Material Content of the Universe: Meeting Summary

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Material content of the Universe: meeting summary

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We have considered what might be said about the large-scale distribution of mass in the Universe and in particular whether the mean value might agree with the Einstein–de Sitter cosmological model; what might be said about the composition of the mass as a function of position, and in particular whether we can convince ourselves that exotic matter plays a significant role in some regions; and what might be said about the cosmic evolution of the mass distribution and composition. The present state of our debate is notable for the broad variety of interesting-looking clues and the lack of general agreement on how they might fit together in some general synthesis.

I am beginning to feel uneasy about the emphasis people are placing on the argument that the Einstein–de Sitter cosmological model (with zero space curvature and zero cosmological constant) is the only reasonable model. Observations of galaxy clustering dynamics can be reconciled with the Einstein–de Sitter model by the assumption that galaxy formation is biased to tighter clustering than the mass. However, rather a special arrangement, or bad luck, is needed to explain why we have not observed the consequence, that the mean mass per galaxy continues to increase with increasing clustering scale beyond about 300 kpc. If the remarkably precise isotropy of the Universe is explained by inflation then space curvature has to vanish, but we can still adjust the mean mass density by introducing a cosmological term, Λ. That would require that the contribution of Λ and the mass density to the expansion rate are comparable just at the present epoch, which would be a curious coincidence, but then we all can think of other curious coincidences we have learned to live with.

The observational evidence for the presence of dark matter has been subject to careful, and, it is important to note, even on occasion sceptical review. The conclusion seems firm: either Newtonian mechanics fails or there are regions where the mass exceeds what would be expected from the starlight (and other probes). The first interpretation has been ably advocated by Milgrom. The focus of most current discussion, including this conference, is on the latter possibility.

If dark matter is present, is it an exotic (not baryonic) form? We have discussed an impressive variety of clues. Bahcall has argued that the seen objects in the Milky Way account for something less than half the mass indicated by stellar dynamics, and we have heard arguments that the deficit is plausibly accounted for by the tail of the stellar mass function extending to 'brown dwarfs and Jupiters' below the cutoff for sustained nuclear burning. If so, we will have an example of a dark matter problem with an unexotic resolution, and we might be forgiven if we were tempted to apply the same resolution to other dark matter problems.

I am impressed with the point brought out by van Albada and Binney, that mass: light ratios (M/L) are remarkably uniform, after a modest allowance for the distribution of star ages, in a broad range of sites. This suggests stellar mass functions are insensitive to initial conditions, which would argue that where M/L is large the mass is not stellar, but exotic. On the other hand, as Rees has discussed, it is easy to think of dark matter in halos that are baryonic (or derived from baryons). For example, the plasma pool around M87 seems to indicate the presence of an extended massive dark halo. The diffuse optical emission from the halo has a colour close to that of the starlight from the central part of the galaxy. Thus it appears that Nature can produce smooth distributions of stars in regions of large M/L and low density. Given that stars are present in such an unusual site it is not hard to imagine that the mass function in the halo has been skewed far enough toward the low mass end to make M/L unusually large. The simplest test would be to ask whether the slope of the mass function between *ca.* 0.2 × solar mass and turnoff might be a function of the local M/L, but even this is an exceedingly difficult observation.

Van Albada discussed the curious coincidence that in some spiral galaxies the inner part of the gravitational field is plausibly attributed to the mass in the stellar disc, the outer part to the mass in a dark halo, yet the resulting rotation curve is quite flat. In Newtonian mechanics this means mass scales roughly as the first power of radius. This scaling law considered as an ensemble average extends to larger lengths, for velocities within galaxies and on up to clusters of galaxies do not vary all that much. Possibly this reflects a property of the (non-Newtonian) physics of gravity on the scale of galaxies and beyond. If, as most of us assume, it reflects a regularity in the character of the mass distribution it surely is a clue to how galaxies formed and what they are made of. We see a promising start to an interpretation in the beautiful N-body model simulations described by Frenk. These assume an Einstein–de Sitter model dominated by initially cold weakly interacting dark matter (CDM). The model produces systems that look very much like proto-galaxies with about the right mass-radius scaling law. It seems not unreasonable to imagine that the baryons can settle relative to the CDM in such a way as to hold the rotation curve flat down to the inner disc-dominated part of the galaxy.

An additional argument for the CDM picture, as described by Efstathiou, is that it naturally reconciles the very low bounds presented by Wilkinson on the anisotropy of the microwave background with the density fluctuations needed if galaxies were to have formed by gravitational instability. This is because mass density fluctuations in CDM start to grow before baryons are released from the radiation drag. In a model universe without exotic matter galaxies and clusters of galaxies can form without overperturbing the microwave background, but it probably requires the assumption of primeval isocurvature fluctuations with an appropriately shaped spectrum, which on the face of it is not as simple and natural as the CDM picture.

The most serious immediate challenge to the CDM picture comes from the character of the galaxy distribution on scales not less than about 30 Mpc (with $H_0 = 100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$), where the galaxy autocorrelation function is quite small but there are occasional prominent features (that would be reflected in higher order functions). I doubt the standard CDM picture can account for this because in the model the large-scale power is so small. Adjustment of the shape of the primeval spectrum of the mass distribution would help. However, my guess is that it may be difficult to account for the large-scale features as gravitationally amplified Gaussian noise, that we may need something more exotic, like non-Gaussian primeval density perturbations, or the remarkable cosmic string scenario described by Kibble.

Wolfe showed us the very exciting prospects for piecing together a picture of what galaxies were like at redshifts of 2–3. I have the impression that the proto-galaxies in Frenk's models look rather immature and disorganized at $z \approx 2$. In a primeval isocurvature scenario we might expect that by $z \approx 2$ galaxies would have been well formed and relaxed. The cosmic string model, and the accretion and explosion models, also might have something fairly definite to say about this epoch. And the observations, although difficult, offer the possibility of an exceedingly important guide to what things really were like at $z \approx 2$.

The computation of light-element production in the standard hot Big-Bang model yields a beautiful result, agreement with three observed abundances by adjustment of one parameter, the mean baryon density, to a not unreasonable value. Pagel has shown us the art of measuring these abundances, with due cautions about the uncertainties. Of course, we can hardly claim that the theory is free from uncertainties. Wilkinson described the remarkable agreement of the microwave-submillimetre background measurements with a Planck spectrum. It is difficult to avoid the conclusion that the Universe really did expand from a dense state where the radiation could have been thermalized, but there is the possibility that the thermalization occurred as 'recently' as $z \approx 100$. If the radiation were present at $z \approx 10^9$ we would still have the possibility of adjustment of details of the nucleosynthesis computation, such as local inhomogeneities in the photon–baryon or baryon–exotic-matter mass densities.

In the conventional hot Big-Bang model with a conventional value for Hubble's constant the mass density in baryons is less than the critical Einstein–de Sitter value. If the Einstein–de Sitter model were valid the deficit would have to be non-baryonic (or else baryons shielded from the nuclear reactions), in brilliant agreement with the CDM model. If there were no dark matter then the maximum value Pagel would allow us for the density parameter is $\Omega \approx 0.05$, which is less than what is derived from galaxy clustering dynamics, $\Omega \approx 0.1$–0.3. That could be the result of biased galaxy formation: the presence of a galaxy may inhibit the formation of neighbours, so mass is more strongly clustered than are galaxies. This is opposite to the usual biased galaxy formation picture, and, to my mind, somewhat easier to arrange.

The classical cosmological tests for Ω and Λ are not much discussed but perhaps are due for a revival. As pointed out by Loh & Spillar 1986, a measurement of the joint distribution in galaxy redshift and apparent magnitude in a fair sample of sky yields a good deal more information than the usual measures, such as apparent magnitude as a function of redshift, and may even permit a separation of the effects of galaxy evolution and cosmology. Their preliminary result is $\Omega \approx 1$. This is the one measurement I can think of that calls for mass in excess of that which can be provided by baryons consistent with nucleosynthesis.

If exotic objects are wanted to account for dark matter or to act as seeds for galaxy formation then as Ellis and Kibble have shown us there is no shortage of promising candidates from particle physics. We have heard exciting prospects for laboratory detection of exotic matter, and we have seen that it is not inconceivable that nature will offer us a more or less unambiguous signal from astronomy, perhaps a sharp edge in the microwave background from a cosmic string, perhaps an indication of phase space bounds from dwarf galaxies. It would be hard to overstate the stimulus and focus that would be given to cosmology by a convincing demonstration that exotic matter really is (or is not!) present at an interesting mass density. Failing that I suspect we are going to see the development of a schism between those who continue to study cosmological models with exotic matter and the apostates whose attention drifts back to mass, that we are sure is present, in baryons.

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