COSMOLOGICAL PARAMETERS AND THE EVOLUTION OF THE UNIVERSE: PROGRESS AND PROSPECTS

MALCOLM S. LONGAIR
Space Telescope Science Institute,
3700 San Martin Drive, Baltimore MD 21218.

Cavendish Laboratory, Madingley Road,
Cambridge CB3 0HE, UK.

1. Introduction

I have been invited by the organisers to provide an overall perspective on the subject of this Symposium. Necessarily, this will be a subjective impression of topics in which there has been quite remarkable progress since the last General Assembly of the IAU, and which are of the greatest interest for the whole of science. In preparing a review of such an enormous field, one veers between optimism and pessimism about the successes and problems which have arisen. I hope to steer a realistic course between these extremes. Fortunately, there are many experts participating in this Symposium who will be able to neutralise my personal biases and provide authoritative opinions on all the topics I will cover.

I will divide the review into four sections:

1. The cosmological infrastructure;
2. The cosmological parameters;
3. The formation of galaxies and the large-scale structure of the Universe;
4. Observations of distant objects.

References to the authors of relevant reviews presented at the Symposium are indicated in upper-case letters in square brackets.

2. The Cosmological Infrastructure

First of all, I list four recent pieces of key information about the infrastructure we use in cosmological investigations.

1. The first of these concerns the remarkable maps of the Cosmic Microwave Background Radiation which have been created from the complete four-year data set observed by the Cosmic Background Explorer (COBE). From the point of view of the underlying structure of cosmological models, the key observation is the fact that the Microwave Background Radiation is isotropic on the large scale to a precision of better than one part in 10^5 (Bennett *et al.* 1996). There is no evidence for features, which might have been expected in the simplest of anisotropic world models. This is clear evidence that isotropic world models are the correct starting point for the construction of viable cosmologies.

2. The second piece of data concerns the homogeneity of the distribution of galaxies in the Universe. The variation of the amplitude of the two-point correlation function with increasing apparent magnitude has for some years been convincing evidence that, in broad terms, although the Universe is highly irregular on small scales, the same degree of irregularity is found as more and more distant samples of galaxies are observed (Maddox *et al.* 1990). This approach washes out a great deal of the fine-scale structure in the distribution of galaxies, in particular, the giant voids and filamentary structures seen in, for example, the Harvard-CfA survey of galaxies (Geller and Huchra 1989). This survey can now be compared with the Las Campanas Redshift Survey (LCRS), which extends to about a factor of four greater distance than the Harvard-CfA Survey (Lin *et al.* 1996). It is remarkable that the same large-scale features appear on that deeper map of the distribution of galaxies. These data show that, although the distribution of galaxies is highly irregular on a fine scale, qualitatively, the same degree of irregularity is present out to much greater distances, indicating that these structures are homogeneously distributed throughout the Universe at the present time. The helpful analogy that the distribution of galaxies is sponge-like seems to hold good out to large distances.

3. The third key piece of information concerns direct observational evidence for cosmological time-dilation from the light curves of Type 1A supernovae (Goldhaber *et al.* 1997). These supernovae are found to be remarkably uniform in their light-curves and luminosities, particularly if account is taken of the correlation between luminosity and decline-rate. According to all Robertson-Walker models of the expanding Universe, whatever its dynamics, the time-scale of phenomena should scale as

$$\Delta t_0 = \Delta t_1 (1 + z)$$

where Δt_1 is the proper time interval in the frame of reference of the source, Δt_0 is the proper time interval observed at the present epoch and z is redshift. This is precisely the relation found for Type 1A supernovae by Goldhaber *et al.* (1997).

4. An equally important result is found from estimates of the temperature of the Cosmic Microwave Background Radiation at large redshifts from the study of the fine-structure absorption lines of neutral carbon in the spectra of damped Lyman-α absorption systems seen in the spectra of large redshift quasars (Cowie *et al.* 1994, Ge *et al.* 1997). These lines are excited by the Microwave Background Radiation field and, from their strength, the temperature of the background radiation field can be found. For the absorption line system at a redshift $z = 1.776$ in the spectrum of the quasar Q1331+170, Cowie *et al.* inferred the temperature from the CI line to be 7.4 ± 0.8 K, consistent with the expected temperature of the radiation field, $T(z) = T_0(1+z) = 7.58$ K. For a similar system in the spectrum of the quasar QSO 0013-004 at a redshift $z = 1.9731$, Ge *et al.* found a temperature $T = 7.9 \pm 1.0$ K, consistent with the expected temperature of $T = T_0(1+z) = 8.105 \pm 0.030$ K.

The consequence of these four basic observations is that we can have increased confidence that world models based upon the Robertson-Walker metric are an excellent description of overall large-scale structure of the Universe. In what follows, I will write the Robertson-Walker metric in the following, slightly unconventional form:

$$\mathrm{d}s^2 = \mathrm{d}t^2 - \frac{R^2(t)}{c^2}[\mathrm{d}r^2 + \Re^2 \sin^2(r/\Re)(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)]$$

where $R(t) = (1+z)^{-1}$ is the scale factor normalised to unity at the present epoch. $\Re$ is the radius of curvature of the spatial geometry of the Universe at the present epoch, which is real for closed, spherical geometries and imaginary for open, hyperbolic geometries; r is the radial comoving distance coordinate.

3. The Cosmological Parameters

The standard world models can be described by a small number of parameters:

1. *Hubble's constant*, H_0, describes the present rate of expansion of the Universe

$$H_0 = \left(\frac{\dot{R}}{R}\right)_{t_0} = \dot{R}(t_0).$$

2. The *deceleration parameter*, q_0, describes the present dimensionless deceleration of the Universe.

$$q_0 = -\left(\frac{\ddot{R}}{\dot{R}^2}\right)_{t_0} = -\frac{\ddot{R}(t_0)}{H_0^2}.$$

3. The *density parameter*, Ω_0, describes the present dimensionless mass density of the Universe in terms of Hubble's constant

$$\Omega_0 = \frac{8\pi G\rho_0}{3H_0^2},$$

where ρ_0 is the present average mass density of the Universe. For astrophysical cosmology, it is important to determine separately the density parameter in baryonic matter $\Omega_{\rm B}$, as well as the overall density parameter Ω_0, which includes all forms of non-baryonic dark matter.

4. The *curvature of space* at the present epoch, $\kappa = \Re^{-2}$. Note that $\Re$ changes with scale factor as $\Re(z) = R\Re = \Re(1+z)^{-1}$.
5. The *cosmological constant* Λ, which can be parameterised in terms of the density parameter of the vacuum fields Ω_Λ

$$\Omega_\Lambda = 8\pi G\rho_{\rm v}/3H_0^2 = \Lambda/3H_0^2.$$

6. The *age of the Universe*, T_0

$$T_0 = \int_0^{t_0} \frac{\mathrm{d}R}{\dot{R}}.$$

The equations which are the basis of the standard models are:

$$\ddot{R} = -\frac{\Omega_0 H_0^2}{2R^2} + \Omega_\Lambda H_0^2 R \quad ; \quad \dot{R}^2 = \frac{\Omega_0 H_0^2}{R} + \Omega_\Lambda H_0^2 R^2 - \frac{c^2}{\Re^2}.$$

At the present epoch, $t = t_0$, $R = 1$, these reduce to

$$q_0 = \frac{\Omega_0}{2} - \Omega_\Lambda \quad ; \quad \kappa\left(\frac{c}{H_0}\right)^2 = (\Omega_0 + \Omega_\Lambda) - 1.$$

Expressed in this way, the equations describe two different aspects of the cosmological models. Those involving $\ddot{R}$ and q_0 describe the deceleration (or acceleration) of the Universe under the competing influences of gravity and the vacuum fields. The deceleration parameter provides a measure of the difference between half the density parameter Ω_0 and the density parameter in the vacuum fields Ω_Λ. In contrast, those involving $\dot{R}^2$ and κ describe how the curvature of space, $\kappa = \Re^{-2}$, depends upon the total mass-energy density in both the matter and the vacuum fields.

It is worthwhile making the pedantic footnote that q_0 can be measured independently of both Ω_0 and $\Re$ at small enough redshifts. It is a useful exercise to show purely kinematically that the comoving radial distance coordinate r is

$$r = \frac{c}{H_0}\left[z - \frac{z^2}{2}(q_0 + 1) + \ldots\right],$$

to second order in the redshift z, and the same is true of the distance measure $D = \Re \sin(r/\Re)$, which appears in the formulae which relate intrinsic properties to observables. The problem is that q_0 is only independent of Ω_0 and $\Re$ at rather small redshifts, $z \leq 0.25$. When astronomers claim to measure q_0, they usually mean within the context of uniform Friedman world models parameterised by Ω_0 and Ω_Λ. Ideally, q_0 should be determined absolutely and then compared with estimates of Ω_0. This would require the determination of exquisitely precise distance measures at small redshifts, a very difficult, but important, observational challenge.

3.1. HUBBLE'S CONSTANT H_0

One of the more pleasurable events of the last year has been the gradual convergence of estimates of Hubble's constant. At the Princeton meeting on *Critical Dialogs in Cosmology* held in the summer of 1996, Wendy Freedman and Gustav Tammann quoted the following values:

$$\begin{aligned} \text{Freedman} \quad H_0 &= 70 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1}; \\ \text{Tammann} \quad H_0 &= 55 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1}. \end{aligned}$$

These bald figures disguise the enormous progress which has been made in measuring accurate distances to nearby galaxies, observations of Cepheid variables in galaxies as distant as the Virgo cluster by the Hubble Space Telescope being an essential part of this story. The errors quoted above take account of systematic as well as random errors – the systematic errors, which can be asymmetric with respect to the mean, are now the dominant source of uncertainty. It should be recalled that the objective of the HST Key Project is to measure the value of Hubble's constant to 10% with 1-σ precision. This means that the 95% uncertainty limits, which correspond closely to $\pm 2\sigma$, would correspond to 20% of the best estimate. Both teams have now made very substantial progress towards achieving this goal [FREEDMAN, TAMMANN]. An item of great interest is the impact of the revision of the local distance scale as determined by observations made by the Hipparcos astrometric satellite upon these estimates. Feast and Catchpole (1997) have suggested that the distance scale should be increased by about 10%. This has two effects. First, it would reduce the value of Hubble's constant and, second, the luminosities of the stars would increase, leading to a reduction in their ages. We need to hear from the experts about these important developments.

There has been excellent progress in the use of physical approaches to the determination of H_0 which eliminate the use of primary and secondary distance indicators. Turner and his collaborators (Kundic *et al.* 1997) used the technique of measuring the time delay of the variability of the components of the gravitationally lensed images of the double quasar 0957+561 to find a value

$$H_0 = 64 \pm 13 \text{ km s}^{-1} \text{ Mpc}^{-1} \text{ (95\% confidence limits)}$$

The security of the estimate depends upon the accuracy of the modelling of the gravitational lens, but this is now rather well defined by the studies which have been made of the detailed radio structures of the gravitationally lensed images.

A second developing theme has been the use of the Sunyaev-Zeldovich effect in hot diffuse gas clouds in rich clusters of galaxies to measure H_0. The combination of the bremsstrahlung emissivity of the hot gas, its temperature distribution and the pressure distribution determined from the Sunyaev-Zeldovich effect, overdetermine the properties of the gas cloud and so its physical dimensions can be found. Myers *et al.* (1997) have estimated a value of $H_0 = 54 \pm 14$ km s^{-1} Mpc^{-1} from detailed studies of the Abell clusters A478, 2142 and 2256. Similar values are found from studies with the Ryle Telescope at Cambridge, which has now measured Sunyaev-Zeldovich decrements in 12 rich clusters. According to Richard Saunders, the clusters used in these studies must be selected with care. There are complications in the interpretation if the clusters are irregular, possess cooling flows or contain diffuse, non-thermal radio emission. If the clusters pass the selection criteria, he estimates that typically Hubble's constant can be measured to about 30% accuracy for an individual cluster, consistent with the findings of the Myers *et al.* (1997).

Recently, there has been an intriguing discussion, stimulated by the studies of Professor Itoh and his colleagues, concerning the formulae to be used for the Sunyaev-Zeldovich effect when relativistic effects are taken into account. Challinor and Lasenby (1997) have shown that, in order to obtain self-consistent results, it is necessary to expand the Kompaneets equation to fourth order, because the series expansion converges very slowly. The results they find are consistent with the alternative approach taken by Rephaeli and Yankovitch (1997). The net result is that, in the Rayleigh-Jeans region of the spectrum, the expression for the decrement in the background, correct to second order in $\theta_e = kT_e/m_e c^2$, becomes

$$\frac{\Delta T}{T} = -2y(1 - 1.7\,\theta_e + 3.075\,\theta_e^2)$$

where y is the Compton scattering optical depth, $y = \int \sigma_T \theta_e N_e \, dl$. For a typical cluster temperature of $kT = 8$ keV, the relativistic corrections lead to a reduction in the estimate of Hubble's constant by about 5%.

3.2. Q_0 THE DECELERATION PARAMETER

After years of inconclusive efforts to find suitable standard candles for estimating q_0, a clear market leader has appeared – the Type 1A supernovae. These supernovae have remarkably standard properties, their luminosities at maximum light having a small dispersion in absolute magnitude, particularly when account is taken of the correlation between luminosity and the decline rate of the supernova light curve. There are good astrophysical reasons for the apparent constancy of the maximum luminosity. These supernova explosions are associated with the collapse of white dwarfs, which are taken over the Chandrasekhar stability limit by the accretion of matter from a companion star. Although there remains a great deal to be understood in terms of the detailed physics of the collapse of the white dwarf and the formation of the supernova light curve, it can be appreciated why, in principle, the luminosities of such explosions might well be similar. In addition, it is plausible that such explosions should not be too different at different cosmic epochs and so the problems of cosmological evolution, which bedevil the standard approach to the determination of q_0, should be minimised. The preliminary estimate of q_0 of Perlmutter *et al.* (1996) using observations of one of the best studied large redshift supernovae is $q_0 = 0.8 \pm 0.35(\text{stat}) \pm 0.3(\text{syst})$. This result already provides a useful limit to Ω_Λ. As they state, if $\Omega_0 + \Omega_\Lambda = 1$, then since $q_0 = \Omega_0/2 - \Omega_\Lambda$, it follows that, if Ω_Λ were 0.5, the expected value of q_0 would be -0.25, which provides a poor fit to the data [PERLMUTTER].

3.3. Ω_0 THE DENSITY PARAMETER

For me, this story poses a dimemma. On the one hand, most of dynamical tests, involving, for example, the mass-to-luminosity ratios of clusters of galaxies and the cosmic virial theorem, yield values of $\Omega_0 \sim 0.2 - 0.3$ (see, for example, Bahcall 1997). On the other hand, the very impressive computations using the POTENT technique for reconstructing the local mass density distribution in the Universe have found consistently larger values, the lower limit to Ω_0 at the 95% confidence limit being $\Omega_0 \geq 0.3$ [DEKEL].

It is not clear how this discrepancy has come about. Is the difference due to some form of large-scale biasing, or is there some technical aspect of the way the data are analysed which leads to these somewhat different conclusions? In any case, there is a clear consensus that $\Omega_0 \geq 0.1$.

3.4. $\Omega_{\rm B}$ THE DENSITY PARAMETER IN BARYONS

Primordial nucleosynthesis remains the most powerful means of estimating the present overall baryon density of the Universe. An upper limit to the baryon density comes from the lower limit to the amount of deuterium which could have been created by primordial nucleosynthesis. Hogan (1997) derived an the upper limit of $\Omega_{\rm B} h^2 = 3.6 \times 10^{-2}$, if the primaeval abundance of deuterium were to be $[{\rm D/H}] = 10^{-5}$, where $h = H_0/100$ km s^{-1} Mpc^{-1}. If one is more ambitious and seeks to explain the abundances of all the light elements by a single value of the baryon density, Hogan suggested a value of

$$\Omega_{\rm B} h^2 = (6.2 \pm 1.1) \times 10^{-3}.$$

The problem with adopting this rather low value of the baryon density is that it results in a high primordial deuterium abundance and there would have to be a large amount of destruction of primordial deuterium to account for the uniformly low values found in the local interstellar medium, $[{\rm D/H}] \approx 1.5 \times 10^{-5}$. Models of the chemical evolution of the interstellar medium are hard pressed to account for such large amounts of destruction of primordial deuterium. The discovery of a high deuterium abundance of 2.0×10^{-4} in Lyman-limit absorption cloud at $z = 0.7$ by Webb *et al.* (1997) has suggested that we may be forced to adopt inhomogeneous models of primordial nucleosynthesis models, which would complicate the story.

3.5. Ω_Λ THE COSMOLOGICAL CONSTANT

The cosmological constant has overshadowed observational cosmology since its introduction by Einstein in 1917. It has always struck me as remarkable that, if $\Omega_\Lambda \neq 0$, why has it proved so elusive? Every test which would convince everyone that the cosmological term should be present in the field equations has given a null result. Of these tests, the most powerful is the use of the statistics of gravitational lenses to set limits to the value of Ω_Λ. The reason that this is a powerful test is that, if the cosmological constant were positive and to play a significant role in cosmology, it would have the effect of stretching out the cosmological time-scale and also the distance measures between the observer, the lens and the background sources. As a result, many more lenses are expected in cosmologies with finite positive values of Ω_Λ, as compared with those with $\Omega_\Lambda = 0$. A detailed analysis of the problem has been presented by Kochanek (1996), who finds that the numbers of gravitationally lensed images in statistically complete quasar samples are best accounted for by world models with $\Omega_0 \sim 1$ and $\Omega_\Lambda = 0$. Expressed another way, if $(\Omega_\Lambda + \Omega_0) = 1$, the upper limit to Ω_Λ at the 95% confidence level is $\Omega_\Lambda \leq 0.65$. This is, in itself, an important constraint since one of the favoured models to account for the large scale distribution of galaxies involves combinations of parameters such as $\Omega_0 = 0.1$ and $\Omega_\Lambda = 0.9$. If $\Omega_\Lambda = 0$, Kochanek finds that, in order to account for the observed numbers of lenses, Ω_0 must be greater than 0.15 at the 95% confidence level.

3.6. T_0 THE COSMIC TIME-SCALE

The two classical methods for measuring the cosmic time-scale are by nucleocosmochronology and by estimating the ages of the oldest stars. The relative abundances of radioactive pairs such as $({}^{232}\mathrm{Th}-{}^{238}\mathrm{U})$, $({}^{235}\mathrm{U}-{}^{238}\mathrm{U})$ and $({}^{187}\mathrm{Re} - {}^{187}\mathrm{Os})$ indicate that the present age of the Universe must be greater than 9.6×10^9 years (Schramm 1990). To account for the observed ratios of these radioactive species, Schramm finds a best-fit value in the range $T_0 = (12 - 14) \times 10^9$ years.

The physics of age determinations of the oldest stars we know of, those in the globular clusters, was persuasively reviewed by Bolte (1997) at the Princeton meeting. He concluded that the ages of the oldest globular clusters are

$$T_0 = 15 \pm 2.4(\mathrm{stat}) \begin{array}{c} +4 \\ -1 \end{array} (\mathrm{syst})\ \mathrm{Gy}$$

Since that meeting, the first results of the determination of the local distance scale from the Hipparcos astrometric survey have been announced. As discussed above, it has been suggested that the local distance scale should be increased by 10%, which has two effects. Firstly, all extragalactic distances should be increased by this factor. Second, the stars in globular clusters would be more luminous, which would have the effect of reducing their ages. Both of these effects tend to improve the consistency of the ages of the oldest stars with the expansion age of the Universe [CHABOYER].

4. The Formation of Structure in the Standard Picture

There is not space here to go into the enormous amount of work which has been devoted to the dark matter/gravitational instability picture of the origin of galaxies and the large-scale structure of the Universe. Suffice to say that, personally, I find the logic behind the picture remarkably compelling. Specifically:

1. The evidence described in Section 3 strongly suggests that the dynamics of the Universe is dominated by non-baryonic dark matter at the

present epoch. The natural consequence is that the dynamical history of the Universe has been dominated by the same dark matter since the epoch of equality of the radiation and dark matter densities at $z_{\rm eq} \approx 2.4 \times 10^4\,\Omega_0 h^2$.

2. The dark matter must be dominant dynamically at the epoch of recombination, if the predicted amplitude of the fluctuations in the Cosmic Microwave Background Radiation are not to exceed the rather stringent observational limits now available on a wide range of angular scales.

My own perspective on these studies is that many of the most important parts of the story are not tied to any particular view of the hypothetical physics which took place in the very early Universe. Rather, the astronomers can hope to derive the initial conditions *on the horizon scale* from which galaxies and large-scale structures formed. This seems to me a philosophically healthy approach, in that it is not dependent upon the physics of the early Universe which, whilst a wonderful area for theoretical virtuosity, lacks any independent validation beyond theoretical self-consistency. My view has its roots back in the late 1960s when Zeldovich and Sunyaev showed me how it was possible to reconstruct the spectrum of initial perturbations back to the epoch when objects on different scales came through the horizon (Sunyaev and Zeldovich 1970). Indeed, it was partly this reasoning which led to Zeldovich's spectrum of initial perturbations, a power-spectrum of initial fluctuations of the form $P(k) \propto k^n$ with $n = 1$, the famous Harrison-Zeldovich spectrum – Zeldovich had looked at the answer! The modern version of the same procedure is very nicely illustrated by the work of Peacock and Dodds (1994), who performed a remarkable reconstruction of the processed power-spectrum of initial perturbations necessary to create the large-scale structure of the Universe now. Thus, many of the key elements of the theory of the formation of structure in the Universe are independent of what took place in the very early Universe.

It is encouraging for many aspects of astrophysical cosmology that many of the features of the large-scale structure of the Universe can be accounted for by dark matter theories. For example, it can give a natural account of the observed 2-point correlation function for galaxies. It is also encouraging for particle physicists, in that, a persuasive case can be made that the relevant masses for the non-baryonic dark matter particles probably lie in the range 10 to 1000 GeV, coinciding with mass-scales of the greatest interest for particle physics – the scale of the $W^{\pm}$ and Z^0 bosons, the Higgs scale and that of the lightest supersymmetric particles. Thus, it is understandable that the particle physicists take these cosmological studies very seriously indeed.

On the other hand, the simplest models do require a bit of patching up. The analysis of Peacock and Dodds (1994) illustrates the types of biasing needed to tie all the correlation functions together, but this is a subject which will eventually be susceptible to astrophysical analysis. In trying to understand the plethora of models present in the literature, it is simplest to take the point of view that the best fitting simple models are the open cosmologies with $\Omega_0 h \sim 0.255$. All the other models can be thought of as being different ways of making a Universe with $\Omega_0 + \Omega_\Lambda = 1$ look like a simple standard model with $\Omega_0 h \sim 0.255$ [STAROBINSKY, OSTRIKER]. I believe that it is a matter of taste which of these variants is to be preferred.

What is abundantly clear is that an enormous amount of information can potentially be derived from observations of the power-spectrum of temperature fluctuations in the Cosmic Microwave Background Radiation [SUGIYAMA]. On large angular scales, $\theta \gg 1^\circ$, the dominant effect is the Sachs–Wolfe effect acting on primordial perturbations which are still in the linear stage of development and these can be related to the power-spectrum of density perturbations on the scales of superclusters and greater. There is the possibility of detecting the presence of primordial gravitational waves.

The physics of the acoustic peaks on angular scales $\theta \leq 1^\circ$ provide information about many different aspects of the early Universe, including the determination of cosmological parameters [SUGIYAMA, LINEWEAVER]. It is important to emphasise that the peaks observed in the temperature power spectrum are associated with well-defined physical scales on the last scattering layer at redshift $z \sim 1000$. For example, the first acoustic peak is associated with the scale of the sound horizon $r_{\rm s} = c_{\rm s} t_{\rm rec}$ on the last scattering surface, where $c_{\rm s}$ is the sound speed and $t_{\rm rec}$ is the epoch of recombination. It turns out that the appropriate sound speed is likely to be very close to the relativistic sound speed $c_{\rm s} = c/\sqrt{3}$ and so $r_{\rm s}$ is a 'standard rod' at the epoch of recombination. Hu and Sugiyama (1995) and Hu *et al.* (1997) provide excellent introductions to the physics of the details of the predicted temperature power-spectrum of the Cosmic Microwave Background Radiation. This is a wonderful story, but there might be complications. For example, the standard theory is based upon a scale-free spectrum of perturbations with random phases. Although strings, defects and textures are not thought to be the dominant source of the initial perturbations, they might well be present at a modest level, sufficient to complicate the standard picture.

It is a very major technical challenge to measure these tiny temperature fluctuations in the Cosmic Microwave Background Radiation [PARTRIDGE]. In addition to the spectacular COBE observations, ground-based experiments are beginning to give a first impression of the shape of the power spectrum in the crucial range of angular scales $3^\circ > \theta > 10$

arcmin. The Princeton Saskatoon experiments provide a clear hint that there is a peak in the temperature power spectrum, roughly in the region of the first acoustic peak (Netterfield *et al.* 1997), and the Cambridge CAT experiments are consistent with the lower fluctuation spectrum expected beyond the first acoustic peak (Scott *et al.* 1996). Thus, the general shape of the fluctuation spectrum bears some overall resemblance to that predicted by the dark matter models. There is plainly great scope for dramatically improving the determination of the power spectrum of the perturbations and this is the objective of the NASA *MAP* and the ESA *Planck Surveyor* missions. These will enable the features in the power-spectrum of the preturbations to be determined with very high precision. It is rare to find cosmologists in unanimous agreement about anything, but the universal recognition of the singular importance of these missions is very impressive and persuasive.

5. Distant Galaxies

The last few years have seen a deluge of new results on distant galaxies. An important aspect of these studies is that they point clearly to the types of observation which will be the foundation of the astrophysics and cosmology of the 21^{st} century. To mention just a few examples, there have been projects such as the Canada-France Redshift Survey, the Hubble Deep Field, and the Keck Telescope studies of Lyman-α absorption line systems and Lyman-limit galaxies. These can be thought of as the beginning of the exploration of the ordinary stuff of the Universe in the redshift range $1 < z < 5$.

Let me highlight just a few of these exciting results:

1. There is now excellent agreement concerning the number counts of faint galaxies in the blue, red and infrared wavebands. The large excess of faint blue galaxies at $B > 22$ is in striking contrast to the counts of galaxies in the infrared waveband at 2.2 μm, which display at best a small excess of faint galaxies, relative to the expectations of uniform world models [ELLIS].
2. It is certain that a significant part of the excess of faint blue galaxies is associated with irregular/peculiar/merging systems, which are present in much greater numbers than in bright galaxy samples. A glance at the magnificent image of the Hubble Deep Field shows that about 25% of the blue galaxies look far from normal (Williams *et al.* 1996) [GRIFFITHS]. Ellis (1997) has, however, cautioned that the interpretation of these counts is far from trivial because of our lack of knowledge of the structures of normal galaxies in the ultraviolet waveband.
3. The Lyman-limit galaxies at $z \sim 3$ discovered by Steidel and his colleagues using multicolour techniques have given important insights into

the processes of star and galaxy formation in very distant galaxies (Steidel *et al.* 1996). The remarkable result they find is that the average star formation rate at these large redshifts is not so different from what we observe at the present epoch.

4. The results of the Canada-France Redshift Survey (Lilly *et al.* 1995) and of the somewhat deeper survey of Cowie *et al.* (1996) have, however, shown that there must have been much more star formation activity at redshifts $z \sim 1 - 2$ as compared with what is observed today.
5. The statistics of star-forming galaxies in these samples can be converted into a plot of star, or metal, formation rate as a function of redshift. These suggest that there was a maximum in the star formation rate at redshifts $z \sim 1 - 2$ (Madau *et al.* 1996).
6. These observations are pleasingly complementary to the decrease in comoving number density of HI absorbing clouds as a function of cosmic epoch observed by Storrie-Lombardi *et al.* (1994) from the statistics of Lyman-α absorbing systems in high redshift quasars.
7. These complementary results can be elegantly tied together in the formalism developed by Fall and Pei (1993) for the evolution of the enrichment of the heavy elements as a function of cosmic epoch.

One concern about the interpretation of these observations has been the extent to which the optical observations have been influenced by the effects of interstellar dust within the galaxies themselves. Star-formation activity takes place in dusty, obscured regions which can significantly influence the observability of young star-forming galaxies. One way of estimating the significance of such obscuration is to make observations of the distant Universe in the millimetre and sub-millimetre wavebands. The dust associated with star-forming regions is an intense emitter in these wavebands and the total millimetre/sub-millimetre luminosity of the galaxy is also a direct measure of the star formation rate. What makes this approach feasible observationally is the fact that the spectrum of dust in these spectral regions is strongly 'inverted'. The resulting K-corrections are so large and negative that a typical star-forming galaxy is expected to have essentially the same flux density, whatever its redshift in the range $1 < z < 10$ (Blain and Longair 1993).

Deep surveys in these wavebands have only recently become feasible as a result of the construction of instruments such as the sub-millimetre bolometer array receiver SCUBA operating on the James Clerk Maxwell Telescope. Smail, Ivison and Blain (1997) have made the first deep sub-millimetre surveys in the fields of two clusters of galaxies with SCUBA and have discovered a large population of faint sub-millimetre sources. Although only six sources were discovered in the two fields, their number density on the sky suggests that the population of these galaxies has evolved strongly with cosmic epoch. It is already known that one of these sources is at a redshift of 1 and the other at 2.9. The numbers of these sources are such that they suggest that there are many more distant star-forming galaxies at large redshifts than indicated by the numbers of faint blue galaxies in the Hubble Deep Field. These are important new results and open up yet another way of probing the evolution of galaxies over the critical redshift interval $1 < z < 10$.

One final remark concerns the relation of these observations to the evolution of active galaxies, such as quasars, radio galaxies and X-ray sources [HASINGER, KELLERMANN]. It has been established for some time that these classes of object display strong evolutionary changes with cosmic epoch. To a good approximation, the cosmic evolution of these classes of objects can be accounted for, if it is assumed that their luminosity functions were shifted in luminosity as $L(z) = L_0(1+z)^3$ over the redshift interval $0 < z < 2$. There has been some debate as to whether the source distributions continue with this enhanced comoving number density to larger redshifts, or whether their comoving number density decreases from the maximum value about $z \sim 2$ to larger redshifts.

There is now clear evidence, both from studies of complete deep radio samples and from large redshift quasar studies that the population of active galaxies does indeed decrease at large redshifts (Dunlop 1997) [BOYLE]. As pointed out by Dunlop, the star-formation rate derived from the optical observations by Madau *et al.* (1996), and the integrated non-thermal emission of the active galaxies have very similar forms, as a function of cosmic epoch. This would still be the case, if the sub-millimetre star-forming galaxies discovered by Smail *et al.* (1997) are taken into account. This provides an important clue to the relation between the evolution of the normal stellar populations of galaxies and the powerful non-thermal processes associated with their nuclei. The sum of these observations suggests that they have the same origin, namely, the presence of large amounts of gas in a young galaxy, which is available either to form stars, or to power an active galactic nucleus. This close relation between the active nuclei of galaxies and their stellar populations is reinforced by our HST observations of the properties of the 3CR radio galaxies. These powerful radio sources partake in the strong cosmological evolution of the radio source population and those at large redshifts are clearly evolving in a much denser gaseous environment than their counterparts at low redshift (Best, Longair and Röttgering 1997).

6. Perspectives

There has only been space to discuss selected highlights of the vast amount of new observational material which has recently become available relevant to the subject of this symposium. In parallel with these, the theoretical underpinning of these developments has been quite remarkable. No one could have guessed how rapid the advances would have been in observational and theoretical cosmology, say, ten years ago. A great deal remains to be sorted out but these observations and their theoretical interpretation indicate clearly the very rich areas of cosmological investigation which have been opened up by the new technical capabilities of the coming generation of 8-10-metre class telescopes and space facilities such as the HST. The importance of developing new facilities for tackling these problems is self-evident. The Next Generation Space Telescope, the *MAP* and *Planck Surveyor* space missions, the large sub-millimetre array programmes being developed in Japan, the USA and Europe are central to the continuing exploitation of some of the greatest scientific discoveries of the final years of the 20$^{\rm th}$ century.

7. Acknowledgements

The writing of this review was undertaken while I was a Visting Fellow at the Space Telescope Science Institute. I am most grateful to Dr. Bob Williams and his colleagues for their splendid hospitality and support during my visit.

References

Bahcall, N. (1997). In *Critical Dialogues in Cosmology*, (ed. N. Turok). World Scientific (in press).
Bennett, C.L., Banday, A.J., Gorski, K.M., Hinshaw, G., Jackson, P., Koegstra, P., Kogut, A., Smoot, G.F., Wilkinson, D.T. and Wright, E.L. (1996). *ApJ*, **464**, L1.
Best, P.N., Longair, M.S. and Röttgerig, H.J.A. (1997). *MNRAS*, (in press)
Blain, A.W. and Longair, M.S. (1993). *MNRAS*, **264**, 509.
Bolte, M. (1997). In *Critical Dialogues in Cosmology*, (ed. N. Turok). World Scientific (in press).
Challinor, A. and Lasenby, A. (1997). *ApJ*, (in press).
Cowie, L.L., Gardner, J.P., Hu, E.M., Songaila, A., Hodapp, K.-H. and Wainscoat, P.J. (1994). *Nature*, **371**, 43.
Cowie, L.L., Songaila, A., Hu, E.M. and Cohen. J.D. (1996). *AJ*, **112**, 839.
Dunlop, J.S. (1997). In *Observational Cosmology with the New Radio Surveys*, (eds. M. Bremer *et al.*). Dordrecht: Kluwer Academic Publishers.
Ellis, R.G. (1997). *ARA&A*, **35**, 389.
Fall, S.M. and Pei, Y.C. (1993). *ApJ*, **402**, 479.
Feast, M.W. and Catchpole, R.M. (1997). *MNRAS*, **286**, L1.
Ge, J., Bechtold, J. and Black, J.H. (1997). *ApJ*, **474**, 67.
Geller, M.J. and Huchra, J.P. (1989). *Science*, **246**, 897.

Goldhaber, G., Deustra, S., Gabi, S., Groom, D., Hook, I., Kim, A., Kim, M., Lee, J., Pain, R., Pennypacker, C., Perlmutter, S., Small, I., Goobar, A., Ellis, R., McMahon, R., Boyle, B., Bunclark, P., Carter, D., Glazebrook, K., Irwin, M., Newberg, H., Filippenko, A.V., Matheson, T., Dopita, M., Mould, J. and Couch, W. (1997). In *Thermonuclear Supernovae*, (eds. P. Ruiz-Lapuente, R.Canal and J. Isern), 777. Dordrecht: Kluwer Academic Publishers.

Hogan, C.J. (1997). In *Critical Dialogues in Cosmology*, (ed. N. Turok). World Scientific (in press).

Hu, W. and Sugiyama, N. (1995). *ApJ*, **444**, 489.

Hu, W. and Sugiyama, N. and Silk, J. (1997). *Nature*, **386**, 37.

Kochanek, C.S. (1996). *ApJ*, **466**, 638.

Kundic, T., Turner, E.T., Colley, W., Gott, J.R. III, Rhoads, J.E., Wang, Y., Bergeron, L.E., Gloria, K.A., Long, D.C., Malhorta, S. and Wambsganss, J. (1997). *ApJ*, **482**, 75.

Lilly, S.J., Tresse, L., Hammer, F., Crampton, D. and LeFevre, O. (1995). *ApJ*, **455**, 108.

Lin, H., Kirshner, R.P., Shectman, S.A., Landy, S.P., Oemler, A., Tucker, D.L. and Schechter, P.L. (1996). *ApJ*, **471**, 617.

Madau, P., Ferguson, H.C., Dickenson, M.E., Giavalisco, M., Steidel, C.C. & Fruchter, A. (1996). *MNRAS*, **283**, 1388.

Maddox, S.J., Efstathiou, G., Sutherland, W.G. and Loveday, J. (1990). *MNRAS*, **242**, 43P.

Myers, S.T., Baker, J.E., Readhead, A.C.S, Leitch, E.M. and Herbig, T. (1997). *ApJ*, **485**, 1.

Netterfield, C.B., Devlin, M.J., Jarolik, N., Page, L. and Wollack, E.J. (1997). *ApJ*, **474**, 47.

Peacock, J.A. and Dodds, S.J. (1994). *MNRAS*, **267**, 1020.

Perlmutter, S., Boyle, B., Bunclark, P., Carter, D., Couch, W., Deustua, S., Dopita, M., Ellis, R., Fillipenko, A.V., Gabi, S., Glazebrook, K., Goldhaber, G., Goobar, A., Groom, D., Hook, I., Irwin, M., Kim, A., Kim, M., Lee, J., Matheson, T., McMahon, R., Newberg, H., Pain, R., Pennypacker, C. and Smail, I. (1996). *Nuclear Phys. B, Proc. Suppl.* **51B**, 20.

Rephaeli, Y. and Yankovitch, D. (1997). *ApJ*, **481**, L55.

Schramm, D. (1990). In *Astrophysical Ages and Dating Methods*, (eds. E. Vangioni-Flam, M. Casse, J. Audouze and T. Tran Thanh Van, . Gif-sur-Yvettes: Editions Frontieres.

Scott, P.F., Saunders,R., Pooley, G., OSullivan, C., Lasenby, A.N., Jones, M., Hobson, M.P., Duffett-Smith, P. and Baker, J. (1996). *ApJ*, **461**, 1.

Smail, I., Ivison, R. and Blain, A.W. (1997). *ApJ*, (in press).

Steidel, C.C., Giavalisco, M., Pettini, M., Dickenson, M. and Adelberger, K.L. (1996). *AJ*, **112**, 2519.

Storrie-Lombardi, L.J., McMahon, R.G., Irwin, M.J. and Hazard, C. (1994). *ApJ*, **427**, L13.

Sunyaev, R.A. and Zeldovich, Ya.B. (1970). *Astrophys. Sp. Sci.*, **9**, 368.

Webb, J.K., Carswell, R.F., Lanzetta, K.M., Ferlet, R., Lemoine, M., Vidal-Madjar, A. and Bowen, D.V. (1997). *Nature*, **388**, 250.

Williams, R.E., Blacker, B., Dickinson, M., van Dyke Dixon, W., Ferguson, H.C., Fruchter, A.S., Giavalisco, M., Gilliland, R.L., Heyer, I., Katsanis, R., Levey, Z., Lucas, R.A., McElroy, D.B., Petro, L. and Postman, M. (1996). *AJ*, **112**, 1335.