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CONDENSED DARK MATTER?

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ABSTRACT

It is proposed that cold dark matter is condensed into a liquid or solid after sufficient adiabatic expansion. If it constitutes present-day dark matter, the rupture that results from overextension of the dark matter can cause large-scale structure. Luminous matter could sit in nonspherical potentials and experience flattening without rotating. Nonspherical dark matter distributions could possibly be revealed via weak lensing by galactic halos.

Subject headings: dark matter — elementary particles

1. INTRODUCTION

Large-scale structure displays two peculiarities. One is that galaxies appear to distribute themselves in a surprisingly small subvolume of the universe around large voids. The other is that there is no evidence in the cosmic microwave background of sufficiently large fluctuations at recombination to have grown into the present-day large-scale structure (LSS) if the density contrast between voids and galaxy-rich regions is of order unity. Typical discussions of LSS thus invoke "biasing," though the origins and extent of such biasing remain largely imponderable. Cold dark matter (CDM) may lessen this problem, but minimal CDM models have problems reproducing all the observations.

Large-scale structure and the suddenness with which such structure forms out of a homogeneous universe can be both understood if due to nongravitational forces that become important after recombination and cause fluctuations to grow faster than the Hubble timescale. In this paper, I propose specifically that dark matter (DM) is in a sufficiently low entropy state that it is condensed into a liquid or solid state by nongravitational forces. At some cosmic epoch, which we denote by the redshift z_*, dark matter would pass from positive to negative pressure, and voids would nucleate and propagate at about the sound velocity in the case of dark liquid and the stress fracture velocity (which is also of order the sound velocity) in the case of a solid. The nongravitational forces would maintain a roughly constant volume of the condensed dark matter, so that at later cosmological epochs, the voids are constrained to grow merely as a consequence of the Hubble expansion and eventually occupy most of the cosmic volume. In the case of solid dark matter, void formation is particularly efficient in that a stress fracture could propagate a large distance without the energy-consuming task of moving matter around significantly, as opposed to many cosmological blast-wave scenarios (reviewed and classified by Ostriker & McKee 1988). Moreover, any release of nongravitational energy is in the dark matter component and need not lead to distortion of the microwave background (Nath & Eichler 1989). Eventually the walls separating the voids undergo gravitational fragmentation, but only after significant perturbation of the Hubble flow.

The idea of using rupture as a source of cosmological inhomogeneity was proposed by Zeldovich (1963), Hively (1973), and Layzer (1975) in the context of familiar matter at ~ 1 g cm^{-3} and by Hogan (1982) in the context of matter at nuclear density. However, the horizon scale at such cosmic densities is too small to account for large-scale structure. There have also been several earlier proposals for making large-scale structure (Wasserman 1986; Hill, Fry, & Schramm 1991, and references therein) in which a bosonic field spontaneously breaks its symmetry in a "late-time" phase transition at a postrecombination epoch, but it is not clear why a phase transition at a temperature of at least $\sim 10^{-3}$ eV leads to large-scale structure on scales of megaparsecs. Residual topological defects extending across the horizon scale have a very large scale, but such defects contain only a small fraction of the original nongravitational energy, and in any case they would have had to exist to some degree prior to recombination. By contrast, the present proposal features a conserved fermion number as a cause of rupture of the dark matter, and no density fluctuations whatsoever are required prior to z_*. (The distinction is analogous to that between freezing water into ice and fracturing ice. The former is a phase transition that creates long-range crystalline order but no large-scale density fluctuations. The latter is more of a mechanical effect than a thermodynamic one and creates large-scale density fluctuations very efficiently.) It should be noted for completeness that even in the present proposal, the nongravitational forces in any case merely seed the growth of voids in the case of a flat universe. The negative self-gravity of a void relative to the background eventually comes to play a role over the Hubble timescale.

2. CONSTRAINTS

The dark matter would probably have to be a sort of shadow matter, interacting with itself nongravitationally and interacting with familiar matter only gravitationally. As such, there are numerous free parameters at first. However, the following constraints render the hypothesis far more specific.

1. In order to be cosmologically significant, the dark matter at zero pressure must be of order the critical density ρ_c, i.e., $\Omega_* = \rho(z_*)/\rho_c(z_*) \sim 1$, at the redshift z_*, and this redshift must follow recombination, i.e.,

$$z_* < 2000 , \tag{1}$$

in order to affect the distribution of normal matter without distorting the cosmic microwave background (CMB).

2. The density of the dark matter at z_* is arguably at most the inferred density at the peripheries of galaxies, roughly 10^{-25} g cm^{-3}. We cannot say for sure that the

density is lower than in clusters, superclusters, etc., because the liquid (solid) could have beaded (fractured) into droplets (pieces) by now, but we will adopt tentatively the constraint that the droplets must be at least as massive as galaxies, that they would thus coincide with at least some galaxies, and thus that their density at zero pressure cannot exceed the minimum inferred for galaxies in general. If the droplets were smaller than galaxies but larger than $10^6\ M_\odot$, they would probably heat galactic disks beyond observed limits (Lacey & Ostriker 1985). If they are smaller than $10^6\ M_\odot$ but less dense than about 10^6 times the average galactic density, then they would conglomerate via dissipative collisions, reestablishing a large mass with density of order $\rho(z_*)$. The most liberal consideration would permit a density no larger than that of a typical galactic disk. By the previous constraint, the dark matter density at zero pressure is close to the critical density at z_*, and this implies that

$$z_* < 20(\Omega_0 h^2)^{-1/3} , \tag{2a}$$

where Ω_0 is the present day cosmological density in units of the present critical density and h is the present-day Hubble constant in units of 100 km s^{-1}/Mpc^{-1}. This is the stronger version of the constraint. If observations permit dark disks, then the constraint can be relaxed to

$$z_* < 10^2(\Omega_0 h^2)^{-1/3} . \tag{2b}$$

For $z_* > 10^4$, where the density is more than 10^6 times a typical galactic density, the scenario presented here is still cosmologically acceptable, but it would probably resemble either black hole or cold dark matter scenarios, since nongravitational forces would not then generate structure of sufficiently large scale.

3. The sound velocity in the dark matter must be at least comparable to the escape velocity of galaxies, otherwise it would cluster with galaxies. The gravitational field of the galaxies would then compress the dark matter into something smaller than the Galaxy itself, and this would probably not be consistent with the inferred distribution of dark matter within galaxies. For the purposes of discussion, we adopt

$$[(5/3)P/\rho]^{1/2} > \eta \times 10^3 \text{ km s}^{-1} , \tag{3}$$

where η is of order unity and could be subjected to much refined calculation.

4. The dark matter could not have sped up the expansion of the universe greatly prior to helium synthesis in the big bang. The quantity *nmv*, the product of the number density and the average (in magnitude) momentum of the lightest particles in the dark matter, must therefore be not much larger in magnitude than that of the blackbody photons at z_*. Since the matter is assumed to be condensed, this limits the Fermi momentum to about the momentum of CMB photons at z_*. Quantifying this constraint depends on how accurately the cosmic "floor" on He abundance can be determined observationally, and this may be a matter of some debate, but we shall assume here that the Fermi momentum p_F of the lightest shadow particles is limited by

$$p_F < 10^{-3} \text{ eV}(1 + z_*)/c . \tag{4}$$

The nongravitational force may be either an Abelian or non-Abelian gauge group. To facilitate the discussion, assume tentatively that the shadow matter consists of equal numbers of shadow electrons and shadow protons (the latter defined to be the heavier of the two species) that interact via a U(1) gauge group with a fine-structure constant α_s. Given the above assumptions, the free parameters are the value of α_s, the electron and proton masses. The redshift at which the shadow matter attains zero pressure follows from these parameters. Constraint (4) applies to the electrons.

The Fermi velocity at z_* is just about α_s; hence, the pressure in the shadow electrons is less than $\sim \alpha_s P_{bb}$, where P_{bb} is the pressure in blackbody photons. Other numerical factors of order unity enter depending on how accurately one presumes to derive the expansion rate of the early universe from present-day observations of He abundance. Noting that the sound velocity due to the CMB pressure in a fluid having a density $(1 + z_*)^3\Omega_0 \rho_{c0}$ would, by coincidence, be just about $(1 \times 10^3 \text{ km s}^{-1})[\Omega_0 h^2]^{-1/2} (1 + z_*)^{1/2}$, we can then write constraint (3) on the sound velocity in the dark matter as

$$\alpha_s > \eta^2(1 + z_*)^{-1}\Omega h^2 . \tag{5}$$

The constraint (2a) on the density at z_* then implies that

$$\alpha_s \gtrsim (1/20)(\Omega_0 h^2)^{-2/3} . \tag{6}$$

Condition (2) on the density of shadow matter at z_* is

$$(4\pi/3)p_F^3 m_p \sim \rho_c(z_*)\Omega_* \sim \rho_{co}\Omega_*(1 + z_*)^3 \tag{7a}$$

where p_F is the electron Fermi momentum. The condition that the dark matter be condensed implies that the electron Fermi momentum p_F be a sizable fraction of the total electron momentum, so that condition (4) on the electron momentum implies that

$$m_p > 10\Omega_* h^2 \text{ eV} . \tag{7b}$$

Finally, we note that because the individual particle momenta $p(z_*)$ at z_* must be less than the CMB photon momentum, 10^{-3} eV $\times (1 + z_*)$, the mass of the lightest fermion, which must equal $\alpha_s^{-1} p_F(z_*)$, must be at least about 10^{-1} eV if constraint (2a) is adopted. (This last condition, however, will not generalize to the case of strong coupling, e.g., as in non-Abelian gauge forces [see below], since the Fermi motion is relativistic and the rest mass becomes irrelevant. It is replaced by the confinement scale as a parameter and the coupling constant, of order unity, is thus not free.) The mass ratio of the heaviest to lightest fermion as implied by equation (2a) is thus at least about 100 if they exist in about equal numbers. If the weaker constraint (2b) is adopted, the masses can be about equal, and perhaps this can be viewed as a scenario with one less free parameter. A mass ratio of less than 10^4 would probably guarantee fluidity at zero temperature if the heaviest fermions can form light, bosonic nuclei, e.g., shadow He nuclei in a manner similar to normal matter in the early universe.

Solid dark matter is allowed by the above analysis as much as liquid dark matter. Solid dark matter would probably fracture into irregular polyhedrons after expanding to negative pressure, but the roles of gravitation and inertia of the Hubble flow on the morphology (see below) may muddle this distinction somewhat.

The scale at which gravitation can spontaneously rupture the condensed dark matter, i.e., the scale R at which $GMm_p/R^2 > e^2/r^2$, where r is the interatomic separation and e is the electric charge, is much larger than the universe, so that gravity cannot by itself alter the topology of the fluid unless it has been stretched into extremely narrow filaments. On the other hand, the droplet scale, i.e., the scale R above which the gravitational energy GM^2/R exceeds the surface energy, is given by $N > \alpha_G/\alpha_s$, where $\alpha_G = Gm_p^2/hc$, and N is the total number of shadow protons contained within that scale, and this is negligibly small in a cosmological context. Thus, we expect gravitational beading of any sheet or filament that has formed in a hypothetical dark liquid. This is not necessarily true of a dark solid, though the inertia of the Hubble flow can cause it to crumble.

If the shadow fermions interact via a non-Abelian gauge group, then the scenario works more in analogy to neutral nuclear matter (e.g., strange matter (e.g., strange matter) than to atoms, but it is basically the same. The α_s, in any case constrained to be 1/10 or more in the above, is now replaced by unity. The confinement scale is chosen to be about the Compton wavelength of the shadow electron in the above, and the heaviest stable quark is assigned a mass of the proton. The phenomenon of "neutron drip," which prevents normal neutrons from condensing at zero pressure, does not necessarily apply here, as the constituent mass of the heaviest quark is larger than the mass associated with the confinement scale. Also, the force may respect a symmetry group other than SU(3). Whether the shadow matter would be a solid or liquid depends on various other assumptions and will not be discussed here. In either case, there are basically two free parameters, the mass of the heavy particles and the separation between them. They are determined by the mass density and sound speed of the condensed dark matter.

When the dark matter passes from positive to negative pressure, it essentially becomes a bubble chamber (or, in the case of solid DM, a stress fracture chamber), and the pattern of large-scale structure induced is very sensitive to the nature of the trigger mechanism. As *COBE* has probably detected structure in normal matter, the latter cannot be overlooked as a possible trigger mechanism. In this case, the stored tension in the dark matter fuels the growth of ruptures. The spectrum of fragments is difficult to calculate and is beyond the scope of this paper. But clearly the maximum correlation length L is the maximum allowable sound speed

$$c_s \sim (1 \times 10^3 \text{ km s}^{-1})(\Omega_0 h^2)^{-1/2}(1 + z_*)^{1/2} , \qquad (8)$$

times the Hubble time at z_*, roughly $3h^{-1} \times 10^{17}$ s $(1 + z_*)^{-3/2}$, assuming Ω_* close to unity. The void length then grows under its own negative self-gravity roughly like a self-similar blast wave, with a central pressure that vanishes and that is therefore above the value at infinity Λ as long as the material outside the void does not disintegrate. Using the results of self-similar blast waves, we write the absolute radius of the void as At^α. In the absence of energy input, $\alpha = 0.8$ (Ostriker & McKee 1988, and references therein). If energy is added to the void as a power law in t, $E(t) = E_0(t/t_0)^\Gamma$, then $\alpha = (\Gamma + 4)/5$ (Nath & Eichler 1989). In comoving coordinates for a flat universe, the void length grows as $t^{\alpha-(2/3)}$.

The above discussion then implies a maximum present-day void scale of L_0 of

$$L_0 \sim 10\Omega_0^{-1/2}h^{-2}(1 + z_*)^{(3/2)\alpha-1} \text{ Mpc} , \qquad (9)$$

which is interestingly close to the observed scale of large-scale structure given the uncertainty in h and Ω_0.

As has been noted by Hogan (1982), the maximum correlation length of ruptures due to quantum tunneling could be smaller than the sound horizon by 2 or 3 orders of magnitude. The reason for this is that if the material is brittle, the time elapsed is small between the epoch at which an occasional (e.g., one per void scale) rupture develops because of quantum tunneling and the epoch at which the material disintegrates into a powder or mist due to copious rupturing. That is, the cosmic density need only change by 10^{-2} to 10^{-3} between these two epochs because rupture is so sensitive to the amount of strain in the material. This raises a formidable difficulty in associating the void length with the sound horizon in this picture. Possible solutions to this problem are that (*a*) the microphysics establishes an extremely rubbery consistency to the dark matter, or (*b*) the large-scale structure follows the imprint of some other low-level fluctuation, such as that responsible for the fluctuations at the 10^{-5} level reported by *COBE*, and it is merely amplified by the bubble chamber effect. Possibility (*a*), in the limit of infinite resilience, is just a cosmological constant. If the fabric that establishes the cosmological constant ruptures only occasionally with the remainder maintaining a finite constant tension Λ, then the tension would accelerate the void growth. A slight elaboration of the discussion by Nath & Eichler (1989) shows that then $\alpha = 2$. Equation (9) then allows extremely large voids if they have sufficient time to grow under this tension. (However, when the void scale approaches the event horizon scale, if means that Λ is large enough to affect the cosmological expansion, an effect that is not included here.)

3. DISCUSSION

The scenario offers a natural reason for the universe becoming clumpy having once been smooth. Its numerology parallels scenarios of low energy phase transitions (e.g., Wasserman 1986); the two free parameters, essentially the density and sound speed of the condensed dark matter at zero pressure, parallel the two free parameters of a ϕ^4 Lagrangian that allows spontaneous symmetry breaking. But the physics is different in that there is no phase transition, merely hyperextension of material that relaxes by rupturing, roughly conserving its total volume. (For example, the symmetry and subsequent breaking would occur even if the temperature were zero at all times.) The material was in an ordered state prior to the rupturing, so that long-range order can be established well in advance of z_*. The conserved particles are responsible for the ability of the dark matter to leave themodynamic equilibrium temporarily, and their origin is left unexplained. In contrast, we know of no reason why a scalar field with a simple, fixed potential should ever deviate significantly from equilibrium under cosmologically slow adiabatic expansion or why its adiabatic cooling should not result in a glassy state. (Early versions of inflationary scenarios invoked this assumption, but justification for it may have been an artifact of the one loop approximation.) The reason we propose is obtained at the cost of invoking a field of many conserved particles. The order parameter of the conserved particles can, of course, be represented by a field, but in this case the effective potential would be state dependent.

Observational consequences specific to this scenario, though hard to make precise here, should be based on the ability of the dark matter to (*a*) dissipate energy via its coupling to a gauge field, and (*b*) be highly granulated into dark "asteroids" held together by nongravitational forces. If dark matter in clusters of galaxies is clumpy in this manner, then it naturally develops an isothermal-like density profile in about one gravitational relaxation time τ_r, in analogy to globular clusters. By contrast, the timescale for mergers by close, dissipative encounters is about 2 orders of magnitude longer and is probably longer than a Hubble time as long as the surface density of the clumps exceeds the cluster average by the number of crossings per Hubble time, i.e., a factor of 10 or so. Moreover, the clumpiness of the dark matter allows it to lose energy via dynamical friction and thus be considerably more condensed than the diffuse X-ray–emitting gas. The observation of David, Jones, & Forman (1995) that the X-ray–luminous gas of rich clusters is more extended than the dark matter component is consistent with this, although other scenarios may work also. Rough estimates suggest that a zero pressure density for the condensed DM of order 10^{-25} g cm^{-3}, give or take an order of magnitude, and a clump mass of order 0.1–1 galactic mass would fit the existing cluster data.

Angular momentum can be exchanged between neighboring protogalaxies via multipole interactions, as in other cosmological scenarios. It is also conceivable that a large chunk of dark matter could be captured tidally by a luminous galaxy. If less dense than galaxies, the DM could be tidally disrupted by galaxies and form large, flattened rings around field galaxies playing the role of Saturn. It could thus be distributed differently from weakly interacting massive particles (WIMPs). The luminous part of galaxies could appear flattened by the nonspherical potential of the ring or disk of dark matter, even if the former is not rotating significantly. This scenario, though limited to a particular range of density and mass of the dark matter chunk, provides a possible alternative to the interpretation of nonspherical, nonrotating galaxies as being triaxial.

Nonspherical dark matter distributions may be identified in a more convincing way by weak lensing of background galaxies by intervening galactic halos. Observational programs to map dark matter distributions in this way are beginning.

If accreting onto quasars and active galactic nuclei (AGNs), the dark matter could punctuate their activity on the timescale of $(G\rho)^{-1/2} \sim 10^7$–10^{10} yr with attendant inscription in jets. The difficulty in predicting is that the processing that dissipative dark matter is likely to experience at the hands of familiar astrophysical systems, which may be complex, makes it hard to predict its final state. But the matter is perhaps worthy of future study.

The scenario demands that the photon entropy in the shadow sector be considerably smaller than in the normal sector, and in fact that it be of order unity or less. If shadow fermiogenesis proceeded in the now familiar charge-parity (CP) violating way that normal baryogenesis is often attributed to, this may be problematic. The conventional tendency to assume that any matter distributed on a large scale would be gaseous is certainly justified by the likelihood of inefficient fermiogenesis.

But a moderate entropy per fermion may also be possible if charge-party-time (CPT) symmetry is broken spontaneously at the Planck scale (Cohen & Kaplan 1987). This can occur when the fermionic current j^μ couples to the derivative $\partial_\mu \theta$ of a scalar field θ via the coupling term $q\, \partial_\mu \theta j^\mu$. While Cohen & Kaplan seek parameters yielding low baryogenic efficiency, i.e., a high entropy per baryon (10^9), their mechanism is extremely efficient if (*a*) all energy and timescales are of order the Planck scale (*b*) the coupling constant q is of order unity, and (*c*) the θ field decouples from the fermions during its rollover phase.

If the temperature (or more generally the pressure) of the shadow matter is close to that of the normal CMB (e.g., due to thermal contact in the very early universe), then the following coincidence observed in the familiar matter sector could be understood by combining the anthropic principle that we live in an era just after galaxy formation with the hypothesized similarity in the pressures of normal and shadow universes. The proximity of the present-day void size to $[(P_{BB}/\rho_c)^{1/2} H_0^{-1}]$ follows naturally, since the latter is by hypothesis close to the sound speed of the shadow matter. In other words, we live in a cosmological era not long after the time at which shadow matter attained zero pressure, and the largest scale of structure is the "planetary" mass—i.e., the mass at which nongravitational forces compete with gravitation: $(\alpha_s/\alpha_G)^{3/2} m_p \sim 1.4 \times 10^{15}$ $M_\odot\, (30\ \mathrm{eV}/m_p)^2 \alpha_s^{3/2}$—of the shadow matter.

The largeness and lateness of large-scale structure in this model is simply a consequence of gravity being weak compared to other forces. The genetic information for the structure is thus carried in the forces of nature as opposed to quantum fluctuations in the early universe (though the latter should certainly not be discounted given the bubble chamber effect). No other small number needs to be introduced such as the flatness of the potential in which the inflaton rolls.

At a philosophical level, attributing large-scale structure to the condensation of matter may solve what could be termed the "fickleness" problem in cosmology, that the universe chose to be homogeneous and isotropic for much of its history, but then became strongly inhomogeneous on some scales while retaining its homogeneity on the largest scale. Condensed matter does precisely this when decompressing from positive to just negative pressure.

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