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4. Galaxy formation
(Bernard J.T. Jones)

This article surveys the literature from July 1981 to June 1984. It is neither possible nor desirable to refer to all papers on the subject, and accordingly only papers that are generally representative of some particular idea are explicitly mentioned. Galaxy Formation by its very nature has considerable overlap with other areas of cosmology such as the anisotropy of the cosmic background radiation, the question of the mass density of the universe, the nature of the large scale clustering, and detailed observations of galaxies. These are all topics covered by other reports to Commission 47 and the reader will therefore find only scant attention paid here to these important subjects.

1. GENERAL TRENDS DURING THE PERIOD

These past years have been dominated by two major developments. Firstly there has been the input to Cosmology from high energy physics which has provided us with the "inflationary" models for the early stages of the cosmic expansion and a plethora of exotic particles that might constitute the substantial amounts of "unseen mass" that are thought to pervade the universe. Secondly gravitational N-body simulations of cosmic evolution have provided a workbench for testing hypotheses for the formation of galaxies and the clustering process in general. The possible role of galaxy mergers has attracted a lot of attention. Observations of the large scale galaxy distribution have revealed a filamentary structure that is an important target for clustering theories. There has also been substantial input from observations of galaxies that have served to delineate specific chemical and dynamical processes taking place during the birth of a galaxy.

There have been a number of conference proceedings published during this period, these are cited in a separate bibliography. Review articles by Efstathiou and Silk (1983), Matzner (1984), and Peebles (1984c) have appeared. IAU Symposium N° 104 (see ref [E]) contains a remarkable variety of papers on the subject.

The material for this review covers theory and observation as relates to galaxy formation. The evolution that ensues once the final system is assembled and has reached a quasi stationary state will only be touched on here : thus no reference is made to the important issues of the chemical evolution of the disk of our Galaxy, dynamical friction in clusters of the relaxation processes that take place in globular clusters once they have formed. This is inevitably subjective and not without ambiguity, but it is essential in the interests of limiting the length and scope of the article !

2. EXOTIC PARTICLES AND DARK MATTER

There is growing (indirect) evidence for the existence of substantial amounts of dark invisible matter in the universe. Indeed, the inflationary model universes demand that the present universe be extremely close to the Einstein de Sitter case and so demand considerable quantities of dark nonbaryonic matter. (See Bean et al., 1983 for the current observational situation). Suggestions as to the nature of this material range from light .001 eV axions at the low mass end of the scale, through 100 eV neutrinos to primordial black holes at the other. The invention by high energy physicists of numerous exotic particles that could be of relevance to the earliest moments of the cosmic expansion leads naturally to reconsidering how

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galaxies might form it such particles were the major contributors to the present mass density.

The general features of galaxy formation in a universe dominated by massive (10 - 100 eV) neutrinos were outlined by Chernin (1981), Klinkhammer and Norman (1981), Doroshkevich and Khlopov (1981), Davis et al. (1981), Wasserman (1981, 1982). Problems of how the neutrinos got into galactic halos were examined by Melotte (1982, 1983) and by Bond et al. (1983).

Galaxy formation in a universe dominated by 1kev gravitinos was considered by Blumenthal et al. (1982), and by Bond et al. (1982b) who showed that the spectrum of fluctuations is flat between galactic and cluster scales in that theory.

Cosmological models that are presently dominated by axions are discussed for example by Axenides et al. (1983), Fukugita and Yoshimura (1983), Ipser and Sikivie (1983), Stecker ans Shafi (1983) and Turner et al. (1983). Models dominated by primordial black holes are considered by Freese et al. (1983). Turok (1983) considers fluctuations arising out of strings and Axenides and Brandenburger (1984) contemplate the consequences of para-photons.

3. N-BODY SIMULATIONS OF COSMIC EVOLUTION

Numerical N-body models have played an important role in seeing how nonlinear structures may have developed in the universe. Frenk et al. (1983) compared 1000 body models having different initial fluctuation spectra and concluded that the pancake-like theories gave a better visual impression for the appearance of the final state than did the hierarchical clustering models. White et al. (1983) also simulated neutrino dominated universes and concluded that such models appeared to be ruled out because they gave characteristic length scales that were unacceptably large. Dekel (1983) has modelled superclusters as large scale non dissipative pancakes. The filamentary structure is most clearly shown up in the very large simulations of Centrella and Melotte (1983) (the largest simulation to date) and of Miller (1983).

The origin of galaxy angular momentum has most recently been studied using N-body cosmological models by Efstathiou and Barnes (1984).

4. THE CLUSTERING AND SUPERCLUSTERING OF GALAXIES

While the N-Body simulations provide a graphic image of the clustering process, they do not actually explain why it develops the way it does. There have been a number of attempts to describe the clustering process by simple analytic models, the most recent of which is that of Hamilton and Saslaw (1984). With a simple thermodynamic ansatz they are able to reproduce the galaxy distribution functions of all orders which are in substantial agreement with observations. Schaeffer (1984) has also shown that these distribution functions can be obtained from the hypothesis that the N-point correlation functions are simply related to lower order correlation functions. Fry (1984) has discussed the evolution of the galaxy correlation hierarchy in perturbation theory.

The role of dynamical friction and mergers between galaxies in the evolution of the clusters themselves has been simulated by Roos (1981a,b), Roos and Aarseth (1982), Miller (1983), Farouki et al. (1983), Duncan et al. (1983), Cavaliere et al. (1984), Giuricin et al. (1984), Allen and Yabushita (1984) and Barnes (1984). Mass segregation arising during cluster evolution has been simulated by Barnes (1983) and by Farouki et al. (1983); the competition from tidal stripping has been considered by Merritt (1983). Analytic approximations for mass segregation based on simple N-body models were given by Farouki and Salpeter (1982). It has been suggested by Shaya and Tully (1984) that it is the supercluster tidal field that is responsible for the origin of galactic spin, and ultimately for the distinction between spirals and ellipticals.

A model for the evolution of a spherical supercluster has been given by Rivolo and Yahil (1983).

5. FORMATION OF GALAXIES AND GLOBULAR CLUSTERS

Peebles (1984a, 1984b) shows how naturally the characteristic scales of gala-

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xies and globular clusters can emerge in a cosmology dominated by weakly interacting matter with negligible primeval pressure. A number of papers have appeared trying to follow the formation of individual galaxies having dynamically dominant dark massive halos. Jones and Wyse (1983a), Wyse (1983), treat the problem of the formation of the thick and thin disk components of galaxies, and Kashlinsky (1982, 1984a,b) looks at rotational properties. Fall (1982) has reviewed the significance of galactic rotation for theories of galaxy formation.

Silk (1983c) comments that the surface density versus velocity dispersion data for galaxies is telling us that dissipation is the key factor controlling galaxy evolution. (See also articles of Struck-Marcell, 1981; Faber, 1982; and Gunn, 1982). Wang and Scheuerle (1984) present a model showing how dissipation may work to govern the eventual morphological and dynamical properties of galaxies. The collapse of a protocloud, and its fragmentation through the generation of turbulence and shock waves is shown by Sabano and Tosa (1984) to lead to globular cluster sized fragments. (See also McCrea, 1982). The evolution of collapsing protogalactic clouds was earlier considered by Struck-Marcell (1982a,b) and by Miller and Smith (1981).

Epstein (1983, 1984) has discussed the origin of the galactic mass function in terms of the gravitational amplification of initially Poisson irregularities. Palmer (1983) has investigated the tidal interactions between protostructures; the effect may be in part responsible for the observed shapes of galaxies and clusters of galaxies.

There have been a number of relevant N-body simulations of galaxy formation. Dissipationless collapses have been modelled by Noguchi (1984). McGlynn (1984), van Albada (1982). Wilkinson and James (1982) looked at the dissipationless collapse of a rotating triaxial galaxy.

The question of the hierarchical merging of stellar systems to form ever larger ones is of considerable interest. Tremaine (1981) has given a clear account of this and the role of dynamical friction. Kashlinsky (1984a,b) discusses the problem of merging in rotating haloes, and in particular the relationship between the final spin and core radius of the merged system. The sinking of a satellite into a parent galaxy has been discussed in detail by White (1983) in response to a paper by Lin and Tremaine (1983). Numerical simulations of the merger process have been attempted by Villumsen (1982, 1983) using a collisionless N-body code. The merging and stripping of halos in binary galaxies was studied by Carlberg (1982). Gerhard (1981); and Farouki and Shapiro (1982), used N-body simulations to study the merging of two disk galaxies to assess the hypothesis that ellipticals could formed in that way. Negroponte and White (1983) simulated mergers between disk-halo like systems, including a set of particles that collide inelastically to simulate a gaseous component. The role of merging in the centers of galaxy clusters is discussed by Merritt (1984a,b) and by Malumuth and Richstone (1984), with differing conclusions.

5. THE ROLE OF OBSERVATION, ELLIPTICAL AND SPIRAL GALAXIES

The relationship between the absolute magnitude, central velocity dispersion and spectral line strength among elliptical galaxies is an important datum for theories of galaxy formation. It is generally thought that the galaxies form a two parameter system (Terlevich et al. 1981), the "second" parameter has been identified as surface brightness by Wyse and Jones (1984) or mass to light radio by Efstathiou and Fall (1984). Dressler (1984) has presented data on galaxies in the Coma and Virgo clusters that suggests that the second parameter effect may be environment dependent.

In spiral galaxies an important datum is the bulge to disk ratio (Whitmore, 1984). This is probably related to the so-called "thick disk" component that is thought to play an important role in the formation of the familiar "thin" disk. The model of Jones and Wyse (1983a) for the formation of a disk galaxy makes us of this and provides an explanation for the important Fisher-Tully relationship (see also Burstein and Sarazin, 1983). There is a very well defined infrared colour magnitude relation for spirals, but not for ellipticals (Wyse, 1982; Tully et al.,

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1982); this may in part reflect a variation of bulge to disk ratio with absolute magnitude.

The relationship between environment and galaxy morphology is certainly an important clue to way in which galaxies have been formed. Postman and Geller (1984) have displayed a correlation of morphology with local galaxy density that extends over six orders of magnitude in density.

Davies et al. (1983) have studied the rotational properties of elliptical galaxies and suggested that rotation is dynamically more important in the intrinsically fainter ellipticals than in the brighter ones studied previously. Wyse and Jones (1984), however, have suggested that these observations are best explained in terms of rotation being more important in galaxies of higher surface brightness. It is interesting that the bulge components of disk galaxies are rotationally supported (Kormendy and Illingworth, 1982). (See Kormendy and Illingworth (1983) for a comparison of the velocity dispersion - absolute magnitude relationships for ellipticals and bulges).

Whether globular clusters are precursors of galaxies, or a consequence of the halo formation mechanism is quite unclear. The observational situation is reviewed by Freeman (1981), van den Bergh (1983, 1984), De Young et al. (1983) and by Pilachowski et al. (1983). It is possible that the globular clusters we see are the few survivors of an ongoing attrition by the tidal field of the Galaxy (Caputo and Castellani), 1984).

The situation as regards the origin of dwarf galaxies of various kinds is no less uncertain. Some way be the tidal debris of galactic encounters (Lynden-Bell, 1983; Gerola et al. 1983) or the dwarf spheroidals could be dwarf irregulars that have lost their gas by ram pressure sweeping (Lin and Faber, 1983).

6. PANCAKE THEORIES

The general features of pancake theories have been looked at in a number of papers (Arnold et al. 1982), and N-body experiments have proven particularly useful (Doroshkevich et al. 1983, Klypin and Shandarin, 1983).

The stability of shocked pancakes was studied by Jones et al. (1981) and by Palmer (1981a). Doroshkevich (1983) considered a gaseous pancake in the presence of massive neutrinos and Bond et al. (1984) did some numerical gasdynamic simulations of collapsing pancakes in a universe dominated "warm" or "hot" dark matter. Szalay et al. (1984) considered the effect of such collapse on the spectrum of the microwave background radiation. Chernin and Ushakov (1983) and Ushakov and Chernin (1983, 1984) have looked at the generation of angular momentum in the shock front and find values consistent with the angular momenta attributed to spiral galaxies. Gurevich and Verner (1983) looked at the origin of the angular momentam of ellipticals. Shapiro et al. (1983) did extensive numerical simulation of pancake hydrodynamics, including collisionless neutrinos.

Doroshkevich (1984) has calculated the expected separation between pancakes in neutrino universes and argued that this is consistent with the distribution of Ly-α absorption systems along the line of sight. Dekel (1982) on the other hand seeks to explain the observations in terms superclusters that collapsed recently and nondissipatively.

Peebles has offered some criticism of the pancake theory and suggested that the primeval departures from homogeneity may not have been Gaussian (Peebles 1982b, 1983). Schaeffer and Silk (1984a,b) attempt to counter some criticisms, especially those of White et al. (1983) concerning lengthscales.

The evidence for pancake theories mostly concerns the statistical nature of the large structure of the observed universe, and the impression of "filamentary" structures (Einasto et al. 1984). Interesting support for the idea has come from Djorgovski (1983) who claims that there is a genuine alignment of the galaxies in the Coma cluster.

7. THE FIRST STARS

What were the first gravitationally bound objects to form in our Universe, and when did they form ? The question is considered in general cosmological scena-

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rios by Carr and Rees (1984a, 1984b), and with reference to objects having masses between 10 and 100 $M_\odot$ by Silk (1983a, 1984). The role of molecular cooling ad redshifts 30-1300 has been considered in detail by Lepp and Shull (1984) and by Shchekinov and Ehntehl' (1983b). Izotov and Kolesnik (1984) study molecular hydrogen and suggest that the rotational J = 2 -> 0 transition should be looked for.

The contribution of pregalactic object to nucleosynthesis of light elements D and Li has been looked at by Rees (1984) and by Audouze and Silk (1983,1984). Bond et al. (1983a) and Carr et al. (1984) have studied the effect of hypothetical very massive primordial stars on He generation and the microwave background radiation. Tarbet and Rowan-Robinson (1982) imposed constraints on hypothetical populations of pregalactic stars.

A detailed hierarchical scenario for galactic evolution starting from primordial stars has been giben by J. Jones (1983). The collapse of a uniform metal poor protogalactic cloud can lead to a first generation of massive stars (Zinnecker and Drapatz, 1984). Silk (1983b) and Shchekinov and Ehntehl' (1983a) looked at the general problem of thermal instability in collapsing primordial clouds. Kashlinsky and Rees (1983) describe a specific scenario for the formation of the first stars. Chiosi and Matteucci (1983) consider the chemical enrichment of the galactic disk on the basis of models of primordial (zero metal) stars.

8. OTHER THEORIES OF GALAXY FORMATION

There has been copnsiderable interest in the idea that the large scale structure was generated subsequent to the formation of galaxy sized systems by explosive events that were the consequence of galaxy formation or quasar like activity (Ostriker and Cowie, 1981; Ikeuchi, 1981). Hogan (1983, 1984), Hogan and Kaiser (1983) and Carr and Rees (1984c) have looked at various aspects of this and other nonstandard models. Time dependent numerical solutions of the effects of cosmic shocks that might lead to galaxy and cluster formation have been presented by Ikeuchi et al. (1983).

Lyubarsky and Sunyaev (1983) calculate the expected distortion of the microwave background radiation spectrum and the generation of spectral features when energy is injected into the universe at an early time. Freese et al. (1983) explore the consequences of assuming that the dark matter consists of planetary sized black holes. Clusters of these will form objects that may subsequently explode, leading to galaxy formation. See also Bertschinger (1983).

9. COSMIC VOIDS AND FILAMENTS

Enormous voids in the universe have attracted considerable attention (Silk, 1982; Silk et al. 1983). The existence of voids is an attractive aspect of the pancake theories (Doroshkevich et al. 1982; Zel'dovich et al. 1982). The large scale topology of the universe in the Pancake theory has been examined from a very general point of view by Arnold et al. (1982) and by Shandarin and Zel'dovich (1983). Analytic models for spherieal voids are discussed by Filmore and Goldreich (1984), Occhionero et al. (1983, 1984) and Sato (1982). Icke (1984) has commented that voids are likely to be roughly spherical, whereas condensations are likely to be filamentary. The numerical simulations of Melotte (1983b) show this. The evolution of voids and condensations of ellipsoidal shape were studied by numerical solution of the equations by Fujimoto (1983) and by Santangelo et al. (1983) respectively.

The shell that forms around the void is of interest (Hausman et al. (1983). The density profile in voids has been discussed by Palmer and Voglis (1983). More complex multi-void models ("honeycombs") have been presented by Hoffman et al. (1983) and there have been some N-body studies (Aarseth and Saslaw, 1982; Saslaw and Aarseth, 1982).

10. THE ORIGIN AND EVOLUTION OF INHOMOGENEITIES

The various "inflationary universe" scenarios have provided a strong stimulus for studying the origin of perturbations in terms of quantum fluctuations prior to and at the time of vacuum phase transitions (Lindley, 1984; Bardeen et al. 1983;

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Hawking and Moss, 1983; Lukash and Novikov, 1983; Turner, 1983; Guth and Pi, 1982; Kompaneets et al. 1982; Chibisov and Mukhanov, 1982).

Khlopov and Polnarev (1983) show that when the universe is dominated by superheavy metastable particles, the evolution of small inhomogeneities leads to the formation of primordial black holes. The role of primordial black holes in the context of Grand Unified Theories has been discussed by Lindley (1982). Fluctuations arising out of quantum gravitational vacuum polarization have been evaluated by Starobinskij (1983). The generation of isotherm perturbations was considered by Bond et al. (1982a).

Collisionless damping of density perturbations in the early universe was discussed by Doroshkevich and Khlopov (1981), Davis et al. (1981), Wasserman (1981, 1982) and by Bond and Szalay (1983), and showed that massive neutrino and gravitino dominated cosmologies gave respectively supercluster and galaxy-like characteristic scales. Weakly nonlinear adiabatic and isothermal perturbations were considered by Vishniac 1982a,b, 1983), who also treated linear adiabatic perturbations as they cross the horizon of a universe with massive collisionless neutrinos (Vishniac 1982c). Cosmologies that deviate substantially from Friedmann models generally require numerical solution of the Einstein equations (Centrella 1983). The techniques for numerical modelling of planar inhomogeneous cosmologies have been presented by Centrella and Wilson (1983, 1984).

Brandenburger et al. (1983) have discussed fully the description of the evolution of fluctuations within general relativity. The evolution of adiabatic density perturbations through the recombination period was discussed in terms of an analytic model by Jones and Wyse (1983b). Kaiser (1983), Szymanski and Jaroszynski (1983), Zabotin and Nasel'skij (1982a,b, 1983) and Peebles (1981, 1982c,d) have calculated the expected anisotropy and polarization of the microwave background radiation arising from this epoch, using diverse assumptions about the cosmology. The evolution of perturbations subsequent to recombination in the weakly nonlinear regime has been calculated by Juszkizwick (1981) and in the nonlinear regime on the assumption that they have triaxial shape by Palmer (1981b).

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