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ASTROPHYSICAL COSMOLOGY*

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The last several years have seen a tremendous ferment of activity in astrophysical cosmology. Much of the theoretical impetus has come from particle physics theories of the early universe and candidates for dark matter, but what promise to be even more significant are improved direct observations of high z galaxies and intergalactic matter, deeper and more comprehensive redshift surveys, and the increasing power of computer simulations of the dynamical evolution of large scale structure. Upper limits on the anisotropy of the microwave background radiation are gradually getting tighter and constraining more severely theoretical scenarios for the evolution of the universe.

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The inflation paradigm

Inflation continues to be very attractive as a paradigm in cosmology (Turner 1987), in spite of the lack of any one particularly compelling detailed model for inflation based on well-founded particle physics. Fortunately, the astrophysical consequences of inflation are to a large degree independent of details. The present universe should be spatially flat, and coupled with the normal theoretical preference for a zero cosmological constant this means the cosmological density parameter Ω should equal one (Guth 1981). Deviations from homogeneity are generated by quantum fluctuations in the scalar field driving the inflation. These evolve into adiabatic density perturbations with an initially scale-independent spectrum (Starobinsky 1982; Guth & Pi 1982; Hawking 1982; Bardeen et al 1983). The final density perturbation spectrum, which is responsible for galaxy formation and the present large scale structure of the universe, is easily calculated once the matter content of the universe is specified (Peebles 1982; Bond & Szalay 1983). The linear density perturbation theory can be used as an initial condition for numerical simulations of the nonlinear gravitational clustering.

The presumption that $\Omega = 1$ means that most of the matter in the universe must be nonluminous, nonbaryonic (according to conventional models of nucleosynthesis), and must be distributed more uniformly than the light. Various dynamical estimates of mass-to-light ratios on scales from galaxy clusters to superclusters (see Peebles 1986a for a review), when extrapolated to the universe as a whole, give values for Ω in the range 0.1-0.3. However, recent direct determinations of Ω from the distribution of galaxy counts with redshift (Loh & Spillar 1986) and from the dipole anisotropy of galaxies in the IRAS infrared survey (Yahil et al 1986) do at least tentatively suggest that the true global Ω is close to one.

There are many candidates for dark matter, ranging from massive neutrinos to more exotic kinds of hypothetical particles such as axions, photinos, weakly interacting Gev mass fermions, lumps of quark matter, primordial black holes, etc. Of course, at least some of the dark matter may well be baryonic. The cosmologically dominant dark matter may or may not be the same as the dark matter associated with galactic halos. While there are many interesting questions concerning possible direct detection of some types of dark matter, the effects on cosmology largely depend on the primordial velocity dispersion, hence the classification into "hot", "warm", or "cold" dark matter (Bond & Szalay 1983). Hot dark matter (massive neutrinos) has a large enough velocity dispersion that free streaming damps out primordial perturbations on scales less than clusters of galaxies, leading to a "top down" scenario for galaxy formation. Cold dark matter has a small enough velocity dispersion to allow primordial density perturbations to survive and grow on subgalactic scales.

Galaxy formation proceeds "bottom-up", with hierarchical clustering (Blumenthal et al 1984).

Hot dark matter received a lot of attention in the early 1980's (Centrella & Melott 1983; Klypin & Shandarin 1983; White et al 1983), but has fallen out of favor in recent years. The numerical simulations indicate that it is difficult to reconcile the present observed strength of clustering of galaxies with a reasonably early epoch of galaxy formation, and the experiment of Lubimov et al (1980) claiming a measurement of the electron neutrino mass has not been confirmed. However, for counter arguments see Melott (1986).

Cold dark matter (CDM) has the problem that dynamical segregation of the dark matter from baryons is not expected on scales much larger than galaxies. To reconcile cold dark matter with $\Omega = 1$ requires that galaxies form more efficiently in overdense regions (protoclusters) than in underdense regions (protovoids). A particular scheme for accomplishing this biasing is to associate galaxies with peaks in the smoothed linear density perturbation field whose height relative to the root mean square fluctuation level exceeds a threshold determined by the requirement that the comoving number density of these peaks be equal to the number density of bright galaxies in the present universe. Numerical simulations (Davis et al 1985) and quasi-analytic studies (Bardeen et al 1986) have had rather good success in fitting the clustering properties of "galaxies" on scales of a few megaparsecs with the actual galaxy-galaxy correlations measured, for instance, in the CfA redshift survey (Davis & Peebles 1983). There are even reasons to believe this kind of biasing may arise naturally, in that high peaks collapse to bound objects with high virial velocities which are able to keep their gas despite the heating from supernova explosions (Dekel & Silk 1986; Frenk et al 1985).

White et al (1987) argue that the biased CDM simulations show much the same frothy structure of voids, sheets, and filaments seen in redshift surveys of the distribution of galaxies on scales of tens of megaparsecs (Davis et al 1982; de Lapparent et al 1986), though it is a bit disturbing that the new deeper survey shows no tendency to fill in the voids with fainter galaxies. Other indications that more power is present in density perturbations on these large scales than predicted in the standard CDM scenario are harder to argue away. The correlation amplitude for Abell clusters seems to be a factor of 18 larger than that of galaxies (Bahcall & Soneira 1983; Klypin & Kopylov 1983) and to remain positive out to separations of 100 h^{-1} Mpc. Statistical biasing, as first suggested by Kaiser (1984), only predicts a factor of 5 enhancement, and the cluster-cluster correlations should be negative beyond 50 h^{-1} Mpc. Recent determinations of a streaming velocity relative to the Hubble flow of 700 km/sec or more for a sphere of radius about 60 h^{-1} Mpc (Burstein et al 1986; Collins et al 1986) conflict with a maximum of about 200 km/sec expected from the standard biased CDM models (Vittorio et al 1986). There are suggestions of even larger peculiar velocities for the Abell clusters (Bahcall et al 1986).

The conflict with observations on large scales may eventually go away as sources of systematic error in the selection of data samples or in the methods of distance determination are better understood. However, at face value it would seem we are forced to consider more complicated versions of the inflation-inspired scenarios or go to some entirely different scheme for the generation of large scale structure. Some possible variations include composite models, in which the large scale structure still arises from inflation-generated density perturbations with a flat spectrum, but there is more than one kind of dark matter. Examples include hot-cold or hot-warm models (Achilli et al 1985; Ikeuchi & Norman 1987) which can have more power on large scales as in the hot models (Melott 1986), but avoid some of the difficulties of the pure hot models with the time of galaxy formation. A non-zero cosmological constant shifts the break in the evolved density perturbation spectrum associated with the transition to a matter-dominated universe to larger scales, and if baryons are a substantial fraction of the non-relativistic matter a feature in the density perturbation spectrum associated with the baryon-radiation Jeans mass at recombination may add even more power on large scales (see Dekel 1984). Another possibility is to complicate the model of inflation in order to break the scale invariance of the primordial density perturbation spectrum (Kofman & Linde 1987; Silk & Turner 1987), though to get a feature on the desired scale requires very special values of parameters and initial conditions. Unfortunately, once the models are opened up in these ways the beauty of the simple inflation-inspired CDM model, with its small number of free parameters, is lost.

Alternative paradigms

Inflation is nice because it simultaneously is a theory for the large scale homogeneity of the universe and the existence of structure on smaller scales. However, there are alternative ways of trying to understand the structure in the universe in which there is little or no connection between the present distribution of galaxies and clusters of galaxies and primordial density perturbations. One of these is the theory of galaxy formation based on explosions, starting from small seeds (Cowie & Ostriker 1981), and on the largest scales generating the voids in the redshift surveys. Unless the explosions occur at quite early times (high z) they have difficulty producing the larger voids seen. Still, explosions may play some role, at least in heating the intergalactic medium (Ikeuchi and Ostiker 1986).

An approach to large scale structure and galaxy formation based on cosmic strings has attracted increasing interest over the last few years. Cosmic strings are topologically stable relics of a phase transition in the very early universe (Kibble 1976). Loops can form by reconnection of self-intersecting pieces of string and act as seeds for accretion of matter, forming galaxies and clusters of galaxies (see a review by Vilenkin 1985). There is no need for primordial density perturbations generated by inflation. While inflation might still be desirable to explain large scale homogeneity and isotropy, the existence of strings and inflation tend to be incompatible (Vishniac et al 1986). Particularly interesting from the point of view of large scale structure are claims the strings naturally give rise to the correct number densities of galaxies and clusters and galaxy-galaxy and cluster-cluster correlation functions of the right slope and amplitude with only one free parameter, the mass per unit length μ (Turok & Brandenberger 1986). This is a rapidly developing area of research and detailed calculations and simulations of the quality of those done for conventional models have yet to be made. There are suggestions that large scale sheets of galaxies might arise from cosmic string wakes (Stebbins et al 1986), but the large scale streaming velocities seem hard to explain, as in conventional models. Other potential difficulties with the string scenario are discussed by Peebles (1986b).

CONTRIBUTED PAPERS

Brief reports follow on some of the more interesting papers contributed to the Astrophysical Cosmology Symposium.

Multiple weak gravitational lensing

Gravitational lensing can be an important probe of the lumpiness of the distribution of matter in the universe. L.M. Oattes presented a paper coauthored by C.C. Dyer on the effects of multiple weak lensing on the apparent brightness of distant sources, with density inhomogeneities modeled by a "Swiss Cheese" universe, a zero-pressure Friedmann model in which randomly placed spherical regions have all their mass concentrated at the center. The lensing is calculated by integrating the optical scalar equations along the line of sight from source to observer, in order to properly take into account the nonlinear interaction between the shear and convergence of the beams. The distribution of apparent luminosities for standard candle sources is found to be highly non-Gaussian. Most of a random sample of sources have their apparent luminosity decreased by the lensing, but there is a high amplification tail. The effects demonstrated need to be taken into account when considering the statistics of high redshift quasars.

Cosmic microwave anisotropy

Robert Schaefer discussed his work with L.F. Abbott (Abbott & Schaefer 1986) on a general gauge-invariant analysis of large scale microwave background anisotropy. On the assumption that the perturbations generating the anisotropy obey Gaussian statistics, they calculate mean square amplitudes and dispersions for the lowest several angular multipoles of the fractional perturbation in the microwave background temperature. The photons are treated as a perfect fluid up until recombination, and the Sachs-Wolfe formula, rewritten in gauge-invariant variables, is used to extrapolate to $\delta T/T$ at the present. Results are obtained for scalar, vector, and tensor perturbations in both open and closed background spacetimes.

Particularly interesting is the comparison between the dipole and quadrupole moments from scalar (density) perturbations. The dipole moment depends on the local motion of the observer, but as long as short wavelength perturbations are uncorrelated with long wavelength perturbations, a lower bound to the mean square value of the dipole moment is obtained by considering only wavelengths longer than a cutoff wavelength, which Abbot and Schaefer take to be 60 h^{-1} Mpc. Requiring the long wavelength contribution to the dipole to be less than the observed value puts an upper limit on the expected quadrupole anisotropy from scalar perturbations, as a function of the cosmological density parameter Ω. The upper limit is about 1×10^{-5} for $\Omega = 1$ and a flat Harrison-Zeldovich initial density perturbation spectrum and is higher for $\Omega < 1$ and $\Omega > 1$.

Multiply-connected universes

An amusing look at an unconventional type of cosmological model was presented by Li Zhi Fang. He points out that if the real universe is assumed to be multiply-connected with points identified to give a toroidal topology, as is done for mathematical convenience in numerical simulations of large scale structure, density perturbations can have higher amplitudes without violating microwave background constraints. Also, correlations are suppressed on scales larger than the toroid and quasars would have multiple images.

PANEL DISCUSSION

An informal panel discussion was held to highlight some of the important current issues in astrophysical cosmology. Participants included Michael Turner, Franco Occhionero, and Bernard Carr. Turner emphasized the testability of inflationary models, in particular the predictions for Ω and the density perturbation spectrum. Occhionero discussed work done jointly with R. Scaramella on hybrid warm-cold dark matter models. They calculate the number density of peaks in the density perturbation field as a function of mass along the lines of Schaeffer and Silk (1985) and relate this to the luminosity function of galaxies. A model with 10% cold dark matter and 90% warm dark matter (particle mass about 800 eV) is consistent with quasars forming at redshifts in the range 2-3 and with the Schechter luminosity function. Carr remarked on the coincidence that the baryons and the non-baryonic dark matter should have comparable mass densities and what constraints this places on fundamental physics.

SUMMARY

Astrophysical cosmology should continue to be exciting and stimulating, with rapid developments in both observation and theory, for the foreseeable future. Completion of a redshift survey of extragalactic IRAS sources in 1987 may allow us to begin to converge on an observational value for the global Ω. As optically selected galaxy redshift surveys probe more deeply and cover wider areas of the sky the statistics of the large scale distribution of galaxies will become more sharply defined. If the large scale streaming velocities are real, we should already be close to seeing anisotropy in the microwave background on angular scales of a few degrees. Perhaps we will have a clear positive detection by the time of GR12. The Hubble Space Telescope should tell us if there is intergalactic gas in the voids as expected in the biased CDM scenarios. As more high z galaxies are studied and more is learned about the gas clouds seen in absorption against quasars we should be able to understand much more about the nature and timing of galaxy formation, and perhaps begin to have good data on the evolution of galaxy clustering and galaxy correlations, which is a critical test of many of the theoretical models. No doubt there will be many more new questions than answers.

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