47. *COSMOLOGY (COSMOLOGIE)*

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I INTRODUCTION

For the preparation of this report, I solicited recommendations from all members of the Commission, and also invited them to submit very brief statements of activities of themselves or others that they believed should be considered for inclusion. I received a large number of replies (unfortunately, many in the form of extensive reprints and preprints). I have tried to incorporate most suggestions, and to summarize the activities of Commission members as well as activities described in other sources to provide as broad an account as I have been able of the developments relating to cosmology since the last General Assembly in 1979. In am sure, however, that this report falls short of being complete, especially in the areas of theoretical cosmology, in which I am not really expert.

II OBSERVATIONAL PARAMETERS DESCRIBING THE STRUCTURE OF THE UNIVERSE

(a) *The Hubble constant and age of the universe.*

De Vaucouleurs (21.162.150, 22.158.021, 22.160.009, 22.162.035, 25.162.009 and 031, and 26.162.028) has completed a reassessment of the extragalactic scale. He uses primary distance indicators (calibrated within the Galaxy), with corrections for galactic absorption that differ somewhat from those used by Sandage and Tammann (18.162.060 and references contained therein), to derive distances to Local Group galaxies. In these he calibrates secondary distance indicators, which he uses to establish distances to neighboring groups. In the latter, he calibrates tertiary indicators, which eventually lead to distances to a large sample of spiral galaxies, from which de Vaucouleurs calculates the Hubble constant. Although he finds H_0 to be smaller for nearby than for remote galaxies, and especially smaller in the direction of the center of the Local Supercluster, his global solution gives $H_0 = 100 \pm 10$ $km{\cdot}s^{-1}$ Mpc^{-1}, about a factor of two larger than the Sandage-Tammann value.

The most significant new study of the distance scale is that based on comparison of infrared magnitudes and 21-cm line widths in spirals by Aaronson, Mould, and Huchra (27.158.214, 27.160.098, and 28.160.007). Although not specifically stated, the procedure depends implicitly on the assumption that the disk surface density is the same in all late spirals. Then the mass, m, contained within radius, R, and presumably the light as well, is proportional to R^2. The maximum width, W, of the 21-cm line is a direct measure of the circular velocity, V, where it reaches its maximum value. At any R beyond that point, V(R) is observed to be roughly constant. Elimination of R with Kepler's third law thus leads to $m \sim V^4$. For a given m/L ratio, we thus have:

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$$M = \text{constant} - 10 \log W$$

where M is the absolute magnitude.

The approximate validity of the above relation was first found by Tully and Fisher (19.158.045), but Aaronson, Mould and Huchra have shown that it is much tighter when the magnitude is measured in the infrared at 1.6 μm, first because the infrared is less affected by internal absorption in the galaxy observed, and second because it provides a closer approximation to the light radiated by the old disk and halo population stars. Aaronson et al. calibrate the relation with two Local Group galaxies, M31 and M33, and use it to find distances to other nearby groups, and to obtain results in good agreement with other observers. They then show the relation to be valid with apparent infrared magnitudes of many galaxies in each of several rich clusters, so once calibrated they can use it to find distances to those clusters.

For 23 Virgo cluster spirals, Aaronson et al. find $H_o = 65 \pm 4$ km s^{-1} Mpc^{-1}, but for distant clusters they find what appears to be a "global" value, $H_o = 95 \pm 4$ km s^{-1} Mpc^{-1}, in satisfactory agreement with de Vaucouleurs. The smaller value for the Virgo cluster is interpreted as gravitational drag in the Local Supercluster, and is consistent with the large-scale anisotropy in the microwave background radiation, which suggests a peculiar motion of the Local Group, relative to the smooth Hubble flow, that has a component toward the Virgo cluster of about 480 km s^{-1}.

In the Friedmann cosmologies with $\Lambda = 0$, the maximum a age of the universe corresponding to $q_o = 0$ is H_o^{-1}; at closure density ($\Omega = 1$; $q_o = 1/2$) it is $2/3\ H_o^{-1}$. The Sandage-Tammann value of H_o thus allows the universe to have an age of nearly 20 Gyr, while the more recent values limit the age to under 10 Gyr (less than 7 Gyr for $q_o = 1/2$). The larger Hubble constant would therefore seem to be incompatible with the ages of globular clusters (13 to 16 Gyr) derived from stellar evolution theory, and also with the ages of the elements derived, for example, from the ratios Re-187/Os-187 and U-235/U-238 (11 to 18 Gyr). If this incompatibility is not removed by further research, it may be necessary to consider seriously Lemaître cosmologies (with $\Lambda > 0$), or other even less conventional models.

On the other hand, Huchra informs me that the Aaronson et al. calibration may still be uncertain by up to 30 percent, and Noerdlinger and Arigo (27.154.026) report that gravity diffusion of helium in old stars could conceivably lower the ages of globular clusters by about 22 percent from those of earlier models. In my judgment, the calibration of the extragalactic distance scale, as well as the theory of stellar structure, and especially of the radioactive dating of the elements over many Gyr are all uncertain enough that it is not yet established that there exists a problem with the age of the universe.

There is a good recent review of the extragalactic distance scale by Hodge (1981).

(b) *The deceleration parameter, q_o.*

A large amount of new redshift data has become available. In addition to magnitude-limited redshift surveys in selected regions of the sky (Section II), Hoessel, Gunn and Thuan (28.160.047) have now published redshifts for all Abell clusters of richness Class 1 or more, out to distance Class 4, and at galactic latitudes greater than 30°. At the other end of the scale, Spinrad (1981) now reports new optical redshifts for six clusters that range from z = 0.621 to

$z = 1.132$; four of these are at $z > 0.9$. Nevertheless, our knowledge of the deceleration parameter has not significantly improved, partly because of subtle selection effects that enter in the determination of relative distances of remote clusters, but especially because of uncertainties in the evolution of galaxian magnitudes and colors. For example, Hoessel et al. attempt a formal solution for q_o by comparing their data with Gunn and Oke's (13.162.005) sample of high redshift clusters, and find $q_o = -0.55 \pm 0.45$, but with no correction for evolution. But using a completely different approach, Baldwin, Gaskell and Wampler have recently completed a long-term project to establish luminosity criteria in QSOs. They report that their study confirms that the C IV 1549 emission line is a useful "standard candle" in flat-spectrum QSOs. They are now observing C IV 1549 in low-redshift quasars with the IUE satellite to attempt a measure of q_o. Preliminary results (without evolution) suggest $q_o \sim 1$. (For a preliminary report, see Wampler 27.141.207.)

If the standard hot big bang model is correct and if the observed deuterium is primordial, the observed ratio $D/H \sim 10^{-5}$ points strongly to a low value of q_o. A small deceleration parameter would also make it easier to reconcile the young age of the universe suggested by the recent large measures of H_o with the old ages implied by stellar evolution theory -- provided that all the uncertainties are in the right directions. Otherwise, the best, but still shaky, evidence for q_o comes from determinations of the mean cosmic density, which appears to be too low by at least a factor of ten to close the universe. Neutrinos, if recent evidence that they may have non-zero rest mass turns out to be correct, could have a profound effect on the dynamics of stellar systems, and even on galaxy formation, but probably cannot contribute enough global density to affect significantly the evolution of the universe as a whole.

(c) *Evidence for galaxian evolution*

There are now good observational data on the counts of galaxies with increasing magnitude in widely separated areas of the sky, and most are in good agreement with each other. At the bright end, to about B = 20, are counts by Rainey (1977) and by Brown (26.158.148). Kron (28.158.072), Ellis (27.158.292), Peterson et al. (26.158.092), Karatchentzev (27.158.181, 27.158.291), and Tyson and Jarvis (25.158.171, 27.158.289) have all extended the counts to beyond J = 24 (Karatchenzev to B = 26 with an electronographic camera attached to the 6-m telescope). Kron's data show a larger number of galaxies near J = 24 than the others, which may be due to a different magnitude scale; Kron attempted to derive total magnitudes, while most other observers used isophotoal magnitudes. Now, the predicted number-magnitude relation for galaxies is somewhat sensitive to K-corrections, slightly sensitive to the luminosity function assumed, and very insensitive to the choice of Friedmann models over a wide range of q_o. These kinds of data are thus not useful in discriminating between cosmologies. On the other hand, the n(m) relation is very sensitive to evolution in magnitude or color (or both) of galaxies between the time of emission of their light (at moderate-to-large redshift) and the present epoch, and thus the observation of n(m) provides our best hold on galaxian evolution.

The most recent discussion of the interpretation of galaxy counts in terms of evolution is by Tinsley (28.151.051). She has calculated new evolutionary models based on an assumed distribution of galaxy types that make up a redder mixture of galaxies than in her earlier work. She finds that typically galaxies are about one magnitude brighter (in their rest frames) at $z = 1.0$ than at present. Her most rapidly evolving model shows a small hump in the galaxy distribution at J = 24, in qualitative agreement with a somewhat weaker feature in Kron's counts. The counts of the other observers do not show this "hump" (perhaps, as stated above, because of their definitions of magnitudes), but they do show evidence of slow evolution, and even this modest evolution can affect the value of q_o found from the Hubble diagram by unity! Interestingly, Tinsley shows that Kron's counts are also compatible with the predictions of Barnothy's FIB cosmology, which demonstrates the problem of separating evolution effects from effects of adopting an entirely different, unconventional cosmology.

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II. DYNAMICS AND STRUCTURE OF THE UNIVERSE

(a) *The Local Supercluster*

The modern description of the Local Supercluster as a flattened aggregate of field galaxies, groups and small clusters, and centered near the Virgo cluster was first formulated by de Vaucouleurs (1953). The last several years have seen an accelerated interest in the system. The Shapley-Ames catalogue, most of whose entries are members of the Supercluster, has now been updated and revised (Sandage and Tammann 1981) and Yahil, Sandage and Tammann (28.158.225 and references therein) have used the new material to reanalyze the structure and kinematics of the Local Supercluster. The velocity field in the system has also been studied by Aaronson et al. (1981), and its geometrical structure has been rediscussed by Tully (1981).

Tully finds 60 percent of the members of the Local Supercluster to be in a flat disk with diameter-to-thickness ratio of 6:1, and that the rms dimension of the short axis is ± 1.1 h^{-1} Mpc ($h = H_0/100$ km s^{-1} Mpc^{-1}). The remaining 40 percent of the galaxies form a "halo" structure of a few elongated clouds, with long axes more or less directed toward the center of the Supercluster. (Some of these same features seem to show on the Yahil et al. stereoscopic projections of the galaxies in the Revised Shapley-Ames Catalogue.) Tully concludes that either we see the disk at the moment of collapse, that there is a great amount of dark matter stabilizing it, or that the rms velocity perpendicular to the disk does not exceed 100 km s^{-1}; the latter case would suggest that the Local Supercluster formed before its individual galaxies and groups condensed by dissipative processes.

Yahil et al. find only a modest perturbation on the Hubble flow in the Local Supercluster (less than 200 km s^{-1}), while the data of Aaronson et al. (Section I) indicate a somewhat larger peculiar velocity for the Local Group, consistent with the large-scale anisotropy of the background radiation, and also with a study by Joeveer (1981a) that shows the Hubble flow to be reduced by a factor of 1.45 in the Supercluster. Joeveer (1981b) also finds a group of galaxies in Virgo with a peculiar velocity of 300 km s^{-1} with respect to nearby galaxies.

The new kinematical study of Aaronson et al. (1981) proposes a model that takes into account deceleration of galaxies by the gravitation of the Local Supercluster. They find the velocity field to be compatible with general expansion of the system, but at a rate reduced from the general Hubble flow; they give a peculiar velocity toward Virgo of 331 km s^{-1}. Their model, which is adjusted to minimize the scatter about the infrared Tully-Fisher relation, also has the Supercluster differentially rotating, with a velocity at the Local Group of 180 km s^{-1}. It is interesting that this picture is very similar to conclusions reached by de Vaucouleurs at least 20 years ago.

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The disagreement between the various studies, however, suggests that the data are still open to too many variations in interpretation to reach a definite conclusion about the kinematics of the Local Supercluster. Nevertheless, there seems to be a consensus regarding its discrete nature, and most especially its considerable degree of flattening.

(b) *Other superclusters.*

In addition to the Local Supercluster, more than a half-dozen other individual superclusters have been studied, some since about 1974. Recent investigations have included those by Ford et al. (1981) on two rich superclusters with mean redshifts of $z = 0.12$ and 0.14, each covering a linear extent of at least 50 h^{-1} Mpc. Velocity data suggest that these great superclusters are nearly stable dynamically, and have probably evolved to near Hubble flow turnaround. Comparison of the density of galaxies and clusters in the superclusters and in the surrounding fields leads the authors to conclude that a high enough cosmic density to close the universe is strongly excluded, and in particular that q_o is less than 0.2. They do not, however, find that the observations suggest that their superclusters are flattened.

In contrast, Einasto et al. (28.160.037), from their investigations of individual superclusters, find that chains of galaxies and clusters are basic elements of superclusters, and that cluster chains (or sheets) comprise 50 percent of all galaxies; of the remainder, 30 percent of the galaxies are in poor chains and 20 percent are in the field. They report that the brightest cluster galaxies are ellipticals, with $M_B = -22$ (for $H_o = 100$ km s^{-1} Mpc^{-1}), while the brightest in the field are spirals and irregulars with M_B near -19. The larger superclusters have diameters of about 50 Mpc, and the poorer chains from 15 to 20 Mpc. They find the chains to form a continuous network (albeit irregular), suggesting a cellular structure of the universe. Similar conclusions are reached by Corwin (1981) who has just completed an exhaustive study of a large supercluster in Indus. Einasto and Rees (1981) point out that the small ($\sim$ 100 km s^{-1}) velocity dispersion that is typical among the systems within superclusters provides significant limitations on the process of their formations.

At least since the Chincarini and Rood (17.160.031) study of the Coma/A1367 supercluster, it has been known that magnitude-limited redshift surveys show galaxies to be bunched up into limited regions in depth (superclusters) with large regions in between that are nearly or entirely devoid of galaxies. One of the more dramatic examples of this phenomenon has been demonstrated recently by Kirshner et al. (1981), who have done magnitude-limited redshift surveys in six fields in the northern and southern hemispheres. In three northern fields, mutually separated by about 35°, they have measured redshifts of 133 galaxies that comprise a sample at least 90 percent complete to $R = 16$. With reasonable assumptions about the galaxian luminosity function, they expected a peak in the number of galaxies with velocities near 16 000 km s^{-1}; instead, they found a gap between 12 000 and 18 000 km s^{-1}, which includes only one galaxy. This spatial gap seems to be at least 50 h^{-1} across. In a continuation of their study, now in progress, they are examining about 100 additional fields within the triangle defined by the original three northern fields, and report (private communication) that evidence for the large gap seems to be holding up, although it is a far more complex structure than a single spherical void. D Weedman (private communication) has looked at all Markarian galaxies in the same region that have published redshifts (mostly in the Soviet literature). Of 113 such galaxies, he finds 12 with velocities in the range 12 000 to 18 000 km s^{-1}, about as expected for a random distribution in depth. Because of the complex structure of superclusters and the expected intersupercluster regions, however, Weedman's findings are not necessarily in contradiction to those of Kirshner et al.

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Kirschner et al. also consider what density inhomogeneities are required at recombination to produce such large-scale inhomogeneities at the present epoch, and conclude that they should lead to velocity dispersions perpendicular to the main planes of superclusters that are typically only 150 km s^{-1}, consistent with the value Tully finds for the Local Supercluster. Peebles (1981) calculates the evolution of density perturbations in an expanding Einstein-de Sitter universe consisting of concentric spherical shells, and arrives at a similar conclusion.

In summary, the unequivocal results of recent studies are that large-scale structures exist in the universe on scales up to at least 50 h^{-1} Mpc. Moreover, magnitude-limited redshift surveys show that most, if not all, visible matter is concentrated in these structures. The structures themselves -- superclusters -- consist of a few rich clusters of galaxies, many groups and smaller clusters, and probably individual galaxies not associated with clusters and groups, but still within the superclusters. Most superclusters appear to be expanding, but there is strong evidence for gravitational perturbations on the global Hubble flow. The empty, or nearly empty, regions between superclusters have extents at least as great as those of the superclusters. There is suggestive evidence that some, but by no means conclusive evidence that all, superclusters are flattened systems consisting of chains and sheets of matter, and slight evidence that they may form an irregular spongy or honeycomb structure for the universe at large. The latter idea is hotly debated, however, and is crucial, for if correct it would suggest that superclusters in the form of cells or Zel'dovich "pancakes" came first, with galaxies and clusters fragmenting later, while if galaxies came first and subsequently segregated into clusters and superclusters, the largest-scale inhomogeneities in the universe should be more or less individual entities.

(c) *The mean cosmic density; possible role of massive relic neutrinos*

There have been no recent major discoveries (except the possibility that neutrinos may have non-zero rest mass -- see below) of matter or objects that can contribute appreciably to the mean cosmic density. Estimates based on visible matter, e.g., by Abell (17.160.037), are generally heavily weighted by virial masses of rich clusters, within which any unseen matter (such as hot gas) is already included in the estimates of cosmic density. These estimates are typically of the order 10^{-30} h^2 g cm^{-3}, a factor of at least ten below the closure density. Estimates based on the dynamics of superclusters and on the assumption that superclusters are true density enhancements lead to similar results.

Two recent experiments suggest that neutrinos may have a small rest mass. One of these (Reines, Sobel and Pasierb 1980) suggests that neutrinos alternate between different states or types (electron, muon, and tau), with a mass difference of the order of 1 eV/c^2 between the electron and either the muon or tau neutrino. The other experiment (Lyubimov et al. 1980) suggests that the beta decay of tritium indicates a neutrino rest mass in the range 14 to 46 eV/c^2. The possible cosmological consequences of a non-rest mass for relic neutrinos was probably first discussed by Gerstein and Zel'dovich (1966). A number of papers has appeared recently, including those of Tremaine and Gunn (25.162.087), Doroshkevich et al. (28.162,013), Schram and Steigman (1981), Bisnovaty-Kogan and Novikov (28.162.058), Zel'dovich and Sunyaev (28.162.012) and others.

For the conventional cosmological models the ratio of neucleons to photons is constrained by the observed abundance of deuterium and helium to be less than 4×10^{-10}, which gives an upper limit to the nucleon density corresponding to $\Omega < 0.06$, which is probably less than the density indicated by the dynamics of galaxies in clusters, and suggests that an appreciable part of the mass of the universe is not in nucleons (Schram and Steigman 1981). Neutrinos, if their rest mass is not zero, can provide that "missing mass." Neutrinos gravitationally clump

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with nucleons, however, if they become nonrelativistic at an early enough epoch, and the higher their rest mass, the earlier is that time. Neutrinos of rest mass near 20 eV/c^2 can collapse with large galaxies or binary galaxies and contribute to the massive halos now derived from galaxy dynamics (e.g., Faber and Gallagher 26.158.090). Those with mass less than 10 eV/c^2 cannot collapse with galaxies but can do so in clusters. Those with mass $<$ 3 eV/c^2 are unable to collapse even in the largest structures, but could still provide the dominant mass of the universe. Very massive neutrinos ($\gtrsim$ 30 eV/c^2), on the other hand, should provide not only enough mass to close the universe but would result in an uncomfortably young age, unless $\Lambda > 0$ or conventional cosmologies are wrong. As stated above, however, neutrinos of such high mass should collapse with galaxies where their dynamical effects are already taken into account, so that their contribution to the cosmic density would already be included in the density estimates given above.

According to De Rújula and Glashow (28.162.105), muon neutrinos should decay and emit ultraviolet radiation, with half-lives ~ 10^{24} s or longer. Recent analysis by Henry and Feldman (1981) of the Apollo 17 observations of the far ultraviolet flux from the direction of the Virgo cluster shows that even if the cluster's mass were entirely in neutrinos of rest mass in the range 16 to 20 eV/c^2, their half-lives would have to be greater than 10^{25} s.

In any case, if neutrinos should turn out to have non-zero rest mass, they can play an important role in the evolution of the universe, and especially in the formation of galaxies and clusters.

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III. QUASISTELLAR OBJECTS AND RADIO SOURCE COUNTS

In a recent review Schmidt (1981) combines the results of faint surveys (e.g., Osmer 27.141.204) and that of Green (e.g., Schmidt and Green 27.141.203), to find an extremely steep increase in the numbers of QSOs with redshift, leading to estimates (for $q_o = 0$) of 360 Gpc^{-3} at $z \sim 0$, and 3×10^4 Gpc^{-3} at $z = 3$. (By contrast, there are about 13 000 Seyfert galaxies per Gpc^3 at $z \sim 0$.) Unless we are in the center of

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a spherically symmetric distribution of QSOs of radially increasing space density (in violation of the Copernican cosmological principle), their sharp increase must indicate cosmological distances and a strong luminosity evolution. QSOs could account for all the excess in the X-ray background from 3 keV to 300 keV, although such a conclusion cannot yet be verified because the QSO spectra are unknown at energies greater than 2 keV. There has still not been a single QSO found with $z > 3.53$, despite some surveys to $B = 20.5$, so a cutoff in their distribution above $z > 3.5$ is probably real.

Further evidence that the redshifts of QSOs are cosmological and that they are active galactic nuclei is provided by a study by Wyckoff et al. (28.141.161), who have detected nebulosity around 3C273 out to a radial distance of 15", corresponding to a linear isophotal diameter of 90 kpc. The integrated red magnitude of the nebulosity (not including the quasar) is 16, corresponding to $M_R \sim -25$. In another study, Wyckoff et al. (1981) resolve similar nebulosity around 13 of 15 other QSOs. The nebulosities have isophotal diameters in the range 7" to 40", corresponding to a mean linear diameter of 90 ± 30 kpc. The mean integrated absolute red magnitude is $M_R = -21.8 \pm 0.8$ (for $H_o = 60$ km s^{-1} Mpc^{-1}, and $q_o = 1$). The "nebulosities" fit a Hubble law like that for galaxies, but 2 mag below the relation for m_1 in rich clusters, and with $\sigma_M = 3.0$. The plausible conclusions are that QSOs are the nuclei of typical galaxies, but that the QSOs are more luminous, relative to their host galaxies, than are other active nuclei.

Current studies of the ultraviolet radiation from QSOs by H E Smith, B T Soifer and others suggest that dust, although sometimes present, is not the dominant mechanism in determining the emission line intensity ratios in QSOs and in at least some Seyfert I galaxies. The observations support the hypothesis that the emission lines are formed in clouds that are very optically thick in the hydrogen lines.

In a recent review, Cohen and Unwin (1981) report that of some 50 QSOs that have been mapped by VLBI, six (as of August 1981) have resolved features that show motions with "superluminal" velocities, ranging from 2.8 h^{-1} to 10 h^{-1} times c. The conventional explanation for the apparent superluminal speeds rests on a combination of fortuitous geometry and the finite speed of light, but even then relativistic ejection speeds are required, with Lorentz factors in the range 5 to 10, and the ejection must occur in a direction within, typically, 10° or 20° of the line of sight to the earth. With so few objects resolved, it is rather surprising that even six are observed with superluminal motions if the popular explanation is correct; at least, it would seem that most if not all QSOs eject matter at relativistic speeds.

Zwicky (1937) suggested that galaxies, acting as gravitational lenses, should image background galaxies, and in his later life he often commented on his surprise that not even a single gravitational lens had been discovered. Subsequently, the Barnothys (1968) suggested the idea that QSOs might be gravitational lens events. Finally, the first probable gravitational lens has been found (Walsh et al. 25.141.094); that object, the double quasar 0957+561, has now been studied extensively, and appears to be actually several images of a distant quasar produced by a foreground cluster of galaxies. Roeder (27.158.325) showed that a transparent extended gravitational lens (as opposed to a point mass) must produce an odd number of images of a single source; in the modern models of 0957+561, the theory appears to be consistent with observations. Other likely gravitational lenses have been found since.

In an interesting paper, Tyson (1981) uses the recent data on counts of galaxies with increasing magnitude to predict how many quasistellar objects might actually be enhanced images of early active nuclei galaxies, such as Seyferts, produced by gravitational lensing by intervening galaxies and clusters. He estimates K corrections for Seyfert galaxies and derives for the gradient of quasar counts with magnitude, $d \log N_{QSO}/dm = 0.9$, in agreement with present observations to 18th magnitude. The result is independent of lens model adjustable parameters, which directly affect only the absolute numbers of QSOs. Tyson finds that if most QSOs to 18th magnitude are lens events, then an unreasonably large integrated mass of galaxies is required ($\Omega_{gal} > 1$). On the other hand, it is an interesting possibility that a significant fraction of QSOs could be accounted for with this mechanism.

I D Novikov (private communication) reports that the number, N, of sources as a function of the rate of radio flux, S, has been studied at $\lambda = 7.6$ cm in the range 1 to 100 mJy with the RT-600 radio telescope in the Soviet Union. The log N - log S curve has a sharp slope at 1 mJy, contradicting earlier estimates made with statistical arguments. The behavior of the curve may be explained by either a rapid evolution of sources, or an approach to the "red horizon."

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IV COSMIC BACKGROUND RADIATION

There is still no definite detection of small-scale anisotropies in the cosmic background (3 K) radiation. I D Novikov (private communication) reports that the following upper limits have been obtained by observations with the RT-600 radio telescope:

Wavelength	Angular Resolution	$\frac{\Delta T}{T}$
7.6 cm	3' to 7'	10^{-4} (near to 10^{-5})
1.38 cm	7"	5×10^{-3}
2 cm	10"	5×10^{-3}

A large-scale dipole anisotropy, however, seems now to be well-established (Gorenstein and Smoot 1981; Fabbri et al. 27.066.306; Boughn et al. 1981). The combined data show a maximum of 3.78 ± 0.30 mK toward $\alpha = 11^{h}.6 \pm 0^{h}.2$; $\delta = -12° \pm 5°$. Boughn et al. also report a quadrapole component at the 4-σ level, whch they believe to be intrinsic, and Fabbri et al. report a "quadrapolelike" anisotropy as well. Their combined data suggest $\delta T/T \sim 3 \times 10^{-5}$ at $\theta = 6°$, and $\delta T/T \sim 10^{-4}$ at $\theta = 90°$. Peebles (1981) shows that such an anisotropy can result from gravitational potential gradients in an early universe with a fixed initial entropy per baryon number, even without large-scale mass fluctuations; indeed, he finds that the mass fluctuations need only be on a scale that would lead to the presently observed scale of clustering ($\sim 30\ h^{-1}$ Mpc).

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Richards and Woody (27.141.218) report what appear to be significant deviations of the cosmic background radiation from a blackbody spectrum, in the sense that the observed spectrum is more intense than a blackbody at the peak and less intense at higher frequencies; this distortion contains about 20 to 30 percent of the total energy. The observations of this deviation of the 3 K radiation from a perfect radiator are still in need of independent confirmation, but if real are difficult to account for by scattering mechanisms at a later epoch, which would be expected to heat rather than cool the radiation. Many authors, including Layzer and Hively (09.066.004), Rees (22.162.004), and Carr (1981) have thus suggested the possibility of creating the cosmic background radiation after the big bang, leading to a cold big bang in which formation of galaxies and stars is greatly facilitated. Although an early generation of stars (Population III) is easily produced, the difficulty is creating a near-blackbody spectrum. Rowen-Robinson et al. (26.162.026) and Wright (1981a) have suggested silicate dust heated by Population III stars at $z \sim 200$ to produce the excess radiation needed, but there are still difficulties in reproducing the long-wavelength tail. In a recent study, Wright (1981b) has found a solution with a combination of Population III stars that burn from $z = 300$ to $z = 134$, and needle-shaped conducting dust grains; the total metal abundance required in this model is only $Z \sim 10^{-7}$. In another study, Rana (1982) suggests that the microwave background radiation could be produced by thermalization of stellar and other radiation by long needle-shaped grains of graphite; in his model the thermalization is of recent origin, at epochs of $z \sim 10$.

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V. COSMOLOGICAL MODELS

The conventional (Friedmann) evolving relativistic cosmologies with $\Lambda = 0$, combined with the "standard" model of the big bang, have achieved some remarkable success in predicting: 1) the expansion of the universe; 2) the correct (or nearly correct) H/He abundance ratio; and 3) the cosmic background radiation. A number of other observations are compatible with the conventional cosmologies, but are still to uncertain to be regarded as confirming specific predictions or even providing a firm basis for the selection among possible Friedmann models; these include: 1) the shape of the Hubble law; 2) number counts of galaxies with magnitude, or of radio sources with flux; 3) number counts of galaxies or clusters with angular size; 4) D/H abundance ratio; 5) the mean cosmic density; 6) the possibility of massive relic neutrinos. Some observations, however, provide some problems with the conventional view, although none of these problems can yet be considered insurmountable. They include: 1) the short age implied by the most recent determinations of the Hubble constant, compared to those predicted by stellar structure theory; 2) the absence of observed small-scale anisotropies in the background radiation and consequent difficulty in understanding galaxy formation; 3) the deviations, if real, in the spectrum of the background radiation from that of a perfect radiator; 4) the large-scale isotropy of the universe, and problem of communication at $t = 0$; 5) the present excess of baryons over antibaryons (perhaps no longer much of a problem); 6) the unanswerable question about the nature of the universe at $t < 0$.

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Perhaps these various problems along with the fact that abstract mathematical models are difficult to test (and hence eliminate), have been largely responsible for the considerable amount of work done recently in the field of theoretical cosmology. A number of such studies has been brought to my attention. It is difficult for me, as an observer, to evaluate all of them, but I shall at least attempt to summarize, or mention, a few.

Particularly interesting results have been obtained from numerical simulation studies, such as those of Aarseth et al. (25.151.055 and 56) and Gott et al. (26.160.042), in which the behavior of from 1000 to 4000 point masses with random initial conditions, have been followed in expanding universes with Ω in the range 0.1 to 1. These simulations show that gravitational interactions between the masses result in a picture of clustering and superclustering that strongly resembles the present universe, and in particular produces a covariance function that is remarkably like that found from observation (e.g., Peebles and Growth 13.162.015). These simulations, however, do not in themselves account for the differences between the types of galaxies found within and outside rich clusters. Nor do they predict that most or all of the mass points assemble into sheets or "pancakes"; of course, it is by no means established that the "pancake" picture describes the real universe.

McCrea and Rees organized a meeting of the Royal Astronomical Society in February 1979 to consider the problems of galaxy formation; a report of the meeting appears in the *Phil Trans Roy Soc London A,* 296, pp 269-435, 1980. In particular, McCrea (1979) suggests that if sufficiently massive clouds of raw material of galaxies collide, a layer of shocked material is produced, which, with plausible parameters, breaks up into condensations with the masses of globular clusters. The primary condensations could produce high-mass, short-lived stars that soon explode, ejecting heavy elements for the production of the first "normal" stars. McCrea suggests that all original stars may have been so formed in globular clusters.

The formation of primordial acoustic waves in the expanding universe, and their evolution near a singularity, have been considered by several Soviet cosmologists (Kompaneets et al. 1981; Lukash 1980; see also Mukhanov and Chibisov 1981). They propose that galaxies probably form from such waves, and consider the hypothesis that all physical modes of fluctuations have equal equipartition energies at t_0. The hypothesis leads to a new relation between the initial perturbation modes, and shows that an amplification of the potential perturbations near the singularity leads to a significant growth of the initial fluctuations, so that the initial amplitude of the perturbations can be less by orders of magnitude than was assumed previously.

It has also been shown that the possibility of non-zero rest mass for neutrinos can have important effects on the processes of perturbation development and the formation of galaxies, improving the agreement between theory and observation (Bisnovatyi-Kogan, Lukash, and Novikov 28.162.057; Zel'dovich and Sunyaev 28.162.012; Doroshkevich et al. 28.061.002).

Berstein and Shwartzman (1980) have derived the relation between the curvature and size of three-dimensional spaces with arbitrary topology. They find that for a constant negative curvature (k = − 1) the diameter of closed spaces is greater than 1.128 R, and for positive curvature (k = + 1) it is greater than 0.328 R, where R is the radius of curvature. The "simplest" model of the universe as a flat closed space (three-dimensional torus) is suggested, with all its parameters given in terms of atomic constants and current universal time. The total number of particles in this case is 2.87×10^{76}, and the present diameter of the universe is $0.102\ c\ H_0^{-1}$.

Grishchuk and Zelmanov report on recent theoretical work at the Sternberg Astronomical Institute. Zelmanov (20.162.119) considered the Friedmann model with hyperbolic comoving space filled with dust-like matter ($\Lambda = 0$) in some non-comoving

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reference frames, and finds that in different frames of reference (including the comoving one) such features of the expanding (or contracting) universe as infiniteness or finiteness, the volume of space, the amount of mass, and the number of particles are not invariant, but are finite in some frames and infinite in others. The same is true of the age of the expanding universe. Spatial and temporal finiteness and infiniteness of the non-empty world is thus relative. Kharbedia (20.162.120, 22.162.009) has continued the work, and gives new examples of the relativity of spatial and temporal finiteness and infiniteness of some non-empty Friedmann models. Zalmanov and Kharbedia (21.162.009) have derived some necessary conditions for such relativities in the non-empty homogeneous isotropic cosmological models. Agakov (22.066.210; 1980; 1981) has found all homogeneous, stationary, rotating metrics that satisfy the Einstein field equations with the energy momentum tensor of a perfect fluid. He also considered the properties of solutions of the Einstein equations with a regular minimum of the scale factor of the comoving space, and investigated the behavior of the solutions near this regular minimum. Grishchuk and Popova (1981) and Grischuk and Polnarev (1980) have continued research on the physical processes in the very early universe and their possible consequences for its present structure. In particular, they show that modern theories of particle physics (namely, supergravity), as well as standard general relativity, admit the quantum process of graviton creation in the very strong gravitational field of the early universe. As a result the nonthermal background of gravitational waves should exist now and in principle should be detectable.

G.E. Tauber (private communication, 27 September 1981) reports that he finds time-dependent spherically-symmetric solutions of Einstein's field equations containing an arbitrary pressure and density distribution, which connects smoothly to a Friedmann universe for any desired equation of state. He matches the pressure at the boundary and finds conditions that limit the number of solutions to two. He suggests that these solutions may be applied to the description of lagging cores or initial inhomogeneities in the early universe.

Davidson and McCrea (1981) have found an interesting development of Dirac's large number hypothesis (LNH). They show that if the LNH is assumed, then not only does the Newtonian gravitational constant decrease on an atomic time scale ($G \propto t^{-1}$), as inferred by Dirac, but the electrical force between two charged particles becomes stronger relative to their mutual gravitational force regardless of which of Dirac's two spacetime scales, atomic A or gravitational E (Einstein), is used. They conclude that the LNH implies an interesting reciprocity between atomic (or electrical) and gravitational phenomena in the A and E spacetimes, but it leaves open the problem of how to discuss simultaneously a combination of atomic and gravitational effects as they occur in the real world.

Demaret (25.162.007, 28.162.009 and 92; 1980) and Demaret and Moncrief (28.066.070) have considered spatially homogeneous cosmological models of Bianchi types I, V, and IX, filled with a perfect fluid with an equation of state of the type $p = (\gamma - 1)\rho$ (for values of γ in the range 1 to 2). He finds the Bianchi models to be non-singular, in the sense that the quantum wave function becomes zero at the classical singularity. Such a model can be interpreted as a contracting universe bounding into an expanding one, due to quantum gravitational fluctuations.

Among the more unconventional cosmologies is the G-varying cosmology of Hoyle and Narlikar. Narlikar and his associates have continued their study of the model (Canuto and Narlikar 27.162.006; Canuto et al. 1981; Narlikar and Rana 28.066.080) and argue that the model is consistent with magnitude-redshift relation for galaxies, with the number-flux relation for radio sources, with the metric and isophotal angular size-redshift relation, and with the 3 K background. They further hold that it gives a better fit to the diffuse γ-ray background than does the standard cosmology.

Finally, Narlikar et al. say that the G-varying cosmology gives a better fit to the non-Planckian spectrum of the microwave background (as reported by Woody and Richards) than the standard cosmology.

Also unconventional is the FIB cosmology of Barnothy and Barnothy. It is based on a perfect cosmological principle and a static Einstein universe. Time, length, and mass units of photons (and neutrinos) shift in relation to those of elementary particles; both the energy and wavelength of a photon increase exponentially with distance travelled, such that E and λ are proportional to $(1 + z)^{-1}$. The total energy in a beam of photons, however, is constant, so photons must decay (otherwise, their growing energy would increase the beam energy). Now, when $\Delta E/E = \Delta\lambda/\lambda = 1.22$, the spin of the photon goes from 1 to 1.5; then the photon decays into another photon of the same wavelength, but of spin 1, and a neutrino or antineutrino of spin 1/2. The photon thus loses 1/3 of its energy to a neutrino. Thus, after each such decay, the brightness of the source drops, which means that we would expect the number of sources as a function of redshift to show a periodicity with minima corresponding to steps in z of a factor 1.22. The Barnothys (1981) claim that 416 QSOs in seven complete samples show just this effect, as do 869 QSOs in another collection of incomplete samples.

Still another cosmology is the chronometric one of Segal. In this model the universe is closed and static, and the redshifts are due to "aging" of light. One of the predictions of the model is a quadratic, rather than linear, Hubble law. In a number of recent papers (e.g., Segal 1979, 28.158.020; Segal and Segal 28.162.033); Nicoll and Segal 27.031.520; Nicoll et al. 1980), Segal and his collaborators present elegant arguments based on statistics of bright galaxies and on quasars to show that the quadratic law provides the closer fit to the observations. Most observers, however, find the case unconvincing, especially in view of the very tight Hubble relation for first-ranked cluster galaxies, and they prefer to interpret the excess of large redshift QSOs as an evolutionary effect.

One of the most exciting areas of modern cosmology, albeit one of the most speculative, concerns the relation between conditions of the very early universe and the nature of fundamental particles and forces. This union of theoretical physics and astrophysics at the earliest instant of time has resulted in the development of the *grand unified theories* (GUTs). There is a recent review by Zel'dovich (1981). There was also a special conference sponsored by the National Science Foundation, "The Interaction of Particle Physics and Astrophysics," held in May, 1981, at the Institute of Theoretical Physics, University of California, Santa Barbara. There are no formal proceedings of that conference, but a summary, entitled "The Early Universe," has been prepared by Kolb and Turner (1981).

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