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Dark Matter, Tooth Fairies, Fractals and Strings

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ABSTRACT

It is shown that there are at least 3 different types of dark matter problems and that no simple, single new particle candidate satisfies them all. All current solutions require at least two ad hoc assumptions. Of these, more complex but complete solutions, the ability to produce large scale free structures, known as fractals, with fractal Dimension ~ 1.2 may be critical. It is shown that models which incorporate strings from GUT phase transitions may do this particuliarly well. The fact that Superstrings, which are the in vogue candidates for the Theory Of Everything (T.O.E.), yield cosmic strings is encouraging. It is also shown that the location of the dark baryons may be the way to resolve the different, currently ad hoc solutions.

For children in the United States, the Tooth Fairy is the creature which magically changes a child's baby-tooth, which fell out during the day, into a shiny new dime (or some higher denomination due to non-cosmic inflation) if the tooth is placed under the pillow at night. According to Turner's law[1], the invocation of the Tooth Fairy should not occur more than once in any scientific argument. Unfortunately, all solutions to the cosmological dark matter problems seem to, at present, require a double invocation. That is, each requires at least two ad hoc assumptions which are motivated by no other reason than to solve the dark matter problems.

It should be noted that Turner's law may be in conflict with T.H. White's law[2]: "Everything not strictly Forbidden is Mandatory". This latter viewpoint has appeared to guide theoretical particle physics and cosmology in recent years but may not be a guiding principle of the universe. However, to be on the safe side, we should minimally determine which dark matter problems are mandatory and which solutions are, therefore, strictly forbidden. To do this, we will first look at the various arguments regarding dark matter. In so doing, it will be emphasized that there are several cosmological dark matter problems[3], not all of which require exotic (NON-baryonic) stuff. In fact, it will be shown that some dark baryons are necessary, and how these dark baryons are distributed may eventually prove to be the day for resolving the nature of the

bulk of the matter of the universe. We will review the fact that no simple solution which uses only an exotic particle works.

It will then be shown that the additional constraint, that the large scale structure of the universe be scale-free[4], may severely constrain the allowable dark matter solutions even if we allow violations of the double tooth fairy law. Such a scale-free solution tells us that clusters are laid out in a fractal; since the fractal is close to dimension one, it may point in the direction of cosmic strings or other linear phenomena.

The conclusion will be that the correct, "best", solutions may tell us something about phase transitions in the early universe. While, at present, the properties needed appear like invocations of tooth fairies, it is possible that future observations will restrict us to a mandatory solution.

The Dark Matter Problems

As emphasized in ref. 4, there are at least 3 classes of dark matter problems:

1. Dynamics
2. Galaxy Formation
3. Inflation

The first is the well established[5] fact that the light emitting regions of the Universe have relatively low mass-to-light ratios so that if there were only that much mass in the Universe, the cosmological density parameter $\Omega \equiv \rho/\rho_{crit}$ would be ~ 0.007, a very open universe. However, if those same light emitting galaxies are observed interacting with more distant galaxies in binaries and small groups, then the implied mass of each galaxy is about a factor of ten larger and the implied Ω is ~ 0.07. This tells us that galaxies have massive halos which are dark. (As Schramm and Steigman[6] emphasize, it is the *light*, not the mass, which is missing.) If the dynamics of large clusters of galaxies are observed, then the implied mass per galaxy is even larger. If all galaxies have that much mass, then Ω is from 0.1 to ≤ 0.4. It is important to emphasize that *no system* implies an $\Omega > 0.4$.

To put these numbers in perspective, remember that Big Bang nucleosythesis[7] puts an upper limit on the density of baryons in the universe of $\Omega_b < 0.15$ for a present backround temperature of $T_0 \leq 2.8$K. Thus, within the uncertainties, all of the dark halo material could be baryonic, although the higher super-cluster masses may require something additional.

Hegyi and Olive[8] have shown that if the halo material is non-baryonic, then it must either be in blackholes (that were baryonic at the time of Big Bang nucleosynthesis) or low mass, astronomical objects (Jupiters or low mass, dim stars). This latter class would require a very strong peak at low mass in the initial mass function.

Freese and Schramm[9] have combined the nucleosynthesis arguments with age arguments to conclude that $\Omega \geq 0.03$. Thus, it is argued that the density in baryons exceeds the density of shining stuff. In fact, it can be said that the bulk of the baryons must be dark. As we will see, it is not clear whether these dark baryons make up the dark holos or whether they are distributed elsewhere. However, it should not be forgotten that the dynamical and the nucleosynthetic arguments are still consistent with $\Omega \sim 0.1$ and everything being baryonic[10].

The arguments for non-baryonic matter center on two additional dark matter arguments. galaxy formation and inflation. While the inflation argument is the most theoretical, it is perhaps the most mandatory from a logical sense. As we will see, the galaxy formation arguments may have some intriguing loopholes and so are not as mandatory.

The inflation argument comes from the proposal of Guth[11]. Although the detailed mechanism has been modified considerably (see review in ref. 12 and references therein), the basic paradigm is still there. Inflation is the name given to the process which sets the initial conditions of universe by a rapid, de-Sitter phase, expansion. Such a phase will solve the horizon problem, the flatness problem, the monopole problem and it will produce fluctuations which might eventually yield galaxies. The detailed particle models which produce inflations consistent with observations still appear very ad hoc[12]. However, the flatness problem alone tells us that something like inflation must have occurred, or else we live in a very special epoch in the history of the Universe. In particular, since Ω varies with time on a gravitational time scale, we can conclude that, since we still don't know whether Ω is significantly different from unity after $\sim 15 \times 10^9$ years that at the Planck time (10^{-43} seconds), Ω had to be fine tuned to be unity to 60 decimal places. Inflation, or anything like it, solves this problem by making $\Omega = 1$ to far greater accuracy and thus avoids forcing us to live in the special epoch where Ω first deviates from unity. Since $\Omega = 1$ is in excess of Ω_b, this tells us that the bulk of the matter of the Universe is non-baryonic. Note also that since $\Omega_{clustered} < 0.4$, inflation tells us that the bulk of the matter of the Universe is not clustered with the light emitting stuff.

The above sequence of arguments tended to favour massive ($\sim$10eV) neutrinos as dark matter since they would be non-baryonic and would not strongly cluster with the light emitting stuff. Then the galaxy formation arguments came along and the shift from neutrinos to "cold" matter occured. One point to be emphasized is: the galaxy formation arguments may have a significant loophole and the large scale structure arguments may force us to go through the loophole.

The galaxy formation arguments[13] center on the following points:

1. Quasars exist at redshifts[14] $z > 3$.

2. Anisotropies in the microwave backround are small[15], $\delta T/T \lesssim 2 \times 10^{-5}$.

3. Baryonsynthesis requires primordial, adiabatic fluctuations[16].

4. Fluctuations, $\delta\rho/\rho$, grow linearly with the expansion until $\delta\rho/\rho \sim 1$ or until redshift $z \sim 1/\Omega$ for $\Omega < 1$.

5. Fluctuation growth does not start until matter domination.

If the universe were baryon dominated, then from arguments 2, 3, 4 and 5, $\delta\rho/\rho$ would only reach $\sim 2 \times 10^{-2}$ today since the background radiation decoupled at redshift $z \sim 3000$. But we know that $\delta\rho/\rho$ exceeds 1 today. Thus we need something in addition to baryons. If the additional material were in the form of neutrinos or other particles which are relativistic, "hot", until just before galaxy formation, then condensed objects wouldn't form until $z \lesssim 1$, violating argument 1. The best candidate thus appears to be "cold" matter which is moving slowly and can begin clustering rapidly on galactic scales. It has been shown[13] that argument 4 also implies that Ω must exceed ~ 0.4 in order to have sufficient growth. This latter point appears to violate the dynamic argument that matter in clusters has $\Omega < 0.4$ since cold matter will cluster on smaller scales than superclusters. Thus superclusters should contain all cold matter *if* light emitting stuff goes along with it.

Problematic Solutions

From the above discussion, it is apparent that in the simple picture, no single dark-matter candidate works: hot particles don't form galaxies fast enough and cold particles put too much mass on small scales where it is not seen. Even hybrids of hot and cold particles fail.[17,18] Two classes of solution have been able to work: one is to have light, not trace mass[19]; the other is to have cold particles decay to hot.[20]

If light does not trace mass, then many (most) clumps of cold matter and baryons do not turn on their baryons and fail to shine for some reason. Such a failure to universally ignite requires a tooth fairy, albeit a thermodynamic one (rather than a particle physics one). This thermodynamic tooth fairy is added to the particle physics tooth fairy (the one which produced the cold particles: axions, photinos, heavy leptons, planetary mass black holes, quark nuggets, etc). The decaying scenario requires two toothfairies as well, but both are of the particle variety.

Some people have preferences for one or another variety of tooth fairy. Thermodynamic ones might, in principle, be eliminated since they only require classical physics, *but remember we still can't predict the weather*. On the other hand, particle ones might, in principle, be eliminated by future accelerator experiments.

Another way out is to duck the galaxy formation argument by having something other than matter carry the primordial fluctuations[21]. Under such a scenario, the fluctuations would not be

smoothed by the free streaming of the matter and radiation. They would be sitting, waiting for the baryons to fall in once the baryons decouple from the radiation and the Universe is no longer matter dominated. Such fluctuations behave like the old isothermal fluctuation model. Cosmic strings[22] are a fine example of such fluctuations if energy density in strings ρ_s, relative to the total matter energy density ρ is, $\rho_s/\rho \sim 10^{-3}$, then fluctuation growth in ρ to $\delta\rho/\rho \sim 1$ can occur for the baryons and rapid galaxy formation is no problem. Strings would have mass scales smaller than $\sim 10^{12}\ M_\odot$ damped by gravitational radiation, but otherwise behave like isothermals, with, however, an equal power on all mass scales, Harrison-Zeldovich spectrum. Strings are also capable of producing non-random phases[23] which may be valuable for explaining large clusters and voids[24].

While baryosynthesis argues against primordial isothermals on scales larger than the horizon, it does not prevent subsequent phase transitions from producing isothermal-like fluctuations on scales smaller than the horizon at these phase transitions. An example is the possible generation of planetary mass Black holes[25] or quark nuggets[26] at the Quark-hadron-chiral transition. Such objects can serve as small scale isothermal seeds that baryons can condense upon[27,28] after recombination. Such objects can serve as the seeds for the Ostriker-Cowie[29] explosive galaxy formation scenarios.

Thus, galaxy formation either requires cold matter or isothermal-like fluctuations, which require some phase transition action in the early Universe, either generating strings or some other remnant.

Large Scale Structure

The distribution of matter in space has been described in detail by Peebles[30] using the two-point correlation function $\xi(r)$. This is the excess probability over random that two objects are separated by distance r. The correlation function for galaxies ξ_{gg} has been shown to have the form $\xi_{gg}(r) = \alpha_{gg} r^{-1.8}$. Similiarly, it has been shown[31,32,33] that the correlation function of rich clusters ξ_{cc} also has the form $\xi_{cc} = \alpha_{cc} r^{-1.8}$; but for Abell R=1 clusters α_{cc} 20 α_{gg} and α_{cc} is even larger for Abell R = 2 clusters.

At first glance, this appears strange, since the larger separated clusters would not have had as much gravitational clumping as the more closely separated galaxies. However, Kaiser[34] and Fry[35] pointed out that if clusters are merely the 3σ peaks in the galaxy distribution function, then one would obtain a factor of $\sim$20 enhancement, since the less clumped galaxies would dilute the amplitude for ξ. Such biasing would mean that $\xi_{gg}(r) \propto \xi_{cc}(r)$ so that when ξ_{gg} goes negative, ξ_{cc} should also be negative, only more so. Current data[36] indicates that ξ_{gg} deviates from the $r^{-1.8}$ power law and goes negative at $r \approx 20\ h_o^{-1}$ Mpc (where $h_o = H_o/100$ km/sec/mpc), but ξ_{cc} is positive out to $r \gtrsim 100 h_o^{-1}$ mpc. Thus, simple biasing seems in trouble. Of course, the

negative correlations may be due to unfortunate statistical fluctuations in our neighborhood, but it should be remembered that essentially all models of galaxy formation with a Harrison-Zeldovich type fluctuation spectrum yield ξ_{gg} going negative for some r which is well below 100Mpc. Therefore, a positive ξ_{cc} at 100Mpc is in conflict with the biasing interpretation for all the standard galaxy formation scenarios.

This problem has been reexamined using a dimensionless approach[37] where all distances are measured in units of $L \equiv n^{-1/3}$ (where n is the density of objects in the catalogue). With this proceedure, $\xi(r) = \beta(L)(hr/L)^{-1.8}$. This is analogous to the renormalization approach that is used in condensed matter physics to analyze scale-free transitions. In particular if, $\beta(L)$, were found to be constant for all, this would imply that $\xi(r)$ is scale free. It is interesting that $\beta(L)$ is approximately the same for both $R > 1$ and $R \geq 2$ as well as the Schectman[36] catalogue. However, $\beta(L)$ for galaxies is about a factor of 3 larger. Thus, this dimensionless approach has eliminated the dependence on cluster richness and reduced the entire dynamic range to a factor of ~3. That all the various cluster-cluster functions have the same $\beta(L)$ seems to imply that there is a scale-free process operating from scales of Mpc to 100's of Mpc. The slight enhancement of β_{gg} is simply implying that galaxies have had their clustering enhanced by gravity a factor of ~3 over the scale- free process which produced the $r^{-1.8}$ behavior.

A scale free process of this type is known as a fractal.[38] The $r^{-1.8}$ power law tells us that the dimension D of the fractal is $D = 3 - 1.8 = 1.2$. This is pretty close to a linear, $D = 1$, fractal. It is interesting to note that if large scale structure is scale-free, then the dispersion in the velocity-field about the Hubble flow should saturate rather than continue to grow with r. Preliminary observations[36] seem to support this.

There are several possible scale-free processes which might yield a $D=1.2$ fractal for laying out galaxies and clusters in the Universe.

1. **Biasing** This can yield a scale-free process if the primordial fluctuation spectrum is scale-free. However, as mentioned above, the lack of negativity at large r in ξ_{cc} seems to argue against this mode.
2. **Strings** If the primordial fluctuations are created by cosmic strings, they would be laid out along a pattern left by the primordial string before it fragmented. The fractal dimension of this pattern depends on how the strings move and fragment but a near linear $D \geq 1$ fractal is not unreasonable.
3. **Percolation** If galaxy formation is related to explosions of primordial seeds, and if the density of such seeds is sufficiently high, percolation can occur and a scale free pattern can form. The fractal dimension of such a pattern depends on the geometry of the explosion (jets, disks, spheres, or?) and on the geometry of the region where the seeds are dense (neutrino pancakes?).

Conclusions

Combining the need for a scale-free, large-scale structure mechanism with $\Omega = 1$ and with the requirement that galaxies form rapidly with $\delta T/T$ small, restricts us to:

1. biasing and cold dark matter
2. strings and hot dark matter
3. percolated explosions and hot dark matter.

In the "bias and cold" case, the dark baryons are in non-shining clumps of cold matter, unrelated to clusters of galaxies. Contrary to the present reports, such a solution also requires ξ_{cc} to be negative at large scales.

The "string and hot" case requires the dark baryons to be in the halos of galaxies. The hot x-ray gas in rich clusters[6] implies that galaxies in clusters had significant baryonic matter associated with them which fell into the deep potential well of the cluster and was heated to x-ray temperatures. If all galaxies had this much baryonic material, it would support dark baryonic halos. A strong (recent) plus for the string model comes from the work on superstrings which is the current best candidate for the Theory of Everything (T.O.E.). While ten dimensional superstrings are themselves not directly related to the cosmic strings needed for galaxy formation Witten[39] has shown that the two superstring models 0(32) and E(8) x E(8), which are anomoly-free, finite and have chiral fermions, naturally lead to cosmic strings. These cosmic strings form when the supertheory breaks at the GUT epoch.

The "percolation and hot" case also has the dark baryons in halos, but this model uses baryons in early explosions so that the early universe is quite active, which should lead to observational consequences. This model requires early universe phase transition activity since the seeds can only be sufficiently plentiful if isothermal-like fluctuations are generated on scales that eventually produce seeds. The quark-hadron transition is the best candidate for such a transition. However, while current estimates imply a first-order transition, it is still quite difficult[40] to get long-lived quark nuggets or planetary-mass black holes.

In summary, the way to distinguish possibilities is to find the dark baryons. While the best, current estimate might lean towards strings and hot stuff, the data is by no means conclusive. In fact, the solution with the least Toothfairies is that either one of our assumptions or one of our pieces of input data is wrong!

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