THE EPOCH OF GALAXY FORMATION

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1. INTRODUCTION

Unfortunately, there is as yet no direct observation of a forming galaxy, nor of a manifestly "young" galaxy. It is not even clear what such galaxies might look like. There are, however, some lines of attack that will yield indirect information about the environment in which galaxies formed. There is no lack of theories of galaxy formation, many of which provide quite different scenarios for the birth-process. The hope is that theories of galaxy formation may indicate what young galaxies ought to look like and thus guide us in our search for such objects.

2. OBSERVATIONAL EVIDENCE

There are several ways in which we might hope, in the near future, to obtain information about the evolution of galaxies, clusters of galaxies and QSO's.

a. The correlation function of the distribution of faint samples of galaxies may yield evidence for the evolution of clustering out to redshifts $z \sim 0.4$ or so. One of the problems with this approach is that the all-important K-correction is poorly known. The recent work of Phillips et al. (1977) on deep UK-Schmidt plates already suggests that galaxies were less clustered at redshifts $z \sim 0.4$ than now.

b. Butcher and Oemler (1977) have recently studied over a hundred galaxies in each of two very distant galaxy clusters (Cl 0024 + 1654 at $z = .39$ and the cluster around 3C 295 at $z = .46$) and found that the galaxies in these clusters are considerably bluer than the galaxies in the Coma cluster. Not only may this be telling us about the evolutionary history of S0 galaxies, but it may also be construed as evidence that these clusters collapsed in the relatively recent past. The K-correction is an underlying uncertainty in this work also.

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c. Dube, Wickes, and Wilkinson (1977) have reported measurements of the extragalactic background light which serve to constrain some models of galactic evolution in which galaxies form at redshifts $z < 10$ with a bright flash of star formation. Observations of this kind in the near infra-red may be of considerable value.

d. Quasar absorption lines can serve as an important probe of physical conditions at different redshifts along the line of sight. B.A. Peterson has obtained good evidence that the absorption lines are mainly due to intervening material rather than matter being ejected relativistically from the quasar. Interestingly, Peterson's results also suggest that the state of the intervening material is steeply dependent upon redshift, in the range $z = 2 - 3$.

e. Future X-ray telescopes (notably HEAO B) should be able to detect individual galaxy clusters at considerable distances ($z \sim 1 - 3$). Evidence for evolutionary effects in the temperature or gas density will certainly help to discriminate between various schemes for cluster formation.

f. Small-scale angular variations in the microwave background radiation temperature, if detected, would provide information on the structure of the universe at very early epochs. Such variations would arise as a result of motions on the "last scattering surface". Distant clusters of galaxies, if they contain hot gas, might be detected in this way as isolated "dips".

g. The origin and evolution of quasars and related objects poses even more problems than galaxy formation. If quasars represent activity in the nuclei of galaxies, then the fact that we observe them out to at least $z = 3.5$ sets a lower limit to the redshift when galaxies had developed to the stage of having acquired well-defined centres. The redshift distribution of quasars in principle provides clues to galactic evolution, but as yet no firm conclusions can be drawn. Extended radio sources are indirectly relevant, insofar as they serve as probes of the external gas density at different epochs (cf Blandford and Rees 1977).

3. THE SCENARIO OF DOROSHKEVICH ET AL.

Doroshkevich et al (1974, and references cited therein) have explored the consequences of a model in which the primordial fluctuations were purely adiabatic or "isentropic", so that all those on mass-scales below $10^{13} - 10^{14}$ $M_\odot$ had damped out by t_{rec}. The first bound systems to condense would then be gas clouds with masses appropriate to clusters of galaxies. These clouds must have turned around at a "recent" epoch ($z \lesssim 5$). They collapse in an aspherical or centrally condensed manner, and before they have contracted by more than a factor ~ 2, shock waves would have heated most of the gas, even if it were previously cold, to the temperature T_{virial}. Galaxies would form later in the manner discussed by other speakers at this conference.

The most basic question one could ask about galaxies is "What determines their characteristic sizes?" The analogous question about stars can be answered - there are good and well-known reasons why stable main-sequence stars are restricted to within an order of magnitude or so of the mass $(\hbar c/Gm_p^2)^{3/2}\, m_p$. An advantage of the idea that galaxies and clusters form directly from massive gas clouds is that a very simple physical argument does yield a characteristic radius and mass in crude but suggestive accordance with actual galaxies (Rees and Ostriker 1977, Silk 1977, Binney 1977). The key feature of this argument is a comparison of the collapse or dynamical timescale ($t_{dyn} \propto \rho^{-\frac{1}{2}}$) and the radiative cooling timescale t_{cool} (which depends on ρ^{-1} and is a function of the gas temperature T_{virial}). Fragmentation readily occurs only if $t_{cool} \lesssim t_{dyn}$. This condition is generally fulfilled only for clouds of mass $\lesssim 10^{12}\, M_\odot$ and/or radii $\lesssim 75$ kpc; and these are in gratifying order-of-magnitude accordance with the properties of actual galaxies.

In this type of model, the covariance function on scales smaller than clusters would bear only a very indirect relation to the spectrum $(\delta\rho/\rho)_{rec}$ of density inhomogeneities at recombination.

4. NON-DISSIPATIVE GRAVITATIONAL CLUSTERING

As an opposite extreme from the above, we may imagine a scenario in which all the star formation is completed early (soon after recombination) and the subsequent evolution is stellar-dynamical (i.e. of a kind that could in principle be simulated by N-body computations). Some key expected features were clearly expounded by Press and Schechter (1974). If, at some initial instant, point masses are distributed in a "random" fashion, then at later times clustering develops on progressively larger scales. At any epoch t, there is a characteristic mass-scale $M_c(t)$ on which the density fluctuations have amplitude of order unity (the corresponding length-scale r_c would be that for which $\xi(r) \simeq 1$). The initial conditions satisfy

$$(\delta\rho/\rho) \propto M^{-\alpha} \tag{1}$$

where α is in the range 1/3 - 2/3 ($\alpha = \frac{1}{2}$ corresponding to "white noise" or a poisson distribution of the number of particles within a comoving cell). If the background universe is of Einstein-de Sitter type (and, for $(1 + z) \gtrsim \Omega^{-1}$, in low density models also) then

$$M_c \propto t^{2/3\alpha} \propto (1 + z)^{1/\alpha} \quad . \tag{2}$$

On scales >> $M_c(t)$ the perturbations are of small amplitude, the kinematics being close to those of the background universe. But on scales << M_c, "virialised" systems would have condensed out.

The observed clustering of galaxies tells us that, at the present epoch, $r_{co} \simeq (5 - 10)$ Mpc and $M_{co} \simeq 10^{14}\, M_\odot$, and (2) allows us to infer the scale of clustering at t_{rec} (the earliest epoch at which the model could be relevant). This scale is in the general range $10^7 - 10^{10}$ $M_\odot$, depending on α: in other words, smaller than galaxies but larger than a present-day globular cluster.

Insofar as a naive gravitational clustering model is relevant, we expect the scales that virialise at time t (i.e. have $M \simeq M_c(t)$) to be subsequently subsumed into larger-mass systems. The subclustering will then eventually be erased, and its binding energy redistributed (if $\alpha < 2/3$ the energy is mainly associated with the largest scales anyway); internal dynamical relaxation processes will have time to operate on progressively larger scales. In view of this, it should perhaps come as no surprise that the N-body simulations by Aarseth, Gott and Turner (these proceedings) suggest that the form of $\xi(r)$ is insensitive to the initial conditons (i.e. to the value of α in (1)) when $\xi(r) >> 1$. Indeed, it is conceivable that some redistribution of binding energy between different scales could occur even in the so-called "linear" domain where $\xi \lesssim 1$.

If the clustering proceeds in the kind of "self-similar" fashion discussed by Press and Schechter (1974), there is no natural preferred scale for galaxies. At any time, material will be clumped into units of typical mass M_c (equation (2)); these units will each contain a few subunits (which themselves turned around a factor ∿ 2 earlier) but any finer substructure would have been erased.

The origin of cosmic angular momentum is a major problem in such a scheme. The sugestion that angular momentum would be generated by tidal torques between neighbouring protogalaxies has been a subject of considerable controversy. Recent numerical simulations of this theory by Efstathiou and Jones lend strong support to the earlier simulations by Peebles (1971a), and show that the tidally generated angular momentum is not dynamically important unless protogalaxies undergo a significant amount of collapse before settling down to their final configuration. In the usual dimensionless units, the generated angular momentum is

$$\lambda = \frac{\mathcal{H}}{\sqrt{GMr}} = 0.06 \pm .03 \quad . \qquad (3)$$

A protogalaxy would have to collapse by almost a factor 10 in radius in order to make this amount of angular momentum dynamically important. This result is a further argument that dissipation must play an important role in the formation of galaxies. (The existence of a disk is manifest evidence of dissipation, though it does not tell us by how much the galaxy has collapsed.)

It might be remarked that tidal torques are not the only means of producing galactic spin in this theory. The coalescence of substructure at various levels of the hierarchy will lead to spinning stellar systems. There is an upper limit on the amount of angular momentum generated in this way because systems colliding with high relative velocity will not stick together. (This is a possible explanation for the observation that elliptical galaxies - interpreted as low-angular momentum systems - lie predominantly in rich clusters of galaxies where such collisions will be high velocity collisions.) A certain amount of dissipation will be required in such a model, but possibly not as extreme as in a pure tidal torque theory.

5. COSMIC TURBULENCE

In this theory, galaxies are supposed to grow out of primordial turbulence thrown into a state of supersonic chaos at the epoch of decoupling. The recombination of cosmic plasma takes a finite time during which there is considerable damping of primordial eddy motions on galactic scales (Chibisov, 1971). Dense lumps can form as a result of centrifugal compression during recombination (Peebles, 1971b; Jones 1977), though the origin of cosmic angular momentum on galactic scales becomes as serious a problem in this theory as in the gravitational instability theory.

6. CONSEQUENCES OF EARLY ($z > 100$) STAR FORMATION

If the spectrum of inhomogeneities surviving the recombination period extends to masses smaller than $\sim 10^5$ $M_\odot$, and if the amplitude of the spectrum increases towards smaller masses, then the first objects to condense out would be those of the Jeans Mass at recombination

$$M_J^{rec} \simeq 10^6 \, (\Omega h^2)^{-1/2} \tag{4}$$

There is no reason, apparently, why such objects (incorporating most of the primordial gas) should not quickly collapse and fragment, but we cannot predict the characteristic masses of these "Population III" stars. The left-over material would be re-ionised, (unless too few high mass stars are formed), and indeed this re-ionisation may be responsible for turning off the star formation process. There are three interesting consequences of such early star formation. 1. Galaxies "born" in this way would make little contribution to the background cosmic light (Dube et al. 1977). 2. "Young" galaxies (by which in this scenario one means stellar systems of galactic mass undergoing their violent relaxation towards the smooth symmetric systems observed today) are not strikingly luminous objects of the kind described by Partridge and Peebles, Tinsley, Larson, Meier and others. 3. The small-scale angular variations of the microwave background radiation would (as we explain below) be undetectable. Astronomers could hardly hope to obtain direct evidence for galaxy formation under these circumstances!

If at epoch z a fraction f of the cosmic matter is left over as uncondensed gas, and has ionisation x_e, optical depth unity corresponds to a redshift of order

$$z_{\tau=1} \sim 7\ (fx_e)^{-2/3}\ (\Omega h^2)^{-1/3}\ , \qquad (5)$$

where Ω and h describe the present universe. The uncondensed gas is still dynamically coupled to the cosmic radiation field if the "Compton drag" timescale $t_{drag} \simeq (m_p/m_e) n_H/n_e\ t_{comp}$ is shorter than the cosmic expansion timescale. (f, the gas fraction, does not appear in this expression.) This condition amounts to

$$1 + z > 140\ x_e^{-2/3}\ (\Omega h^2)^{-1/5}\quad . \qquad (6)$$

If star formation maintains a high level of ionisation the cosmic radiation field can prevent the generation of large scale gas motions until redshifts on the order of 100 or so. Optical depth unity corresponds to mass scales

$$M_{\tau=1} \simeq 10^8 \left(\frac{1 + z}{1000}\right)^{-6} (fx_e)^{-3}\ (\Omega h^2)^{-2}\ M_\odot\quad . \qquad (7)$$

Combining (6) and (7) gives another expression for the mass-scales involved in this process:

$$M < 10^{13}\ (fx_e)^{-3/5}\ (\Omega h^2)^{-4/5}\ , \qquad (8)$$

where (6) demands the constraint $x_e \gtrsim 0.05$ in order that the matter-radiation coupling should persist after recombination.

If the fraction of uncondensed gas, f, were sufficiently low (say on the order of a few per cent), according to equation (5) astronomers would be seeing back to redshifts where, owing to Compton drag, there were no gas motions on scales smaller than M given by (7). A fluctuation of mass M subtends angular scales

$$\theta \simeq \left(\frac{M}{10^{12}}\right)^{1/3} (\Omega h^2)^{2/3}\ h^{-1}\ \text{arc min}\ . \qquad (9)$$

Because the temperature fluctuations would be mainly due to scattering off matter moving relative to the general cosmic background, the radiation temperature would have no detectable variations on scales less than several arc minutes.

Whether or not we can see as far back as this time depends on the details of the ionisation history and precisely how much matter is left in gaseous form. If the ionisation is maintained near unity all the time, and $f \simeq 0.1$, then according to (5) the last scattering "surface" lies at a redshift $z_1 \sim 30\ (\Omega h^2)^{-1/3}$, and there has been a considerable time since $z \sim 140$ in which to generate gas motions. (The gas moves around in the fluctuating potential of the stellar matter aggregates.) Now an additional effect comes into play due to the "fuzziness" of the last scattering surface: a large number of inhomogeneities contribute to the temperature fluctuation observed on any one line of sight. The number of such inhomogeneities is roughly the ratio of the horizon scale at the redshift of last scattering to the inhomogeneity scale at that epoch:

$$N \sim 60 \left(\frac{M}{10^{12}}\right)^{-1/3} \left(\frac{1000}{Z}\right)^{\frac{1}{2}} (\Omega h^{2})^{-1/6} \tag{10}$$

The angular scale is still of the order (9) provided $\Omega z >> 1$. The relative temperature fluctuation $\delta T/T$ produced by one fluctuation is on the order of v/c where v is the gas velocity generated. Because the ionisation is held constant in this version of the model, the observed $\delta T/T$ is a factor N down on this. The mass scale observed depends on the angular scale being looked at via relation (9). On galactic scales θ or smaller, where the observed fluctuation scale would be less than an arc minute, the relevant velocities would be typical gas inflow velocities: a few hundred kilometers per second. On larger scales like $M \sim 10^{15}\ M_{o}$, we are looking at angular scales $\theta \sim 10^{1}$. The clusters will not have turned around and collapsed at the last scattering surface, so the relevant gas velocities are at most several hundred kilometers per second. Considering (10) then, the expected temperature fluctuations $\delta T/T$ will be at most a few times 10^{-5} on angular scales $\theta < 10^{1}$. The temperature fluctuations on angles $\theta >> 10^{1}$ would be due to mass-scales where the density enhancements are still in the linear regime: the gravitational effects of such large perturbations on the last scattering surface would affect the observed temperature; and the whole "local supercluster" would acquire a detectable peculiar velocity if it lay (off-centre) within one such irregularity.

As a last comment on these ionised remnant gas models, it should be noted that while the matter and radiation are Compton-coupled, the electrons remain at the temperature of the cosmic radiation field. The gas is thus ionised without being "hot" ($> 10^{40}$ K). Consequently, the distortions to the microwave radiation spectrum (estimated via the famous y-parameter) due to this prolonged period of non-neutrality are small. The coldness of the neutral component means also that much neutral hydrogen could be in molecular form.

7. CLUSTERS AT $z \gtrsim 2$.

Evidence on the gas content within clusters (or protoclusters) at large redshifts would help to discriminate between the types of model discussed in §3 and §4 respectively. In the Doroshkevich *et al* scheme, a protocluster is predominantly gaseous when it turns around and is shock-heated, the gas content being thereafter gradually depleted as galaxies condense via thermal and/or gravitational instability; on the other hand, those theories in which clusters form from pre-existing galaxies predict that the gas content, perhaps very low at turnaround, may increase with time owing to infall, ejection from individual galaxies, etc.

Two observational handles on this question (Fabian et al 1977) which are already feasible (or should soon become so) are:

(i) HEAO B observations of thermal emission from clusters at z = (1 - 3) may be responsible for the bulk of the observed X-ray background below ∿ 10 kev. Individual clusters should be resolvable; and "counts" in small areas of sky would indicate at least the sign of the evolutionary effect and also constrain the epoch at which cluster formation in the Doroshkevich et al scenario could have occurred (cf Kellogg (these proceedings), Cowie and Perrenod (1977), Cavaliere et al (1977)).

(ii) If clusters of galaxies at (say) $z \simeq 2$ contained more hot gas than present-day clusters, then each should produce a larger fractional dip in the microwave background (by the Sunyaev-Zeldovich Compton scattering effect) than nearby clusters in which the effect may already have been measured (Parijskij 1973, Gull and Northover 1976, Lake and Partridge 1977). If τ_{es} is the optical depth of a cluster to electron scattering, then the effect is of order $\tau_{es}\ (kT_{virial}/m_e\ c^2)$. The temperature perturbation due to the straightforward doppler effect on the cluster material (even if it is undergoing systematic rotation or collapse) could not be larger than $\tau_{es}\ (V_{virial}/c)$. Since $kT_{virial} \simeq (V_{virial}/c)^2 m_p\ c^2$, the Sunyaev-Zeldovich effect must be the dominant one if $V_{virial} > (m_e/m_p)\ c$, which is certainly the case for clusters. Note, however, that this argument applies only after the gas in the protocluster has been shock-heated.

8. A "SYNTHETIC COMPROMISE" MODEL FOR THE FORMATION OF GALAXIES AND THEIR HALOS.

Although all scenarios involve a systematic conversion of gas into "stellar" material between $z \simeq 1000$ and the present epoch, they make different predictions about how (and exactly when) this happens, and about the order in which the various mass-scales separate out. The resemblance between what is seen in the real sky and the results of N-body simulations by Aarseth and his associates and by Peebles suggests that unadulterated gravitational clustering has basically determined the large-scale distribution of luminous matter. On the other hand, the basic properties of galaxies - their high-luminosity cut-off, the flattening of disc systems, and the gradient of M/L with radius - seem inexplicable without assigning some role to dissipative gas-dynamical processes.

White and Rees have developed a theory for galaxy evolution which is in some sense a compromise or synthesis between the schemes described in §3 and §4. The basic hypothesis is that by z = 100, about 80 per cent of the primordial material condensed into "dark stars". These stars would originally be grouped in units smaller than galaxies, but clustering would develop on progressively larger scales. This material eventually constitutes the halos of massive galaxies. (For the purposes of the model, all that is required is that this material undergoes non-dissipative gravitational clustering as in §4. More exotic possibilities such as heavy neutrinos or primordial black holes would work equally well). In this respect the theory is like the gravitational clustering theory. The remaining gas subsequently settles into the potential wells associated with these dark halos, and fragments into the stellar populations we now see. The characteristic upper limit to the mass and size of galaxies is determined by the requirement that the gas must be able to cool and fragment in the available time.

The theory is motivated by the following remarks:

(a) A galaxy formation theory should account for the existence of a large amount of non-gaseous "dark matter" which apparently provides at least 80 per cent of the virial mass of cluster like the Coma cluster, and which may reside in massive halos around large galaxies. The "luminous" material is much more "clumped" than the "dark" matter.

(b) Dissipation almost certainly played a role in the formation of disk galaxies (and perhaps in the central luminous parts of elliptical galaxies).

(c) Uncondensed gas exists in clusters of galaxies (it is also enriched with heavy elements).

(d) The characteristic mass and size of galaxies has no natural interpretation in a purely gravitational picture.

If the hierarchical clustering is described in discrete steps, each lasting twice as long as the preceding step, the total number of steps since recombination is $\sim 15\ \Omega^{-1/2}$. The characteristic mass which is on the verge of collapse at each step increases by $2^{2/3\alpha}$ at each step (cf (2)). The parameter F_i denotes the initial fraction of left-over gas, so that $1 - F_i$ is the fraction of "dark matter" in the universe. The fraction of the gas available at the i^{th} stage of the hierarchy that forms into stars is denoted by f_i. This fraction presumably depends on the binding energy of the "dark halo" into which the gas is falling, and the simplest assumption is

$$f_i \propto \frac{M_i}{R_i} \tag{11}$$

where M_i and R_i are the mass and maximum radius of the dark component at that level of the hierarchy (cf Larson 1974). For different masses, f scales as

$$f_i \propto M_i^{2/3\ -\alpha}\ , \tag{12}$$

so for $\alpha < 2/3$ the fraction of infalling gas that gets turned into luminous stars is very small for the early stages of the hierarchy.

The value of f_i is chosen by requiring that some 50 per cent or so of the available gas has been turned into luminous material by the present epoch. The 50 per cent is chosen on the basis of the observation that the mass of uncondensed gas in the Coma cluster is of the same order as the luminous mass. The assumption that M/L for the Coma cluster is the same as that for the whole Universe favours $\Omega \simeq 0.2$. From the equation

$$\frac{\text{gas}}{\text{gas + luminous matter}} = \prod_{\substack{\text{hierarchy}\\ \text{steps}}} (1 - f_i)$$

we can deduce the value of f at the last step of the hierarchy, f_{max}. (We know the characteristic mass M_i at each step.)

The only parameter for which we have little basis for choice is α, which is generally taken to lie in the range 1/3 - 1/2.

Several conditions must be satisfied in order that the gas falling into a dark-halo potential well should fragment into stars. The cooling time of the gas must be shorter than the Hubble time. It must also be short enough so that the gas can cool before the dark matter itself is absorbed into the next level of the hierarchy. It is also necessary that gas should be able to cool and collapse enough for its self gravity to dominate over that of the dark matter into which it is falling. Otherwise it cannot fragment efficiently. The radius of the gas cloud should therefore satisfy a condition like

$$R_{gas} \lesssim (fF)^{1/3} R,$$

where R is the halo radius, F is the ratio of gas mass to halo mass, and f is the fraction of the gas that can be turned into stars. (The exponent in this expression in fact depends on the details of the density distribution.)

It can be shown that with the preferred values of F_i, f_{max}, Ω and α, the conditions that the infalling gas should be able to fragment into stars yields an acceptable upper limit to the mass and radius of the luminous part of a galaxy.

Low-mass galaxies would tend to have formed by gas that accumulated and fragmented into lower-mass "halos" which existed at earlier stages in the development of the hierarchy. These "luminous cores" could preserve their identity even if they are embedded in halos that coalesce when the next stage of the hierarchy builds up. On this assumption, one can calculate a luminosity function which turns out to be rather too steep at the faint end (ϕ (L) varying about as $L^{-1.8}$ rather than the canonical $\sim L^{-1.25}$). Mergers may however occur (large galaxies with several smaller satellites being a common expected phenomenon on this model). Dynamical friction in clusters, and differing M/L (arising from variations in the star formation rate, even for a universal IMF), are further effects which modify ϕ(L). There would be a general correlation between metal abundance and galactic mass (though an important constraint on the Population III objects is that they should not produce too high a heavy element abundance). But the most important feature of the model is that it suggests what physical processes distinguish a characteristic galactic mass from a typical cluster (or group) mass (cf Press & Schechter 1974); and also accounts for the distinction between the relatively diffuse "dark" material which is gravitationally dominant and the 10 per cent of "luminous" material that arises from "secondary" star formation in the potential wells.

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DISCUSSION

Ostriker: One of the principal reasons for believing that galaxy formation is late is the relatively low velocity dispersion or density. The halo density is even lower indicating a very recent epoch for its formation. Does this present any difficulty for the theory?

Jones: It is certainly a good point. I am not sure to what extent this rules out such scenarios.

Silk: If star formation occurs as early as z = 100, how does the proposed model arrange to have just 20 per cent of the initial mass left over in gaseous form for subsequent dissipational galaxy formation at a much later epoch?

Jones: When stars first form the gas may be reionized and thus recouple to the cosmic radiation field. This may prevent further star formation. Why 80% we cannot as yet say of course: that is a difficult problem. Observationally it has to be about that value.

Tifft: Statements such as "80% of dark matter unequivocally exists" ignore the fact that observations, good observations, exist which undermine the dynamical concepts upon which the existence of the mass depends. There are no direct observations of this mass. Redshift-magnitude bands in clusters (5 or 6 now), the evidence for a discrete or periodic redshift (especially in radio redshifts), and other observations strongly imply a part or all of the redshift is an intrinsic phenomenon. We should at least admit of this possibility. There are no observational inconsistencies in this type of model and we are naive to believe we understand all of physics.

Fall: How is your calculation of small scale fluctuations in the microwave radiation specific to the White-Rees model and different from other models?

Jones: In this model, there is only a small fraction of the matter in the Universe in the form of gas at any redshift and a low value of the density parameter, $\Omega = 0.1$, is adopted. Therefore, one can see very much further back in redshift than in the conventional model so that the peculiar velocities of the perturbations are much smaller and consequently give rise to smaller fluctuations of the microwave background radiation.

Tinsley: Jones pointed out that to get enough angular momentum in galaxies, a lot of dissipation is required. This requirement is consistent with the picture I discussed yesterday, in which disk galaxies form gradually and late. They could form from matter that was a long way out, falling in slowly and bringing angular momentum (cf. the model of Ostriker and Thuan, 1975, *Astrophys. J.*, and comments by Binney, 1977, Yale conference).

Jones: That is encouraging, but I do think we should look at Ostriker's point more closely before being carried away.