Concluding Remarks

M. J. Rees

Phil. Trans. R. Soc. Lond. A 1980 **296**, 431-435
doi: 10.1098/rsta.1980.0187

Phil. Trans. R. Soc. Lond. A **296**, 431–435 (1980) [431]
Printed in Great Britain

Concluding remarks

By M. J. Rees†
Institute of Astronomy,
*Madingley Road, Cambridge CB*3 0*HA, U.K.*

At an I.A.U. Symposium in 1977, Y. B. Zel'dovich said, 'It will only be a few years before the origin and evolution of galaxies is understood.' It is hard to guess whether the talks at this Discussion Meeting would have reinforced or moderated his optimism, but I have no doubt that Professor Zel'dovich would have been impressed by the variety of new observations and new ideas presented here.

There has certainly been *some* progress towards understanding galaxies and their origins. A few years ago we were worse than ignorant about some crucial points: we 'knew' some things that were not so. Let me mention two such things in particular. It used to be tacitly accepted that elliptical galaxies owed their shape to rotational flattening. But the observations now show that the rotation rates are too slow. The internal dynamics are complex: elliptical galaxies may be triaxial – bars spinning end-over-end – and the random component of the stellar velocities may be anisotropic. According to Dr Binney (who was persuasively advocating such ideas even before the rotation data forced the problem on everyone's attention) the shape of elliptical galaxies offers clues to the way in which they originated in an asymmetrical collapse. A second tacit assumption was that the 'luminous' content of galaxies dominated their dynamics – that the total gravitating mass is distributed in the same way as the stars we see. But, as Dr Gunn and others have told us, the luminous content of galaxies may be swamped by ten times as much dark matter: this material forms a halo around massive isolated galaxies, and provides the virial mass in rich clusters.

But the advances in recent years amount to more than just an abandonment of earlier misconceptions. Dr van den Bergh gave us a clear review of galactic morphology. The rate and history of star formation is the crucial determinant of final morphology. Dr Larson suggested that the process of star formation occurs inhomogeneously, being concentrated in places where gas has been compressed (and has then cooled) behind shock fronts. The degree of 'turbulence' and the efficiency of cooling are thus the key parameters.

But galaxies are not isolated systems. S0 galaxies are plainly influenced by the cluster environment in some way, having perhaps been swept by the intergalactic medium. The X-ray evidence for intergalactic Fe also indicates that galaxies may eject substantial amounts of processed material. Increasing attention is now focused on the effects of mergers of galaxies in groups and in clusters: as Dr White described, this may account for the slow rotation of ellipticals; and 'galactic cannibalism' in clusters could give rise to giant cD galaxies.

At the moment, all questions involving galactic evolution are too uncertain to enable us to predict the evolutionary correction that is needed for pursuing classical cosmology and measuring the deceleration parameter. Dr Ellis discussed number–magnitude counts of faint galaxies. These provide evidence for some evolution (galaxies having been somewhat brighter

---

† Elected F.R.S. 15 March 1979.

28-2

in the past), but the effects are no larger than should have been expected. There are some small differences between the galaxy counts obtained by different investigators, but it is perhaps encouraging that one has got to the stage of worrying about fine discrepancies.

Dr Tinsley reviewed for us the prospects of discovering young galaxies at large red shifts. If galaxies form from the collapse and fragmentation of 10^{11}–10^{12} $M_\odot$ gas clouds, these would be irregular objects; they might be as bright as magnitude 22 owing to large numbers of young stars and supernovae (10^6 'Orion nebulae'). The existing counts of faint galaxies thus already place some constraints on how bright young galaxies could have been. One uncertainty concerns the amount of dust: if this is large, young galaxies might emit predominantly in the infrared.

Active galactic nuclei, detectable out to red shifts of order 5, provide another probe of early epochs. If quasars are indeed active galactic nuclei, one can infer that galaxies must have been 'assembled' – at least to the extent of having already developed well defined centres – by the epoch corresponding to $z \approx 3$. As Dr Wall explained, quasars and radio galaxies display a strong evolutionary trend, indicating that young nuclei had a greater propensity to give rise to active outbursts. This could perhaps mean that there is more uncondensed gas in a young galaxy available for fuelling a central compact object.

Even if quasars are not properly understood, their optical spectra provide valuable probes for the intervening gas. Dr Weymann reviewed for us the observations of quasar absorption lines. The detailed interpretation of the systems remains controversial. Nevertheless there seems a general consensus that most of the systems displaying large velocities relative to the quasar itself are due to intervening clouds unrelated to the quasar. The amount of material needed to give an absorption feature is rather small; the absorption systems could be due to cool filaments in the haloes of young galaxies or to clouds embedded in a hot intergalactic medium. The distribution of absorption lines in quasar spectra thus provides, in principle, evidence on the process whereby gas gradually condenses into galaxies, and/or is ejected from galaxies.

The most remote quasars so far observed are at a distance such that we are looking back 80 % of the time until the big bang when we study them. Even so, we are still completely ignorant about the whole range of red shifts between 5 and 1000 (or, equivalently, the range of times between 10^6 years and 10^9 years). During this era the contents of the Universe must have gradually transformed from the almost homogeneous gas decoupling from the 'fireball' at recombination into bound galaxies or dark discrete objects. This era has received disproportionately little attention from theorists as compared to that lavished on the first million years, or even the first minutes or microseconds.

Dr Jones described for us two contrasting models or scenarios for galaxy formation. In the first of these, most of the primordial material condenses at red shifts greater than *ca.* 100 ($t \lesssim 10^7$ years) into bound systems that now constitute the dark matter in galactic haloes and clusters. Subsequently there is a process of hierarchial clustering, individual galaxies being the largest aggregates whose internal substructure has already been erased and homogenized. The 'luminous' content of these galaxies arises from the small percentage of gas that did not make it into the first generation of bound systems but subsequently falls into the potential wells and turns into stars. In this scenario the missing mass would be contributed by 'first generation' objects: either high mass remnants or else unevolved stars of very low mass ('Jupiters'). Star formation is poorly understood even in sites such as the Orion nebula in our own galaxy, so we cannot confidently predict the mass spectrum of the stars forming at

$z \approx 100$. The computations reported by Dr Tohline – in which most of the material in a collapsing cloud ends up in lumps no smaller than the *initial* Jeans mass – suggests that the first generation of objects would be as massive as *ca.* $10^6\ M_\odot$.

According to a second rather different scenario, espoused particularly by the Moscow group, the Universe would have been essentially quiescent until 10^9 years. At that stage massive, *ca.* $10^{14}\ M_\odot$, clouds would have turned around and evolved into clusters of galaxies. These clusters would then fragment into individual galaxies. This scenario requires that the initial fluctuations in the fireball should have been strictly adiabatic (isentropic), so that all scales less than *ca.* $10^{14}\ M_\odot$ would have been smoothed out by viscous damping.

It is gratifying that several types of observations can soon help to decide between these contrasting pictures. HEAO-B will certainly tell us how the gas content of clusters has evolved, and may reveal X-ray emission from protoclusters at large red shifts. As Dr Davies has discussed, 21 cm emission from neutral gas clouds at large red shifts may also be detected. Higher sensitivity observations in the infrared might aid in detecting in young galaxies with red shifts so large that even Lyman α radiation is shifted into the infrared. The precision of existing data on microwave background isotropy is tantalizingly close to the level at which fluctuations of small angular scales might be expected to show up. It would thus be disappointing if the proposed COBE satellite did not find any positive evidence for such fluctuations.

The evolution of individual galaxies is complex: the properties of the galaxies we now see must be a consequence of all kinds of astrophysical processes. On the other hand, the large-scale distribution of galaxies might be simpler to explain, being dominated by a process of gravitational clustering. The statistics of galaxy clustering have been studied by many astronomers over the years, culminating in the elaborate analyses by Dr Peebles and his associates. The main message of these investigations is that there is no preferred scale for a cluster of galaxies. As Dr Fall explained, the galaxies are grouped in a manner indicative of a gravitational clustering process, where the initial fluctuations had a smooth power-law form. N-body calculations, in which masses representing galaxies, set down at random at an epoch corresponding to $z \approx 20$, are allowed to cluster gravitationally, yield a final distribution which certainly mimics the real sky: the simulations by Dr Aarseth and Dr Efstathiou have more than a propaganda value, and suggest rather insistently that the large-scale distribution of matter is basically just a consequence of gravitational clustering. Indeed the fit is so good that it encourages us to go on to estimate Ω, and to attempt to infer the slope of the initial power law fluctuation spectrum.

It would, however, be interesting to see the results of an N-body simulation where the initial conditions were very different. Until this has been done one cannot be quite sure how strongly the evidence really favours a hierarchical clustering picture of galaxy formation rather than the view advocated by the Moscow school. Another question is whether the apparent filaments seen in the real sky are significant: in other words, is the mere fact that the 2-body and 3-body correlation functions for the real sky agree with those of the simulations sufficient evidence that the actual distributions are statistically similar? At the moment a problem with the observational data is that one is deprojecting a two-dimensional distribution to infer the spatial clustering. Much more accurate tests will be possible when enough red shifts for normal galaxies are available.

It is really very surprising that a simulation that neglects all complex physics can account so well for clustering. However, Dr Aarseth was careful to emphasize the limitations of current studies. It may indeed be safe to assume that gravity dominates on large scales, where the fluctuations are still in the linear régime; but in the nonlinear domain there are complications arising from the extended nature of galaxies and from the effects of mergers.

The N-body 'number crunchers' can perhaps explain clustering if they are given galaxies at a red shift of 20, but it may be the cosmologists' job to set up the starting conditions. In his introductory remarks, Professor McCrea emphasized that galaxy formation lies on the interface between cosmology and astrophysics. Galaxy formation occurred at a cosmic epoch very different from the present, and thus falls in the cosmologists' province. On the other hand, once galaxies have formed, the phenomena within them that interest astrophysicists proceed more or less regardless of the broader cosmic context. (At least this is true unless $\Omega > 1$ and the Universe eventually collapses on top of them!)

In the context of the hot big bang primordial fireball model, Dr Barrow reviewed the processes occurring in the early Universe that might imprint certain preferred mass scales on the Universe by the epoch of recombination. But in my view we are still unclear whether it is up to the cosmologist or the astrophysicist to explain the masses and sizes of galaxies. There are some straightforward physical ideas (mentioned by Dr Jones in his review), based on the cooling, collapse and fragmentation of massive gas clouds, that predict a characteristic mass and radius which seem relevant to galaxy formation. If these ideas indeed have something in them, there is no more need to relate the masses of galaxies to a preferred scale of initial cosmic irregularities than to invoke a preferred fluctuation scale in the interstellar medium to explain the masses of stars. But if one adopts a view based purely on hierarchical clustering, the characteristic scales of galaxies would be a function of cosmic epoch. If we came back in 10^{11} years, we should find that our galaxy and Andromeda would have merged into a single elliptical system, and that the entire content of a cluster like Coma would be an amorphous cD galaxy. Likewise, if we had observed the Universe when it was only 10^9 years old, smaller aggregates, now merged into larger units, would have been separately identifiable.

It is thus not clear whether galaxies are permanent structures manifesting some 'magic mass' for which we should seek a physical explanation. Even if so, it is unclear whether this mass scale (and the corresponding length scale) stems from local physics, or is a consequence of selective growth or damping mechanisms in the early Universe.

Any scheme for galaxy formation must however invoke *some* initial fluctuations. These fluctuations cannot have been merely infinitesimal, otherwise the Universe would still be smooth and unstructured today; on the other hand, the initial curvature fluctuations have amplitudes much less than unity (the Universe is certainly not chaotic, and is indeed remarkably smooth on the largest observable scales). The fluctuations needed to give rise to galaxies and clusters correspond to curvature perturbations of initial amplitude 10^{-4}; it is consistent with all data to suppose that fluctuations with this amplitude are present initially on all scales. There is no explanation for this number 10^{-4} which characterizes the initial roughness of the Universe. Cosmologists here divide into two camps. Some, bemused by the mathematical simplicity of a strictly homogeneous Cosmos, adduce arguments from thermodynamic equilibrium, etc., to suggest that such a model is in some sense more natural. They are therefore surprised that the fluctuations are so large compared with the very tiny value expected from initial $N^{-\frac{1}{2}}$ fluctuations in the baryon distribution. Other cosmologists, on the other hand, would regard a chaotic Universe, with more macroscopic degrees of freedom open to it, as more 'likely' than one described by the Robertson–Walker metric. They are correspondingly surprised that the fluctuations have amplitudes as small as 10^{-4} – that the initial state did not more fully avail itself of these other degrees of freedom – and regard the Universe's large-scale smoothness, rather than its small-scale roughness, as the major enigma. As Dr Barrow emphasized, to explain a specific amplitude like 10^{-4} is a daunting task which must entail exploring nonlinear processes, perhaps at some very early epoch indeed. The solution to this problem lies at the interface of relativity and particle physics, and may even demand a full theory of quantum gravity.

The main goal of astrophysical cosmology is to delineate how the content of the Universe evolved from being primarily gaseous to being conspicuously aggregated into the units we call galaxies. At the moment few statements can be made with anything beyond what Dr Reeves would have called 'weak credibility'. The processes that lead eventually to the different morphological categories and correlations that Dr van den Bergh discussed are complex and interdependent, involving interaction between the intergalactic medium, galaxies, stars and galactic nuclei. This interdependence means that it may be a long time before any single simple well posed question can be decisively answered. But as a corollary, it encourages the hope that solutions to all these interlinked questions may be illuminated together if we pursue our investigations on a broad front. Observational advances in the next decade should offer us a chance to firm up the very vague framework of ideas that we now have on galactic evolution. These advances will need to be complemented by theoretical and interpretative work with the use of the best physics and dynamics, and incorporating the best evidence we can glean on star formation from observations within our own Galaxy. I come away from this meeting encouraged by the impression that these research programmes are all in competent and energetic hands.