VIII. THE SPHEROIDAL COMPONENT

THEORETICAL OVERVIEW - INTERACTIONS AMONG THE GALAXY'S COMPONENTS

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ABSTRACT. The structure and evolution of the Galaxy are reviewed in terms of interactions among various components, including its immediate surroundings. Emphasis is given to the large-scale processes responsible for star formation and chemical evolution, which are seen to be controlled by interactions between the ISM and other components and by gas flows. A model for formation of the Galaxy is outlined, in which the spheroidal component results from mergers of former small galaxies, and the disk has been accreted from outlying diffuse matter.

1. INTRODUCTION

Many advances in understanding the Galaxy have been due to a recognition of separate components, either conceptually, as in Baade's division of stars into two populations, or factually, as in the discovery of the interstellar medium (ISM). In trying to see the whole Galaxy in theoretical perspective, we find that much of its structure and evolution can be described in terms of interactions among such components. Figure 1 shows a subdivision of the Galaxy that is convenient in this context.

Disk	galactic center		old disk stars		young stars, spiral arms	ISM
Spheroidal component		nuclear bulge		stellar halo		
Surroundings			satellite galaxies		invisible corona	IGM

Figure 1. A conceptual division of the Galaxy and its immediate surroundings into components.

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 431 440.

Most of the borderlines between components in Figure 1 are intended to be only vaguely defined, because physical continuity makes any such divisions rather arbitrary. For example, stars of the nuclear bulge might be described as the innermost halo population, and there is a continuous distribution of ages between the oldest and the youngest disk stars. The intergalactic medium and satellite galaxies are included because they cannot be ignored in a large-scale picture of the Galaxy's structure and evolution; as Saar and Einasto (1977) convincingly argue, the whole hypergalaxy forms an interacting system. The term "halo" refers throughout this paper to ordinary halo stars in the classical sense - a spheroidal subsystem traced by the globular clusters; outlying gas is denoted "intergalactic medium" (IGM); and any extended hidden mass consisting of neither gas nor visible stars is referred to as the "corona".

Many of the processes that are familiar in studies of galactic structure and evolution can be seen as interactions between the components given in Figure 1. For the large-scale picture of interest here, two broad classes of interactions are especially relevant:

i) Exchange of matter between components. Many changes in the structure, stellar content, and chemical composition of the Galaxy are due to exchanges of matter between components, either by local physical processes such as stellar aging, or by bulk motions such as infall. Examples to be discussed below are the formation of stars from the ISM, ejection of matter (after nuclear processing) from stars back to the ISM, formation of the Galaxy itself from IGM and even from smaller satellite galaxies, and continued accretion of IGM onto the disk.

ii) Gravitational interactions. Several current problems in galactic dynamics involve questions of how the mass distribution in one component of the Galaxy affects the form and kinematics of others. Examples are whether density waves in the old disk underly spiral structure (Roberts, 1977), whether an inner halo stabilizes the disk (Ostriker and Peebles, 1973), and whether motions of satellites indicate a hidden corona (Hartwick and Sargent, 1977). This paper will emphasize processes that affect the stellar content and chemical composition of the Galaxy, rather than dynamical problems as such, which are reviewed elsewhere in this Symposium and in IAU Colloquium No. 45 (Basinska-Grzesik and Mayor, 1977). Although the corona may contain most of the mass of the Galaxy, it will be ignored here since the processes of interest are not necessarily affected by the depth of the potential well in which the hypergalaxy lies. Gravity is of course the force behind the large-scale motions that have shaped the Galaxy itself, which could in turn be important in star formation, according to some of the ideas discussed below.

This picture of the Galaxy as an interacting system will be kept in mind in discussing recent ideas on its current evolution (§ 2) and formation (§ 3), as a fairly typical spiral galaxy.

2. SOME EFFECTS OF PRESENT INTERACTIONS

Viewed on large scales, the evolution of the Galaxy now and during most of its past history is controlled by processes involving interactions among its constituents and immediate environment, some of which are reviewed here. The past several billion years are thought to have witnessed only mild changes as a result of such processes: the conversion of some ISM into stars, growth of the disk by accretion, a small fractional increase in the mean metallicities of stars and gas (especially in the outer disk where the time scales for change are longer), and evolution toward redder integrated colors as the ratio of old to new stars has increased (Audouze and Tinsley, 1976; Saar and Einasto, 1977; Tinsley and Larson, 1978a). Spiralling-in of satellites may also be adding sporadically to the Galaxy's mass (Tremaine, 1976). At the galactic center, more dramatic changes may have occurred.

This Section focusses on two related aspects of long-term evolution of the Galaxy: star formation and chemical evolution.

2.1. Causes of Star Formation

Still taking an overview that ignores small-scale physical processes, we can consider star formation to be caused primarily by dynamical compression of the ISM (Larson, 1977). Several different compression mechanisms have been suggested as contributing to star formation in the disk, each of which can be seen as an interaction between the ISM and another component of the hypergalaxy. One set of possibilities involves young stars: dense interstellar clouds can be compressed by blast waves from supernovae (Herbst and Assousa, 1977) or by ionization-shock fronts from hot stars (Elmegreen and Lada, 1977). Another idea is that star formation is due to infall of extragalactic gas (Larson, 1972), in particular to infalling clouds that collide with diffuse interstellar gas (Saar and Einasto, 1977). A third possibility is that interstellar clouds are compressed by shocks due to a galactic density wave (Roberts, 1969). There is at least one major site of star formation in the Galaxy, its center, where a density wave cannot be held responsible. The strongly non-circular or non-coplanar motions observed there suggest, however, that star formation is associated with some kind of dynamical disturbance (see reviews by other authors at this Symposium); further evidence that violent disturbances lead to rapid bursts of star formation is obtained from the colors of interacting galaxies (Larson and Tinsley, 1978; see below).

An important question is whether processes inside the Galaxy itself can sustain star formation in the disk, or whether a continual external impetus is required. If the main mechanism involves short-lived stars, such as supernovae or OB stars, then star formation may spread epidemically; and if old stars form a stable density wave that initiates star formation, the process could again be sustained indefinitely over much of the disk. But if infall is a major source of the necessary interstellar compression, then star formation is strongly linked to the Galaxy's environment.

Of the compression mechanisms mentioned above, only standard density wave theory implies direct involvement of old-disk stars in spiral structure; if instead star formation is due primarily to shock fronts from supernovae or OB stars, or to infall, spiral arms can be a dynamically superficial result of differential rotation (Larson, 1972; Mueller and Arnett, 1976; Saar and Einasto, 1977; Gerola and Seiden, 1978). Of course the differential rotation is itself due to the mass distribution of spheroidal and old-disk stars, so these components still play an indirect role in spiral structure. Moreover, Gerola and Seiden (1978) and Saar and Einasto (1977) have shown how the tightness of spiral winding then naturally increases with the bulge/disk ratio, as observed along the Hubble sequence.

It has often been hoped that the star formation rate could be regarded simply as an increasing function of the mean gas density in a region (Schmidt, 1959, 1963; de Jong and Maeder, 1977, pp. 169-172), but both theory and observation tell against any unique dependence of this form (Larson, 1977). A recent study shows, moreover, that Local Group galaxies with the most efficient present star formation, measured as the rate per unit mass of HI, are those with the *smallest* ratios of interstellar to total mass (Lequeux, 1978). It thus appears that the quantity of gas is determined by the efficiency of star formation, not vice versa; other factors, such as compression and cooling of the gas, must therefore be the chief elements in star formation.

An interesting case arises if infall of extragalactic gas gives the main *dynamical* impetus to star formation, since the infall rate in the Galaxy is thought to be comparable to the star formation rate. In this situation, the consumption and supply of gas in the Galaxy are closely related, and one can understand both how the ISM is not entirely consumed into stars in a few billion years and why chemical abundances change only slowly with time (Larson, 1972; Tinsley, 1977, and references therein).

2.2. Chemical Evolution in the Disk

The histories of chemical abundances in different regions of the Galaxy are thought to depend strongly on both star formation and gas flows, as reviewed by Audouze and Tinsley (1976). If gas flows are negligible, abundance levels depend logarithmically on the relative masses of ISM and stars, and the time scale for enrichment is given by the ratio of interstellar mass to the star formation rate. But if inflow and star formation occur at comparable rates, abundances approach equilibrium values on a time scale given by the ratio of interstellar mass to inflow rate.

For long-term evolution of the disk, the main factors are star formation, gas return from stars of both the disk and spheroidal components, accretion of IGM, radial inflow, and the chemical composition of gas involved in these processes. Many schematic models have illustrated how these factors can help explain salient chemical properties of the Galaxy, and relevant data and models were recently reviewed by many authors at IAU Colloquium No. 45 (Basinska-Grzesik and Mayor, 1977). It has become clear that a realistic picture of evolution in the disk should consider gas inflows from both the spheroidal component and the IGM. When these are included in calculations of chemical evolution, many formerly *ad hoc* model parameters - such as "prompt initial enrichment" and "infall" - appear as natural consequences of dynamical processes. (Of course, small-scale factors, such as nucleosynthesis and mixing of stellar ejecta into the ISM, also play key roles in chemical evolution. They are discussed in the reviews cited above.)

Three examples of possible large-scale dynamical effects on chemical evolution are the following: (1) Supernovae in the halo at its formation time could have produced a rain of metals sufficient to give the disk a substantial fraction of its present metallicity before many disk stars formed; thus there need be no problem in understanding the paucity of metal-poor dwarfs in the solar neighborhood (Ostriker and Thuan, 1975). (2) Further increase of the disk's metallicity would be suppressed by continuing infall of IGM, at a rate comparable to the star formation rate, as is predicted in dynamical models where the disk forms by accretion on a time scale of billions of years; this effect can explain the weakness of the age-dependence of metallicities of nearby disk stars (Tinsley and Larson, 1978a), and some other interesting details such as the near constancy of the interstellar beryllium abundance during the past 5 billion years (Reeves and Meyer, 1978). (3) The time scales for infall and consumption of gas by star formation increase radially outward in the slow collapse models just mentioned, so that the metallicities of stars and gas are predicted to decrease outward in the disk (Tinsley and Larson, 1978a), as observed.

Although these effects have led to plausible solutions to some puzzles concerning chemical evolution of the galactic disk, they show how complicated is the task of understanding other galaxies or the anomalous center of our own. Models that treat galaxies as closed systems, converting a given mass from gas into stars, are probably as misleading for other regions as for the solar neighborhood. In general, no part of any galaxy is likely to be isolated from its surroundings, and gas flows may play important roles both in chemical evolution and in star formation. The colors of a region are, in turn, determined mainly by the ratio of its present star formation rate to the integrated past rate (Larson and Tinsley, 1978), so even the photometric properties of galaxies depend in part on large-scale interactive processes. Finally, the present shape of the galactic disk is another property that could be strongly influenced by the spheroidal component and the IGM (Ostriker, 1977; Saar and Einasto, 1977).

3. FORMATION OF THE GALAXY FROM SUBSYSTEMS

The picture of disk formation reviewed above is one of accretion of IGM (and possibly gas-rich companion galaxies) around the nuclear bulge of the Galaxy, during many billions of years. As a final example of how interactions among various subsystems can be important in galactic evolution, the formation of the spheroidal component will also be considered as due to the coalescence of formerly separate components.

One piece of evidence favoring this view is that a gaseous protogalaxy of a few times 10^{11} $M_{\odot}$ would probably have a Jeans mass of only $\sim 10^7 - 10^9$ $M_{\odot}$, and so consist initially of many lumps (Larson, 1969). Another suggestive argument is that the present frequency of collisions between galaxies is such that most or all of them could have experienced mergers with others during their lifetimes (Toomre, 1977; Vorontsov-Velyaminov, 1977). In particular, Toomre (1977, p. 420) has commented that present-day collisions could be simply the "dregs" of a process that was very common in the past.

It is therefore interesting to replace the conventional view of a rather smoothly collapsing protogalactic cloud with one of an initial cluster of small gas clouds that collide and merge among themselves. Tinsley and Larson (1978b) suggest that spheroidal systems form by a hierarchical sequence of such mergers; the mergers are assumed to induce bursts of star formation, as suggested by an earlier result that many strongly interacting galaxies have colors consistent with recent bursts (Larson and Tinsley, 1978). Each time a given galaxy grows by merging with another of comparable size, some of the residual gas is turned into stars, so that the metallicities of both gas and stars increase with the total mass of the system. Star formation in mergers is cut off before the gas is completely used up, because the gas eventually becomes too hot to cool and form stars between collisions. However, in most cases the violent growth process stops before this stage is reached, because there are no more neighbors to merge with. If the residual gas is swept away by an ambient IGM, an elliptical galaxy remains, but if diffuse outlying gas stays bound to the system, it may be accreted gradually in a disk.

This picture accounts qualitatively for the relatively low frequency of disk galaxies in dense clusters, it explains the observed iron content of intracluster gas as due to residual enriched gas lost by ellipticals, and it predicts that the spheroidal components of spiral galaxies should be identical to elliptical galaxies. An increase of metallicity with mass for ellipticals is a direct consequence of the proposed star formation in mergers; Tinsley and Larson (1978b) find that this relation has approximately the form suggested by the empirical color-magnitude relation of ellipticals if the efficiency of star formation is allowed to increase with successive mergers, i.e. to increase with the mass of the merged system. This requirement is itself found to be plausible in terms of the amount of ISM that would be compressed enough to form stars in a given collision.

The nuclear bulge and halo of the Galaxy are, in this view, simply an elliptical galaxy. Direct evidence for its formation by mergers of subsystems would have been almost obliterated, since tidal disruption and evaporation would have destroyed clumping on scales larger and smaller, respectively, than globular clusters (Rees, 1977). Nevertheless, indirect support for the model is given by Searle's (1977) result that the metallicity distribution of globular clusters can be explained if halo stars formed in isolated subsystems that later merged. A metallicity gradient in the nuclear bulge and inner halo is also consistent with star formation in mergers, since at each stage the gas would cool and condense toward the center before forming new stars, which would always be more metal-rich than the stars formed earlier. Some of the gas that later made the disk would have been enriched during the formation of the spheroidal component, so the initial disk gas could have a significant metallicity, as in the earlier models discussed in § 2.

In many respects, the merger picture is just a close-up view of previous models of galaxy formation, in which spheroidal systems result from rapid star formation during the initial collapse and disks form from dissipative gas with less efficient star formation (Larson, 1976; Gott, 1977). The main innovation is to provide a specific mechanism - collisions between galaxies - for the early efficient star formation needed to produce an elliptical system. Moreover, the main processes envisioned during galaxy formation can be studied directly by interpreting observations of present-day interacting systems: occasional collisions between gas-rich galaxies appear to result in mergers that form elliptical systems and involve bursts of star formation (Toomre, 1977; Larson and Tinsley, 1978); and cD galaxies appear to be growing continually by accretion of other ellipticals at the centers of dense clusters (Ostriker and Hausman, 1977).

As for our own Galaxy, infall and the spiralling-in of satellites represent continuations of the processes of dissipation and dynamical friction that have shaped the system from its start as a swarm of small clouds. It is not difficult to imagine that the bulge and halo are essentially an elliptical galaxy, whose signs of former substructure are the globular clusters and outlying dwarf spheroidal companions, while the disk is still the site of conversion of intergalactic into interstellar matter and ultimately into stars.

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DISCUSSION

Yahil: It is worthwhile pointing out that the buildup of large galaxies from smaller subunits, by means of dynamical friction and subsequent merger, can proceed at a reasonable rate only if the size of the subunit is comparable to their mean separation at the time of merger. Once the mean separation becomes too big, the process will quickly stop. The spectrum of initial perturbations which leads to galaxy formation must therefore have a hierarchial structure which will enable the continued growth of galaxies from small subunits to present-day galaxies. The continued growth of galaxies today in turn depends on the extent of their massive halos (for which there is no secure upper limit) in relation to their mean separation.

Tinsley: The work by Simon White and his collaborators on this point is very relevant. White and Sharp have noted that halos cannot be too extensive, or else a large number of binary galaxies would be within an orbit of merger! The present luminosity function and clustering of galaxies are of course constraints on the initial perturbation spectrum in the merger model, as they are in any view of galaxy formation.

Verschuur: If galaxies form by accretion of smaller units would not the size correlate with age in some way?

Tinsley: This is true, but there would not necessarily be any observable consequences. For one thing, mergers and star formation could go to completion in a few dynamical times of the resulting present-day elliptical galaxy, so even the final star-forming stages of large galaxies could have taken place within 1 or 2 billion years of the start of the process. It would be impossible to detect such age differences among elliptical galaxies, but there does seem to be an age spread among halo stars in the Galaxy suggesting that the very metal-poor globular clusters (e.g., M92) formed before 47 Tuc (Demarque and McClure 1977, at the Yale conference). Another point is that the very biggest galaxies, which might be noticeably young according to their long collapse times, are here seen as forming simply by mergers of stellar systems; there is no further star formation because any gas is too hot. This is just Ostriker's view of the formation of cD galaxies. They were made recently, but of old stars.

Rubin: I would like to call attention to an observation which may be relevant to your model of a spiral as an elliptical plus disk. Some spirals (i.e., M31) have nuclear velocity dispersions of a few hundred km s^{-1}, and in spectra centered in the red, the Na D doublet (separation $\sim$6A) is completely blended. Other spiral galaxies show incredibly narrow, well-resolved nuclear Na D lines, which reproduce the velocity gradient shown by the excited gas. For these galaxies, the disk must extend within a few pc of the center. Why a larger velocity dispersion is not apparent, arising from the bulge stars, is a puzzle. For your model would you expect the disk to extend into the nucleus?

Tinsley: The merger model need not differ from any other in the inward extent of the disk, which we have not tried to predict. In general, the velocity dispersion of the disk need not correspond to that of a spheroidal system in which it is embedded.

Sullivan: How do S0's and other gas-deficient disk galaxies fit into your scheme? What is the relative time scale of disk formation and various possible stripping mechanisms which may occur in the cluster environment?

Tinsley: The origin of gas-deficient galaxies need not be any different in this model than in alternative models of galaxy formation. Perhaps some constraints on the time scale for gas loss or stripping of disks can be obtained from the recent studies by Butcher and Oemler of clusters of galaxies at redshifts ~ 0.4 that are morphologically as regular as Coma: although Coma's galaxies are nearly all red S0's and ellipticals, these clusters are dominated by systems as blue as active spirals. The implication is that many disks were still actively forming stars a few billion years ago, even in cluster environments most favorable to stripping. Butcher and Oemler's results indicate that disk formation can occur on a very long time scale. They are consistent with the apparent youth (mostly $< 10^9$ yr) of disk stars near the Sun, according to Demarque and McClure.

Graham: Dr. Tinsley's talk reminded me of some observations that I have made recently of the radio galaxy NGC 5128. Here, in the middle of a giant, non-rotating elliptical galaxy we see a rapidly rotating but apparently stable gaseous disk in which the stellar density is sufficiently low to enable strong interstellar sodium D-lines to be observed in absorption against the background elliptical stellar component. The rotation of the disk shows some irregularities which suggest that its formation may have occurred relatively recently, less than 10^9 years ago.

Tinsley: Thank you for mentioning this galaxy and your exciting new results. We had also thought of NGC 5128 as a possible example of a disk in formation around an elliptical galaxy, since Larson (1972) suggested that the material could have been recently accreted.