Chaos in Cosmology

The idea that the structure in the universe originated from some primordial vortical motion has had a remarkably long history and central role in cosmological speculation. The earliest instance of a “vortex cosmogony” is probably due to Kepler,¹ who pictured the sun as being at the center of a vortex which . . .

4. Judging from the historical record, turbulence cosmologies will not easily be dismissed.

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DISTORTIONS OF THE MICROWAVE BACKGROUND RADIATION SPECTRUM IN THE SUBMILLIMETER WAVELENGTH REGION

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ABSTRACT

Our numerical calculation shows that the linear approximation of the Compton-distorted radiation spectrum falls seriously in the submillimeter range.

Numerical results agree with the Zel'dovich, Illarionov, and Sunyaev approximation in the limiting case when the matter temperature $T_e$ is much higher than the initial radiation temperature $T_0$. With a certain modification on the ZIS approximation, we use it to estimate the amplitude of Compton effect and perform a $\chi^2$ test on the possible combinations of $T_0$ and $Y_{\text{eff}}$ (cf. Appendix for notations) allowed by observations.

Subject heading: cosmic background radiation

1. INTRODUCTION

In a previous paper (Chan and Jones 1975, hereafter CJ) we have numerically computed the distortions on a Planckian radiation spectrum due to the Compton process and the bremsstrahlung process. In that paper we showed that there is a small but important difference between the numerical spectra and the first-order perturbation of Zel'dovich and Sunyaev (1969) in the submillimeter wavelength region (see Fig. 1). Relative to the first-order perturbation, the numerical spectra have enhanced flux in the submillimeter region. In fact, the linear approximation fails for $x = \hbar v/kT_0 \gg 1$ (cf. Appendix for definitions of notations) because the perturbation $\Delta \eta$ is much larger than the initial value $\eta_0$ in this region.

A better analytical approximation of the distortions due to Compton process has been given by Zel'dovich, Illarionov, and Sunyaev (1972). (Hereafter, we shall call it the ZIS approximation.) Assuming the matter temperature $T_e$ to be much larger than the initial radiation temperature $T_0$ so that nonlinear effects on the spectrum can be neglected, this approximation is expected to hold in the whole frequency range $x > x_{\text{crit}}$ and for any value of $\gamma$. Comparing the numerical spectra with this approximation, we found that for a fixed value of $Y_{\text{eff}} = Y(T_e - T_0)/T_0$, the numerical spectra converge to the analytical spectrum as $T_e/T_0$ increases.

In the Rayleigh-Jeans region, a Planckian spectrum cannot be distinguished from a Compton-distorted spectrum of a higher initial radiation temperature but with the same $T_{e 0}$ (cf. CJ). The presence of the Compton effect on the observed background radiation adds a degree of freedom to the estimation of the
The situation in 1970: the triangle is a rough indication of measurements above the atmosphere by three groups.

Berkeley-Nagoya 1988: the anomaly is much reduced from 1970, but it appears to be quite significant.

The CMBR Spectrum Anomaly, 1970-1990
Jones and Chan (1975-1980) analyzed the idea that primeval turbulence could have transferred energy to the plasma and the plasma perturbed the CMBR spectrum in a process analogous to the thermal Kompaneets Compton-Thomson analysis.

Jones (1979) concluded that the fit of this model to the Woody-Richards spectrum anomaly is not attractive.

But there was no shortage of other ideas. Energy sources that might account for a spectrum anomaly include supermassive stars, accreting massive black holes, superconducting cosmic strings, matter-antimatter annihilation, and decaying or annihilating nonbaryonic matter, with the energy transferred to the CMBR by plasma or dust, or maybe emitted at submillimeter wavelengths by decaying dark matter.
The CMBR Spectrum Anomaly went away in 1990

In 1970-90 we were quite willing to imagine living in a universe in which the transfer of energy from matter to radiation greatly exceed the limits we have now.

I count this as an example of the chaos of good science.
The Search for the Physics of Structure Formation, 1970 to 2000
THEORIES OF GALAXY FORMATION

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OTHER THEORIES OF GALAXY FORMATION

The ability of the cosmologist to devise new schemes for galaxy formation is quite remarkable. I shall review the current status of some of the theories that are consistent with the hot big bang origin of the universe. Of course, if we abandon the idea that the cosmic background radiation field is born with the universe, and replace it with a scheme such as that proposed recently by Rees wherein the radiation field is created relatively recently, we could consider a whole new set of theories, or revive some of the ideas of Layzer on galaxy formation in cold universes. The recently reported observations of the spectrum of the cosmic background radiation by Woody and Richards (see the review by Muller in these proceedings) may provide some reason to take this seriously, though it should be remembered that in doing so one has to solve the problem of making the helium in the universe.

including eventually adiabatic and isocurvature initial conditions; explosions, maybe driven by annihilating matter and antimatter, dark matter, or superconducting cosmic strings; ordinary cosmic strings, textures or monopoles; decaying dark matter; warm or mixed dark matter, primeval turbulence and/or magnetic fields; as well as a cold Big Bang.

Note the efficient recycling ideas from the CMBR spectrum anomaly.
An example of the situation: in 1980 two groups found evidence for a relatively large CMBR quadrupole anisotropy

1980: if the quadrupole anisotropy is large here’s a theory for it

LARGE-SCALE FLUCTUATIONS IN THE MICROWAVE BACKGROUND AND THE SMALL-SCALE CLUSTERING OF GALAXIES

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ABSTRACT

Two groups have discovered large-scale irregularities in the microwave background in excess of the dipole part that might be due to our peculiar motion (Fabbri et al.; Boughn, Cheng, and Wilkinson). More observations are needed before we can decide whether this is a local effect, perhaps emission from dust clouds, or a true irregularity in the microwave background. My purpose here is to point out that if the effect is extragalactic there is a ready interpretation. The irregular distribution of mass in clusters of galaxies causes large-scale gradients in the gravitational potential that in turn perturb the microwave background. If the mass autocorrelation function \( \xi(r) \) is negligibly small on large scales, the fluctuations in brightness on angular scale \( \theta \) vary as \( (T_1 - T_2)^{\alpha} \propto \theta^{\alpha} \). If \( \xi(r) \) agrees with the galaxy two-point correlation function observed at \( r \approx 30h^{-1} \text{Mpc} \), the brightness fluctuations produced by this effect are comparable to the recent observations.

1982: so the quadrupole anisotropy is small. Here’s a theory for a small anisotropy, the CDM model

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-ININVARIANT PRIMEVAL PERTURBATIONS

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ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum \( P \propto k^\alpha \) wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, \( m_s \), if \( m_s \gtrsim 1 \text{keV} \). The expected background temperature fluctuations are well below present observational limits.
There are quite a few adjustable elements in this beautiful fit to the CMBR anisotropy spectrum and the other cosmological tests. That includes the model for structure formation: the community settled on CDM because it was seen to offer a promising fit to the data.

But this model also passes a rich suite of tests.
The independent checks of the ΛCDM theory include consistency with

- the spectacularly precise CMBR temperature anisotropy spectrum
- the WMAP3 CMBR temperature – polarization spectrum
- the galaxy power spectrum (with modest bias)
- the Lyα forest power spectrum
- the baryon oscillation signature
- $\Omega_{\text{baryon}}$ from the standard model for the light elements (though we did have the lepton number as a free parameter)
- $\Omega_m$ from dynamics, weak lensing and the cluster baryon mass fraction
- $\Omega_\Lambda$ from the SNeIa $z$ - $m$ relation
- the cluster mass function
- the ISW effect (at a modest number of standard deviations)

We arrived at the impressively successful ΛCDM theory by the usual chaotic interaction of theory and practice.
Does the ΛCDM cosmology contain all the physics relevant to astronomy and cosmology at modest redshifts? Or might this model, with its close to trivial physics in the dark sector, be just the simplest approximation we can get away with at the present level of the evidence?

If there is physics to be added to the ΛCDM cosmology where might we seek it? Among other places, we might look to ideas with a long history.
GOLDEN OLDIES
Ideas that have been pursued for a generation or so

1. The steady state philosophy
   The 1948 cosmology is ruled out. Eternal inflation seems promising. Is there a viable intermediate cosmology? The rich tests we have now challenge the idea, but we should remember that we’re drawing large conclusions from limited data.

2. Evolving physics
   The idea that dimensionless parameters such as $Gm_p m_e/\hbar c$, $e^2/\hbar c$ and $m_e/m_p$ might vary with time has been under discussion, off and on, since Dirac (1937).
   We might add the proposal that Einstein’s $\Lambda$ is a function of time and maybe position.
   The tests do not encourage this line of thought, but it certainly is durable.

3. Nongravitational stresses
   Winds, jets, explosions and magnetic fields certainly affect structure formation, but the evidence now is that they are subdominant to gravity on scales larger than galaxies.
   Other Golden Oldies are cosmic strings & textures, and primeval antimatter, magetic fields & black holes. Might they enter the standard model in subdominant roles?

4. Physics in the dark sector
   Ideas for more interesting physics include dark matter that is decaying, annihilating, warm, has a short-range interaction, or an inverse square fifth force, or maybe is not even particles.
   Detection of a signature, as a glow from annihilation (e.g. Finkbeiner) or a compelling improvement of the fit to the cosmological tests (maybe by a sterile neutrino mass $m \sim 1$ to 10 keV) would be an exciting — though maybe enigmatic — clue to better physics.
Another Golden Oldie

5. What is in the voids defined by the visible galaxies?
6. The dwarfs should be present also in the regions void of bright galaxies, and, in general, the galaxy luminosity function is expected to vary with the background density: the ratio of faint to bright galaxies should be larger in regions of lower density.

The evidence for segregation in the Perseus-Pisces Supercluster (Giovanelli, Haynes, and Chincarini 1986), which confirms our predictions, seems strong. On the other hand, the angular correlation differences (Sharp, Jones, and Jones 1978; Davis and Djorgovski 1985) are only indicative: redshift surveys of dwarfs versus bright galaxies, in high versus low density regions, are needed in order to test the predictions. An
This is a pure DM LambdaCDM simulation. Notice the Dekel-Silk (1985) effect.
On the distribution of DDO galaxies

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Summary. We have examined the distribution of DDO galaxies on the sky and their relationship to normal galaxies. The results appear to contradict the universality of the luminosity function for galaxies. They also indicate that DDO galaxies are preferentially found in the vicinity of normal galaxies, but not uniformly in that they tend to avoid clusters. This may be due to the dependence of distribution upon morphological type.

1 Introduction

DDO galaxies (van den Bergh 1959, 1966) are a special class of galaxy characterized by a generally lower surface brightness and the presence of diffuse surrounding material. They have been the subject of a detailed study by Fisher & Tully (1975) who have, among other things, determined radial velocities for a number of them. It is thought that most of these galaxies may have intrinsically faint luminosities (generally in the range $-18 < M < -15$). They will be referred to simply as ‘dwarfs’ for the rest of this paper.
What is in the voids defined by the visible galaxies? Consider DDO 154

The Carignan and Purton 21-cm surface density and velocity maps of DDO 154

Stellar mass: $3 \times 10^7 M_\odot$
HI plus He mass: $2 \times 10^8 M_\odot$
total mass within 6 kpc: $3 \times 10^9 M_\odot$
Why does this map look so different from what Dekel & Silk (1986) point out might reasonably be expected in the LambdaCDM cosmology?

The Karachentsev et al. (2004) Catalog of Neighboring Galaxies. The larger circles show the galaxies at $v_{LG} < 550$ km s$^{-1}$. The smaller circles show galaxies at somewhat greater distance. The red squares are, left to right, the gas dwarfs ESO 215-G?009 DDO 154 UGCA292 NGC3741 The local sheet at SGZ = 0 is part of the Local Supercluster. The Tully Void is really empty.
Yet another Golden Oldie

6. What are the effects of late time galaxy merging and accretion?

Merging certainly happens at the present epoch. But do merging and accretion from redshift $z = 1$ to the present significantly alter the galaxy population or act instead as a perturbative correction to the island universe picture?

What do the observations say?

What does the CDM cosmology predict?
Matthias Steinmetz, Astrophysical Institute Potsdam

Formation of a disk galaxy in the Lambda CDM cosmology
Steinmetz’s demonstration of spiral galaxy formation in the ΛCDM cosmology is impressive and important.

But Steinmetz’s example reminds me of the old argument that galaxies form relatively late in this cosmology.

Does ΛCDM form enough galaxies like the Milky Way in which, I am informed, the thin disk was in place well before $z = 1$?
Fig. 2.— Images of the mass distribution at $z = 0, 1$ and $3$ in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within $r_{200}$ of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each image is $5h^{-1}$Mpc on a side in physical (not comoving) units.

Early Formation and Late Merging of the Giant Galaxies

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Fig. 3.— The total mass within physical distance $10h^{-1}$ kpc of the center of the most massive progenitor of the final halo at each time plotted and for each of our 8 simulations. Symbols switch between filled and open each time the identity of the most massive progenitor changes.

The colour–magnitude relation as a constraint on the formation of rich cluster galaxies

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ABSTRACT
The colours and magnitudes of early-type galaxies in galaxy clusters are strongly correlated. The existence of such a correlation has been used to infer that early-type galaxies must be old passively evolving systems. Given the dominance of early-type galaxies in the cores of rich clusters, this view sits uncomfortably with the increasing fraction of blue galaxies found in clusters at intermediate redshifts, and with the late formation of galaxies favoured by cold dark matter type cosmologies. In this paper, we make a detailed investigation of these issues and slope of the relation and to increase its scatter. We show that random mergers between galaxies very rapidly remove any well-defined colour–magnitude correlation. This model is not physically motivated, however, and we prefer to examine the merger process using a self-consistent merger tree. In such a model there are two effects. First, massive galaxies preferentially merge with systems of similar mass. Secondly, the rate of mass growth is considerably smaller than for the random merger case. As a result of both of these effects, the colour–magnitude correlation persists through a larger number of merger steps.
This shows Nigel Sharp’s list of Messier galaxies in the Virgo cluster, with projected distances from M 87. The images, from NOAO and 2MASS, have a roughly common angular scale, but contrasts can differ.

Future mergers by M87 won’t be all that dry, and I suppose mergers since z = 1 have been wetter.
THE DEPENDENCE ON ENVIRONMENT OF THE COLOR-MAGNITUDE RELATION OF GALAXIES

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(bowdlerized)
Can this cD have grown in the manner suggested by the CDM simulations?
Chaos in Cosmology

There still is chaos at the frontiers of research in cosmology. This is a Good Thing: it means the subject is alive and well.