $\rho_\gamma > \rho_a$ and at later times $\rho_\gamma < \rho_a$. Defining $\rho_a/\rho_\gamma \equiv \kappa(t)$, we expect that for a non-relativistic decoupled gas[7], its density perturbations will be given by

$$\Delta_a \equiv \frac{\delta\rho_a}{\rho_a} \simeq [1 + \frac{3}{2}\kappa(t)]\,\Delta_i \text{ for } \kappa_i \ll 1 \qquad (t < t_{eq}) \tag{2}$$

where Δ_i is the initial density perturbation, so that during the radiation dominated era (i.e., $t < t_{eq}$, $\kappa << 1$), the axion perturbations are frozen in.

A special feature, shared by all axion models, is the occurence in these theories of extended structures consisting of domain walls and strings[8]. The presence of these structures provides a mechanism for generating density perturbations in the very early universe. As we shall see, the presence of a very special kind of structure, called walls bounded by strings[9] (WBS) plays an essential role.

The spontaneous breaking of the global $U(1)_{PQ}$ symmetry at $T \sim 10^{12}$ GeV produces topologically stable strings[10] since $\Pi_1(U(1)) \sim Z$, the set of integers. As one moves around a minimal string the angle Θ(equal to ϕ_a/f_a, where ϕ_a is the axion field and $f_a \sim 10^{12}$ GeV is the Peccei-Quinn $U(1)_{PQ}$ breaking scale) changes by 2π. The string network evolves with time and by the time t_Λ when the temperature is of order Λ (the QCD scale), the scale of the string network is of order t_Λ ($c = 1$). Friction effects on the strings are completely negligible.

At $T \sim \Lambda$, the QCD phase transition takes place and, among other interesting events that occur as a consequence, the strings undergo a remarkable metamorphosis. They get connected to domain walls[8]. This comes about as follows. The QCD instanton effects produce an effective interaction term $\Lambda^4 \cos \Theta$ for the angular field Θ . Since the phase Θ changes by 2π as one moves around the string, it is reasonable to suppose that at $T \sim \Lambda$, Θ settles down to zero everwhere except within a wall of thickness $\sim m_a^{-1}$, where m_a is the axion mass. One thus obtains WBS extended structures. The presence of extended structures such as domain walls and strings can cause density perturbations on scales up to the appropriate horizon size. In particular, they would also create density perturbations in the axion field, which would remain frozen in till the end of the radiation dominated era and begin to grow thereafter. These induced perturbations are more important than fluctuations in the axion field itself.

Domain walls can only exist for a limited period. A prolonged presence of these structures will cause the universe to enter a wall dominated era and lead to a cosmology totally different from what is observed. Thus, one must insure that the domain walls disappear before the universe becomes wall dominated. Remarkably enough, this condition can be met by the axion models. We first note that closed walls not connected to strings may also appear in axion models. However, the intersections of WBS with the closed walls would cause the latter to become 'holey'. Thus, large closed walls also are able to break up into pieces that are themselves smaller walls bounded by strings. The motion of typical WBS is totally determined by its domain wall (the string part is unimportant). A WBS that is completely within the horizon loses energy through gravitational radiation at a rate [8,9]

$$\frac{dM}{dt} \sim - GM^2R^4\omega^6 \sim - G\sigma M \tag{3}$$

where M is its mass, R its size, $\omega \sim R^{-1}$ is the typical oscillation frequency and $\sigma = M/R^2 \sim \Lambda^2 f_a$ is the wall mass per unit area. The lifetime of the WBS against gravitational radiation therefore is

$$t_{WS} \sim (G\sigma)^{-1} \sim \left(\frac{M_{PL}}{f_a}\right)^2 m_a^{-1} \sim 10^4\text{-}10^5 \text{ s} \qquad (M_{PL} \simeq 1.2\times10^{19}\text{GeV}). \tag{4}$$

The scale of the closed domain walls is of order t at cosmic time t. Thus, the energy density ρ_W in a closed domain wall at time t is $\rho_W \sim \sigma/t$. One requires $\rho_W \lesssim \rho_\gamma$ to prevent a wall dominated era. However,

$\rho_W \lesssim \rho_\gamma$ for $t < t_{WS}$ and $\rho_W \approx \rho_\gamma$ at $t \sim t_{WS}$. In other words, the wall-string system disappears (owing to gravitational wave emission) just at the time when it would begin to dominate the energy density of the universe!

At the time of their disappearance, the walls induce density perturbations $\Delta \sim 1$. The perturbations in the radiation field and the coupled baryon plasma (until decoupling) are strongly damped on scales up to $O(\lambda_H)$ (see eq (1))[11] so that these perturbations on scales $\lambda_H(t_{WS})$ are damped out at $t > t_{WS}$. However, those in the axion gas are not damped since the axions are decoupled from the radiation. Indeed, it follows from eq. (2) that the axion perturbations are frozen in for $t < t_{eq}$.

The mass of axions within the horizon at time t is

$$M_a^H = 1.5t^{3/2}M_\theta \quad (M_\theta \equiv 1 \text{ solar mass} = 2 \times 10^{33} \text{ gm}) \tag{5}$$

which is just the standard result for non-relativistic matter with $\Omega=1$. For string-wall induced perturbations on a scale t_{WS} immediately before wall decay ($10^4 \lesssim t_{WS} \lesssim 10^5$ s), this gives

$$1.5 \times 10^6 M_\theta \lesssim M_a \lesssim 5 \times 10^7 M_\theta \tag{6}$$

Since $\Delta_a \sim 1$, the perturbations of mass M_a given by eq. (6) may collapse in a time less than the Newtonian linear free fall time $t_{coll} < (G\rho)^{-1/2} \approx t$. As the axion field collapses, a gravitationally induced outward pressure p_a in the axion field ϕ_a develops which is of the same order as the kinetic energy term in the Lagrangian as expressed in terms of the field gradient induced by the perturbation

$$p_a \sim (\partial_\mu \phi_a)^2 \sim \langle\phi_a\rangle^2/\ell^2 \lesssim \langle\phi_a\rangle^2/R_s^2 \tag{7}$$

while the perturbation remains outside of the Schwartzschild radius $R_s = 3\times10^5\, M_a$ cm $\approx 3\times10^{11}$ cm. The inward gravitational pressure is given by

$$p_g \sim 10^{-1}\,\frac{GM_a^2}{\ell^4} \tag{8}$$

We find from eqs. (7) and (8) that for $t_{WS} \lesssim t \lesssim t_{eq}$ $p_g \propto t^{-2}$, $p_a \propto t^{-5/2}$ and, $p_g(t) \gg p_a(t)$ for $R_s \lesssim \ell \lesssim \lambda_H(t_{WS})(t/t_{WS})^{1/2}$. Thus, for $\ell \gtrsim R_s$, the axion pressure is insufficient to stop the perturbation from falling into its Schwartzschild radius. We expect that the collapse will likely lead to black holes[12] of mass M_a as given by eq. (6). Such black holes are consistent with cosmological limits[13] for $M_a \sim 10^6\, M_0$.

At $t \sim t_{eq}$, the axions start to dominate the energy density of the universe and the axion perturbations or black hole clumps become gravitationally bound[7]. The perturbations or black holes which were formed on a scale $\ell \sim \lambda_H(t_{WS})$, evolve confined to a scale $\ell \lesssim \lambda_H(t_{WS})(t/t_{WS})^{1/2}$ and then cluster at t_{eq}. We now proceed to consider the gravitational clustering of these objects, hereafter regarded as large numbers of point particles of mass M_a. This has been considered within other contexts. (It should be noted that in what follows it is irrelevant whether the axions end up as black holes or highly bound self-gravitating spheres[14,15]). Press and Schecter[14] find that the self-similar solution for gravitational clustering of point masses leads to a typical clustering mass, mass spectrum and size scale

$$M_{CL} \propto (1+z)^{-1/(1-\alpha)}$$
$$n(M) \propto M^{-(1+\alpha)} \qquad (9)$$
$$\ell \propto M^{(4-3\alpha)/3}$$

where $\frac{1}{3} \leq \alpha \leq \frac{1}{2}$.

Using numerical experiments, Press and Schecter find solutions favoring $\alpha = \frac{1}{2}$. Substituting this value in eq. (9), we find

$$M_{CL} \propto (1+z)^{-2}$$
$$n(M) \propto M^{-3/2} \qquad (10)$$
$$\ell \propto M^{5/6}$$

Clustering here starts at t_{eq}, since both axions and black holes are decoupled from the radiation field. (This differs from the baryonic scenario considered by Press and Schecter where clustering starts at t_{dec}.) Thus, our typical clustering mass at redshift z = 0 follows from eqs. (6) and (10)

$$M_{CL}\ (z = 0) = M_a(z_{eq})\ (1 + z_{eq})^{-2}$$
$$\simeq 10^9\ M_a(z_{eq}) \simeq 10^{15}\ M_\odot \qquad (11)$$

and the typical length scale for this clustering is given by eq. (10) as

$$\ell_{CL}(z = 0) = \lambda_H(t_{WS})\left(\frac{t_{eq}}{t_{WS}}\right)^{1/2}\left(\frac{M_{CL}(z=0)}{M_a(t_{eq})}\right)^{5/6} \qquad (12)$$

$$\simeq 3\text{x}10^{25}\ \text{cm} = 10\ \text{Mpc} \qquad (1\ \text{Mpc} \equiv 3\text{x}10^{24}\ \text{cm}).$$

The second factor in eq. (12) comes from the expansion of the axion field perturbations for $t_{WS} < t < t_{eq}$ when $\kappa < 1$. The third factor comes from equation (10), representing the growth by clustering for $t > t_{eq}$.

The values obtained are in excellent agreement with typical observational values for the total dark mass and size of superclusters. It has been argued that the general galaxy distribution is compatible with the clustering hypothesis[15,16]. The development of structure in the visible (baryonic) mass of the universe will follow the potential wells formed by the dark mass after decoupling. A treatment of this type of process has also been given[17].

To summarize, in our axion dominated universe scenario, the initial density perturbations are produced by the string-wall system. Note that we do not postulate an arbitrary spectrum of initial perturbations; our perturbations come naturally and causally from the physics of the Peccei-Quinn symmetry breaking which produces the axions to begin with!

The axion perturbations most likely collapse to black holes of mass $\sim 10^6\ M_0$. The black holes (or axion clumps will do) then cluster and provide the missing mass hierarchy up to a scale $\sim$ 10 Mpc and $\sim 10^{15}\ M_0$. They also provide the seed potential wells needed for galaxy formation. We may call this the ABC (axion-black hole-clustering) scenario for galaxy formation.

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