THE QUEST FOR FINE-SCALE ANISOTROPY IN THE RELICT RADIATION

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Up to Symposium Session IV, the observed properties of the large scale structure of the Universe have been discussed in terms of studies based on the spatial distribution of galaxies with redshift less than one; studies which indicate clustering on characteristic scales up to $\sim$20 Mpc or equivalently $\sim 10^{15} M_{\odot}$. Such a survey is rather local in scope compared to what in principle could be inferred from the measurement of temperature fluctuations in the relict radiation surviving from $Z \simeq 1000$ as the fossil imprint of "primordial" density fluctuations on scales up to the horizon at the epoch of decoupling, $M \simeq 10^{19} M_{\odot}$. However, the investigation of structure over a still-larger sample volume and scales greater than $10^{15} M_{\odot}$ is not a possibility which I wish to stress in this paper. Rather, given our present state of ignorance about the formation of structure, perhaps a more fruitful first approach would be to examine small angular scales in the relict radiation for insight into the evolution of density perturbations by a careful comparison between the observationally inferred "initial" spectrum of mass inhomogeneities present back at the epoch of decoupling, and the mass spectrum of clustering which characterizes the present Universe.

Unfortunately, reference must continually be made to the <u>possibilities</u> implicit in a study of fine-scale temperature anisotropies because <u>none</u> have yet been observed. However, the upper limits on amplitudes over various angular scales are being forced lower and lower each year by determined observers; and if this process continues, we may be forced into a situation reminiscent of the paradox posed by the extreme isotropy of the relic radiation on large scales (that is, on scales large enough to comprise regions which we naively expect to be acausally related). The corresponding fine-scale predicament might be stated: "How can the early Universe appear so isotropic on angular scales corresponding to currently existing mass associations?" Or, "How can we explain the evolution of the highly structured Universe observed today from a virtually featureless past?" In fact, we are not yet compelled to take such an extreme position for, as shown below, the current upper limits

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are not so low as to pose a paradox. On the contrary, most of us probably expect that an order of magnitude improvement in sensitivity will inevitably reveal the texture of the early Universe. Despite that mystical confidence, the detection and measurement of temperature/density fluctuations present during the recombination era remains a primary goal of observational cosmology (Rees and Sciama 1969, Weinberg 1972).

The following sections of this brief review are devoted first to a summary of those elements of gravitational instability theory which are necessary to establish a meaningful comparison between theory and fine-scale anisotropy data, and also to motivate the direction of future observational effort. Currently available upper limits on temperature fluctuations are then tabulated; many announced within the past few months are still unpublished at the time of this Symposium. Finally, a possible "next-generation" fine-scale observing technique is suggested; one with adequate sensitivity to force a confrontation between theory and fact.

I. GRAVITATIONAL INSTABILITY - OBSERVATIONAL IMPLICATIONS

Many currently envision the evolutionary transition from the relatively featureless, homogeneous, early Universe to the manifestly inhomogeneous cosmos of the present epoch, to proceed through the growth of density perturbations due to gravitational instability. Within the context of the hot Big Bang, this process yields a rather rich variety of behavior with details which depend on the mass scale of the particular perturbation (Field, 1967; Silk, 1968; Rees and Sciama, 1969; Sunyaev and Zel'dovich, 1970; Peebles and Yu, 1970; Silk, 1974). However, for purposes of the following discussion, we consider only the final phase of the condensation scenario beginning with the recombination of hydrogen and the consequent decoupling of matter and radiation. Having defined the problem in this way, we must postulate the presence of "seed" perturbations at decoupling (a self-serving gesture, since their origin is considered by many to be inscrutable). Even so, the existence of such perturbations at some minimum amplitude is clearly a logical necessity, and observational verification (at $Z \simeq 1000$) of a mass spectrum of density inhomogeneities appropriate to the precipitation of the current structural hierarchy is a fundamental test of not only the instability picture, but indirectly of many of the details of the Big Bang hypothesis.

An essential question to ask of the theory is to require an estimate of that minimum necessary perturbation amplitude. The value turns out to be rather large because of a curious "difficulty" with the emergence of structure through gravitational instability; namely, that the growth of density perturbations in a Friedmann Universe is merely a power law (Lifschitz, 1946). In the post recombination era perturbations behave as:

$$\frac{\delta\rho}{\rho} \sim (1 + Z)^{-1} \quad (1)$$

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from $Z = Z_{rec}$ up to $Z = Z_f$ where $1 + Z_f = 1/\Omega_o$. That is, in the linear theory (low density contrast) perturbations cease to grow for $Z < Z_f$. Therefore, to assure the formation of high-contrast structure, the non-linear regime, $\delta\rho/\rho \simeq 1$, must be approached for $Z \geq Z_f$. Through this simple condition, the magnitude of density perturbations at recombination ($Z_{rec} \simeq 1000$) is approximately specified:

$$\left[\frac{\delta\rho}{\rho}\right]_{Z_r} \geq \frac{1 + Z_r}{1 + Z_f}\left[\frac{\delta\rho}{\rho}\right]_{Z_f} \qquad (2)$$

Thus, for $$\left[\frac{\delta\rho}{\rho}\right]_{Z_f} \simeq 1$$

$$\frac{\delta\rho}{\rho} \geq 10^{-2} \quad \text{for} \quad \Omega_o = 0.1 \qquad (3)$$

or, $$\frac{\delta\rho}{\rho} \geq 10^{-3} \quad \text{for} \quad \Omega_o = 1.0. \qquad (4)$$

These are hardly small perturbations in the customary sense; and correspondingly, such density perturbations, whether adiabatic or isothermal, are expected to produce sizeable temperature anisotropies in the (decoupling) radiation field.

This coupling between density and temperature fluctuations, either through the establishment of LTE conditions and/or through scattering off matter participating in large-scale motions, has been discussed by several authors (Silk, 1968; Sunyaev and Zel'dovich, 1970; Silk, 1974), who also point out a variety of damping and averaging processes which selectively diminish density and temperature fluctuations on mass scales smaller than $10^{15}M_\odot$. A representation of the relationship between observable fractional rms temperature fluctuations, $\Delta T/T$, and perturbation mass (or equivalent angular scale, $\Theta \alpha M^{1/3}$) due to Sunyaev and Zel'dovich (1970) is shown for several values of Ω_o in Figure 1. Each curve is defined so that $\delta\rho/\rho = 1$ at $1 + Z = 1/\Omega_o$.*

II. OBSERVATIONAL TEST - THE STRONG FORM

In Table 1 are listed the currently available upper limits on fine-scale fluctuations in the relict radiation. The more stringent of these limits are also plotted in Figure 1 and labeled by the Table entry number.

*The possible consequences of reheating of the intergalactic medium are not discussed here. Although it seems difficult energetically to produce an optical depth greater than unity back to $Z \simeq 1000$, even in that case the imprint of early density perturbations should be observable in the relic radiation (see paper by Sunyaev in this volume).

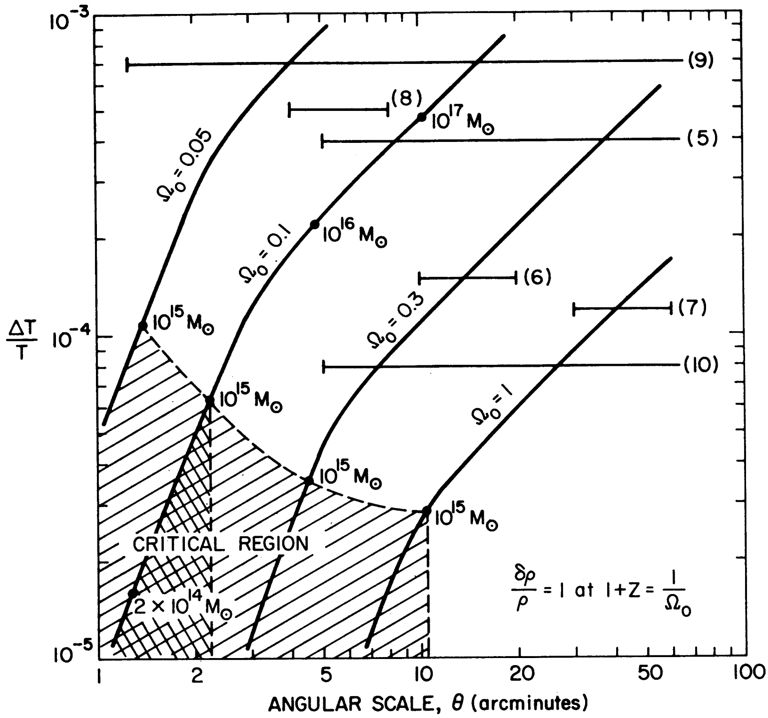

Figure 1. Fine-scale temperature fluctuations, ΔT/T, as a function of angular scale. Bold curves represent the calculations of Sunyaev and Zel'dovich (1970). Horizontal bars indicate current observational limits identified in Table 1. The critical region is defined in the text.

Within the context of the theoretical expectations presented in Figure 1, these 6 observational limits argue against the evolution of high contrast mass associations on scales greater than $\sim 10^{16} M_\odot$ for $0.03 < \Omega_o < 1.0$. Although this is an interesting result, there is no compelling evidence for or against such associations at the current epoch.

As already suggested, perhaps the crux of the confrontation between observation and theory lies in searching for primordial fluctuations (those present at decoupling) on mass scales for which we know high contrast associations exist at the current epoch, that is, for $M \lesssim 10^{15} M_\odot$. The theory then demands that temperature fluctuations be observed at a specified amplitude for a given Ω_o. This "strong form" of the test for primordial fluctuations is characterized (for $\Omega_o = 0.1$) by the double hatched region in Figure 1. That is, in an $\Omega_o = 0.1$ universe, any observational effort which penetrates this region, or its lower extension, should detect fluctuations. The right-hand boundary is somewhat conservatively defined in the sense that the fluctuation spectrum is assumed to plunge to zero for $M > 10^{15} M_\odot$. The union of all such regions

Table I

Observers	Angular Scale	λ (cm)	ΔT/T†
1. Conklin and Bracewell (1967)	10'	2.8	$<1.8 \times 10^{-3}$
2. Penzias et al (1969)	2'	0.35	$<6.0 \times 10^{-3}$
3. Boynton and Partridge (1973)*	1'.5	0.35	$<1.9 \times 10^{-3}$
4. Carpenter et al (1973)	>2'	3.6	$<7.0 \times 10^{-4}$
5. Parijskij (1973)**	>5'	2.8	$<4.0 \times 10^{-4}$
6. Stankevich (1974)	10'-20'	11.1	$<1.5 \times 10^{-4}$
7. Caderni et al (1977)	30'	0.13	$<1.2 \times 10^{-4}$
8. Partridge (1977)***	4'	0.9	$<5.0 \times 10^{-4}$
9. Pigg (1977)	>1'.25	2.0	$<7.0 \times 10^{-4}$
10. Parijskij (1977)****	>5'	2.8	$<8.0 \times 10^{-5}$

†Generally quoted as 2σ or 95% limit.
*Revised downward, see Partridge (1977).
**Revised upward, private communication (1977).
***Tentative upper limit pending completion of analysis.
****See paper by Parijskij in this volume.

for $0.05 < \Omega_o < 1.0$ then generally defines the "critical region" for such observations, as labeled in Figure 1. The shape of the upper boundary of the critical region is consistent with the previous simple argument about the requisite amplitude of density perturbations. That is, to achieve high contrast mass condensations,

$$\left[\frac{\delta\rho}{\rho}\right]_r \gtrsim \frac{1}{(1 + Z_r)\,\Omega_o} \tag{5}$$

and since ΔT/T is a monotonic function of Δρ/ρ, as the upper limit on ΔT/T is forced lower and lower, Ω_o is restricted to larger and larger values. As seen in Figure 1, for an observed $\Delta T/T < 3 \times 10^{-5}$ on all angular scales, Ω_o must be greater than one. In this way one sees that the measurement of the amplitude spectrum of temperature fluctuations ΔT/T(Θ) not only promises insight into the nature of the growth of mass associations, and possibly yields some clues to the origin of the seed perturbations, but also may provide interesting constraints on that ever-elusive label of universes, Ω_o.

III. CONCLUSIONS

1. Comparison of data and theory possible at this time suggests that the density contrast of mass associations may be significantly depressed for $M > 10^{16} M_\odot$

2. The three-way confrontation between evidence for clustering at $Z \lesssim 1$, the properties of density perturbations at $Z \simeq 1000$, and the

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theoretical evolutionary connection between these observations--what I have called the "strong" form of the test of these ideas--has yet to take place. We need fine-scale anisotropy measurements on angular scales down to one arc minute with an rms precision of $\Delta T/T \lesssim 10^{-5}$.

3. The customary radio astronomy techniques previously employed may not be adequate to carry these studies to the precision required above. This last, as yet unjustified, conclusion motivates the following discussion.

IV. NEW DIRECTIONS

How do we make observational incursions into the critical region defined in Figure 1? Temporarily putting aside limitations posed by discrete emission sources, the major difficulty in achieving sensitivities on the order of $\Delta T/T \simeq 10^{-5}$ is the impracticality of attempting to schedule adequate observing time on one of the few filled-aperture radio telescopes capable of 1' to 2' resolution. The integration time requirement, τ, to achieve $\Delta T/T \simeq 10^{-5}$ for N independent pairs of sky elements is given by:

$$\tau \simeq 10^{10}\, N\, B^{-1}\, T_{rec}^{\;2} \text{ seconds} \tag{6}$$

where B is the receiver pre-detection bandwidth in Hz, and T_{rec} the receiver noise temperature. Currently the best maser receivers yield τ/N values of around 24 hours. Improvements in the foreseeable future might reduce that time to $\sim$ 12 hours. Thus a statistically meaningful sample ($N \geq 100$) of sky elements would require concurrent use of a state-of-the-art receiver and one of the largest radio telescopes for a large fraction of a year even under optimal observing conditions.

Far infrared techniques are an alternative approach to the observational challenge posed by the critical region in Figure 1. Existing high-throughput bolometer and filter combinations allow τ/N values as low as 10 minutes with a bandwidth narrow enough to utilize the atmospheric transmission window near λ = 1mm. Ground-based observing seems an inescapable constraint because the requisite angular resolution (at approximately unit throughput) implies apertures too large (i.e. $\gtrsim$ 10m) to consider airborne or satellite platforms for at least the next decade.

Although detector noise is quite favorably small, customarily there have been two principal objections to far infrared observations of fine-scale anisotropy: the first is the spectre of atmospheric emission fluctuations. However, work by Corsi et al. (1974) at $\lambda \simeq$ 1mm suggested that low frequency fluctuations are not substantially larger than detector noise at a good site. Moreover, the use of beam switching comparison of sky elements separated by only a few minutes of arc reduces atmospheric fluctuation noise to the extent that such fluctuations are highly correlated on small angular scales. Recent beam switching measurements over angles of 30 arc minutes (Caderni et al., 1977) failed to record any excess noise due to atmospheric effects at $\lambda \simeq 1mm$; and their anisotropy limit of $\Delta T/T < 10^{-4}$ was consistent with detector noise limited performance. These rather surprising results suggest that $\Delta T/T \simeq 10^{-5}$ might well be attainable for beamswitching angles less than 3 arc minutes under suitable observing conditions.

The second of the two objections concerns the contribution of discrete emission sources to fine-scale anisotropy. The early investigation of observational constraints on fine-scale anisotropy measurements by Longair and Sunyaev (1969) indicated that any reasonable extrapolation of radio source counts to $\lambda = 1mm$ produce a confusion limit (one source per beam) at a negligible level, $\Delta T/T \simeq 10^{-9}$. However, they correctly pointed to possible severe difficulties with "inverted spectrum" sources and the then newly-discovered "infrared galaxies". Their conservatively estimated one-source-per-beam contribution at a level of $\Delta T/T \simeq 10^{-5}$ reflected understandable pessimism. However, we now have the benefit of recent $\lambda = 1mm$ survey by Ade, Rowan-Robinson and Clegg (1976) augmented by further observations of Hildeband et al. (1977) which allow significant constraints on the bright end of the source-count function. Utilizing the Pooley-Ryle N(S) function in the same fashion as Longair and Sunyaev, we find that the source confusion limit at $\lambda = 1mm$ is much smaller ($\Delta T/T < 8 \times 10^{-7}$) than originally estimated, a result which is clearly crucial to this study.

In summary, there may be no severe practical or fundamental limitations to achieving considerably improved measurements of fine-scale anisotropy through a ground-based, high throughput, far-IR bolometric system. However, no survey of this type is meaningful unless the spectral properties of the anisotropy are measured, thereby allowing the identification of non-cosmological components. This crucial extension of the simple technique proposed here implies exploitation of the 2mm and 3mm atmospheric windows and possibly supplemental studies on larger angular scales from the NASA C141 IR Observatory and even the proposed NASA SIRTF Orbiting Infrared Telescope.

As determined observers continue to force the anisotropy limits lower and lower during the next decade, we wait with that aforementioned mystical assurance for the incipient texture of the early Universe to come into view...but will it?

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DISCUSSION

Longair: Will the submillimetre experiment suffer from problems associated with water-vapour fluctuations in the atmosphere? I recall that Webster's experiments at 9 mm from White Mountain were ruined by them.

Boynton: Yes, but recall that Webster's two beams were separated by many degrees, 90° I think, but one expects a high degree of correlation between atmospheric fluctuations in beams that are separated by only three or four arcmin. In fact, we have already found that the atmospheric contribution to fluctuations in $\Delta T/T$ is below 10^{-4} on scales of 30 arcmin near $\lambda = 1$ mm.

Fall: How much do your conclusions about the inevitability of seeing small scale fluctuations depend on the assumption that no reheating occurred?

Boynton: Even in the case of reheating one expects fluctuations stemming from the doppler shift in scattering radiation off mass associations which have inevitably acquired motions through the condensation process.

Fall: Yes, but if rehating lasted for a considerable period of time then these mass motions would be nearly uncorrelated through the depth

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of the reheated gas and the observed fluctuations would be much reduced.

Boynton: It is certainly true that the "averaging" process you mention will reduce the amplitude of fluctuations, and even more so if the motions are anti-correlated as suggested by Sunyaev and Zeldovich. But at some level, the fluctuations still seem inevitable even in the case that reheating produces substantial opacity.

Gott: Have you computed a similar curve for an isothermal density fluctuation spectrum?

Boynton: According to the treatment of Sunyaev and Zeldovich there is only a factor of two or three reduction in $\Delta T/T$, on the angular scales considered here, resulting from isothermal perturbations. Otherwise, the curve is quite similar.

Parijskij: What is the best limit to $\Delta T/T$ in the infrared region of the spectrum?

Boynton: $\Delta T/T < 10^{-4}$ on a scale of 2^o. The limit is $\Delta T/T < 2 \times 10^{-4}$ on a scale of 2 arcmin (see the written version of the lecture).

GENERAL DISCUSSION OF PAPERS BY PARIJSKIJ AND BOYNTON

Ozernoy: Recently Kurskov and myself have estimated the angular scale on which measurements of temperature fluctuations are optimal in order to discover primeval density or velocity perturbations. This angular scale corresponds to the maximum value of $\Delta T/T$. For adiabatic density perturbations the angular scale on which the expected value of $\Delta T/T$ attains a maximum corresponds to a mass approximately equal to the Jeans' mass at the moment of recombination and is about $\theta \sim (15'-30')h$*, independent of Ωh^2 and of the initial spectrum of perturbations which, generally speaking, is uncertain in the adiabatic model. For turbulent velocity perturbations, the value of $\Delta T/T$ is expected to have a maximum value for whirls of the maximum scale which corresponds approximately to the same angle $\theta \sim (15'-30')h$.

It should be emphasized that when one uses beam switching, it is necessary to have the antenna beam width not larger than $\theta_{ant} \simeq \theta/\pi \sim (5'-10')h$ where θ is the angular size mentioned above because otherwise appreciable averaging of fluctuations inside the antenna beam will be important. This averaging is significant if $\theta_{ant} \gtrsim (1+z_{emission})\, k^{-1} (\Omega H_o/2c)$ where k is a wave number of the perturbations at the redshift of emission.

*We use $h = H_o/75$ km $sec^{-1}Mpc^{-1}$.

Silk: I would like to mention that Richards and his colleagues at Berkeley have flown a further balloon-borne telescope to measure the spectrum of the microwave background radiation beyond the maximum of

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the Planck curve. Even the raw unreduced data show definite evidence for the abrupt decrease in intensity at wavelengths $\lesssim$ 1 mm expected of a true Planck distribution.

Boynton: I would like to comment that although Prof. Parijskij's latest results do not violate the "critical region" which I have defined in my presentation, I do not mean to minimize their importance in possibly limiting the perturbation amplitude spectrum for masses greater than 10^{16} $M_{\odot}$. His is a significant contribution and I earnestly hope that Prof. Parijskij will very soon publish a full account of his data, his analysis procedure and his conclusions so that we may all examine the methods by which he has reduced the fine-scale fluctuations limits by almost an order of magnitude over existing observations.

Parijskij: Full details of the experiments and reduction procedures will be published in *Astron. Zh. Letters* in December of this year.