SUMMARY

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OBSERVATIONAL COSMOLOGY 1986

A summary of IAU Symposium No 124, Beijing, China

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> "This symposium marks the real beginning of observational cosmology",
> *Allan Sandage, 29 August 1986.*

INTRODUCTION

It is a pleasure to be invited to attempt to summarise the very intense work of the last 6 days. Virtually all aspects of contemporary observational cosmology have been described and debated and it is my task to try to put this wealth of new material into context. As in all such surveys, allowance must be made for personal bias - like everyone else, I am sure I am giving an unbiased view but you must judge for yourselves!

First of all, my general impressions. I was struck by two aspects of the symposium. First, with a few important exceptions, there is now really quite remarkable agreement between observers about many of the most important observations. Let me list some of the topics on which there was substantial agreement.

- the isotropy and spectrum of the Microwave Background Radiation.
- the existence of voids on scales up to at least 60 Mpc.
- the counts of faint galaxies.
- the counts of radio sources.
- the decrease in the comoving space density of quasars at redshifts greater than about two. This is not a selection effect.
- the spatial distribution of Lyman-α absorbing clouds at large redshifts.
- quasar clustering, or rather, the lack of it.

Second, on the theoretical side, many important advances have been made but there is no complete theory for many of the most important observations and many plausible theories can account for them. I would suggest that, at this moment, there is much better agreement about the observations than there is about their interpretation. I believe this is a much healthier situation than if it were the other way around.

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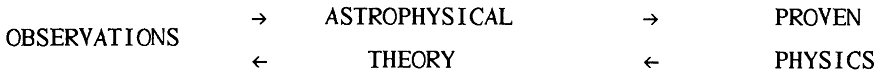
I was moved last night by the remark quoted at the beginning of this review, made to me by Dr Allan Sandage. Coming as it does from one of the most distinguished pioneers of the subject, one can appreciate the huge leaps in observational capability and astrophysical insight which we are now gaining from the efforts of many outstanding observers and theoreticians. I hope I will be able to do justice to his vision.

Let me make two methodological remarks which are appropriate to setting the framework for the discussion. The first concerns *the determination of cosmological parameters.* In principle, we would like to determine independently the five parameters, H_0 the Hubble constant, T_0 the age of the Universe, q_0 the deceleration parameter, Ω the density parameter and Λ_0 the cosmological constant. These are all independently determinable, in principle, and they provide key tests of the applicability of Einstein's General Theory of Relativity on the very largest scales accessible to us. For example, in classical general relativity with $\Lambda_0=0$, $\Omega=2q_0$ and T_0 is a unique function to Ω and H_0. If $\Lambda_0\neq0$, $\Omega=2q_0 + 2/3\ \Lambda H_0^{-2}$ and T_0 again is a different unique function of H_0, Ω, q_0 and Λ. These relations are thus falsifiable. The determination of the parameters has, however, proved to be extraordinarily difficult and I believe it will be a very long time before these tests become possible. I therefore believe that self-consistency is probably the best we can reasonably hope for, although we must not lose sight of the important goal of measuring all the parameters independently.

The second concerns the way in which we undertake astrophysical cosmology. I can represent the procedure by the following flow diagram.



It is important to note the second reversible interaction. In essentially all of the best astrophysical theory, the physics used is based upon proven laboratory experiments. This is why we can have confidence in the models of the thermal evolution of the Universe from temperatures of about 10^{13}K to 3K. My concern is that much currently fashionable theory is based upon vast extrapolations of the physics which has been tried and tested in the laboratory. The Grand Unified Thories of elementary particles, inflation, phase transitions in the early Universe, etc are far outside the present scope of experimental physics. As Dekel emphasised, there are no constraints on the particle physics and I worry that we have no experimental control over the theories. Some people rejoice that, maybe only in the very early Universe, can we test the theories of unification of the three (or four) forces of nature and regard this as a "useful" application of cosmology to the "real" world. My view is the opposite. The lack of constraint on the theory is for me a tragedy. Of course, there is no lack of examples of astrophysical problems leading to new fundamental physics. There are examples such as Kepler's laws of planetary motion leading to Newton's laws of gravity and of motion; Fred Hoyle's remarkable prediction of the ^{12}C resonance which leads to the triple-α process and so on. I believe, however, that in none of the previous examples has the extrapolation been so enormous or so ambitious. My worry is that theoretical internal self-consistency may be all that can be achieved but perhaps I am being unduly pessimistic. The ideas are certainly very persuasive

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and have opened up new areas of astrophysical endeavour.

In the summary which follows, I will review the proceedings of the Symposium, not from the point of view of the expert but from the point of view of what I will tell my students about the impact of the new work upon the standard lecture course on Astrophysical Cosmology which I have been delivering for the last few years. It has seven chapters as follows:

1. Fundamental Observations
2. Classical World Models of General Relativity
3. The Determination of Cosmological Parameters H_0, T_0, q_0, Ω and Λ
4. Astrophysical Evolution with Cosmic Epoch
5. Thermal History of the Universe - First Approximation to the Real Universe
6. Second Approximation - The Universe with Small Perturbations
7. Third Approximation - The Non-Linear Universe

I will tell my students what was *and* what was not said at the Symposium.

Chapter 1. Fundamental Observations

1.1 *The Isotropy of the Universe.* The Microwave Bacground Radiation still provides us with the best evidence that, on the global scale, the Universe is isotropic. **Partridge** and **Lukash** presented reviews of the large scale isotropy and the independent surveys are now in excellent agreement. Lukash's images of the whole sky showing clearly the dipole anisotropy were particularly impressive. There is agreement that on the large scale there is a dipole component with amplitude $\Delta T \approx 3$mK with maximum intensity in the direction 11^{h} -5°. No other higher moments in the distribution of the radiation on the celestial sphere have been detected, the limits on the quadruple and octopole moments being $\Delta T/T < 5 \times 10^{-5}$. The significance of this level of smoothness for possible anisotropic behaviour of the models in the early Universe was alluded to by Lukash.

There is also excellent agreement about the thermal spectrum of the radiation. **Partridge**, **Halpern** and **Mandolesi** showed that the observations are all now consistent with a Planckian spectrum at $T = 2.75$K. It is of astrophysical importance that independent measurements of the brightness temperature in the Rayleigh-Jeans and Wien regions of the spectrum give the same temperature. This sets important constraints on the amount of Compton heating which could have occurred since the effects of this scattering is to shift the whole spectrum to higher frequencies but conserving the numbers of photons, thus leading to a higher temperature in the Wien region as compared to the Rayleigh-Jeans region.

Restricting attention to large angular scales, there is now excellent evidence for the isotropy of the Universe as defined by discrete objects such as galaxies, quasars and radio sources. The radio sources have long been known to display an isotropic distribution on the sky, limited only by counting statistics. The faint galaxy counts now also show good agreement. **Ellis** and **Koo** showed independent galaxy counts to 24-25 magnitude in which there were small variations in the numbers of galaxies counted from area to area but both obtained the same average numbers and variations. Furthermore, the origin of these flucuations could be

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elegantly accounted for in terms of the clumpiness of the distribution of galaxies with redshift. The latter is associated with the "spongy" distribution of galaxies and how many galaxies are observed depends upon how many "sheets" are intersected along the line of sight.

Large unbiassed samples of quasars are now becoming available specifically to test their clustering properties. **Chu, Clowes, Shaver** and **Boyle** described the results of these studies. Thanks to the use of high speed measuring machines, it is now possible to generate large samples of quasars objectively over several Schmidt telescope fields. For example, Clowes and Shaver discussed a major programme in which over 1000 quasars were found in about 100 square degrees. Objective prism redshifts enabled their three as well as two diminsional clustering to be tested. The quasars at redshifts $z>2$ appear to be randomly distributed on the sky. Shaver and Chu showed that there is some evidence for small-scale clustering at redshifts $z<2$ but this needs further investigation because the quasars were not drawn from homogeneous catalogues, although these authors have made every attempt to make allowance for inhomogeneities and incompleteness. In their complete samples, Boyle finds evidence at the 3σ level for quasar clustering on scales less than $10h^{-1}$ Mpc but Crampton does not.

1.2 *The Homogeneity of the Universe.* The observations described in Section 1.1 show that on large enough scales the Universe is isotropic and hence homogeneous but this is certainly not true on small scales. Holes, voids, sheets and filaments are apparent in the distribution of galaxies. The Centre for Astrophysics (CfA) redshift survey of galaxies, described by **Geller** is one of the most important surveys ever carried out. She described how the aim is to measure the velocities of over 30,000 galaxies from the Zwicky catalogue of galaxies, a task which is already more than half completed but which it is estimated will take a further 5 years to complete. The areas now completed present a quite remarkable picture of the distribution of galaxies, convincing evidence being observed for large voids. Geller made a number of important points about the interpretation of these pictures. First, it is likely that the largest of the voids observed, about 60 Mpc, is simply limited by the size of the survey - larger voids might well be present but would not be readily identifiable in the CfA survey. Second, from slices taken in neighbouring redshift intervals, it appears that the filamentary structure seen is not in linear filaments but rather in surfaces about holes or voids. This picture is fully supported by the much deeper redshift surveys described by **Ellis** and **Koo** in which pronounced clumping of galaxies in redshift along the line of sight is observed. Third, many of the sheets appear to be remarkably thin.

Many questions can be asked about the nature of the voids. For example, what is the void-probability distribution, a function introduced by **Lachièze-Rey** and his colleagues? How empty are the voids? **Dekel** quoted a galaxy density of only 10% of the surrounding distribution. **Chincarini** showed that dwarf galaxies have been found in some of the voids. These are potentially important clues which need to be substantiated by much large bodies of data.

On larger scales, **Bahcall** described the two-point correlation functions for clusters and superclusters. These indicate clearly the existence of structures on scales up to 150 Mpc in the case of supercluster-supercluster associations. The exact nature of these correlations is, at the moment, limited by the available samples of clusters

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and superclusters, the best data being drawn from the Abell catalogue of clusters. The clear trend exhibited by these data is that the large scale structures are more strongly correlated than the galaxies and the very largest scale structures more strongly correlated than clusters. These observations are broadly consistent with a hierarchical picture in which only a certain fraction of galaxies are associated with the cluster-cluster associations and only a certain fraction of the cluster-cluster associations with the supercluster-supercluster associations. These observations should be greatly improved over the next few years as the major galaxy and cluster surveys of the southern hemisphere become available, one of which was described by **Olowin**.

There remains the question of what one means by a two-point correlation function in the presence of voids. Everyone recognises that $\xi(r)$ is a crude but simple measure of the clustering tendency of objects about any given object. It remains to be seen what the best statistic for the distribution of galaxies on the large scale will turn out to be.

Another hot topic was the observation of large scale streaming velocities of galaxies. The history of these studies dates back to the much-discussed Rubin and Ford effect and is a good example of an observation, which many people wished would go away, suddenly becoming eminently respectable. **Davies** reported streaming velocities of ≈ 600 km s^{-1} from a study of the distances and recession velocities of elliptical galaxies. To complicate the issue, the streaming velocity is not in the direction of the maximum of the dipole component of the Microwave Background Radiation. No simple picture emerged from the debate but I found it interesting that the magnitudes of the random velocities of galaxies seemed to be creeping up, velocities of 300 - 400 km s^{-1} being typical.

It is amusing to note that these velocities have been discovered just when the voids have become an integral part of the large scale distribution of galaxies. There is a positive and negative side to this story. On the positive side, a streaming velocity of 600 km s^{-1} will move galaxies about 10 Mpc during the age of the Universe. Thus, considerable regions could be evacuated of galaxies, but not on the scale of the largest structures known. On the negative side, such velocities would destroy the rather narrow sheets of galaxies observed in the CfA survey. The situation is unclear.

1.3 *The Hubble Flow.* It is worthwhile emphasising the point made by **Sandage** that the Hubble flow, $v \propto r$, is very well defined in the redshift range $0.01 < z \lesssim 0.5$ by the brightest galaxies in clusters. Indeed, I believe this must be one of the best defined linear correlations in all astronomy. The same result is found if one selects strong radio galaxies. The purist would want to know *why* these objects are apparently such good standard candles. In the case of the cluster galaxies, one can make a good case on the basis of the universal form of the luminosity function of galaxies and adding on, if desired, the effects of cannibalism. In other words, the case can be made very compelling that $v \propto r$ out to $z = 0.5$. In the case of the radio galaxies, we do not understand yet why it is that it is only the brightest galaxies which become strong radio sources and so the case is not so compelling. However, empirically, it is found that the presence of strong radio emission selects galaxies with a remarkably small spread in absolute magnitude.

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Another important point is that it is *only* necessary to find $v \propto r$ in the range 0 to 0.5. At larger redshifts, the Universe was much younger than it is now and hence the dynamics of the Universe and the luminosities of galaxies may well have changed as we discuss in Chapter 4.

1.4 *Conclusion.* I conclude that the basic observations that we are necessary to derive the Robertson-Walker metric are now in rather good shape. Since all participants in this Symposium can derive the classical Friedmann models of the Universe, we can proceed directly to Chapter 3. (If you really want a **Chapter 2**, see, for example, Chapters 14 and 15 of my book "Theoretical Concepts in Physics", Cambridge University Press, 1986).

Chapter 3. Determination of Cosmological Parameters.

I stress again that H_0, T_0, q_0, Ω and Λ are all in principle observable parameters.

3.1 *Hubble's Constant H_0.* **Tammann** presented the problem of determining H_0 with his usual clarity and forcefulness. He emphasised the key problems of eliminating Malmquist bias and of measuring accurate distances to nearby galaxies. His results favour values of H_0 close to 50 km s^{-1} Mpc^{-1}. **Aaronson** used the infrared Tully-Fisher relation to find a value of H_0 of about 90 km s^{-1} Mpc^{-1} in data which showed no Malmquist bias. **Giraud** found evidence from an analysis of the Tully-Fisher relation for groups at different distances for an increase in H_0 with distance, high values of H_0 being favoured at larger distances. I have simply stated what was said at the symposium. It has a familiar ring to it. As I tell my students, you should *not* take averages in this case in order to find a best estimate of H_0 because the determinations are dominated by *systematic* rather than *random* errors.

This is an unhappy situation which has lasted for many years now. I believe that part of the problem is the need to use distance indicators which are found from empirical studies of the properties of galaxies and one would dearly love to have these founded upon a firm astrophysical basis with predictive power. This will eventually come about but, at the moment, we seem to be faced with an impasse.

Tammann listed a number of reasons why H_0 = 100 km s^{-1} Mpc^{-1} is unpleasant and, indeed, I believe each of his arguments can be used to make independent estimates of H_0 which would favour values close to 50 km s^{-1} Mpc^{-1}. Among these arguments, was the determination of T_0, the age of the Universe, from the ages of globular clusters. The quoted estimates are about 17±3 billion years which is uncomfortably large if H_0 = 100 km s^{-1} Mpc^{-1} unless we consider models with $\Lambda \neq 0$. Narlikar correctly urged us not to use this argument as a way of estimating H_0 for the reasons I outlined in the introduction. I believe every astrophysicist has to make up his or her own mind about their attitude to this problem. My own approach is highly pragmatic. There is no evidence that $\Lambda \neq 0$ and I find the classical Friedmann models to have the great appeals of simplicity and elegance. Therefore, if I need H_0 in my calculations, I prefer to use H_0 = 50 km s^{-1} Mpc^{-1} as a "safe" value consistent with stellar evolution as we understand it just now. I realise this value is in conflict with the values favoured by de Vaucouleurs, Aaronson and others.

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Ideally, we need new *physical* methods of estimating H_0. **Birkinshaw** described the Sunyaev-Zeldovich-Gunn test using the hot gas clouds in clusters and produced the remarkably unhelpful result $H_0 > 11$ km s^{-1} Mpc^{-1}. **Canizares** and **Burke** showed that, in principle, we can find H_0 if we can observe the time delays in well-modelled gravitational lenses. This still remains something for the future because, as Canizares pointed out, we have yet to observe the time delay expected in any of the gravitational lenses.

Dr Sandage suggested to me that we might propose a moritorium on estimates of H_0. I would certainly put a moritorium on Birkinshaw's estimates until there is a real prospect of getting considerably improved precision by the SZG technique. I am against a moritorium on the 50/100 dichotomy because there is important astrophysics to be unravelled and we can only hope that, as the data are better understood astrophysically, the origins of the discrepancies can be resolved.

3.2 *The decleration parameter* q_0. **Spinrad** brought us up to date on the infrared redshift-magnitude relation for clusters and radio galaxies. It will do no harm if I repeat my admiration for his perseverence in pressing on with the difficult task of measuring spectra and redshifts for the very faint radio galaxies in the 3CR and 1-Jy samples which have produced the remarkable results he showed us. I should of course declare an interest in this work, some of which I carried out in collaboration with Dr Simon Lilly. The work described by Spinrad has aroused considerably optimism about the possibilities of determining q_0 and so I will use my "reviewer's privilege" to give my own opinion about some of this work.

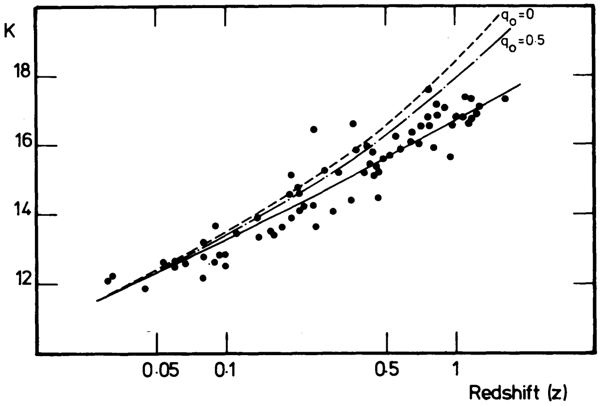

Figure 1. The infrared K-z Hubble diagram. The dashed lines indicate the predicted relation for an elliptical galaxy of constant luminosity for $q_0 = 0$ and 0.5. The solid line is a model-fit to the data showing luminosity evolution of about a magnitude at z=1. (from Lilly, S.J. and Longair, M.S., 1984. Mon. Not R. astr. Soc., 211, page 849).

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I have reproduced our version of the K-z relation for radio galaxies in Figure 1. I would make the following points about the diagram. First, note the small dispersion in intrinsic absolute magnitudes at small and large redshifts. At $z < 0.5$ and $z > 1$, the dispersion remains about 0.5 magnitudes showing that the galaxies display systematic behaviour over this redshift range. The small dispersion is confirmed by the new points Spinrad has added from the 1-Jy sample. Second, we have to look very carefully into the various correlations which might bias the relation. **Yates** described the tests he has made to search for correlations with radio luminosity and finds a small positive correlation which may be related to the environment of the radio galaxy. We need to be convinced about the significance of such effects before we can begin to estimate q_0. Third, the correction for stellar evolution of the parent population is relatively straightforward in the infrared waveband. Fourth, although the results are not yet of much significance, Simon Lilly found that marginally better agreement of the best-fitting line though our data was obtained with $q_0 \sim 0-1$ with the evolution correction rather than a large q_0 without evolution. This indicates that the shape of the K-z relation could be used to help remove the evolutionary corrections if we had large enough statistics in the redshift range 1-2.

Taking all of this into consideration, I believe we can say already that q_0 lies in the range 0 to 1 but I would not be as optimistic as Spinrad just yet. Notice that, with the next generation of large telescopes and infrared spectrometers with low-noise detector materials, we should be able to test the evolution directly by making spectroscopic observations in the near infrared wavebands.

Wampler described an intriguing reanalysis of the optical redshift-magnitude relation for complete samples of quasars and, after making allowance for various known correlations with the data, found a best fitting value of q_0 of about 3, almost exactly the same as we found from the K-z relation for radio galaxies uncorrected for stellar evolution. Does this suggest that the underlying luminosity evolution in quasars is the same as the optical luminosity of the stellar populations in radio galaxies? If this were true, it would be very important because there might be some direct or indirect physical relation between these very different types of activity. This will certainly repay further study and has implications for the evolution of the luminosity function of quasars.

Other methods of finding q_0 were mentioned but many are, at this stage, masked by evolutionary effects. **Kapahi** described the angular diameter-redshift test for double radio sources and **Sargent** the possibility of using absorption lines in distant quasars. **Loh** discussed number counts and claimed good results using multicolour photometric redshifts - this needs detailed scrutiny in the light of what is now known about the spectra of galaxies at redshifts greater than 0.5, a point emphasised by **Ellis**.

3.3 *The density parameter* Ω. **Tully** and **Sancisi** reviewed the various approaches to determining the local density of matter in the Universe. Much of this story was very familiar. Spiral and elliptical galaxies have mass-luminosity ratios of about 10-30, corresponding to $\Omega \sim 0.02$. The spiral galaxies must have haloes consisting of some form of dark matter to maintain the flatness of their rotation curves out to the largest radii measured. Notice that Sancisi quoted an M/L ratio of 5000 in the outermost regions of some of his galaxies. The best studied great

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clusters have M/L ~ 350-500 and, if this is typical of all luminous matter in the Universe, $\Omega \sim 0.2$. Tully reported a new estimate of Ω from his studies of nearby groups of galaxies and found $\Omega \gtrsim 0.1$.

Through all these estimates runs the difficult problem of whether or not the hidden mass is distributed like the galaxies. This problem is particularly problematic for the Virgo cluster infall test described by Tully and for the cosmic virial theorem. In both cases, the velocities are driven by perturbations in the average density distribution of matter. In the case of Virgo cluster infall, the velocity is given by $v \propto H_0 \, r \, \Omega^{0.6} \, \delta$ where δ is the average density enhancement due to the Local Supercluster. If we assume *all* the matter is distributed like the galaxies, $\delta = 2$ and $\Omega = 0.3$. However, suppose the hidden mass is much more evenly distributed than the galaxies. Then $\delta < 2$ overall and hence Ω is greater. Exactly the same argument bedevils the cosmic virial theorem.

Rowan-Robinson reported an intriguing new result on the origin of the acceleration which might drive our peculiar velocity of 600 $\mathrm{kms^{-1}}$ with respect to the Microwave Background Radiation. He used the distribution of IRAS galaxies to work out the local gravitational acceleration $\underline{g}$ due to galaxies, assuming they are tracers of the mass and finds that the acceleration vector is in the same direction as the maximum of the dipole component of the microwave background. His calculations provide an estimate of $\Omega = 1$. This appears to be in contradiction with the results of the cosmic virial theorem and the Virgo cluster infall test which with the same assumptions suggest $\Omega \sim 0.2\text{-}0.3$. The origin of the discrepancy is not understood. Many more velocities are needed for galaxies in the IRAS sample so that more secure estimates of $\underline{g}$ can be made. In all cases, the question of the distribution of the visible and dark matter is crucial. **Sancisi** and **Burke** showed from the rotation curves of galaxies and studies of gravitational lenses respectively that it is certainly not true on the scale of galaxies.

One interesting new result on the possible contribution of massive black holes to the present mass density of the Universe came from **Hewitt's** analysis of the frequency of gravitational lensing among 4000 radio sources surveyed for evidence of this phenomenon. The small number of candidates found among this sample sets limits to the number of gravitational lenses of different masses present in the Universe. The statistical results are now reaching very interesting limits, so that, for example, a value of Ω=1 in lenses of mass $10^{10}\text{-}10^{12} M_{\odot}$ can be excluded.

Chapter 4 Astrophysical Evolution with Cosmic Epoch.

4.1 *Active galaxies and quasars.* I will consider first the cosmological evolution of "non-thermal" sources. The radio sources, both radio galaxies and radio quasars, and the optically selected samples of quasars show similar strong cosmic evolution. **Wall** surveyed the radio data and showed the type of evolutionary behaviour required by both steep and flat spectrum radio sources. **Schmidt** and **Boyle** showed that strong *luminosity* evolution of the population of radio quiet quasars could account for the quasar counts and the redshift distributions at different magnitudes. **Deng** showed how the evolution could be inferred over small redshift ranges, carefully taking account of the selection effects which are present in objective prism surveys. There is good internal consistency concerning the

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secure now. The interpretation of the effect is not clear but the effect of the environment in changing the properties of the double sources at large redshifts was convincingly demonstrated by **Miley** who showed that the double structures of quasars with $z > 1.5$ are much more distorted than those at lower redshifts. According to his observations the environments of radio sources at $z > 1.5$ are less benign than those at lower redshifts.

The galactic environments of radio galaxies and quasars were addressed by **Yee**, his results showing that the quasars at redshifts $z > 0.5$ are in richer cluster environments than those at small redshifts. **Yates** speculated that the same may be true of radio galaxies. In turn the environment, both the numbers of companion galaxies and the ambient gas, can contribute to the evolutionary effects. In an elegant piece of work on Seyfert galaxies, **Byrd** showed how the close companions observed in many of them might lead to Seyfert activity.

4.2 *Lyman-α absorption clouds.* There now seems to be agreement about the evolution of the comoving number density of Lyman-α absorbing clouds in the ultraviolet spectra of quasars. Up to the limit of observation, $z = 3$, **Sargent** and **Chen** reported that the number of clouds increases as $(1+z)^2$. It is interesting that in contrast, the quasar number density at a given luminosity is decreasing roughly as $(1+z)^{-2}$ at $z \gtrsim 2$. The cause of this behaviour is not understood, largely because the nature of Lyman-α clouds is not clear - are they expanding clouds, or are they bound? Are they being eroded by the flux of ultraviolet radiation from quasars? **Webb** reported the interesting result that the Lyman-α clouds are clustered on velocity scales less than 150 km s^{-1}.

4.3 *Galaxies in general.* The beautiful new results of **Ellis** and **Koo** provide important constraints on galaxy evolution at redshifts less than about 0.5. The counts of galaxies show a small excess over the predictions of uniform, non-evolving world models at $m \approx 22$ but not at the faintest magnitudes. There is thus little scope for evolution in the sense that the galaxies were brighter in the past. This result is confirmed by the deep spectroscopic surveys carried out by both groups. No evidence of evolution is found in the redshift distribution at a given apparent magnitude. The redshift distributions discussed by **Ellis** and **Koo** and by **Karachentsev** show a highly non-uniform distribution and they very plausibly suggest that this reflects the fact that the galaxies are confined to sheets which are part of the "spongy" structure of the distribution of galaxies.

The consistency of the counts and redshift distributions can clearly be used to set important limits on when galaxies in general first formed and I look to forward to hearing how useful a constraint this will be.

4.4 *The Radio Galaxies Again* The radio galaxies have already been mentioned in the context of the determination of q_0 where it was indicated that there is strong evidence that the evolution of the stellar populations of these galaxies is playing an important role. **Spinrad** has described his appraoch to these data and our own is very similar. I will indicate some of the differences - I do not believe there is any major disagreement between the actual observations. In our approach, we distinguish carefully between the radio galaxies and the brightest galaxies in clusters. Although these classes of galaxy seem to have similar luminosities at redshifts of 0.4 and greater, there may be differences at lower

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evolution of different classes of active system, although how the radio objects are selected from the population of quasars in general remains a thorny problem and was mentioned by **Machalski**.

There was also good agreement about the large redshift behaviour of the different populations of quasars. For the optically selected samples, the comoving number density of quasars decreases with increasing redshift beyond $z \sim 2$. This has been found in new surveys described by **Crampton** and **Schmidt** and a similar decline has been found by **Véron** who analysed data in the existing catalogues. The maximum in the comoving space density of sources occurs about a redshift of 2 and decreases to larger redshifts. A new largest-redshift quasar was reported by **Hewett**, $z = 4.01$, who had used automatic plate measuring techniques to extract candidate quasars. **Savage** reported the recent upsurge in the discovery of quasars with redshifts greater than 3.5 which has taken place over the last few months. Nonetheless, these discoveries are not sufficient to reverse the decline to large redshifts.

It is important that exactly the same behaviour has been found by Dunlop, Peacock and their colleagues in radio samples of quasars with flat radio spectra. This is a completely independent method of probing the evolution of quasars at large redshifts since the primary selection criterion is radio flux density. It should be emphasised that there is not a cut-off but rather a broad maximum in the comoving number density of quasars. I suspect a gaussian distribution of space density or of luminosity with cosmic time might be a good model which might have implications for the origin of galaxies and the strong cosmic evolution of quasars.

It will eventually be possible to undertake similar studies for discrete x-ray sources but at the moment the major surveys described by **Gioia** refer to bright source samples, similar in numbers to the 3CR survey of radio sources. Her extension of the Einstein medium flux-density survey to over 800 sources promises to be a major advance in the definition of the population of extragalactic x-ray sources. At the moment, the strongest constraint on the cosmological evolution of the properties of the x-ray population comes from the upper limit to their integrated intensity. As mentioned by **Schmidt** and **Setti**, luminosity evolution of the quasar population with a constant optical-x-ray spectral index is consistent with the limits imposed by the observed x-ray background whilst density evolution would result in too great an intensity because of the large numbers of low luminosity x-ray sources. **Boldt** surveyed the thorny problem of accounting for the intensity, spectrum and smoothness of the x-ray background. I fully endorse his point that the origin of the spectral break at 40 keV and the smoothness of the background pose major problems for most known classes of x-ray source.

Kapahi described new analyses of the redshift dependence of the sizes of double radio sources and found that all his results now require the intrinsic size of double sources to decrease with increasing redshift as $l = l_0 (1+z)^{-\beta}$ with $\beta = 1.5\text{-}3$. Although this may not look a difficult achievement, it is in fact a complicated problem because of the strong differential evolutionary effects which can strongly influence what types of source appear in different proportions at different flux densities. Up till now, I have not been wholly convinced that $\beta \neq 0$ because of the sensitivity of the test to small numbers of objects but I think the result looks

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redshifts which might be ascribed to dynamical evolution of the brightest galaxies in the clusters. Therefore, in the work by Lilly and myself, we are careful to consider only the radio galaxies. A powerful probe of the evolution of the galaxies is the use of the optical-infrared colour, R-K, for example. I show in Figure 2 our version of the R-K v redshift diagram. Also shown is the line "passive evolution" which corresponds to the predicted colours if galaxies formed all their stars very early on and the subsequent evolution is simply the decay of that initial stellar population. It is important that none of the observed points lie above this line which, in my view, corresponds to a very reasonable null hypothesis for galactic evolution. Below this line, we find a significant scatter in the observed points which is interpreted as meaning that the galaxies show star formation activity at the epochs observed. Spinrad interprets this in terms of a single model of the Bruzual type with μ = 0.7. We believe that the scatter is too great to be accounted for by a single model and that the evolution is associated with separate star formation events, possibly associated with the events which gave rise to the radio source. It is intriguing that some of points lie close to the "passive evolution" line suggesting that there is little on-going star formation activity in these galaxies.

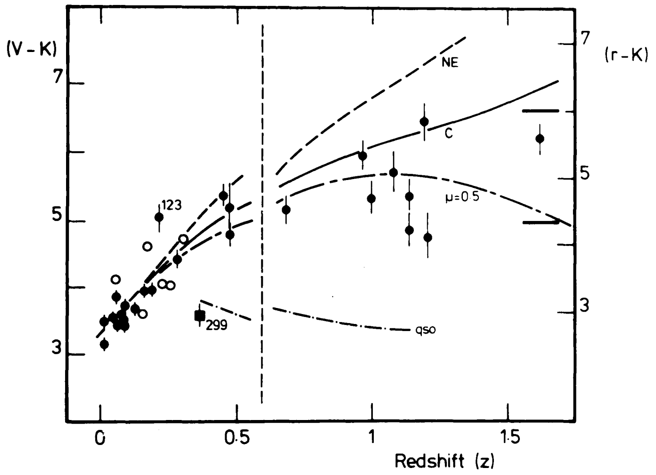

Figure 2. The optical-infrared colours (V-K) and (r-K) for 3CR radio galaxies. The C model represents a model including passive evolution of the stellar population of a standard elliptical galaxy. The model μ=0.5 is from Bruzual (from Lilly and Longair, op. cit., page 845).

Sandage discussed the observations of Spinrad and Hamilton who searched for evidence of evolution of the stellar populations of galaxies from variations in the amplitude of the 400 nm break with redshift. Spinrad finds evidence for a

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decrease in the break with increasing redshift, consistent with evolution of the stellar population whilst Hamilton does not. These and similar indicators of stellar populations provide crucial evidence on the evolution of the stellar populations of galaxies and, with the large telescopes of the future becoming a reality, we can hope that these studies can be extended to the largest redshift galaxies observed.

One of the most interesting results of this programme comes from the study of the 1-Jy sample of Allington-Smith which was designed to test the conclusions of the 3C observations and to extend it to larger redshifts. Figure 3 shows the R-K v K magnitude diagram, in which we have had to use K rather than redshift as a distance indicator because redshifts are not available for all the objects in the sample. It will be noted that there is a group of sources at faint magnitudes which appear to have the colours of passively evolving galaxies. We believe that these are likely to be passively evolving galaxies at redshifts in the range 1.5 to 3. If this is true they are of great cosmological interest because they must have formed at epochs significantly earlier than 3. Indeed, I believe that these data can already be used to set useful limits to the epochs at which these galaxies could

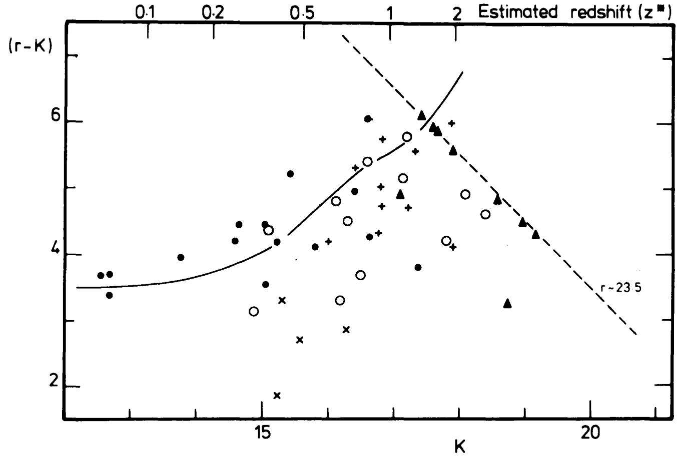

Figure 3. The (r-K)-K colour magnitude diagram for sources in the 1-Jy sample. The dashed line represents the limit r=23.5 to which identifications have been sought and the continuous curve indicates the locus of the passively evolving C model of Bruzual. An estimated redshift scale is shown along the top of the diagram (from Lilly, S.J., Longair, M.S. and Allington-Smith, J.R., 1985. Mon. Not. R. astr. Soc., 215, page 47).

have formed. For example, if the galaxies formed at redshifts of 3 or 4, then even if they undergo only passive evolution, none of them should be fainter than about K = 18 at any lower redshift. Studies of this type are of the greatest interest and much larger samples are needed to test these ideas.

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Chapter 5. The Thermal History of the Universe

What has now become the standard view of the thermal history of the Universe was elegantly described by **Audouze**. The subject is dominated by the necessity of synthesising the light elements ^4He, ^3He, D and ^7Li in their observed cosmic proportions. The beautiful new observations of **Duncan** showed how the abundance of ^7Li is a sensitive tracer of stellar evolution and also how there seems to be a more or less constant "primordial" abundance in those stars in which it is inferred that the convection zones are narrow and hence will not have convected the ^7Li into temperature regimes in which it would be depleted. The result of all these studies is that too little deuterium is produced if the density parameter Ω in baryons is greater than $0.2\ (50/H_0)^2$.

This has become such a compelling result that no-one is very keen to challenge it and it has become the prime basis for assuming that if the density of the Unverse is actually greater than this, we must call upon various forms of dark matter, massive neutrinos, etc. to make up the discrepancy. Indeed, much of the galaxy formation industry thrives upon the fact that dark matter in non-conventional forms may exist. It is therefore very important to test all the ways in which the argument might be circumvented. Most of the astrophysical proposals have proved unacceptable. One possibility raised by Audouze was that it might be possible to build conventional Universes with $\Omega = 1$ in baryons if there is some way of destroying some of the ^4He which is overproduced in these models. To quote some figures, in a standard $\Omega = 1$ Universe, about 26% ^4He and about an order of magnitude too little D is produced. Therefore if only a little of the ^4He were converted into ^3He and D, we could probably produce the observed abundances of the light elements. How this could be done is not clear. One possibility mentioned by Audouze is that there might exist massive unstable particles with half lives of about 10^{5-6} seconds which would leave the nucleosynthesis intact but which, on decaying into γ-rays, can dissociated some of the ^4He nuclei. This is perhaps a rather inelegant solution but I wonder if it is less contrived that the introduction of other forms of matter which have yet to be discovered experimentally such as cold dark matter, axions, cosmic strings, etc.

I only mention this possibility because of the central importance which the synthesis of the light elements now plays in our present best-buy picture of the Universe. If we were to find a way of allowing $\Omega_{\text{baryon}} = 1$, this would have very important repercussions for all cosmology. For example, as **Dekel** mentioned, there are models of galaxy formation with $\Omega = 1$ which can be made consistent with all the observations, including the low level of fluctuations in the Microwave Background Radiation.

Chapter 6. The Universe with Small Perturbations

The crucial confrontation between the theory and the observations lies with the upper limits to the fluctuations in the Microwave Background Radiation described by **Partridge** and **Davies**. **Silk** and **Dekel** expounded our present understanding of the origin of structure in the Universe, Silk talking the view that most of the observations can be accomodated in a single theory involving cold dark matter, Grand Unified Theories, inflation, etc. Dekel took a somewhat less ambitious

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view and delineated the rather wide range of parameter space which is still available for galaxy formation.

There are important issues for observational cosmologists to consider in these debates. There is no question but that a great deal of the relevant theory is currently being driven by the predictions of the theories of elementary particles and the attempts to unify all four forces of nature. It is these theories which have led to the plethora of new particles which could exist if the strong and the electro-weak theories are unified at very high energies. The possibility of inflation in the early stages can come about if the properties of the particles are such that the phase transition from the pseudo to the real vacuum solutions for the elementary particles occurs at a late enough stage. I am not competent to discourse in a meaningful way about the speculative areas in these theories but I would emphasise that we are not talking about any single theory of fundamental interactions which particle physicists have agreed about and which produces the physics we need to understand galaxy formation. Rather, the particle physicists have produced generalised features of the theory which can be adjusted to have cosmologically interesting results. However, this is very far from a real and provable picture of the early universe. I urge astrophysicists to recall **Dekel's** remark that the theory of elementary processes at these very high energies is essentially unconstrained.

I make these remarks simply to emphsaise that whilst we must listen with close attention to developments in the theory of elementary particles, as observational cosmologists we should not be blinded by them nor constrained by them in interpreting our data. Fashions can change quite quickly in the area of elementary particle physics. There are many separate components which are necessary in the theory of the origin of structure in the Universe and many of them are astrophysical questions which fall squarely within the province of observational cosmology.

This consideration leads to a personal conviction of mine that the theory of the origin of the large scale structure in the Universe is not one but many theories. Although Silk claimed that he had great success in discussing the origin of everything in the Universe within a single theory, I believe it is in fact a number of theories put together in a particular way. Let me list some of them:

- The theory of small perturbations in the Universe
- The theory of hierarchical clustering
- The theory of dissipative processes in the cosmological context
- The theory of explosive formation of galaxies and structures
- The astrophysics of galactic evolution

I am sure that one can add to this list. The point is that I have a personal preference to try and solve them one at a time rather than all simultaneously.

The present position concerning the theory of small perturbations was beautifully summarised by **Dekel.** It is worthwhile repeating the rather extensive parameter space which should be considered by theorists and observers

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- Ω = 0.1 to 1; Λ = ?; H_0 = ?
- Dark matter: baryonic, hot, warm, cold, unstable
- Fluctuations: adiabatic, isothermal
- Their origin: inflation, strings, their spectrum and probability distribution
- Explosions - astrophysical processes
- Relative distribution of visible and dark matter

I believe that the parameter space may well expand with time.

One methodological point which I believe may be of interest concerns the way in which the theories are compared with the observations. Many of these involve trying to obtain the correct shape and amplitude of the 2-point correlation function of galaxies $\xi_{gg}(r)$. The problem is that this may not trace the correlation function of the total mass of the Universe if there is dark matter present. I believe it may become of more interest to work in terms of the formation epochs of objects of different masses, since this should be related to the time when the perturbations which gave rise to galaxies, whatever their origin, became non-linear $\delta\rho/\rho \geqslant 1$. In Chapter 4 I indicated how limits can now be set to the epochs when various types of object, galaxies and radio galaxies, formed and other arguments can be made for larger scale systems. It may be that this is a stabler indicator of the point at which perturbations on various mass scales became unstable.

It remains the case that, of the various constraints upon the epoch of galaxy formation, those imposed by the absence of fluctuations in the Microwave Background Radiation are by far the most stringent. In fact, if fluctuations are not found within a factor of 10 increase in the sensitivity of the present experiments, we may be in for a major reappraisal of the theory of galaxy formation.

We should not forget that there may well be important clues about the properties of the initial fluctuations from careful interpretation of data available now. I was particularly impressed by the remarkable analysis described (and presented in three-dimensions) by Gott. His demonstration of how the topology of the large scale distribution of galaxies can be related to the random phases of the initial fluctuations was a remarkable instance of how the observational data on the large scale structure of the Universe can be used to gain important insights. It also gives us a powerful conceptual tool for envisaging the distribution of galaxies in three dimensions. It is this analysis which has instantly converted me to using the term "sponge-like" to describe the large scale distribution of galaxies.

Chapter 7. The Non-linear Universe

The non-linear Universe is the universe we know and love. It is the non-linearities which give rise to galaxies as we know them and one could characterise the problem of the origin of structure in the Universe as being one in which we attempt to unwind the non-linearities back to their linear stages. Essentially I include in this chapter all the astrophysical tools necessary to understand the properties of galaxies, quasars, radio sources, intergalactic clouds, etc. Let me give a brief and incomplete list of some of these phenomena.

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1) *The epoch of galaxy and object formation* I have emphasised this several times. Other observations not yet mentioned include:

   a) the observations of the near infrared background radiation by **Matsumoto** and the follow up observations by **Xie**. If this background is indeed a cosmological component, it is potentially of great importance for cosmology. Matsumoto showed that its intensity is not so different from the background intensity predicted by Peebles and Partridge long ago from young galaxies. The further investigation of the near infrared background seems a very important task.

   b) The mapping of the chemical distribution of the heavy element abundance in the metal-rich absorption systems at large redshifts promises to be an important tool for studying the formation of the general distribution of chemical elements in galaxies. **Hunstead** reported what he believed to be the first detection of low metal abundances in a large redshift absorption line system. Objects like this may help to trace the evolution of the chemical abundances of the elements in galaxies with cosmic epoch.

   c) **Swarup's** proposal to search for intergalactic hydrogen clouds associated with protoclusters is the type of observation which I believe must be pursued to give us further insight into the *terra incognita* which lies between redshifts of about 4 and 1000.

2) *The Reheating of the Intergalactic Gas* This remains one of the cosmological problems which attracts less attention than it deserves. Although **Setti** indicated that it would be pleasant to account for the observed intensity of the X-ray background by the thermal bremsstrahlung of intergalactic gas with $\Omega = 1$ and temperature $kT = 40$ keV, this would result in a very large intergalactic gas pressure which would compress the Lyman-α clouds. **Sargent** reported the rather stringent limits which can be placed upon the properties of the intergalactic gas if it is not to exert too great a pressure on the Lyman-α clouds. He also reported new upper limits to the number density of neutral hydrogen atoms at z=3 from a recent investigation of the Gunn-Peterson test for large redshift quasars. Less than a 5% decrement is observed implying $N_H \leqslant 2 \times 10^{-12} cm^{-3}$ at z=3. **Koo** reported the problem of ionising the intergalactic gas using his best estimates of the numbers of quasars which are inferred to be present at large redshifts. Presumably, a low enough intergalactic gas density could be ionised by the Lyman continuum flux emitted by quasars and it is important to know just how low this density might be. Related to this is the question of the redshift at which it is necessary to make the chemical elements observed in the most distant quasars and in the metal-rich intergalactic gas clouds. These questions are related to the epoch of formation of the first generations of stars.

3) *Astrophysical processes which affect $\xi(r)$ in the non-linear regime* It seems to me that explosions, the formation of quasars, etc quite inevitably lead to the biasing of galaxy formation in one way or another. Indeed, I would quite invert the problem. It seems to me that unbiassed galaxy formation is much more difficult to achieve that biassed galaxy formation and that the bias could easily go either way. This is a purely astrophysical question but the answer

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is important. For example, although the simulations of the hot dark matter picture with neutrinos seem to do too well in producing the spongy structure of the universe, this may well be softened by astrophysical processes such as explosions and quasar formation as described by **Dekel**.

4) *Astrophysics* Finally, I have to make a plea for a better understanding of the tools of astrophysical cosmology. This is not just for objects like galaxies, dwarf galaxies, clusters and quasars as would have been advocated by Baade (see **Sandage's** paper), but also the correlations which play such an important role in, for example, the determination of q_0. This comment applies to correlations such as the Tully-Fisher relation, the velocity dispersion-diameter relation for galaxies and all the other empirical rules of observational cosmology.

CONCLUSIONS

We have been treated to five days of outstanding science and it is very gratifying that our Chinese colleagues have been able to hear so many of the key questions discussed by the eminent workers who have contributed so much to our present understanding. There is no need to summarise the summary except to repeat the quotation of Dr Sandage which I have put at the head of this review. We are on the brink of a new era in astrophysical cosmology and it is especially pleasing that this coincides with the great upsurge in the physical sciences in China.

We have had a wonderful week and I conclude by referring to Francesco Sansovino's delightful interpretation of the name of the city of Venice. He claimed that the name Venezia derived from the Latin phrase *veni etiam* which he interpreted as "come back again, and again, for however many times you come, you will always see new and beautiful things" (F Sansovino, "Venetia città nobilissima et singolare", 1663). No quotation could be more appropriate to the city of Beijing and the Chinese astronomers nor to the magnificant reception we have received from our hosts.

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