THE CONSISTENCY PROBLEMS OF LARGE SCALE STRUCTURE

David N. Schramm
The University of Chicago and Fermilab

Abstract

The combined problems of large scale structure, the need for non-baryonic dark matter if $\Omega = 1$, and the need to make galaxies early in the history of the universe seem to be placing severe constraints on cosmological models. In addition, it is shown that the bulk of the baryonic matter is also dark and must be accounted for as well. The nucleosynthesis arguments are now strongly supported by high energy collider experiments as well as astronomical abundance data. The arguments for dark matter are reviewed and it is shown that observational dynamical arguments and nucleosynthesis are all still consistent at $\Omega \sim 0.1$. However, the inflation paradigm requires $\Omega = 1$, thus, the need for non-baryonic dark matter. A non-zero cosmological constant is argued to be an inappropriate solution. Dark matter candidates fall into two categories, hot (neutrino-like) and cold (axion or massive photino-like). New observations of large scale structure in the universe (voids, foam, and large scale velocity fields) seem to be most easily understood if the dominant matter of the universe is in the form of low mass ($9eV \leq m_\nu \leq 35eV$) neutrinos. Cold dark matter, even with biasing, seems unable to duplicate the combination of these observations (of particular significance here are the large velocity fields, if real). However, galaxy formation is difficult with hot matter. The potentially fatal problems of galaxy formation with neutrinos may be remedied by combining them with either cosmic strings or explosive galaxy formation. The former naturally gives the scale-free correlation function for galaxies, clusters, and superclusters. The latter requires fine tuning and percolation to get the large scales and the scale-free correlation function. However, combining hot matter and strings reduces the ability of the hot matter to give some of the large scale features and still yield $\Omega = 1$. Questions to be examined are raised.

1. Introduction

The major confrontation of early universe studies with the "real" universe now focuses on the problems of galaxy formation, dark matter, and the generation of large scale structure. The observable aspects of these problems came into being shortly after recombination; however, the condition of the universe as it approaches recombination are determined by events taking place much earlier, when nuclear and particle physics effects dominated. Since the recombination epoch is the limiting epoch for direct observations, it is only natural that this epoch serve as the interface between early universe cosmologists and astronomers.

The problems are to produce initial conditions and types of matter which will yield the observable universe, the large scale structure. In particular, the observable universe now appears to have large scale structure on scales of $\sim 40Mpc$ that looks like foam or at least intersecting sheets and filaments with large voids[1,2,3]. In addition, there appear to be large, coherent motions of 40 Mpc clumps with velocities of $\sim 600km/sec$[4]. To this very large scale structure must be added the apparent fact that clusters of galaxies cluster with each other more strongly than galaxies cluster[5], or to use the analysis of Szalay and Schramm[6], the clusters and galaxies appear to cluster in a scale-free manner as if laid out in some fractal pattern.

2. The Dynamical Arguments

To these large scale observations must be added the dynamical measurements of mass and the so-called dark matter problem. In particular, the dynamics of the visible parts of galaxies imply an Ω of ≤ 0.01 (where $\Omega \equiv \frac{\rho}{\rho_{crit}}$ is the critical density of the universe). However, when galaxies interact with other galaxies in binary pairs or in small groups, they interact with ~ 10 times as much mass, implying an $\Omega \sim 0.1$. When galaxies interact with one another in large clusters they interact with possibly even more mass, implying $\Omega \sim 0.1$ to 0.3. (***No well studied system gives anything near*** $\Omega = 1$.)

3. Big Bang Nucleosynthesis

To the dynamical arguments we can add the arguments from Big Bang nucleosynthesis (Yang et al.) which show that observed abundances are consistent only if $\Omega_b \sim 0.1$ (where $\Omega_b \equiv \frac{\rho_b}{\rho_{crit}}$ and ρ_b is the density of baryons).

Thus as Gott et al.[7] pointed out over ten years ago, direct astronomical evidence points towards $\Omega \sim 0.1$ with the dark halos being baryonic and no need for exotic stuff. In particular, it should be noted that the lower bound on Ω_b is $\Omega_b \geq 0.03$[8]. Since this is > 0.01, it implies that the bulk of the baryons are dark. (Note that because of this point, dark halos for dwarf spheroidal galaxies are no problem since they can be baryonic.) Also, it is important to remember that nucleosynthesis contrains $\Omega_b < 0.15$. (This is lower than the 0.19 from Yang et al.[9] due to better current upper limits on the microwave background temperature.) Thus, if $\Omega \sim 1$, the bulk of the universe would be non-baryonic ***and*** could not cluster with the light emitting galaxies and clusters.

The nucleosynthesis arguments are gaining even greater credence now that their predition[9,10] that the total number of neutrino types (generations) is small (three or at most four) is being verified by collider experiments[11] with current experimental limits at < 5. From particle physics theory alone any number of generations might be possible. The preliminary verification of the cosmological prediction is the first time that cosmology has made a prediction which has been verified by a high energy accelerator experiment.

4. Baryonic Halos?

Can halos of galaxies and dwarf spheriodals really be baryonic? While the coincidence of $\Omega_b \sim 0.1$ and $\Omega_{dynamic} \sim 0.1$ is suggestive, it is certainly not compulsory. Different forms of dark matter can mix with baryons in different ways depending on the mechanism of galaxy formation.

With cold dark matter the halos must be a mixture of $\sim 90\%$ cold matter and 10% baryons whereas in hot matter models the halo mixture depends on the galaxy formation scenario.

If the halos do contain significant baryonic materials, what form can it be? Hegyi and Olive and Schramm have argued that most baryonic things do not work. However, they leave two very important loopholes:

1. Black holes left from an early generation of massive stars with the bulk of the stellar material falling into the hole and not producing excess heavy elements. Such black holes are contrained by Big Bang nucleosynthesis baryon limits since they were baryons then (so they count as baryonic material).
2. Low mass objects too dim to be seen in telescope searches. Jupiter-like clumps or even 0.01 $M_\odot$ stars would work. In order for the abundance of such objects to be sufficient, the abundance spectrum for these objects would probably be above the low mass extrapolation of the Salpeter initial mass function. However, that function is strictly empirical and there could certainly be a low mass excess if the initial stellar generation with pure H and He, but more objects low than currently occurs with heavy elements present. (Option 1., of course, requires exactly the opposite behavior for the early stellar mass function.)

5. The Flatness Arguments

If everything agrees so well with $\Omega \sim 0.1$, why do people continue to think $\Omega = 1$? The only astrophysical evidence for large Ω is clearly weak at the present time. It consists of the following:

1. With Gaussian adiabatic initial density fluctuations of the type described by Zel'dovich and expected from simple inflation models, it is impossible to make galaxies rapidly enough when constrained by limits on microwave background anisotropies unless $\Omega > 0.2$[12,13].
2. The velocity field of IRAS galaxies on scales of ~ 200Mpc implies a virial mass on these large scales of $\Omega \sim 1$[14].
3. The density of galaxy counts versus redshift is optimally consistent with $\Omega = 1$ geometry[15].

The first of these is clearly removable if galaxies form by something other than Gaussian adiabatic fluctuations with a Zel'dovich spectrum. In particular, string models which are also derivable from grand unified gauge models do not yield such a stringent requirement on Ω, nor do, for that matter, models where galaxy formation is stimulated by early explosions[16].

The second argument has the problem that a reliable way to determine distances to IRAS galaxies has not been established and a complete redshift survey of IRAS galaxies remains to be done. In addition, IRAS counts may have a significant north–south bias due to induced instrumental variations in sensitivity of the satellite in the northern and southern hemispheres.

The third argument, while potentially the strongest, still requires a more detailed analysis of galactic evolution effects and normalization of distant galaxy counts to nearby where different techniques are used.

Thus, while suggestive, these arguments do not yet establish $\Omega = 1$. However, there is a Copernican-like argument which is sufficiently powerful that most theoretical physicist believe $\Omega = 1$. The argument was best articulated by Dicke and Peebles and later provided Guth with a strong motivation for inflation which gave a physical mechanism for yielding the desired Ω. The argument, simply stated, is that Ω is a time changing quantity going to $\Omega < 1$ and to ∞ if $\Omega > 1$, and only remaining constant if $\Omega = 1$. The timescale of change is the expansion rate of the universe. Thus, the only long-lived values are 0, 1, and ∞. Since we are here, Ω is neither 0 nor ∞. The only other long-lived value is 1. To have any finite value below unity today would require that we live at a very special time, the early epoch in cosmic time when Ω was not 1 or 0. Such a value would require the extraordinary fine tuning at the Planck time of ~ 60 decimal places, or at least 17 decimal places at the time of Big Bang nucleosynthesis. Thus, unless we live at a special time and some unknown mechanism tunes Ω to exactly the right amount to fantastic accuracy, Ω is probably unity.

Since any early deSitter phase for the universe produces a flat universe ($\Omega = 1$ if the cosmological constant $\Lambda = 0$) and since inflation means an early deSitter phase, and since most scalar fields yield inflation, it is reasonable to believe $\Omega = 1$. While many have recently focused on the problems many models of inflation have been producing, the right sized initial fluctuations[17] any inflation model which solves the horizon problem, getting a nearly constant background temperature, will also solve the flatness problem.

6. The Cosmological Constant

Some astrophysicists (who shall remain nameless) have focused on the formal mathematical loophole that flatness can also be obtained with a non-zero Λ and $\Omega < 1$. However, such a solution is missing the philosophical motivation (like killing for pacifism). If today we have $\Omega \sim 0.1$ and non-zero Λ yields flatness, that is an epoch- dependent solution since the contribution of Ω and Λ vary differently with epoch. Such a solution would imply that we live at the only epoch where Λ and Ω contributions to curvature are comparable, again requiring amazing fine tuning (tuning Λ to ≥ 120 decimal places). Unfortunately we don't as yet have a nice physically motivated mechanism like inflation to set $\Lambda = 0$, but if we buy the philosophy, I believe we should also assume Λ is negligible. Of course both arguments are philosophical (or theological) rather than based on physical observation, but the Copernical principal of us not being special has held up well for several hundred years.

7. Dark Matter and Galaxy and Structure Formation

As mentioned before, if Ω is 1, then we need non-baryonic dark matter. Such matter has been classified as either hot (neutrino-like with high velocities just prior to the epoch of matter-radiation equality) or cold (low velocities prior to matter-radiation equality).

Initially, hot, low mass, neutrinos were quite popular as candidates for solving the cosmological dark matter problem, since they were the least exotic of the non-baryonic options, and they naturally clustered only on large scales where the dark matter was needed, rather than on the small scales where the contribution of dark matter was known to be minimal[18]. They received a major boost with the preliminary reports of measured mass[19] for ν_e (although probably only the most massive ν is cosmologically important, and that might well be ν_τ (or a nucleosynthesis-allowed 4th generation) which could still have a $\sim 10eV$ mass, even if $m_{\nu_e} \ll 1eV$). Also, they gained strength when it was shown[5] that the neutrino Jean's mass was

$$M_J \sim \frac{3 \times 10^{18} M_\odot}{m_\nu^2(eV)} \text{ or } \lambda_J \sim \frac{1300 Mpc}{m_\nu(eV)}$$

which for $m_\nu \sim 30eV$ yielded $M \sim 3 \times 10^{15} M_\odot$, and $\lambda \sim 40Mpc$, the mass and scale of large clusters.

Unfortunately, massive neutrinos fell into disrepute as dark matter when it was emphasized[20] that in the standard adiabatic model of galaxy formation with a random phase, Zel'dovich fluctuation spectrum of the type expected by inflation, and with $\delta T/T$ constrained by microwave observations, galaxies did not form until redshift $z \lesssim 1$. This occurred because the initially formed pancakes with mass M_J took a while to fragment down to galaxy size. This contradicted the observations which showed that quasars existed back to $z \sim 3.5$. In addition, if baryons stay in gas form in the potential wells of the large ν pancakes, they light up in the x-rays beyond what is observed[21].

While some[22] have appealed to statistical tails, etc., to escape these conclusions, most cosmologists began abandoning neutrinos and adopting cold dark matter[23], which could enable rapid galaxy formation[24,25].

Cold matter also had its problems[26]. In the standard model, it would all cluster on small scales, and thus be measured by the dynamics of clusters, such as the Virgo infall. Since such measurements implied that $\Omega \sim 0.2 \pm 0.1$ on cluster scales, this meant that $\Omega_{cold} \lesssim 0.3$, and not unity. Remember that $\Omega \sim 0.1$, so observationally, non-baryonic dark matter is not required unless one wants an Ω of unity, so cold matter wasn't naturally solving one problem for which it was postulated. This constraint on cold matter could be escaped if it were *also* assumed that galaxy formation was biased[25,27] and did not occur everywhere. Thus, there could be many clumps of cold matter and baryons that did not shine for some ad hoc reason. Biasing ran into problems when it could not explain the observation[5] of a very large cluster-cluster correlation function, ξ_{cc}, relative to the galaxy-galaxy correlation function[26,27], ξ_{gg}. With biasing $\xi_{cc} \propto \xi_{gg}$ but in all models $\xi_{gg} < 0$ for a few 10's of Mpc, whereas ξ_{cc} was observed to be positive out to scales $\gtrsim 50Mpc$. Hardcore cold matter lovers had to argue that the ξ_{cc} data might be wrong, although no one has been able to disprove it.

A way out of the ξ_{cc} problem was proposed by Szalay and Schramm. There we noted that the correlation functions appear to be scale free, thus implying that large-scale structure is dominated by something other than random noise and gravity, say either percolated explosions or strings. In fact, the scale-free structure is characterized by a fractal of dimension $D \sim 1.2$, not too different from the $D \sim 1$ that naive string theory might yield. String calculations[28] of galaxy formation indeed found support for such a fractal process with the appropriate dimension being valid from galaxy to supercluster scales.

Thus, there were already strong hints that something was wrong with the previous, in vogue, picture of biasing and cold matter with random noise initial fluctuations. To this we now add the new observations of many large voids[1,2] of diameter $50h_{1/2}Mpc$ ($h_{1/2} \equiv H_0/50km/sec/Mpc$), with most galaxies distributed on the walls of the voids, and the observation[4] that our local 40 Mpc region of space is moving with a coherent velocity field of $\sim 600km/sec$ toward Hydra-Centaurus. While at least one large void (in Böotes) had been observed before[3], using a pencil beam approach, until the Harvard redshift[1] survey work, it was not known how ubiquitous voids were. In fact, the Harvard data shows that almost all galaxies are distributed along the "walls" of voids; galaxies and clusters are not randomly distributed, but fit onto a well-ordered pattern.

While the Harvard work only goes out to $\sim 100Mpc$, there is substantial evidence that this sort of pattern persists to redshifts $z \sim 1$ from the Koo and Kron survey[2]. A simple explanation for the peaks and valleys in the distribution of galaxies and quasars with redshift is that one is looking through filaments or shells with voids in between, once again demonstrating that galaxies and clusters are not laid out randomly on the sky, but follow a pattern.

While statistical fluctuations with cold matter might yield a few large voids as well as many small voids[21,25], it is difficult to get all of space filled with large voids and have galaxies appear only at the boundaries unless some special form of "biasing" is used. However, the real killing blow for the cold matter plus biasing scheme comes from the velocity field work. Even if the biasing could be selected so as to give ubiquitous large voids, the velocities of a $40Mpc$ region of galaxies would be relatively small and random, rather than large and coherent[29]. In fact, the more extreme the biasing used to get large voids, the *lower* the large scale velocities. Thus, it appears that the large-scale structure is telling us that we need something that gives us $\sim 40Mpc$ coherent patterns, and cold matter doesn't appear the way to go. (Unless, of course, the large scale velocity field work is in error. In other words, cold matter with gaussian Zel'dovich fluctuation requires *both* ξ_{cc} and the velocity to be completely wrong.

Since neutrinos naturally gave us patterns on this scale, maybe they should be reexamined. In addition, since the voids look rather spherical, and since explosions tend to produce spherical holes after a few expansion times even if the initial explosion is asymmetric, perhaps an explosive mechanism should be considered also. Since the Ostriker–Cowie[16] explosion mechanism by itself cannot yield such large voids, the only way it could work is via a high density network of explosions which percolated[25,30]. However, to get $\Omega = 1$ with an exploding scenario would still require non-baryonic matter that did not cluster with the light emitting stuff. In principal, this could be either neutrinos or cold matter but at least with neutrinos an $\sim 40Mpc$ scale might still be naturally imposed.

8. Neutrinos plus Strings or Explosions

Of course, in order for neutrinos to work as the dominant matter, some mechanism to rapidly form galaxies must be imposed both to enable galaxies to exist at $z \sim 5$, and to condense out the gas before it falls into the forming deep potential wells, and emits x-rays. Two ways that might achieve this rapid formation are either via the aforementioned explosion scheme within the collapsing ν-pancakes, or via cosmic strings[31] which would act as nucleation sites for galaxy formation. Since strings are not free-streamed away by the relativistic neutrinos[32], the galaxy scale fluctuations remain within the ν-pancakes. Notice that since neutrinos are not used by themselves simple arguments based on relating their primordial fluctuation spectrum to observed galaxy velocity and distribution features are not necessarily valid and must be reexamined in the more complete scenario.

It should be noted that even with strings as seeds so that cold matter can cluster in a scale-free way fitting ξ_{cc}, the large scale velocity fields for cold matter are small, and it is difficult to get $\Omega = 1$ while observing $\Omega_{cluster} \sim 0.2$. However, we have the additional problem that the strings might mess up the nice large scale neutrino features and background of ν's will still slow galaxy growth around the strings over how cold matter would form on the strings.

It is interesting that two surviving galaxy formation options, strings and explosions, involve the same two options that the scale-free cluster–cluster correlation function arguments point towards. Let us look at each of these scenarios in a little more detail and see if there might be ways of resolving whether either of them might actually be correct. Also, let us see what each requires for the physics of the early Universe.

Both of these scenarios seem to need hot matter if we want to solve the velocity field, $\Omega = 1$, and large scale problems.If $\Omega = 1$, as is necessary to avoid our living at a special epoch, and as agrees with the recent large-scale galaxy count arguments of Loh and Spillar[15] (but disagrees with the direct dynamical arguments on scales of clusters and smaller, and with the baryonic measurements from nucleosynthesis), then $m_\nu \lesssim 35eV$. Since with $\Omega = 1$ the age of the Universe $t_0 = \frac{2}{3H_0}$, and since globular clusters and nucleochronology require $t_0 \gtrsim 11\times10^9 yr$ (with a best fit of $t_0 \sim 15\times10^9 yr$) we must say that $H_0^{-1} \gtrsim 17\times10^9 yr$. Thus, $H_0 \lesssim 60km/sec/Mpc$, or $h_{1/2} \lesssim 1.2$. From the number of neutrinos and photons in the Universe, we know that the most massive neutrino is bounded by (see ref. 18 and references therein)

$$m_\nu \lesssim (25eV)\Omega h_{1/2}^2 \lesssim 35eV.$$

It is curious that the requirement that we want the neutrinos to give us the large-scale structure, $\lambda_J \sim 40Mpc$, or $M_J \sim 10^{16} M_\odot$, also gives us $m_\nu \sim 30eV$, a mass about what is necessary to get $\Omega \sim 1$. Also, we have a lower bound from the nucleosynthesis argument[26] that the number of neutrino species with $m_\nu \lesssim 10MeV$ is three or at most four. Since the sum of all neutrino masses cannot exceed the $35eV$ limit mentioned above, and since the lowest mass for the most massive one occurs when they are all equal, then if $N_\nu \leq 4$,

$$m_\nu \gtrsim 9eV.$$

The first scale to be able to condense and thus have their density grow will be the horizon scale when the neutrinos become non-relativistic, which is M_J. However, in the string option, loops of string will exist down to scales of galaxy size (scales smaller than galaxy size gravitationally radiate away[31]). So as the neutrinos become non-relativistic they can be trapped on smaller scales. The baryons will not be able to begin clustering until after recombination. However, the slow-moving baryons will rapidly fall on to the pre-existing loops of string plus neutrinos. Thus, galaxies will be able to form shortly after recombination, and well before $z \sim 1$.

9. Problems with Strings?

Unfortunately, just after matter domination the bulk of the neutrinos will still have relatively high velocities so their Jean's mass, while dropping, will not be low enough for most neutrinos to cluster on the galaxy size loops. Even after recombination the characteristics Jean's mass for the bulk of the neutrinos will still be much larger than galaxy size, so there will be a relatively smooth background of neutrinos which will slow the rate of growth of baryons falling onto the loops of string. Thus, strings plus neutrinos do not grow galaxies as rapidly as strings plus cold matter; however, strings definitely help the neutrino picture along. The quantitative question of whether the neutrino-string picture can form rapidly enough remains to be worked out in detail, since quick and dirty calculations indicate that the results are marginal[33]. With neutrinos, the dimensionless string tension 6μ needs to be higher than for strings with cold matter where $6\mu \sim 10^{-6}$. Unfortunately, it cannot be arbitrarily raised since high values ($\geq 10^{-5}$) cause problems in microwave anisotropy and in radiating too much energy at the time of nucleosynthesis, thus running into the equivalent of the neutrino country bound[34].

Also, it is not clear how the combination of ν's and strings deals with the very large scale structure. While strings by themselves give the scale- free correlation function out through the scales of Abell clusters[28], if neutrino pancaking is too strong, it could mess this up. On the other hand, string perturbations existing on scales smaller than $\sim$ 40Mpc may prevent pancaking from ocurring at all. Horizon length strings at matter-radiation equality will produce large scale adiabatic flucturations that could induce pancake formation in the neutrinos, going non-linear at redshift $z \sim 1$. However, the strength of the fluctuations relative to the normal string fluctuations needs to be checked to see which, if any, dominates.

If they really do not go non-linear until $z \sim 1$, they might not mess up the more rapidly forming galaxy and cluster scale fluctuations, so the smaller scale correlation functions might be retained while the neutrino pancake collapse might induce the very large scale velocity field and pancakes, filaments, and voids. Obviously the whole combined picture needs to be examined in much greater detail to see if it really can retain the best features of both models, rather than the two components destroying each others better features.

Because the string picture looks like the current front runner, people have begun looking at it in far greater detail, to see if it really can yield the observable universe. In particular, Peebles has privately circulated a "screed", stating possible problems. At a workshop held at the Aspen Center for Physics, these problems were examined and possible ways out were found. Let us now summarize the Peebles problems and possible solutions.

Problems not previously mentioned:

1. Strings produce loops following a power spectrum $\sim M^{-5/2}$, whereas galaxies are observed from their light to have a much flatter spectrum, up to $\sim 10^{12} M_\odot$ and then exponential fall off. Thus, at first glance, it appears that strings give too many small *and* large galaxies if their spectrum is normalized to fit the L^* galaxies at $\sim 10^{12} M_\odot$.
2. Strings are small relative to their separation distances. Thus, collapse onto static strings appears unlikely to give large quadropole moments, and thus tidal interactions will not produce the angular momentum observed in galaxies.
3. With strings as seeds, both cold and hot dark matter will cluster on small scales so that Ω measured for clusters should be a good estimate of Ω_{total} which would yield ~ 0.2, not 1. Biased suppression of galaxy formation with strings as seeds is evn more ad hoc than normal cold-matter biasing, so is not a convenient escape.

The possible solutions to these problems are:

1.1. Excess amounts of small strings forming galaxies can be supressed in a variety of ways.
 a. For larger 6μ, such as in the neutrino models, gravitational radiation eliminates the excess low mass loops.
 b. Vilenkin[35] has shown that global strings rather than gauge strings radiate Goldstone bosons in addition to gravitational radiation. Thus few mass global strings would also not be a problem.
 c. Strings do not radiate symmetrically. The differential radiation for small strings results in a rocket effect[36] which supresses their ability to acrete.
 d. More fragmentation of the small loops which form early could lower their abundance as the smaller are radiated away.

1.2. The excess amounts of large loops may be a more complex problem and more work needs to be done here. Possible solutions include:
 a. Finite velocity may affect accretion.
 b. Fragmentation of large loops will reduce their numbers.
 c. Big loops may yield CD galaxies at centers of clusters with velocity curves rising as $r^{1/4}$ rather than normal flat rotation curves.

2. Angular momentum may be formed by tidal interactions because accretion is not spherical but sausage-like, due to the finite velocity of loops. Distances moved are comparable to separations so quadropole moments will be approximately large.
3. The solution to the Ω problem requires that somehow clusters don't sample a standard segment of the universe. One way to accomplish this would be if galaxies correlated more with clusters than randomly. Such could occur if large, cluster-producing strings fragment to produce smaller galaxy-producing strings, and the resultant small strings didn't get too far from the clusters. Clearly, this does occur to some degree; however, can it quantitatively yield a factor of three of more enhancement in Ω between its cluster measured value and the true value remains to be shown. The dynamical range of string simulations has not yet enabled such quantitative tests between small and large loops. Note that if galaxy strings are strongly correlated with clusters, then many regions in space will be without loops of strings, and so will not form galaxies even though they have baryons and either hot or cold dark matter.

Another possible problem is that, while the string scenario may naturally yield $D \sim 1$, it does not so naturally give $D = 1.2$. Fine tuning[39] of string parameters may enable such variation on the scale of the galaxy–galaxy correlation function, or some modification of the criteria for the formation of light-emitting regions around the strings may be necessary.

In this regard it should be remembered that because of possible systematic errors, not everyone agrees that 1.2 is significantly different from 1.0, even for the galaxy–galaxy correlation function, which is the best determined[38]. The uncertainties in the exponent of the cluster–cluster correlation functions are *far* larger, thus problems in trying to explain variations from $D = 1$ fractals are not serious at the present time. With strings there is the additional problem of tuning the primordial phase transition so as to inflate first, and then produce strings[39]. While not impossible, this is constraining.

10. Explosive Galaxy Formation

The second way to get neutrinos to work involves explosive galaxy formation. Here we need initial seeds to lead to condensations which produce massive baryonic objects which explode. As mentioned before, such a model does not naturally give us $40Mpc$ structure. If we use neutrinos then the seeds must be in a form which does not get free-streamed away by the relativistic neutrinos. Strings don't work well here because the string scales that might lead to rapidly evolving baryonic objects are radiated away gravitationally. Thus, the seeds must come in some other isothermal-like form. Perhaps the best option would be condensates from the quark–hadron transition, either planetary mass black holes[40] or Witten nuggets[41]. Both have formation problems[42] and the latter have survival problems[43] also. If such objects could form and survive, they do lead naturally[44] to very massive ($\sim 1000 M_\odot$) baryonic objects which would explode on rapid timescales. Another option is cold dark matter clumps, in which case small strings work as seeds, but the large scale problems are aggravated.

The scale affected by explosions of single galaxy size[45] is at most a few Mpc; however, it has been shown[30] that at sufficiently high densities and high trigger rates, the explosions can percolate at least out to scales of a few 10's of Mpc. The fractal dimension of such percolated ensembles is quite sensitive to parameter assumptions and usually varies with scale, thus showing that it is not a true scale-free fractal. If it is made to fit the small scale (few Mpc) with $D \sim 1$ it is usually larger ($D \sim 2$) on scales of $\gtrsim 10Mpc$. Since, as mentioned above, the exponent of the cluster–cluster correlation function is not, at present, well determined, such models cannot be ruled out. With such explosions percolating within ν-pancakes, we might naturally have their pattern superimposed on the $\sim 40Mpc$ neutrino scale. In addition, although percolated explosions will initially be highly non-spherical, their shape will evolve towards sphericity with the smaller axes catching up in length to the largest one. In order for large-scale percolation to occur, several generations[21] of explosions must occur; however, cooling arguments and time to initial explosions, plus the need for condensed objects by $z \sim 4$ and the need to hide from present observers, the radiation produced by the explosions, severely restrict the possibility of such percolation and thus quite a bit of fine tuning is required to escape the constraints.

11. Conclusion

Thus, while we cannot explicitly rule out this latter case, unless some new physics can be developed to show how the fine-tuned parameters are natural for other reasons, we must lean towards the string option as the present frontrunner. Strings, of course, would have other observational consequences[32] like gravitational double lensing of distant objects and shifts in the 3° background across such a line of lenses, and a background of gravitational radiation from the evaporation of small-scale strings which might affect the millisecond pulsar. Thus, observations should eventually be able to confirm or deny this frontrunner. Table 1 gives a summary of current proposed models and their ability to solve the problems. Note that the location of dark baryons may eventually be detectable and a discriminator of models. No model is yet a clear winner. Some require more calculations to see if they can be made to work. Others require some key bit of observational data to be proven wrong.

In summary, we have come full circle and once again massive neutrinos are looking good. However, with them comes the need for galaxy and structure formation triggered by something other than random phase adiabatic fluctuations. The non-random phase fractal initial conditions such as produced by strings[46] or fractal generating explosions[16,30] seem to be the way to go. It is comforting that the exotica of cosmic strings do seem to be a natural consequence[47] of the current, in vogue, superstring Theories of Everything (T.O.E.).

Acknowledgements to co-workers J. Charlton, K. Olive, A. Melott, G. Steigman, A. Szalay, and M. Turner are gratefully given. I also acknowledge many useful discussions with N. Turok and P.J.E. Peebles. This work was supported in part by NSF AST 85-15447, and by DOE DE-FG02-85ER40234 at the University of Chicago, and was prepared at the Aspen Center for Physics.

12. References

1. deLapparant, V., Geller, M. and Huchra, J. 1986, Center for Astrophysics preprint
2. Koo, D. and Kron, R. 1986, in preparation.
3. Kirschner, R., Oemler, G., Schecter, P., and Shectman, S. 1982, *Ap.J.* **248**, L57.
4. Faber, S., Aaronson, M., Lynden-Bell, D. 1986, *Proc. of Hawaii Symposium on Large-Scale Structure.*
5. Bahcall, N. and Soniera, R. 1983, *Ap.J.* **270**, 20; Klypin and Khlopov 1983, *Soviet Astron. Lett.* **9**, 41.
6. Szalay, A. and Schramm, D. 1985, *Nature* **314**, 718.
7. Gott, J.R., Gunn, J., Schramm, D.N., and Tinsley, B.M. 1974, *Ap.J.* **194**, 543.
8. Freese, K. and Schramm, D. 1984, *Nucl. Physics* **B233**, 167.
9. Yang, J., Turner, M., Steigman, G., Schramm, D., and Olive, K. 1984 *Ap.J.* **281**, 493.
10. Steigman, G., Schramm, D.N., and Gunn, J.E. 1977, *Phys.Lett.* **B66**, 502.
11. Cline, D. 1986, The 6th Proton–Anti-proton Conference, Aachen, West Germany, review talk.
12. Vittorio, N. and Silk, J. 1984, *Ap.J.* **L39**.
13. Bond, J., Efstathiou, G., and Silk, J. 1980, *Phys.Rev.Lett.* **45**, 1980.
14. Rowan-Robinson, M. 1986, in The Proc. ESO/CERN Symposium on Cosmology.
15. Loh, E. and Spillar, E. 1986, Princeton University preprint
16. Ostriker, J. and Cowie, L. 1980, *Ap.J.* **243**, L127.
17. Olive, K. and Schramm, D.N. 1986 *Comments on Nuclear and Particle Physics*, in press.
18. Schramm, D. and Steigman, G. 1981, *Ap.J.* **243**, 1.
19. Lubimov, A. 1986, in this volume.
20. Frenk, C., White, S., and Davis, M. 1983, *Ap.J.* **271**, 417.
21. Davis, M. 1986 *Proc. 1984 Inner Space/Outer Space*, University of Chicago Press.
22. Melott, A. 1986 *Proc. 1984 Inner Space/Outer Space*, University of Chicago Press.
23. Blumenthal, G., Faber, S., Primack, J., and Rees, M. 1984, *Nature* **311**, 517.
24. Melott, A., Einasto, J., Saar, E., Suisalu, I., Klypin, A., and Shandarin, S. 1983, *Phys.Rev.Lett* **51**, 935.
25. Efstathiou, G., Frenk, C., White, S., and Davis, M. 1985 *Ap.J.Suppl.* **57**, 241.
26. Schramm, D. 1985, *Proc. 1984 Rome Conf. on Microwave Background.*
27. Bardeen, J., Bond, J., Kaiser, N., and Szalay, A. 1985, submitted to *Ap.J.*.
28. Turok, N. 1985, U.C. Santa Barbara preprint
29. Melott, A. 1986, Univ. of Chicago preprint.
30. Charlton, J. and Schramm, D. 1986, submitted to *Ap.J.*.
31. Vilenkin, A. 1985, *Physics Reports* **121**, 1.
32. Vittorio, N. and Schramm, D. 1985, *Comments on Nuclear and Particle Physics* **15**, 1.
33. Turok, D.N. and Schramm, D.N. 1986, in preparation
34. Bennet, D. 1986, SLAC preprint
35. Vilenkin, A. 1986, Tufts Univesity preprint
36. Rashiputi 1986, preprint
37. Pagels, H. 1986, Rockefeller University preprint.
38. Peebles, P.J.E. 1981, *The Large Scale Structure of the Universe*, Princeton University Press.
39. Olive, K. and Seckel, D. 1986, FNAL preprint.
40. Crawford, M. and Schramm, D. 1982, *Nature* **298**, 538.
41. Witten, E. 1984, *Phys.Rev.* **D30**, 272.
42. Applegate, J. and Hogan, C. 1985, *Phys.Rev.* **D31**, 3037.
43. Alcock, C. and Farhi, J. 1985, MIT preprint.
44. Freese, K., Price, R., and Schramm, D. 1983, *Ap.J.* **275**, 405.
45. Vishniac, E., Ostriker, J., and Bertschinger, E. 1985, Princeton University preprint.
46. Turok, N. and Schramm, D. 1984, *Nature* **312**, 598.
47. Witten, E. 1985, *Physics Letters* **B153**, 243.