EVOLUTION OF GALAXIES

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1. Introduction

There have been several previous discussions of this subject (G. Burbidge [8], M. Burbidge [4], Sandage [34], Roberts [31]), and therefore we wish merely to describe and review more recent ideas and work on the evolution of galaxies. It should be made clear at the outset that there is as yet no complete and satisfactory theory of the way in which a galaxy may evolve. However, the problem may be attacked in at least three distinct ways.

(a) In what may be called the statistical method, one collects as much data as possible (of a kind involving observations that can be carried out on a large number of objects) about as many normal galaxies of all types as possible. Attempts can then be made to correlate the various measurements, in the hope that a consistent picture may emerge.

(b) One may study those galaxies which present peculiarities suggesting that they may be in a stage that is likely to change in a time scale short compared with the Hubble time or the total lifetime of a galaxy. Various kinds of galaxies that are structurally peculiar fall into this category, also the radio galaxies. One may also measure in detail such things as velocity fields in particular galaxies where there seem to be motions other than simple circular rotation of an axially symmetric object under the action of gravitational forces alone. Work under this heading is necessarily carried out on relatively few objects; the aim is to deduce from the observations the way in which a particular galaxy may change from its present configuration to another one.

(c) A purely theoretical approach may be made, with recourse to what is known about related fields such as the theory of stellar evolution. Thus one could consider the way in which a protogalaxy composed of hydrogen gas would gravitationally contract and form into stars, and what its subsequent history would be after the first star formation began. Such an approach is straightforward, but the numerical quantities that have to be inserted are very uncertain.

Obviously a complete and satisfactory theory of galactic evolution will have to combine all three methods of attack, and possibly others as well. The disadvantages of the method (a) alone are that some kind of preconceptions or "working hypotheses" have to be inserted in order to make sense of the correlations. Method (b) can clearly only supplement what is done in methods (a) and (c), while in (c) alone some kind of initial conditions have to be postulated, and in any case there are so many parameters whose time variations lead to such complicated equations that solutions without simplification seem a long way off. Further, the appropriate cosmology, a knowledge of which ought to be included in the "known physical laws" but is not, must be intimately connected with the whole topic of galactic evolution, when evolution is taken, as in stellar evolution, to mean formation, early history, main history, and end point.

Finally, it is evident that a satisfactory theory will have to encompass all the normal forms of galaxies as given in, for example, the Hubble Atlas [33]. In addition, it will have to account for the many peculiar or interacting galaxies which were first catalogued by Vorontsov-Velyaminov [42] from the Palomar 48 inch Sky Survey, and for which an extensive catalogue of large-telescope plates is in preparation (Arp [2]). Also, all those galaxies which are strong sources of nonthermal radio emission must be fitted in, as well as galaxies (some of them radio emitters) with various unusual features such as the Seyfert galaxies (Seyfert [39]), compact galaxies (Zwicky [46], [47]), N type galaxies (Matthews, Morgan, Schmidt [24]), quasistellar galaxies (Sandage [36]), and the blue galaxies of Humason, Zwicky, Haro, Arp, Kinman, and others. The quasistellar radio sources have also to be fitted in, if they are in fact galaxies, and if they are not, their relationship to galaxies has to be understood.

2. The evolution of a rotating gaseous protogalaxy

Before discussing recent work, let us briefly review ideas which have been current for the past few years. Most workers think that a rotating, roughly spherical, mass of gas condenses to the point at which it is able to contract under its own gravitation, and that at some point fragmentation occurs [20] and star formation begins. In a particular contracting protogalaxy that part of the material which is condensed into stars retains the configuration of the gas existing at the time of star formation; the remaining uncondensed material dissipates its motions perpendicular to the equatorial plane of the galaxy and reaches an equilibrium configuration determined by its angular momentum; star formation may occur at any stage of this subsequent contraction. Thus spheroidal star systems with a succession of axial ratios, reflecting an age sequence, will be formed. An enrichment of the material by the products of nucleosynthesis in stars will occur during this epoch.

For many years, growing out of our knowledge of stellar evolution and lifetimes of stars as a function of stellar luminosity and mass, it has been realized that if the Hubble types are to be ordered in an evolutionary sequence, then it must be in the sense Irr → Sc → Sb → Sa → S0 (Shapley [40] and earlier references, Sandage [34]). This would not only be the sense of evolution suggested by the presence of high luminosity, necessarily young, stars in irregular and Sc galaxies, but also because the largest amounts of uncondensed material in the form of ionized and neutral gas and dust are to be found in galaxies of these types. As Sandage pointed out, the much smaller degree of flattening for the elliptical galaxies, compared to those of S0 type, suggested that they could not have evolved from the above sequence. Thus, even if such an evolutionary sequence were followed (and arguments against this are described in section 3) there would have to be an additional factor in determining galactic type, for which only the initial conditions seemed feasible. Initial conditions which might be effective were the mass of a protogalaxy, its initial density, amount of turbulence, angular momentum per unit mass, or magnetic field, or any combination of these.

3. Attack by method (a): arguments against an evolution Irr → Sc → Sb → Sa → S0

In a recent detailed piece of work Holmberg [19] collected a large amount of data on galaxies and analyzed it by means of the statistical method. His conclusion was that the above morphological evolution was not possible, and that all galaxies have the same chronological age. A similar conclusion was reached by Roberts [31], also by method (a). Let us discuss Holmberg's analysis and results, in particular looking at the basic assumptions underlying it.

For those galaxies whose masses had been determined, and for which he had photometric measures, he obtained the mass to light ratio $\mathfrak{M}/L$ and plotted it against integrated color index C; a very good correlation was found and was given by

$$\log \mathfrak{M}/L = 2.23C - 0.36. \tag{3.1}$$

Thus at a constant color index, log $\mathfrak{M}/L$ is a definite quantity, or $\mathfrak{M} \propto L$.

This result is intuitively very reasonable. Because the light of the galaxy is coming from stars, whose luminosities vary as the third and fourth power of their mass, an assembly of stars containing high luminosity young massive stars has a lower $\mathfrak{M}/L$ than an old assembly containing no stars much more massive than the sun. Given a universal luminosity function, $\mathfrak{M}/L$ as a function of age of a stellar assembly has been computed by Limber [23]. Assemblies containing only lower main sequence stars plus evolved red giants will have a red color or a large value of C.

From equation (3.1), Holmberg read off $\mathfrak{M}/L$ for a large number of galaxies for which he had the photometry (giving L and C) but not the mass values (it is important to note that he had found no correlation of C with $\mathfrak{M}$ alone). From $\mathfrak{M}/L$ and L, he thus obtained $\mathfrak{M}$ for all these galaxies.

For those galaxies of known total mass for which 21 cm measures had yielded the mass m of uncondensed H I, he plotted log $m/\mathfrak{M}$ against color index and again found a good correlation given by

$$\log m/\mathfrak{M} = -3.55C. \tag{3.2}$$

He now made the following assumptions: (1) the total mass of a galaxy is independent of time; (2) a galaxy at time $t = 0$ contains only H I gas; and (3) all the galaxies being considered have the same chronological age (an assumption he took to be demonstrated in the later discussion). He combined equations (3.1) and (3.2) and the initial conditions and obtained, by a method like that used by Schmidt [37], [38] and Salpeter [32], a differential equation for the rate of change of m with time in which the rate of consumption of hydrogen by condensation into stars varied as the first power of the H I density, the factor of proportionality being determined by C and going from 1.0 for irregular galaxies to 4.3 for type Sa.

Next he determined the mean densities D of all the galaxies being considered, and plotted this against color index, and again found a good correlation, given by

$$\log D = +2.41C - 2.47 \tag{3.3}$$

for the spirals; when irregulars and S0 types were added they changed the above linear relation to a curved one, but the fit was good and the various types of galaxy lay in distinct regions. This plot of Holmberg's is reproduced in figure 1. The high degree of correlation of log D with color index, combined with the result that the rate of hydrogen consumption was dependent upon color index, led

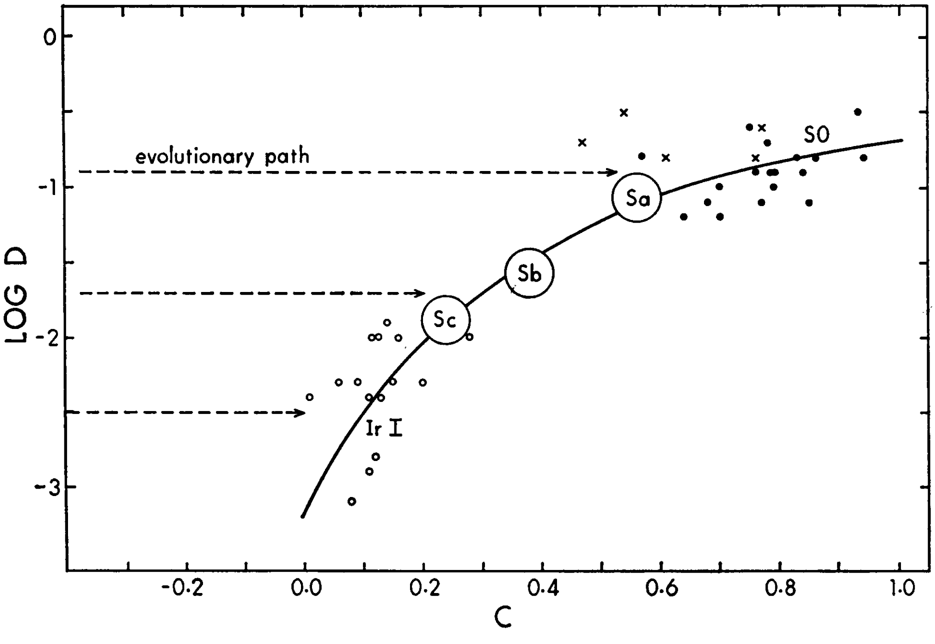

FIGURE 1

Holmberg's plot of log mass density D (in solar masses per pc^3) against intrinsic color index C, for different types of galaxies. Open circles: type Irregular I; filled circles: type S0; crosses: type Irregular II. Evolutionary tracks corresponding to a time independent mass density are indicated by dashed lines. (Plotted from figure by Holmberg [19].)

to the result that the rate at which H I is condensed into stars depends on the total mass density of a galaxy.

Finally, Holmberg argued that in figure 1, on the *assumption* that the mass and volume stay constant during a galaxy's lifetime, evolutionary tracks will be parallel to the abscissa, and hence one morphological type cannot evolve into another. He further argued that since all the galaxies in any one morphological type have the same evolutionary age (given by the color) and the same mass density (which he had shown to determine the rate at which star formation occurred), they must have the same chronological age. That the different morphological types should *all* have the same chronological age was not demonstrated, but was considered to be a reasonable possibility. Study of double galaxies of different types should throw more light on this. Lastly, the absence of galaxies to the left or right of the curve in figure 1 was taken to be evidence against the existence of recently formed galaxies.

We have discussed Holmberg's work rather fully, because it is the most detailed example of the attack based on method (a), and given the initial postulates, the conclusions are logical.

4. The problem of large $\mathfrak{M}/L$ ratios: need to abandon postulate of a universal luminosity function

One problem not touched upon by Holmberg in his analysis concerns the mass to light ratio of galaxies with the redder integrated color indices. Mass determinations in single galaxies yield values of $\mathfrak{M}/L$ as high as 50 or 60, with evidence for a correlation between $\mathfrak{M}/L$ and $\mathfrak{M}$ in the sense that the most massive ellipticals have the highest $\mathfrak{M}/L$, and Page's results for double and multiple galaxies suggest even higher values [29]. Yet a stellar assembly with a luminosity function similar to that in the solar neighborhood in our Galaxy cannot achieve values as high as this in the Hubble expansion time. This problem has been with us for several years. It can be avoided if one makes no assumptions about the stellar luminosity function but adds the requisite number of low mass red dwarf stars and evolved white dwarfs, so long as the composite thus achieved does not violate the observations in, for example, six color photometry and multicolor narrow band pass measures of galaxies (Wood [44]). Although not much published work on this is available (Roberts [31]), the indications are that it is difficult to add mass in the form of luminous stars in any proportions and satisfy both the very large values of $\mathfrak{M}/L$ and the multicolor observations.

Alternatively, one may, still keeping freedom with respect to the past and present stellar luminosity function, consider that dark matter is present in the form of "hidden mass" (Hoyle, Fowler, Burbidge, and Burbidge [21]). If stars which have reached the end of their nuclear evolutionary phase have managed to lose sufficient mass so that they fall below the stability limit for degenerate configurations ($\sim 1\ M_\odot$), then they can become such degenerate white dwarfs or neutron stars. That they should fall below the stability limit requires, however, some detailed physical arguments to be adduced concerning mass loss during evolution, and if they do not, then the classical results of Oppenheimer and Snyder suggest that they will collapse and effectively vanish as far as detection of electromagnetic radiation is concerned. They will, however, still exert a gravitational force, and so a sufficient number of such collapsed stars or "hidden mass" could raise the $\mathfrak{M}/L$ ratio without violating the color measurements.

There is no theoretical reason for believing in a universal luminosity function for all galaxies, or even for any one galaxy throughout its existence. Indeed, there are theoretical arguments based on the fragmentation process against such an assumption, and there may even be observational arguments against it apart from the observed $\mathfrak{M}/L$ and multicolor measures.

Consider the Sc galaxy M33, in the local group. Walker [43] used the technique of composite photography devised and used by Zwicky [45], that is, superposing a negative photograph of the galaxy taken in one color and a positive taken in another color, and published pictures showing very clearly an underlying smoothly distributed population of red stars which form the background to the spiral arms seen so prominently on normal single photographs. These red stars probably constitute most of the mass of the galaxy. Zwicky had used this technique to show that the unresolved yellow red stellar population in the Sc galaxy M51 is distributed in a very smooth spiral structure, with the outer arms lying slightly inside the arms as delineated by OB stars and gaseous H II regions. However, Walker found that in M33, the red star population shows no spiral structure and lies in a very smooth distribution of decreasing density with increasing distance from the center. He also concluded from the luminosity of the brightest red members of this distribution that they are probably red giants of the globular cluster type, rather than M67 type giants.

In the Magellanic Clouds also, the existence of RR Lyrae variables shows that there is a considerable underlying population of old stars, although the supergiants and other extreme population I types indicate a large, young population. One may wonder whether star formation can occur in distinct "bursts" of higher than average activity; possibly the stellar luminosity function may be different at these different times. Why this might be the case is another question, which we will discuss in section 5 below.

5. Is the mass of a galaxy constant?

If the mass is not in fact conserved during the lifetime of a galaxy, then the evolutionary conclusions drawn from figure 1 are clearly not valid.

Mass gain by accretion has not been much discussed in recent years, mainly because applications of the standard accretion formulae do not show it to be a very efficient mechanism [8]. Mass loss by explosive ejection has recently come into prominence, because of evidence from radio galaxies for the occurrence of violent events, but such mass loss has not been thought to comprise a large fraction of the total mass of the galaxy.

That interactions between galaxies and matter lying outside do occur was demonstrated by Burbidge, Burbidge, and Hoyle [12]; a particularly good case was afforded by NGC 4438 in the Virgo Cluster, a photograph of which was published there. Another interesting case is shown in figure 2—this is a more distant galaxy known as Mayall's Object; spectra show the ring to be gaseous and continuous with the long bright galaxy (E. M. Burbidge [5]) but whether it is being captured or ejected is not determined. In any case, if mass growth occurs in any galaxy it may well not be in the form of steady accretion but rather by the sudden acquisition of large dark lumps of matter that might already have a density near 1 atom/cm^3.

FIGURE 2

Mayall's Object, galaxy with recession velocity of 10400 km/sec,
with connected luminous gaseous ring.
Lick Observatory 120 inch telescope photograph.

A very interesting possibility is that suggested by McCrea [25], [26]. In this new version of the steady-state cosmology, with the continual creation of new matter being a property of existing matter depending on its physical state, galaxies grow in mass, and any galaxy might eject a fragment that would become the embryo for growth of a new galaxy. Galaxies would start as embryos and grow until they reach some limiting mass; presumably an instability would need to be invoked to limit the growth so that masses would not be attained that exceed the largest observed masses of galaxies. There is one particular example in the sky that might even be a result of this process—NGC 2444-5 (Vorontsov-Velyaminov [42]; Burbidge and Burbidge [9]; Burbidge, Burbidge, and Hoyle [12]; Sandage [35]). This is shown in figure 3. It consists of a pair of galaxies—one is an apparently normal elliptical, and the other is a highly irregular object containing much uncondensed gas. Although Sandage has suggested that the irregular object might be a normal spiral dissipated by collision with the elliptical, we still believe that the evidence is weighted strongly in favor of the hypothesis that it is a recently formed object.

Hoyle and Narlikar [22] have proposed another version of the steady state cosmology, different from McCrea's, in which inhomogeneous expansion occurs and in local spots mass is created around central mass concentrations which are a remnant of a condensed phase of the universe. These would then form elliptical galaxies; infinite growth of mass is prevented by an instability in the inhomogeneous steady state theory in which the creation process is essentially cut off when the mass has reached $\sim 10^{13} M_{\odot}$.

Both of these proposals in which the cosmology is invoked are examples of the method (c) of approach to the problem of evolution of galaxies. They follow an earlier suggestion by Ambartsumian ([1] and earlier references given there) that active galaxies (in particular radio galaxies like M87) may eject substantial amounts of ordinary matter as well as relativistic particles from their nuclei, and that blue galaxies occurring in the vicinity of giant elliptical galaxies might represent a later stage in the evolution of such ejected matter.

Proposals such as those just described have been applied specifically to elliptical galaxies, of which at least the giant spherical ellipticals may have little angular momentum. The spirals and rotating irregulars present a different problem, because of their observed angular momentum. Burbidge, Burbidge, and Hoyle [12] suggested that fairly large amounts of matter might be captured by such galaxies, and one such example, NGC 3646, was illustrated there. The presence in our Galaxy of high velocity clouds of neutral hydrogen with a velocity of infall has been discovered by the Leiden group [28] and the tentative suggestion has been put forward that these clouds might be coming into our Galaxy from the surrounding universe and be undergoing deceleration by the gas already present.

If we put these various suggestions together, we see a picture in which elliptical galaxies are formed from the creation of matter in a nucleus and the pouring outward of this matter to ever growing distances from the center until the process is stopped, while spiral galaxies are formed from the infall, capture, or condensation of outside matter. This would have to be the sense of the differentiation, because of the large angular momentum of the spirals. The occasional acquisition of particularly large amounts of matter by a spiral might initiate an active phase of star formation after a relatively inactive period; this might

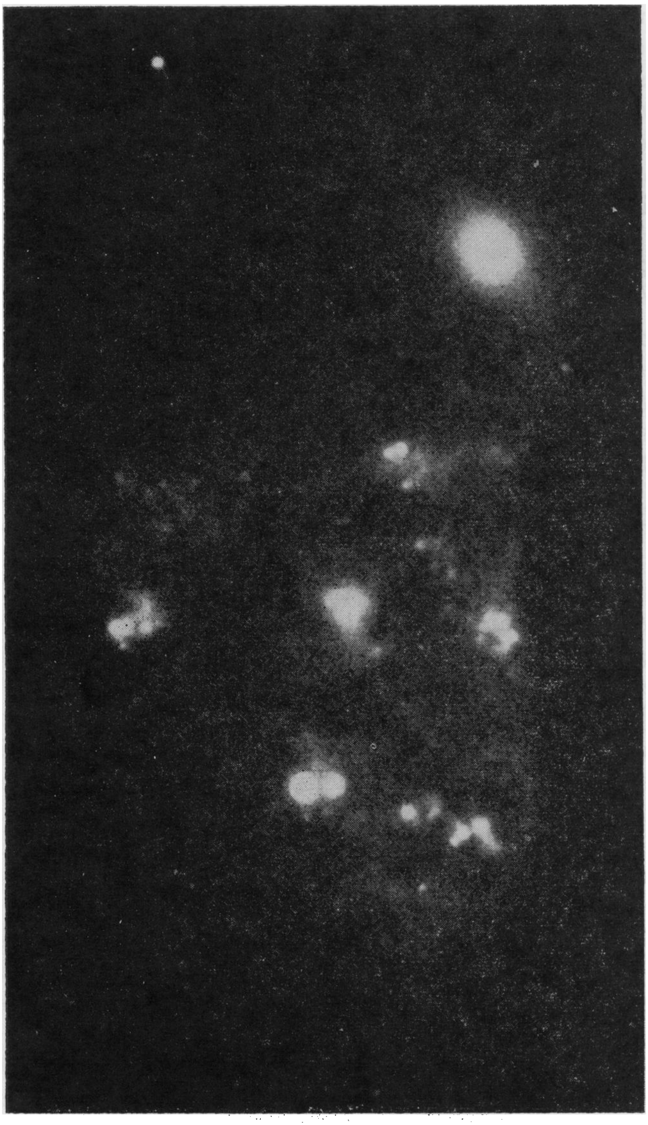

FIGURE 3

NGC 2444-5 (VV 117),
double galaxy consisting of elliptical
and very irregular companion with many H II regions.
Lick Observatory 120 inch telescope photograph.

have happened at any time in the past, remote or not, and the luminosity functions of the stars could well be different in different bursts of activity.

Such ideas are clearly in a very preliminary stage, and do not approach the state of development of the theory of a gaseous contracting spherical protogalaxy formed early in the history of a "big bang" universe. We present them here because it is well to remember that a problem as complicated as galactic evolution should be attacked by more than method (a) alone.

6. Attack by method (b): particular objects, and particular aspects of galaxies

6.1. *Radio galaxies.* Statistics of the strong radio emitting galaxies tell us that the majority are giant ellipticals or type D galaxies (described by Matthews, Morgan, and Schmidt [24]) which have very extended outer parts. When they occur in clusters, radio galaxies tend to be the brightest cluster member (as in Cygnus A, 3C 295, NGC 1275, NGC 6166, and so forth). Because the phenomenon occurs in *galaxies with a predominantly elderly stellar population and not much uncondensed material* (for example, M87, NGC 5128), the most obvious explanation would be that the occurrence of radio galaxies was connected with the actual stellar population; thus, the apparent connection with the central region of the above mentioned galaxies would be connected with the increased *stellar density* in the center. Thus one of us (G. Burbidge [7]) suggested that in such a dense region supernovae could be triggered. More recently Axford, Gold, and Ray [3] and Ulam and Walden [41] independently proposed that steller collisions (perhaps leading to stellar agglomeration into massive single objects) might be the cause of the radio phenomenon. In any case, we note: (a) because of the type of galaxy in which this occurs, the cause seems to have a connection with middle or old age in a galaxy, and a high star density and lack of very much uncondensed gas; (b) nuclei of galaxies are interesting places to study, for this as well as other reasons.

6.2. *Zwicky's compact galaxies.* According to classical stellar dynamics, the gravitational encounters that would be invoked to explain high density nuclei of massive galaxies and extended outer envelopes might also sometimes lead to highly condensed galaxies which could appear nearly stellar on photographic plates. The question of the time scale for the achievement of such high stellar densities, which according to classical relaxation calculations would be very long, is the problem in both cases. Zwicky [47] pointed out that the compact galaxies that he has been cataloguing are similar to the dense nuclei of large galaxies in their luminosity per unit area. Much quantitative work remains to be done on these before we understand their properties, but it is likely that they may point to an important stage of galactic evolution, and may be a link between ordinary galaxies and quasistellar radio sources and the quasistellar galaxies discussed by Sandage [36].

6.3. *Nuclei of galaxies.* Ambartsumian has suggested for many years that the nuclei are seats of activity in galaxies; that the phenomenon of strong radio emission has its origin in some kind of violent event there became clear a few years ago [15]. Ideas on the possible connection of nuclei with creation of matter were described in section 5. Clearly, a great deal of observational work is needed to clarify our theoretical ideas of nuclei.

First, it is often pointed out that nuclei contain little uncondensed gas and have a stellar population only of the old disk type, with K giant stars as the brightest members. While this is true in the best known external galaxy M31 and in many others, particularly of types Sb and Sa, it is certainly not so in a number of irregulars, Sc galaxies of both barred and normal types, and some Sb and SBb types. These often have H II regions right in the center, and the spectra show emission line intensity ratios like those in normal H II regions in our Galaxy, indicating that the sources of excitation are O and B stars which must be young. Many of the galaxies for which mass determinations have been made fall into this category (examples are NGC 2903 and NGC 253, studied by Burbidge, Burbidge, and Prendergast [13], [14]). How has this uncondensed gas persisted in a high density nuclear region in some galaxies, when it has apparently all been used up in others? Does it partake of a circulation through the galaxy, involving the spiral arms? We do not know. Detailed kinematic studies of the gas in nuclei require large telescopes and good conditions; a study of M51 (Burbidge and Burbidge [10]) has revealed noncircular flow of a kind that is not simply an axially symmetric radial outflow. In M31, which does not have much nuclear gas, Münch [27] several years ago found that gas was flowing out from the center, as the 21 cm work of the Leiden astronomers has shown to be occurring also in our own Galaxy.

Even if we go to galaxies that show no evidence for any appreciable amount of gas, there are unexplained features. NGC 4782-3, which is a double elliptical and also a radio source, is a good example. Here the whole luminosity comes only from stars, and its distribution must be determined by the stellar velocity distribution. Yet these two ellipticals, of rather similar luminosities, have quite different nuclei: one is much more centrally condensed than the other (Burbidge, Burbidge, and Crampin [11]). We do not know the reason for this, but until we do, it is clear that we shall not have progressed far in understanding the dynamical evolution of stellar systems.

6.4. *Spiral arms; barred spirals.* The persistence for times of order 10^{10} years of spiral arms which should, by the observed differential rotation curves and rotation periods, wind up in a few times 10^8 years, has long been a puzzle. Recently a number of theoretical workers have been tackling anew the problem of these as manifestations of instabilities in rotating systems containing the stellar component and a gaseous component. The arms would then not be persistent structures but would be traveling waves in the gaseous component, continually renewed as long as there is still uncondensed material, and, during their existence, the seat of star formation. The time scale for star formation as a function of stellar mass may be important here; unless a forming stellar group or cluster is gravitationally stable, the local high density gas wave may have "moved on" before the stars of lowest mass have time to condense; this might be a contributory factor in the difference in stellar luminosity function between galactic clusters and the general solar neighborhood (van Rhijn function) which has a relatively greater number of low mass stars.

The question either of the relative positions in an evolutionary sequence of barred and normal spirals, or of the initial conditions which cause one or the other configuration, is one in which some theoretical progress has been made recently. Fujimoto [18], Prendergast [30], and Danby [16] have studied gas flow in the gravitational field of a prolate spheroid (representing the bar) rotating end over end. Forms of barred spirals can be qualitatively understood, according to Prendergast's work, and an evolutionary sequence in which barred spirals change eventually into normal spirals seems reasonable. There are no models, however, to explain the stellar bars of SBa and some SBb galaxies. Attempts to correlate the observed velocity field in the gas in some SBc and SBb systems with dynamical models of barred spirals are going on, but it is difficult to get results because of the lack of axial symmetry and lack of knowledge of the inclination of these galaxies to the plane of the sky. The role of a magnetic field in spiral arms is being studied by Piddington and by Pikelner and his colleagues.

6.5. *Highly irregular galaxies.* Some of the objects in the Atlas published by Vorontsov-Velyaminov [42] are highly irregular, while at the same time they have much uncondensed gas, large scale motions, and very large dimensions. It would appear, therefore, that the objects cannot be in a long lived phase. Their study is an example par excellence of the attack by method (b) on galactic evolution. A discussion of these objects as possible examples of very recently formed galaxies was made by Burbidge, Burbidge, and Hoyle [12], (see also E. M. Burbidge [6]), and, while some of the assumptions made there about an intergalactic medium need modifying, the empirical deductions made from the observations still appear to be valid. Figures 4 and 5 show some of the best examples of these objects—VV 109, a thin object some 37 kpc long with apparently no nucleus, NGC 3509 which is similar in spectroscopic properties and is 45 kpc in overall dimension, and NGC 4861, a fairly close irregular with a large fireball like nucleus at one end and a thinly spread main body looking like a comet's tail.

6.6. *Quasistellar radio sources.* We will conclude by some brief comments on the newest astronomical puzzle—quasistellar radio sources. There are at present two possibilities being discussed, first, that the large redshifts of these are cosmological in nature so that the objects are very distant, and, second, that the redshifts are due to relativistic speeds of local objects which might be lumps of plasma ejected from our own or a neighboring galaxy. In the second case, the objects are not galaxies and we can place them for discussion with the various problems considered in subsections 6.1 and 6.3 of this section. If, however, the redshifts are cosmological, then the QSRS's must represent some phase of evolution of some kind of a galaxy. Field [17] suggested they might be galaxies in

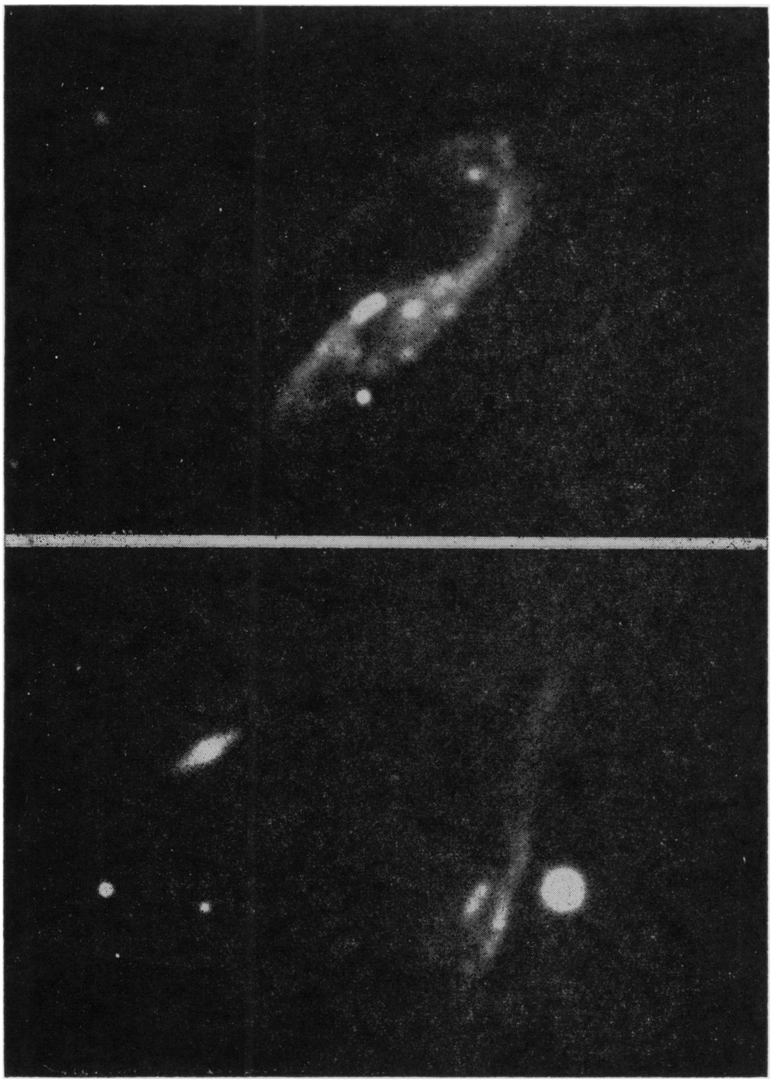

FIGURE 4

Two highly unsymmetrical galaxies with emission line spectra;
upper: NGC 3509 (VV 75), McDonald Observatory 82 inch telescope;
lower: VV 109, Lick Observatory 120 inch telescope photograph.
(Bright round image at right side of object is a foreground star.)

the process of formation. Recent analysis of the number, luminosity statistics of faint radio sources has tended to support this view in suggesting that their frequency was higher in an early (presumed more condensed) stage of the universe. Alternatively, it has been suggested that the QSRS's might truly be

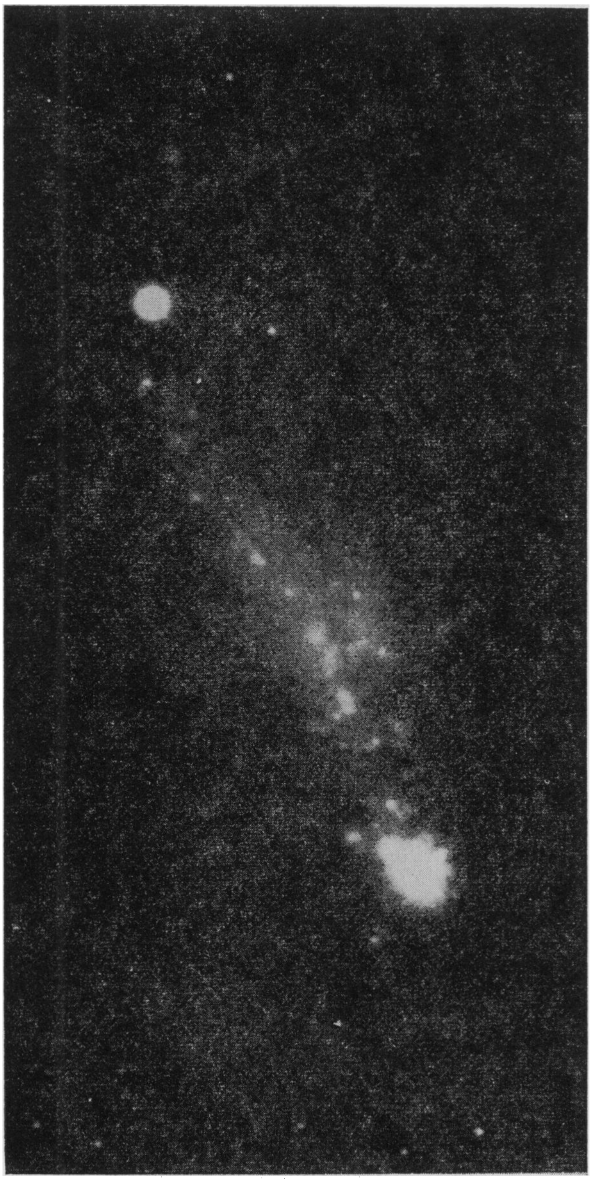

FIGURE 5

Irregular galaxy NGC 4861,
with nucleus at one end and strong emission line spectrum.
Lick Observatory 120 inch telescope photograph.
(Bright round image at upper left is a foreground star.)

extreme cases of Zwicky's compact galaxies, in which complete stellar agglomeration occurs with the release of a vast amount of energy.

A statistical approach to this problem may be the best one at present. We need to know more about their spatial isotropy or otherwise and their redshift-magnitude relation, and we also need the collection of more physical data about a larger sample.

7. Concluding remarks

It is only in recent years that we have begun to study the bewildering diversity of galaxies with a view to understanding the physical processes that are taking place in them. Thus, we are only at the beginning of a long chain of investigation: at one end is the construction of simple theoretical models of elliptical galaxies and the ordering of the observational data in a logical, but not necessarily unique, way; at the other end of the chain is the construction of detailed theoretical models of galaxies containing stars, gas, and dust, with angular momentum and magnetic fields taken into account, and the comparison of these theoretical models with the observations of the large variety of galactic types. The problem is much more complex than that which is encountered in understanding stellar evolution. There are a number of reasons for this. In the case of stars the bulk of them have been formed at an early epoch and we do not know in great detail what the initial conditions were. However, we do know that the more luminous stars are continuously forming and evolving and thus the initial conditions for star formation are those in the interstellar medium today. In the case of galaxies, the initial conditions are tied to the early history of the universe if we live in an evolving universe, and only if we live in a steady state universe can we suppose that galaxies are forming out of the intergalactic medium, as it is at present. In the case of stars much progress has been made by relating the color magnitude diagrams of star clusters with theoretical evolutionary tracks for stars, but the key to our understanding has come from the well-founded assumption that in a cluster the stars formed coevally and that the evolution of a star depends only on its mass and chemical composition. In the case of galaxies it is reasonable to suppose that all of the galaxies in a cluster condensed from the same protosystem, but it is unclear as to whether or not there was a long time spread over which the galaxies condensed. Moreover, the wide variety of forms of galaxy in some clusters (for example, the Virgo cluster) indicates that the initial conditions for the condensation of a galaxy, which presumably determine the forms as well as the masses, can be very different at different places within the same cluster. The angular momentum must be a dominant factor in these considerations. This is probably also the case in star formation, but the stars solve their own angular momentum problems in comparatively short time scales before they reach the main sequence, and, after this time, current theory suggests that their rotational characteristics play only a minor role in the further evolution, at least until they reach the final and perhaps catastrophic phase.

The question of whether there exist many galaxies which are very young in evolutionary terms is a vexed one at the present time. We have concluded that many of the irregular galaxies included in the Vorontsov-Velyaminov Atlas [42] fall into this category. Our reasons for this have stemmed largely from the fact that the bulk of the light that is seen comes either from stars of high luminosity or from gas which is illuminated by such stars, from the forms of the velocity fields and the highly irregular structures, and the large sizes of the objects. However, others have taken the opposite view and have argued that these may be systems which result from the interaction of two or more mature galaxies, or else that there is an underlying population of low mass, old stars, such as is certainly present in the Magellanic Clouds. This question might be resolved if we could find out conclusively the nature of the intergalactic medium—what is its mean temperature, density, and composition; whether there are clumps of matter such as isolated dust clouds (as some have suggested), neutral hydrogen clouds with a density much above the average, or clouds of low mass stars or other condensed objects. Only then shall we be in a position to know whether galaxies accrete during their lifetimes so that their masses steadily increase.

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