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STELLAR POPULATIONS IN GALAXIES*

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This article reviews present-day knowledge of stellar populations and the relation of populations to the forms of galaxies. A historical outline of the concept of populations is followed by a summary of the present picture. After a discussion of the distribution of populations in the various types of galaxies, it is shown that the whole picture can be understood in terms of a simple scheme of the development of galaxies. Problems of heavy-element enrichment through nucleosynthesis are briefly discussed. The article aims at being provocative rather than definitive but retains a basically conservative point of view.

Key words: stellar populations — galaxies

I. Introduction

Much of astronomy is concerned with questions of detail, but its ultimate objective is to answer the really basic questions about the nature of the universe. One vital problem is how the stars became what they are in other galaxies and around us in the Milky Way. This question will eventually be answered in detail by studies of the birth and evolution of stars, but in its broader current aspect it is the question of stellar populations. Most of our understanding of individual stars has indeed begun with the study of groups of stars and their relation to each other. The development of this picture has been one of the most striking achievements of the past two decades in astronomy.

Just as the study of stellar atmospheres and interiors is the physiology of the stars, the study of populations is their ecology. It connects the nature, variety, and numbers of stars with the environment in which they live. These studies have already shown with outstanding success the relationships between the various stellar species, and they now serve equally to map the environment in a galaxy and probe its past development. Compared to the evolution of stars, our understanding of the evolution of galaxies is still quite primitive; but the picture has begun to take shape. We do not know many of the answers yet, but we are perhaps able at least to ask the right questions.

This article will begin by reviewing the concept of stellar populations and its development up to the present point. We will then examine the distribution of populations in galaxies of various types, and finally we will face the question of how galaxies came to be what they are. Many of the topics that I shall treat are uncertain, confused, or even highly controversial. I will try to indicate the uncertainties and to label speculations as such, but I will not avoid a subject just because opinion may be divided.

II. Stellar Populations — A Historical View

The term "stellar populations" means different things to different astronomers, and its general meaning has changed with time. Not only is it desirable for a writer to define what he means by the term, but a general historical outline will serve to clarify the basic concepts.

Although some astronomers, notably Trumpler (1930), ten Bruggencate (1927), and Shapley (1930), had called attention to differences between star clusters, and correlations between physical properties and kinematics had been remarked upon by Oort (1926) and Bottlinger (1932, 1933), the general concept of stellar populations was introduced by Baade (1944). When he succeeded in resolving the central

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bulge of the great Andromeda spiral galaxy into individual red giant stars, he recognized their similarity to the brightest stars in globular clusters and jumped to the generalization that both of these samples represented a stellar population that was fundamentally different from that of the familiar stars surrounding us in the Milky Way. Baade's reasoning and observational techniques are described in the only book that bears his name (1963). Baade could hardly ever be induced to write, but the staff and students at Harvard taped a lecture series of his and developed it into a posthumous book that gives a marvelous picture of an astronomer talking freely about his work.

The early development of the idea of stellar populations is connected in an interesting way with the history of our times. During the Second World War most astronomers were drawn into war work, but Baade, as an "enemy alien," was left to pursue astronomy among the neglected giant telescopes of Mount Wilson. At the same time the wartime dimming of Los Angeles' lights gave Mount Wilson the last dark sky in its history. During this time Baade did the work to which I have just referred. Then, when astronomers returned to peacetime activities, they found available the products of wartime technology. Among them were high-sensitivity, low-noise photomultipliers. These revolutionized photoelectric photometry, bringing within the capability of the average astronomer valuable techniques that had been the province of a few specialized technicians. An almost immediate result was the careful study of HR diagrams of many galactic and globular clusters — the basis for the next stage of understanding of populations.

When the HR diagrams of galactic clusters were compared with each other it appeared that each cluster had a well-defined, narrow main sequence, but that the turnoff at the upper end of the main sequence differed from cluster to cluster. It soon became clear that these different turnoff points were to be interpreted as a sequence of ages (Sandage and Schwarzschild 1952), with the most massive stars coming most rapidly to a stage where their central hydrogen was exhausted and where they therefore evolved away from the main sequence. The departure from the main sequence had been predicted by Schönberg and Chandrasekhar (1942), and Sandage and Schwarzschild had shown that stars evolve toward the red-giant stage, but it was Hoyle and Schwarzschild (1955) who first carried stellar models completely away from the main sequence and into the red-giant region.

In these pioneer evolutionary tracks Hoyle and Schwarzschild encountered a quite different dimension of the population problem: chemical composition. When they followed the evolution of models with a solar-type metal abundance, they reproduced the giant branch of the old galactic cluster M67; they could get their model to evolve up to the brighter luminosities of the giant branch of globular clusters only if they lowered the metal abundance by two orders of magnitude. This fitted beautifully with previous spectroscopic indications. It had long been known that the high-velocity giants, which as members of the galactic halo belong to Baade's Population II, showed an unusual weakening of the cyanogen bands in their spectra (Lindblad 1922). Later, more-detailed studies (Chamberlain and Aller 1952) had identified high-velocity stars as being specifically deficient in the metallic elements, and further spectroscopic studies (Helfer, Wallerstein, and Greenstein 1959) have confirmed this metal deficiency for the globular cluster giants themselves.

These differences in chemical composition helped to clarify the differences between stellar populations, but at this point the meaning of the term population began to change. Baade had emphasized the role of age. The globular clusters, and the amorphous central regions of many galaxies, were old; in this Population II no new stars had been born for a very long time. Population I, by contrast, was characterized by young stars — particularly the bright blue supergiants that *must* be young because they live such a short time. The age differences were indeed correct, but now chemical composition added a new dimension. The HR diagrams of the oldest galactic clusters had main-sequence turnoffs comparable to those of the globular clusters; they must therefore be nearly as old, but with a difference in chemical composition.

How had this composition difference come about? The basic answer was provided at about the same time by studies of nucleosynthesis—the transformations of chemical elements that take place under extreme conditions of temperature and pressure in the interiors of evolving stars. Much of the impetus for this work came not from stellar evolution but from cosmology, where proponents of the steady-state theory postulated a spontaneous appearance of atoms of hydrogen and then set themselves the task of producing the other chemical abundances of the universe by nuclear reactions that began with hydrogen. The detailed nuclear reactions were reviewed by Burbidge et al. (1957), who were able to account for rare elements and abundant elements and even to explain, in many cases, the relative abundances of different isotopes. Today few astronomers put any faith in the steady-state theory itself, but we must recognize that it stimulated an important research area that now stands on its own feet.

In one respect the idea of element buildup through nucleosynthesis actually led astronomers astray, however. The eminent plausibility of the basic idea, along with the success of the theory in explaining many details of element and isotope abundances, had encouraged the assumption that *all* element synthesis happened in this way, starting from primeval hydrogen. This was of course an explicit assumption for Hoyle and his associates, but it became an unconscious and unrecognized premise for other workers in stellar populations who did not in the least believe in the steady-state idea of spontaneous creation of hydrogen. The assumption was, as now appears, almost certainly wrong for helium. Although there were scattered indications that the stars of Population II might have a helium abundance comparable to that in Population I, it was again cosmology that provided the crucial impetus. The discovery of the microwave background radiation (Penzias and Wilson 1965), which suggested a uniform blackbody background at 3° K, gave strong support to the big-bang picture of cosmology. In the big-bang theory the temperature of this background radiation, which is a tremendously redshifted residue of the primeval fireball, is intimately connected with the production of helium at that time. The suggested proportion of helium was between 20 and 30 percent by weight. With this impetus workers in various branches of stellar populations began pulling out of their closets the scattered indications that already existed of "normal" helium—from the fitting of stellar models, from the pulsation theory of RR Lyrae stars, and from studies of gaseous nebulae. One more piece in the picture now fitted a little better. (For reviews of the helium problem see Burbidge [1969] and Danziger [1970].)

With the appearance of nucleosynthesis theory we now had a coherent picture of the development of successive generations of stars. Population II was an older population; its stars were born at a time when the abundance of heavy elements was low everywhere in the Galaxy. The more massive stars of Population II had lived and died quickly, enriching the interstellar medium with the products of the nuclear reactions that went on in their interiors. Thus the stars of Population I, born later of the enriched material, had a much higher proportion of the heavy elements. Since the theoretically determined ages of the oldest galactic clusters, found by fitting evolutionary tracks to their HR diagrams, were somewhat lower than those of globular clusters, there was time for an enrichment period before the Population I stars began to form.

Thus only a few years had led from the bare recognition of stellar populations to the development of a coherent picture of the evolution of stars and their chemical compositions. This stage of progress is elaborated in some detail by the Vatican Conference on Stellar Populations (O'Connell, ed., 1958). In the final summary in that volume the gradation from Population I to Population II is marked off in five different stages. This was the high-water mark of the first era.

The first crack in the neat sequence of stellar populations came with the observation by Morgan and Mayall (1957) that the spectra of M31 and the giant elliptical galaxies have cyanogen bands of normal strength, like the stars of Population I, rather than weak cyanogen like Population II. This appeared to contradict Baade's identification of Population II in the center of M31, but the two could be reconciled by recalling the observation (Baum and Schwarzschild 1955) that Population II, while certainly present in the center of M31, was not the main contributor to the light. There was no denial that the Population II stars of the halo extended in to the center of M31 — as indeed they must in any rational dynamical picture — but the chief population in that region showed the spectroscopic characteristics of Population I. All the characteristics of age were there — the lack of blue upper-main-sequence stars and the smooth spatial distribution — but it appeared to be an old Population I rather than an old Population II.

Further difficulties arose for the simple enrichment picture. Not only did the oldest stars in a galaxy belong to both populations, but chemical-composition differences showed up within each population. Within Population II, the HR diagrams of globular clusters show differences that are most likely to be explained by differences of chemical composition (for a contemporary discussion see Hartwick 1968), while within Population I the Hyades have a higher metal abundance than older stars such as the sun (Wallerstein and Helfer 1959; Nissen 1970; Chaffee, Carbon, and Strom 1971). Even more disturbing, the young open clusters of the Magellanic Clouds probably show HR diagrams that do not match those of young clusters in the Milky Way (Arp 1959; Hodge 1961).

Still another dimension was introduced into the population picture by Spinrad's discovery (1962) that the D lines of sodium are very strong in the spectra of giant elliptical galaxies and the central regions of giant spirals like M31. In stellar spectra these lines are strong only in dwarfs, so their strength in the integrated light showed that dwarf stars must be very much more numerous in those regions than in the standard van Rhijn luminosity function of the solar neighborhood, or in globular clusters. It now appeared that stellar populations differed in age, chemical composition (which might require two or more parameters to characterize it), and in the relative numbers of giant and dwarf stars.

Further disconcerting discoveries followed. After the initial spectroscopic investigations by Morgan and Mayall (1957) and by Spinrad (1962), various attempts have been made to study the integrated spectra of galaxies in a more quantitative way, using photoelectric techniques to measure the strengths of the absorption lines, either by measurements through interference filters or by the scanning of an actual spectrum. In the course of such a study Spinrad and Taylor (1969; Taylor 1970) found that some of the standard stars and star clusters that they had observed for comparison purposes also had line strengths that appeared quite abnormal. In particular, they found a class of stars whose metallic lines were unusually strong; after examining various possible explanations, Spinrad and Taylor named this group the super-metal-rich population. Included in this group are the two oldest well-studied galactic clusters, M67 and NGC 188. Many astronomers are reluctant to accept the super-metal-rich interpretation, but there seems little doubt that the metallic lines are abnormally strong (Spinrad et al. 1970). To concentrate on the observed fact and avoid the controversy, I shall refer to these stars as hyper-strong-line.

Whatever its true chemical composition may be, the hyper-strong-line population is an important constituent of galaxies (Spinrad and Taylor 1971*a*; McClure 1969). Recognition of its presence makes it possible to reconcile Morgan's assertion that galaxy spectra show normal strength of the cyanogen bands — a giant-star characteristic — with Spinrad's assertion that dwarfs contribute a considerable fraction of the light. Apparently only a part of the light comes from giants, but they are stars with abnormally strong cyanogen.

III. Populations — The Present-Day Picture

It is now clear that the term "stellar population" must cover differences in many characteristics. The originally recognized difference in age is still of obvious importance. A second important difference is in chemical composition; although this is often closely correlated with age, it is no longer reasonable to assume a one-to-one relationship. A third important characteristic is the luminosity function. Finally, in addition to these intrinsic differences, populations differ in their distribution between various types of galaxies and their distribution within each galaxy.

In the face of this diversity the old labels of Populations I and II lack the necessary precision. Nor is the 1958 Vatican scheme adequate, with its one-parameter sequence of populations. But we are not now in a position to adopt a new classification and terminology, at a time when knowledge and understanding of populations are so incomplete, so the old terms continue to be used. Different astronomers mean different things by Populations I and II, however. There has been an increasing tendency to use these terms to refer to normal and low metal abundance, respectively; but some astronomers still use the terms to distinguish age rather than composition. Sometimes it is the unfortunate reader's task to find out what the author's terms mean.

In this article I shall use the term Population I to refer to stars whose metal abundance is of the same order of magnitude as that in the sun, while Population II will refer to stars of metal abundance one or two orders of magnitude lower.

The stars of Population II are all old. Although age differences within this population have been suggested (Rood and Iben 1968), there is no conclusive evidence of appreciable age differences — and indeed, arguments about dynamical collapse of the halo suggest that only a small age range is possible. (For a collection of color-magnitude arrays, see White [1970].) The two most striking differences are in the color range of horizontal-branch stars and in the magnitude difference between the horizontal branch and the top of the red-giant branch. Unless the small permissible range in age has a surprisingly large effect, these differences in HR diagrams must be due to differences in chemical composition.

The importance of metal-abundance differences, even within Population II, has been recognized for a long time. Metal abundances of globular clusters can be compared in various ways. First of all, the spectra of individual giant stars can be subjected to abundance analyses. In the past, such observations were at the limit of capability of the largest telescopes and very few were made (Helfer et al. 1959), but with the advent of image-tube spectroscopy more observations of this type are likely to become available. Unfortunately this is the only method that gives abundances quantitatively; the other methods merely arrange clusters in order of abundance. A real abundance analysis requires high-dispersion spectra, but from spectra of lower dispersion at least an estimate of line strength can be made. This has been done for individual stars in a number of globular clusters by Deutsch (1955) and Kinman (1959), both of whom found that they could divide clusters into three line-strength classes. A less direct method was used by Morgan (1956, 1959*b*), who examined integrated spectra of a large number of clusters and was able to distinguish eight classes of line strength. This technique can reach clusters whose individual stars are too faint for convenient observation, but it has the difficulty of mixing the light of stars of many types. In particular, the line strengths may be affected by the differing proportions of horizontal-branch light, which do not correlate perfectly with metal abundance. Integrated spectra have also been studied by van den Bergh and Henry (1962), who measured several spectral indices photoelectrically. Finally, van den Bergh (1967) has used the Q parameter of Johnson and Morgan (1953) as a reddening-free metallicity index.

The population types of globular clusters can also be distinguished by means of their RR Lyrae stars. Variable stars of this type pulsate because of a particular internal structure that occurs in all stars within a certain segment of the horizontal branch. (This region is sometimes misnamed the RR Lyrae gap, presumably because observers of color-magnitude arrays usually leave out the RR Lyrae stars, not wanting to make the large numbers of observations that would be required to determine their average colors and magnitudes. It is not a gap at all but is just as densely populated as other parts of the horizontal branch.) The coarsest population indicator here is the number of RR Lyrae stars — or indeed, whether they occur at all. But this is not a primary population indicator; it merely indicates the extent of the horizontal branch — whether or not it extends through the RR Lyrae region. Furthermore, a globular cluster may lack RR Lyrae stars for either of two reasons; on the one hand, it may have only a short red horizontal branch that does not go as far to the blue as the RR Lyrae region, or on the other hand a cluster may lack RR Lyrae stars because its horizontal branch is so extremely blue that it lies completely to the left of the RR Lyrae region. Incidentally, in judging the population density in the RR Lyrae region, one should normalize to the luminosity of the cluster; that is, the number of RR Lyrae stars should be taken in relation to the total number of stars in the cluster.

There is one physical characteristic of RR Lyrae stars that does appear to be a real population discriminant, although its meaning is not yet clear. The periods — and to some extent the types — differ systematically from cluster to cluster. To examine these distinctions we must first note that RR Lyrae stars fall in general into two types: those of type *a* have asymmetrical light curves and periods around half a day, while those of type *c* have periods around one-third of a day and sinusoidal light curves. Many years ago Oosterhoff (1939) noticed that RR Lyrae stars, within each of these types, have periods that differ significantly from one globular cluster to another. A later collection of data (van Agt and Oosterhoff 1959) confirms this distinction. In clusters of their first type the *a*-type RR Lyrae stars have a mean period $\langle P_a \rangle = 0^{d}65$, while those of *c*-type have a mean period $\langle P_c \rangle = 0^{d}37$. In clusters of the second type, $\langle P_a \rangle = 0.55$, while $\langle P_c \rangle = 0.32$. Furthermore, in clusters of the first type about half the RR Lyrae stars are of type *c*, while in clusters of the second type only about one-sixth are *c*'s. Although the data are limited in extent, it does appear that there really is a statistically significant separation into two distinct types. It has even been suggested (Belserene 1954) that these basic types persist from cluster to cluster, with only the proportions differing and being responsible for separating the clusters themselves into two Oosterhoff types. The reason for the two types is not yet understood, but the distinction between them probably represents a sensitive indicator of chemical abundances, whose interpretation and quantitative calibration stands as a challenge.

Not as obvious as the horizontal-branch differences, but equally important, are differences in the height of the giant branch. This height is usually designated ΔV and is the difference in magnitude between the horizontal branch and the level at which the giant branch reaches color index $(B-V) = 1.4$ (Sandage and Wallerstein 1960). The great advantage of ΔV is that, unlike the shape of the horizontal branch, it can be directly interpreted in terms of abundance. Ever since the original evolutionary tracks were traced by Hoyle and Schwarzschild (1955) it has been recognized that the height of the giant branch depends on the metal abundance. Values of ΔV do, indeed, correlate well with the strengths of the metallic lines (Sandage and Wallerstein 1960; Arp 1965).

The situation is not at all clear, however, when we try to put together the full picture of globular-cluster HR diagrams and chemical abundances. There is, to be sure, a general correlation between the metal abundance and the blueness of the horizontal branch, in the sense that clusters that are very poor in metals also have a very blue horizontal branch. Exceptions were known, however — like M13, which has an intermediate metal abundance and a very blue horizontal branch — but they tended to be swept under the rug. The strict correlation finally became impossible to support after the study of NGC 7006 by Sandage and Wildey (1967). It has very low metal abundance and a red horizontal branch. They supported van den Bergh's (1965) suggestion that a second chemical-abundance parameter was needed and that it was the helium abundance. This seems the most likely explanation — although we must not forget the unconventional suggestion that the difference could be in age (Rood and Iben 1968).

There is unfortunately a large gap between recognizing that two parameters exist and identifying the specific effect of each on the HR diagram. An attempt has been made in this direction by Hartwick (1968) on the basis of the rather fragmentary present-day knowledge of just how the helium and metal abundances affect the detailed shapes of evolutionary tracks. Hartwick's general scheme may be correct, but the detailed picture will require much better studies of the evolution of type II stars than we have available at the present period. Nor are the observations completely adequate. There may be an important abundance discriminant in the shape of the subgiant branch from the main-sequence turnoff to the point of intersection with the horizontal branch, but these fainter stars have not yet been studied accurately in many clusters.

A property of Population II about which very little is known is its luminosity function. The studies made so far have concentrated on the brighter end of the luminosity function, where the present-day distribution of magnitudes depends almost completely on the shapes of evolutionary tracks, and almost not at all on the faint end of the original luminosity function. Although such studies have provided very useful comparisons of observational data with theoretical evolutionary tracks (Simoda and Iben 1970), they tell us nothing about the number of low-luminosity dwarf stars in the halo population. Such information is most likely to come from dynamical mass determinations through studies of the internal velocity dispersions in globular clusters. An observed velocity dispersion, in conjunction with observations of the distribution of stars in the same cluster, can give a value for the total mass of the cluster. Since most of this mass is contained in the unobserved faint dwarf stars, a determination of its value indicates how many such stars are in the cluster. A few such observations have been made (Wilson and Coffeen 1954; Feast and Thackeray 1960; Dickens and Woolley 1967), but this is another type of observation whose number is sure to increase with the availability of image-tube spectrographs. Results so far indicate a ratio of mass to luminosity of about 1, in solar units, which would indicate a rather limited number of dwarfs. Whether the value of $\mathfrak{M}/L$ will vary from cluster to cluster and will depend on population type remains to be seen.

Although our knowledge of the characteristics of Population II is based almost completely on globular clusters, the clusters themselves make up only a tiny fraction of Population II, most of which consists of the field stars of the galactic halo. Some of these stars can be observed in our immediate neighborhood, since halo stars cannot exist on both sides of the galactic plane without passing through the plane, just as the halo of M31 cannot surround the central bulge without permeating the bulge with the stars that Baade observed. In both cases the Population II stars have a higher density *in* the Population I region than *out* of it, but the Population I stars are themselves so strongly concentrated to their own disk region that they predominate overwhelmingly there.

The halo stars in our immediate neighborhood — the high-velocity subdwarfs — offer the only opportunity of studying the low-luminosity dwarfs of Population II. For example, Kapteyn's Star, which is only 4 parsecs away, is a ninth-magnitude star and easily observable. If it were at the distance of a typical, well-observed globular cluster, its apparent magnitude would be fainter than 25. Here in the solar neighborhood such a star can be studied in detail, but unfortunately we do not know just where it belongs within the great inhomogeneity of the type II population. In a globular cluster, on the other hand, we have a well-defined, homogeneous population sample — but we cannot study its faint stars in detail.

It is equally true in Population I that the great majority of stars are in the field rather than in clusters but that the clusters give us our clearest perception of population differences. In this population there are even more differences to study, because age is obviously a primary parameter. In a continuous range of ages, any division into groups is obviously arbitrary; but it is useful to distinguish five age groups in the type I population: (1) the oldest that we can identify, (2) middle-aged groups, (3) the moderately young population, (4) new-born groups, and (5) the unborn — that is, the material from which stars will be born in the future.

The oldest type I population can be recognized by the shape of the subgiant and giant branches in its HR diagram. Such a shape is easily recognizable in the HR diagrams of a few old clusters; and because almost no other stars occupy this part of the HR diagram in general, it is possible to identify isolated subgiant and giant stars in the field as belonging to the oldest Population I. Numerically, however, the great majority of this population must consist of lower-main-sequence stars — but because they have not yet evolved appreciably, they cannot be easily distinguished from the large number of younger stars that also occupy the same region of the main sequence. There is some hope that such stars can eventually be picked out by studying the amount of their chromospheric activity as evidenced by details in their spectra; but these details are not yet well enough studied, nor is their correlation with population type well known.

Our knowledge of the oldest type I population is based chiefly on studies of the oldest known open clusters: M67, NGC 188 (Sandage and Eggen 1969), NGC 6791 (Kinman 1965), and NGC 3680 (Eggen 1969*a*). There are other candidates for this list (King 1964) that have not yet been well enough observed; among them the most likely is King 22 (King 1961). It is unfortunate that from the first half of our Galaxy's lifetime we have only a handful of clusters. Without doubt many more clusters of that epoch existed in the past, but only these few — in our part of the Milky Way, at least — have been able to survive the dynamical processes that destroy star clusters. This is in itself interesting, because theory predicts (King 1958) that all the poor clusters should be gone now but that the rich clusters should have had a good chance of surviving. Indeed, the recognized clusters of great age are among the richest open clusters known — but where are the even richer ones? A cluster as rich as a globular cluster would have had no difficulty surviving in the galactic disk up to the present time. It would appear that the old Population I of the galactic disk never produced clusters as rich as those in the Population II of the halo. It is possible, however, that extremely rich clusters of an old Population I will turn up among the strongest-lined Morgan class of "globular" clusters. None of these has been studied in sufficient detail to be sure that it is underabundant in metals.

Of the Population I clusters NGC 188 appears to be the oldest known. Its HR diagram also appears to define a lower envelope to the distribution of field giants and subgiants in the HR diagram (Wilson 1959). This agreement suggests that there is an upper limit to the ages of stars in the galactic disk — although it is not a sensitive discriminant, because a factor of 2 in age would correspond to a difference of only one magnitude in the height of the envelope.

The characteristics of the oldest type I population become extremely perplexing if one accepts the contention of Spinrad and his associates that a sizeable portion of this population is super-metal-rich (SMR). They observe that the lines of elements heavier than helium are strikingly stronger in many stars than they are in standard type I stars of the same color temperatures and surface gravities. These hyper-strong-line stars can be found among the red giants and subgiants of the field (Spinrad and Taylor 1969), main-sequence dwarfs (Taylor 1970), and the members of the oldest open clusters (Spinrad and Taylor 1969, 1971*a*).

There is no question about the enhanced line strengths in these objects, but many astronomers do not accept the conclusion that the stronger lines are due to an increase in the abundances of heavy elements. Many ways have been suggested in which a spectrum could show the appearance of supermetallicity without any actual increase in metal abundances.

1. There could be a systematic error in the temperature scale employed (Cayrel de Strobel 1967). All of the lines that are employed in these studies would be strengthened even if the temperature were just a little bit lower.

2. An increased microturbulence would increase blanketing because of its widening of line cores and consequent enhancement of medium-strength lines. It would thus produce an ultraviolet deficiency and a corresponding appearance of supermetallicity (Strom, Strom, and Carbon 1971).

3. The boundary temperature might be lower in old stars than in young stars of the same spectral type (Strom, Strom, and Carbon 1971). This might be expected a priori, either as a direct result of the enhancement of the CN bands (which would then itself be interpreted as a real abundance excess of C and N in the atmospheres of highly evolved stars), or as a result of the general tendency of chromospheric activity to be less in the atmospheres of older stars. Since the strong lines used in spectrum-scanner studies are formed close to the boundary, they would have enhanced strengths while there would be no change in the color of the continuum, which is formed at deeper levels.

4. Finally, in the spirit of the CN argument just mentioned, it may be that a few highly evolved red giants really are super-metal-rich but that their abundances are not typical of the original population from which they come (Strom and Strom 1971).

The suggestion that the phenomenon may be confined to giants seems to be eliminated by the observation (Spinrad et al. 1970) that main-sequence stars in both M67 and NGC 188 show the hyper-strong-line characteristic. Furthermore, the microturbulence and boundary-temperature arguments do not seem to apply to the SMR dwarf HR 72, whose abundance analysis (Spinrad and Luebke 1970) depends on weak lines that are insensitive to either of these effects. As for chromospheric activity, its correlation with age is not a strict one, and some hyper-strong-line stars do indeed show chromospheric activity. Finally, stellar-structure studies have suggested (Aizenman, Demarque, and Miller 1969; Torres-Peimbert 1971) that evolutionary tracks can be made to fit the observed HR diagrams only if an enhanced metal abundance is assumed. Spinrad and Taylor (1971*b*) have recently summarized the arguments in favor of their position, but the last word has by no means been said.

The existence of hyper-strong-line stars in the oldest Population I raises interesting questions whether or not we accept the SMR hypothesis. If these stars really are super-metal-rich, then the idea of an orderly, continuous enrichment of the interstellar medium is forever demolished, since the oldest clusters in Population I have a considerably higher metal abundance than any stars that have been formed since. Another interesting conclusion follows from the observations (to be discussed in detail below) that the SMR characteristic is strongly concentrated to the centers of galaxies. This would suggest a spatial segregation of the SMR and normal populations analogous to that between the disk and halo. Thus van den Bergh has suggested (1968) a distinction into three populations: core, disk, and halo. In such a picture the absence of young SMR stars might be explained by the hypothesis that the core population exhausted its star formation at a time in the distant past.

The SMR population presents another problem — that of its own maximum age. The increased metal abundance changes the mass-luminosity relation in such a way as to decrease the masses that we would assign to the stars at the turnoff in the HR diagram; the result is to decrease the age of NGC 188 to about half that of the Milky Way (Aizenman et al. 1969; Torres-Peimbert 1971). The fact that the oldest-known open cluster is only half as old as the Milky Way can perhaps be explained as a statistical accident in an extremely small sample (King 1968), but there would be a real difficulty if there were no SMR field stars below the locus of NGC 188 in the HR diagram. Such an absence would indicate that the relative youth of NGC 188 is not just a statistical accident in our sampling of a population that extends to a much greater age, but rather that the SMR population has no stars more than about half as old as the Galaxy. Conversely, if the same lower envelope applies to all stars, whether SMR or normal, then the differing metal abundances will give different mass-luminosity relations, and the difference in mass-luminosity relation will then imply that the normal stars are twice as old as the SMR stars on the same evolutionary track. The SMR population would then have to be viewed as having appeared only after several billion years had elapsed in the history of the Milky Way. The coincidence of the lower envelopes of the two populations in the HR diagram would have to be regarded as an accidental cancellation of the opposing effects of age and abundance. Torres-Peimbert and Spinrad (1971) have recently suggested that SMR stars do indeed exist below the NGC 188 track; if this is so, then this whole difficulty disappears.

If, on the other hand, we reject the hypothesis that the hyper-strong-line stars are super-metal-rich, other difficulties appear. Perhaps the most serious of these is the fact that the oldest population contains a mixture of normal and hyper-strong-line stars. The oldest population would then appear to contain two races, only one of which is affected by the hyper-strong-line syndrome. Furthermore, the appearance of this characteristic cannot be a mere matter of individual accident, because the hyper-strong-line stars have a systematically different distribution in galaxies from that of stars of normal line strength (Spinrad et al. 1971). Whether or not the explanation of the hyper-strong-line population turns out to be metal abundance, it is a population in the true sense of the term: its members have a recognizable physical characteristic coupled with a different spatial distribution.

Here too we would need to explain away a striking phenomenon — the strong lines — as being due to a mere accident. The validity of line strengths as an indicator of metal abundance would seem to end just at the "normal" solar abundance; weakening of the lines would indicate a metal deficiency, but strengthening of the same lines would not indicate an overabundance. Similarly, ultraviolet excesses, which have been used so strikingly by Eggen, Lynden-Bell, and Sandage (1962) to trace the metal-poor population, would end at zero, and ultraviolet deficiency would have nothing to do with metal abundance.

Although the hyper-strong-line stars are the most striking problem of the oldest Population I, they are not the only problem. An interesting question is raised by the existence of the strong-lined RR Lyrae stars. Preston showed (1959) that these stars have nearly normal line strengths, in contrast with very weak-lined spectra of globular-cluster RR Lyraes; that they have velocity and density distributions characteristic of a disk rather than a halo population; and that in the galactic disk around the sun they outnumber the weak-lined RR Lyrae stars. It is annoying that none of these stars has ever been found in a cluster, for only then will we know in exactly what population to place these stars. Perhaps the globular clusters of Morgan's highest line-strength classes should be searched for these stars. Or perhaps they belong to the oldest Population I but are rare enough to make it statistically reasonable that we have not yet found such a star within the small sample of old clusters that is known to us. To pursue this possibility, note that in the immediate neighborhood of the sun main-sequence disk stars outnumber halo stars by about 100 to 1 (Oort 1965). Since in the same region strong-lined RR Lyraes are only a little more numerous than weak-lined ones, the RR Lyrae stars of the disk must be at least an order of magnitude less numerous, relative to main-sequence stars, than the RR Lyrae stars of the halo. In the oldest Population I the total number of stars in all the known clusters adds up to much less than the equivalent of one good globular cluster, so perhaps it is not significant that RR Lyrae stars are lacking in this small sample. These strong-line RR Lyraes should be kept in mind, however, because they may eventually form a bridge between the two populations — or else prove that no bridge exists.

Other problems are posed by the M giants, which are also numerous in the Galaxy as a whole but rare in as small an aggregate as a star cluster. The Mira variables, which are late M giants, appear from their velocity and density distributions to belong to both populations, but again none is known in an open cluster. (Some Mira variables occur in Eggen's moving groups [Eggen 1969*b*], but the correctness of his assignment of stars to such groups is highly controversial.) The Miras may also bridge the gap between Populations I and II. In the disk population their velocities indicate that they are old, while among globular clusters the Miras favor clusters with strong lines in their spectra. In the direction of the galactic center there also seems to be a systematic difference in the properties of M giants (van den Bergh 1968; Spinrad, Taylor, and van den Bergh 1969). These examples underline the importance of distinguishing stellar populations both in age and in chemical abundance. Both the RR Lyrae stars and the Mira variables, as physical classes, straddle the composition difference between Populations I and II; so also do the planetary nebulae and the novae, which are rarer and therefore not as well-placed in the population pictures.

The few known clusters of the oldest Population I cover a range in age of about a factor of two, from NGC 188 to M67. At about half the age of M67 — but still about twice the age of the Hyades — we first encounter a sizable sample of clusters. A dozen or so members of this middle-aged group can be recognized among the color-magnitude arrays in the admirable collection assembled by Hagen (1970). A sizable fraction of my finding list of "old" clusters (King 1964) will probably turn out to belong to this group — which is only lumped together here for convenience of discussion; it should not be thought of as a discrete age group at all. For this group we have only a little in the way of direct abundance determinations (Gunn and Kraft 1963) or even measures of line strength (McClure 1971), so that the best population discriminant becomes the HR diagram itself. Here, however, we are painfully sensitive to the difference between a color-magnitude array and an HR diagram: the raw observed diagram can be converted into the physically meaningful one only when the reddening and the distance modulus are known. In practice this comes down to a determination of the reddening, since the distance modulus is normally determined by fitting to a standard main sequence that is assumed to be independent of population type. As a result any error in the reddening will cause a corresponding erroneous shift of the cluster's HR diagram up or down the main sequence. Such an uncertainty makes it very difficult to compare the population types of clusters because in this range of main-sequence turnoffs the detailed shape of a cluster's HR diagram is just as sensitive to the absolute magnitude of the turnoff point as it is to possible differences of chemical abundance. The observations suggest that clusters with the same main-sequence turnoff do not have identical giant branches — but can this be due to errors in the reddening correction and the main-sequence fitting? Further investigations of these clusters will certainly be of great interest; in particular, do some of them show a lingering taint of the hyper-strong-line characteristic that affects so many of their elders?

The young Population I dominates our cluster catalogs, where most clusters date from the most recent billion years — because of the dynamical attrition that eliminates older clusters. But even though these clusters represent only a tenth of the life span of Population I, they show a bewildering variety of HR diagrams because the absolute magnitude of the turnoff point of a cluster's HR diagram goes not with the linear value of its age but with the logarithm. Thus within the range of cluster ages from 10^6 to 10^{10} years this brief group represents three-fourths of the logarithmic span. Within this younger group most of the weight of studies of the HR diagram goes into age determination and comparison of stellar-evolution theory with observation; for population differences one must investigate individual stars in the clusters. Fortunately, this group includes the brightest star clusters, whose individual stars are relatively easy to observe.

Line-strength differences among "young" clusters have long been recognized (Strömgren 1958). In particular, the Hyades have consistently shown up as being strong-lined relative to the average of other clusters. Detailed spectroscopic determinations of abundance have confirmed this difference (Wallerstein and Helfer 1959; Cayrel and Cayrel de Strobel 1966), but its amount is still uncertain (Chaffee, Carbon, and Strom 1971; Nissen 1970). In quite another direction, Eggen has suggested (1963) that the Hyades have a different mass-luminosity relation from that of the Pleiades; but this conclusion is controversial, as is the accompanying suggestion that the difference is due to a large difference in helium abundance. All in all, it is a pity that this nearest of clusters, which is so often used as a reference standard, seems to be so far from average.

Another possible indication of abundance differences within the young Population I comes from the cepheid variables, whose period distribution varies systematically with position in the Milky Way (van den Bergh 1958). But it is at least equally likely that this difference reflects only a difference in the age distributions of the stars concerned, since the period of a cepheid is determined by the luminosity at which it crosses the instability region, and this in turn is determined by its luminosity on the main sequence. On the other hand, Kraft (1965) has suggested that the relation between period and amplitude of cepheids varies with position in the Milky Way; if this is so, it must reflect an intrinsic physical characteristic. Also, Williams (1966) has found photometric differences in metallicity indices.

Our best chance of finding a young population that differs appreciably from the Population I of our own neighborhood comes from studies of the Magellanic Clouds, where a rich young population can be observed. There are already indications of differences in the shapes of young HR diagrams (Arp 1959) and perhaps in the colors of cepheids (Arp and Kraft 1961). Furthermore, the Magellanic Clouds have young clusters that are considerably richer than any that we know in the Milky Way. Perhaps this difference in cluster formation is also indicative of a chemical-abundance difference. The large telescopes now under construction in the Southern Hemisphere will contribute much to these problems.

This phenomenon is less easy to observe within the Milky Way, where interstellar absorption obstructs and distorts our view; but Hartwick (1970) has remarked on radial variations of the numbers of red and blue supergiants — similar to an effect observed by Walker (1964) in M33.

At the lower extreme of ages is the newborn Population I. Although few in number, these stars are in a sense the most spectacular, because it is this limiting fringe of the age distribution which produces the objects that we identify with spiral arms — the supergiant stars and the giant H II regions. This is of course the easiest component of Population I to trace in other galaxies. In the Milky Way, however, interstellar absorption makes it much harder to trace; and indeed, our most extensive knowledge of the distribution of this population comes not from optical but from radio studies, based on the recombination lines of hydrogen (Wilson et al. 1970).

Finally, a discussion of stellar populations could not be complete without mention of a population that is not stellar: the gas and dust from which stars can form in the future. Here the question is not composition — about which we know very little — but rather the quantity and distribution within the Milky Way and other galaxies. Like the newborn population, the unborn population is best discussed in connection with the structures of galaxies of various types.

IV. Populations in Galaxies

The study of galaxy types is closely related to the study of stellar populations; in fact, the two topics are simply different manifestations of the same underlying phenomena. Three basic processes are simultaneously at work: the formation of stars out of interstellar gas and dust, the enrichment of the interstellar medium by the products of stellar evolution, and the dynamical development of the whole gravitating system.

The types of galaxies are most conveniently described by the traditional Hubble scheme of classification: a continuous sequence running from ellipticals through spirals to irregulars. Elaborations of this scheme (Sandage 1961; de Vaucouleurs 1959) have emphasized differences of form, especially among the spirals; but from the point of view of populations the most important element to add to the basic Hubble scheme is a size parameter — or, in the most convenient observational terms, a luminosity. For late-type spirals and for irregulars van den Bergh's classification (van den Bergh 1960*a,b*) does this from a morphological point of view, but for ellipticals we can only quote absolute magnitudes — when they are known.

The initial recognition of stellar populations made it obvious that the Hubble sequence is a population sequence, but in today's terms we should be clear about which aspects of population are involved. An improved statement would be that the Hubble sequence is an age sequence; but even this is off the mark because one single aspect of age is fundamentally responsible for the Hubble type: the arrangement and prominence of the newborn population. Ellipticals have no newborn population; spirals have some, with the amount increasing from Sa to Sc; the whole form of irregulars is dominated by the newborn population. (Here we exclude the so-called irregulars of type II, which are more akin to dusty, disturbed spirals.) There are, of course, other differences — some of them more obvious, such as the difference in form — but these go hand in hand with the population parameter. Indeed, we shall see in the following section how the forms of ellipticals, spirals, and irregulars can be understood in terms of the orderly development of their populations. In doing so we will sharpen our sights and will finally identify the population parameter not just with the characteristics of today's newborn population but rather with the history of star formation in the galaxy in question.

If the newborn population were all that mattered it would be easy to jump to the conclusion that elliptical galaxies are old while irregulars are young. But such a scheme immediately falls apart when we look at the spirals: an Sb spiral has a central region with an old population and outer parts with a young population. The truth becomes even clearer when we recognize the existence of RR Lyrae stars in the Magellanic Clouds; even irregular galaxies contain an old population. The conclusion is inescapable that all types — ellipticals, spirals, and irregulars — include old galaxies but that their development has been different. The ellipticals turned all their star-forming material into stars long ago, and now they contain only old stars. The spirals have partly exhausted their star-forming material, but in their outer regions star formation still goes on. The irregulars, by contrast, are still full of star-forming material and are making stars everywhere. Furthermore, it is clear from the spirals that the exhaustion of star formation occurs first at the center and proceeds outward. This picture is of course confirmed by direct measurements of the amount of interstellar material. Observations at 21 cm show that elliptical galaxies have little or no hydrogen (Robinson and Koehler 1965), while the amount of hydrogen rises from a few percent in spirals to nearly half in some irregulars (Roberts 1963, 1971).

The progression of populations is shown beautifully by the Morgan classification of galaxies (Morgan 1958, 1959*a*). Morgan's classification scheme is stated in terms of central concentration of the light; but given the preference of the young population for the outer parts of the galaxy, the central concentration of light serves just as well as a measure of the relative contributions of young and old populations to the light. Morgan classes correlate closely with integrated spectral type and with Hubble classes. Indeed, the correlation with spectral type is so close that anyone explaining the Morgan system must take pains to emphasize that it is a classification of form and does not classify the spectrum directly. The close correlation with Hubble classes is perhaps responsible, in a perverse way, for the fact that this incisive classification scheme is so rarely used; to many astronomers it is just a less familiar way of stating what is usually the same information.

I have tried to simplify this picture so as to make it as clear as possible, but let it not be oversimplified. I believe that the scheme presented here is basically correct and is fundamental to an understanding of galaxy types, but it is a vocabulary in which to express things rather than a set of final answers. There are differences of form that have not even been mentioned here — such as the distinction between barred and nonbarred spirals — and there are peculiar galaxies that do not fit any scheme. In particular, dusty disks such as M 82 are usually classified Irr II, although they are most probably disturbed spirals rather than true irregulars. Nor are the correlations perfect — between central concentration of light and form of spiral arms, for instance (Sandage 1961). And most important for our discussion here, there are further population characteristics that differ from galaxy to galaxy.

Along with age, a second important population characteristic is chemical composition. And indeed, galaxies differ in chemical composition. The most striking difference is among the ellipticals, where there is a sharp distinction between giants and dwarfs. The difference shows up clearly in the colors; giant ellipticals have color indices around $(B-V) = 1^{m}0$, while extreme dwarfs have $(B-V)$ of about $0^{m}6$. The transition is around absolute magnitude -16 (Baum 1959). This is just the color difference to be expected between an old Population I and a Population II, and that is indeed the explanation. The observations are not extensive — chiefly because of the low surface brightnesses of dwarf elliptical galaxies — but spectral scans (Spinrad 1966) show that the lines are weak in NGC 205, and color-magnitude arrays of the nearest dwarfs (Baade and Swope 1961; Hodge 1965; van Agt 1967; Swope 1967) are like those of globular clusters.

Composition differences are easy to study among elliptical galaxies because their integrated light comes from old stars only; since age is not a significant parameter, abundance differences stand out. In spirals and irregulars, on the other hand, the properties of the integrated light depend on the amount of young population and on its detailed age distribution, so that manifestations of chemical composition are submerged beneath the effects of age. It would nevertheless be extremely interesting to know whether there is a similar composition difference between giants and dwarfs among the spiral and irregular galaxies. Again low surface brightness is a practical difficulty. The one indication so far is that NGC 6822 ($M_v = -16$) is moderately deficient in nitrogen and oxygen (Peimbert and Spinrad 1970*b*). Metallic elements are unfortunately not observed in this approach, which depends on analyzing the emission spectra of H II regions. In IC 1613, which is at least a magnitude less luminous than NGC 6822, the H II regions were beyond the sensitivity limit of Peimbert and Spinrad, but equipment now under development should make it possible to extend the range of this investigation to that dwarf.

These composition differences refer to elements heavier than helium. For helium itself there seems to be a greater uniformity. Peimbert and Spinrad (1970*a,b*) find no significant differences in helium abundance among the half-dozen galaxies for which they are able to assemble data.

Galaxy types also differ in the third major parameter of populations, the luminosity function. This is not just a difference in the number of luminous young stars; there are also large differences in the number of faint dwarf stars. Since dwarf stars contribute much more to the mass of a population than to its luminosity, they are best traced by studies of the mass density, which can be found dynamically from observations of internal motions. The convenient observational parameter is the ratio of mass to luminosity; it is normally expressed in solar units. Such studies show that for giant ellipticals $\mathfrak{M}/L$ is around 30 (King, Byrnes, and Minkowski 1967). For ellipticals of intermediate luminosity $\mathfrak{M}/L$ probably drops below 10 (Burbidge, Burbidge, and Fish 1961*a,b*), and the few indications that we have suggest that dwarf ellipticals have an $\mathfrak{M}/L$ of the order of unity. For spirals there is probably a similar tendency, and the $\mathfrak{M}/L$ values also seem to change radially along with the population. The centers of giant spirals have populations just like those of giant elliptical galaxies, including the high $\mathfrak{M}/L$ (Spinrad et al. 1971), but farther from the centers $\mathfrak{M}/L$ seems to drop to around 10 (Burbidge 1961; Roberts 1969). Irregular galaxies, insofar as we have dynamical information on them, have values of $\mathfrak{M}/L$ similar to those of spirals.

Care must be taken in interpreting values of the mass-luminosity ratio. A high $\mathfrak{M}/L$ indicates that much of the mass is in the form of dwarfs of spectral class M, but it does not indicate whether they are early or late M's. Also, the presence of a young population obviously distorts the relation between $\mathfrak{M}/L$ and the number of dwarfs. In an irregular galaxy, for instance, $\mathfrak{M}/L$ is lowered by the sizable contribution of the young stars, so that the number of dwarfs is greater than in an elliptical galaxy with the same $\mathfrak{M}/L$—even though the dwarfs are less visible. If infrared observations could be extended to these faint systems, they might indicate how numerous the dwarf stars are.

What then is the overall picture of the distribution of populations in galaxies? First of all, Population II is present in every galaxy where we have the ability to detect it and may well be present everywhere. It is observed in the halos of the Milky Way and M31, in the resolved stars and count-brightness ratios of M32 and NGC 205, as a small part of the population of the Magellanic Clouds and IC 1613 (Sandage 1971), and as the major contributor to the populations of the dwarf ellipticals of the Sculptor type. Unfortunately no giant elliptical galaxy has a small enough distance modulus for us to detect individual type II stars in it, and there is thus no way of telling whether a type II population makes a small contribution to the integrated light. On the other hand, there is no way of excluding the presence of a type II population in a giant elliptical, and the existence of large numbers of globular clusters in galaxies such as M87 (Racine 1968) would indicate a halo population—although we must recognize the possibility that these clusters have type I abundances.

Because the Population II is relatively inconspicuous except where it is the major constituent, it is quite difficult to estimate how much of the mass of a giant galaxy resides in this component. Even in the Milky Way estimates are quite uncertain. Perhaps the best is that by Oort and Schmidt (Oort 1965); from the local density of high-velocity stars and from Schmidt's reasoning about the gravitational field of the Galaxy, Oort estimates that the halo constitutes between 2 and 10 percent of the total mass of the Galaxy. For other galaxies the uncertainty is even greater—especially since, as we shall see below, in other galaxies it is not even certain that the halo is pure Population II.

The old Population I is nearly as ubiquitous and is much more important numerically. It is the dominant population in ellipticals and S0's. In Sa's and Sb's it obviously dominates the central regions, and even in the region of young population the old Population I is a major contributor to the light and probably the most important contributor to the mass density. In irregular galaxies also, although the young population makes the biggest splash, most of the mass belongs to the underlying substratum of old Population I. If we avoid the question of "missing mass" in the universe, the overwhelming majority of visible material in the universe belongs to an old Population I.

The distribution of the hyper-strong-line population, as a variant of the oldest Population I, has just begun to be studied. Although there had been indications that this might be the most prevalent old population in giant galaxies, it now appears that the hyper-strong-line population is more closely confined to the centers of galaxies than the normal-lined population. Photoelectric observations with spectrum scanners and with interference filters show that the hyper-strong-line population dominates the light in a small central region but that a population of normal line strength becomes dominant at 500 or 1000 pc from the center of a giant galaxy (Spinrad et al. 1971). The hyper-strong-line population is not, of course, confined to the centers of galaxies, however; as we have seen, there are many representatives of it in our own neighborhood, far from the Galactic center. Spinrad (1970) has even suggested, in fact, that the hyper-strong-line population may include the majority of M dwarfs in our neighborhood.

It is interesting to trace, in the same central regions of galaxies, how the luminosity function goes. Spinrad et al. (1971) find that the spectral criteria indicating a dwarf-rich population do not drop off nearly as sharply as those indicating a hyper-strong-line population. It would appear that the dwarf-rich luminosity function in giant galaxies is a property independent of the hyper-strong-line characteristic. There is also some indication of how this property behaves in spirals, where rotation observations allow a more detailed study of the density distributions than is possible in ellipticals. Away from the center, the value of $\mathfrak{M}/L$ seems to moderate from its extreme central value to something of the order of 10 (Burbidge 1961). In our own neighborhood of the Milky Way $\mathfrak{M}/L$ is about 4 (Oort 1965).

Not only does the stellar population in a galaxy show a gradient in line strengths, but so also does the interstellar material. This phenomenon was first noticed by the Burbidges (Burbidge and Burbidge 1965), who remarked on the change in relative strengths of nitrogen and hydrogen emission lines as one goes from the centers of galaxies to the outer H II regions. In an attempt at abundance analysis, Peimbert (1968) found that nitrogen does indeed appear to be overabundant in the nuclei of M51 and M81. More recently Searle (1971) has studied this phenomenon in more detail and finds that the radial line gradient in an individual galaxy is paralleled by a similar gradient with galaxy type, in the sense that Sc spirals show less of a tendency to have stronger nitrogen than Sa's.

A review of compositions in interstellar material is given by Osterbrock (1970).

There is one place where we have information about the line strengths at a point really remote from the center of a galaxy, and the results are quite surprising. Van den Bergh (1969) has found that most of the globular clusters of M31 are strong-lined, rather than weak-lined like the ones of our halo. Not only is the average line strength greater, but the strongest-lined clusters may even reach the hyper-strong-line class. M31 appears to be a somewhat earlier-type spiral than the Milky Way (van den Bergh 1968); it is intriguing to speculate on whether the abundances in the halo of a galaxy might be correlated with its type.

Since the young Population I is the most conspicuous of all, its distribution in galaxies of various types is obvious and well known. There are still interesting problems of detail, however; many of these relate to the distribution of recent star formation in space and in time. In spirals, for instance, it seems most likely that a spiral arm is the locus of a phenomenon that travels through the material (Prendergast and Burbidge 1960; Lin 1967), but we have very little information on how the pattern moves. Since the youngest stars identify the present location of a spiral arm, studies of somewhat older stars show where the arm was at times in the recent past. It may be hoped that investigations of this sort will lead theoreticians to the correct detailed picture (Dixon 1971; Shu 1970). In irregulars there is no clear-cut pattern, but it is again intriguing to ask how star formation has shifted from place to place. Perhaps the first studies in this direction (Wright and Hodge 1968; Gaposchkin 1968) will eventually develop into an understanding of whatever pattern underlies irregular galaxies.

Finally, we should look at the distribution of unborn material — where will stars be born out of interstellar material in the future? Here we must examine the distribution of dust and gas. Although dust may well catalyze star formation, the economics of the process clearly depend on the supply of gas. Most of this is in the form of cool hydrogen, detected by radio surveys. We have already seen how the amount of star-forming material varies from one type of galaxy to another. It is also interesting to examine the distribution of hydrogen within a galaxy of intermediate type; its distribution is quite consistent with a picture of the star-forming process slowly working its way outward. Although the interpretation of the observations has been challenged for some galaxies, there seems to be a general tendency for the neutral hydrogen to lie predominantly near the outer edges of galaxies (Roberts 1967; Hodge 1969). In the Milky Way, for instance, the greatest concentration of H II regions (Wilson et al. 1970) is considerably closer to the Galactic center than is the greatest concentration of neutral hydrogen (Kerr and Westerhout 1965). M31 seems also to have a radial progression of types of interstellar material. Baade (1963) describes how, closest to the center, the spiral arms first show up in the form of dust clouds, and then farther from the center one begins to encounter H II regions. In M31, however, the peak density of neutral hydrogen seems to coincide with that of H II regions (Davies and Gottesman 1970; Roberts 1966). The relative distribution of neutral hydrogen and of young stars is quite important, but it is quite difficult to study in most galaxies because of the low resolving power of radio telescopes.

Along with the relative amounts of the different stellar populations in galaxies of various types, we should also take note of the masses of galaxies, since the total mass certainly has some bearing on the way in which a galaxy forms and then develops. Here there is a striking difference. All the most massive galaxies seem to be ellipticals, although elliptical galaxies also range down to masses as small as any that we know. Spirals do not reach as high a mass as ellipticals; and although spirals exhibit a considerable range in mass we know of no extreme dwarf galaxy that is a spiral. Even among the spirals the most massive seem to be Sa's and Sb's. The irregulars continue this trend; none of them is as massive as a giant spiral. At the lower end, irregulars appear to go fainter than spirals, reaching a lower limit — if indeed, such a thing exists — about as faint as that of the ellipticals.

Other properties that vary systematically with galaxy type are the rotation and the central concentration. The latter goes in a simple way, being high for ellipticals and lowest for irregulars. There is an appearance of low central concentration in the dwarf ellipticals, but much of this is a question of scale rather than concentration; outside the rather large core a dwarf elliptical has as steep a density gradient as a giant elliptical. Extreme dwarfs lack the extended envelope that characterizes giant ellipticals, but this is probably understandable in terms of a dynamical limitation by external tidal forces (Kinman 1962).

The rotational properties of galaxies are most clearly evidenced by the degree of flattening, which is almost certainly a measure of the relative importance of systematic rotational motion and random motion. The elliptical galaxies run the complete range from round to rather flat — or to very flat, if we consider that the S0's are not separated from the ellipticals by any real logical boundary. In this respect again the spirals are hybrids: the central regions of early-type spirals have only a modest flattening, but the outer parts of these, and the entire disks of later-type spirals, are very flat. Irregular galaxies are quite probably rather flat, as evidenced by their small random velocities compared to rotational motion (Feast, Thackeray, and Wesselink 1961) and by the statistics of their shapes (Hodge and Hitchcock 1966), but they are probably not as flat as the spirals.

Throughout this survey of galaxy types, I have tried to emphasize the regularities and the systematic way in which properties vary from type to type. These regularities are the framework on which an understanding of galaxies will be built. But at the same time it would be blind to ignore the existence of galaxies that do not fit into this scheme of classification. There are peculiar galaxies of various types. Some galaxies are merely distorted in shape; perhaps these will find a reasonable dynamical explanation. By far the most interesting peculiar galaxies, however, are those in which a violent explosive event is taking place. Although an extreme view would suggest (Ambartsumian 1961; Arp 1967) that explosive events are fundamental to the formation and development of galaxies in general, the weight of the evidence seems to me to suggest that such events, strikingly powerful though they may be, are superficial to the overall development of the average galaxy. There is no evidence, for instance, that the stellar populations in elliptical galaxies that are strong radio sources differ in any way from the populations in galaxies that are not radio sources. In Seyfert galaxies too, the regions outside the violently disturbed nucleus seem to have the characteristics of normal spirals. In one type of galaxy, however, the explosive event may have a direct effect on the recent development of the stellar population. In M 82, which is the prototype of a class of irregular galaxies, we have a disk-shaped system, full of dust, in which there are no supergiant stars. It may be that somehow the recent explosive event has either prevented star formation or else changed the luminosity function in such a way that no supergiants appear. It is not clear how such an effect could arise — nor is it at all clear how long in the future it will persist.

Most astronomers would feel, however, that the conservative view that I have just expressed is too extreme. The energy released in some explosions is comparable to the dynamical energy that binds a galaxy, and the effects could be quite serious — provided a mechanism exists for transfer of this energy to the bulk of the material of the galaxy. A direct interaction with stars is hard to imagine, but an explosive event might well have a large effect on the gas in a galaxy.

Another possible area of exception should be noted. In the outline presented here, all galaxies are old. It is indeed striking that in every case where we have had an opportunity to make the test, a galaxy turns out to have an old population. Nevertheless one cannot definitely exclude the possibility that more recently formed galaxies exist. Astronomers have long been bothered by the discrepancy between the observed density of matter in the universe, as evidenced by the galaxies discussed in this article, and the considerably higher density that is suggested by provisional estimates of the deceleration parameter in the expansion of the universe. In addition, starting from a quite different direction Oort has recently argued (1970*a*,*b*,*c*) that the observed high-velocity hydrogen clouds imply a considerable intergalactic density and that furthermore under a reasonable picture of the origin of spiral galaxies only about 1/16th of the intergalactic matter should have condensed into galaxies. If this picture is correct we should not be surprised occasionally to find a newly formed galaxy. I say "occasionally" because observations do indicate, as explained above, that the great majority of observed galaxies are old. Perhaps the unusual dwarf irregulars recently described by Sargent and Searle (1970) are examples of such systems — but perhaps not.

V. Understanding Galaxy Types

The preceding sections have sketched the types of stellar population that occur and their relation to the types of galaxies. This relationship can be understood through an examination of the dynamics of galaxies and, in particular, of the dynamics of interstellar material within galaxies.

Fundamental to this problem is the behavior of an extended mass of gas and dust. It is easy to see that such a configuration will collapse rapidly into a disk. The collapse is due to energy losses, its rapidity is due to their time scale, and the final disk shape is due to the angular momentum of the system. To see this, first note that the virial theorem shows that a system can maintain itself in equilibrium only if the cohesive forces — gravitational in this case — are balanced by the outward tendency of internal motions. For this purpose it does not matter whether the motions are rotational or random, or whether they are thermal motions of individual atoms or systematic velocities of clouds; whatever its form, the motion must be there or the system will contract. It is easy to see what size velocities would be required in a galaxy-sized mass of gas. The virial theorem requires velocities whose sizes do not depend on the size of the individual particles; hence a mass of gas with the extent of a galaxy would have to have internal motions of the same order as the velocities that stars have in a galaxy — hundreds of kilometers per second. For a larger cloud that is to collapse to form a galaxy, the velocities could be somewhat lower — perhaps 100 km/sec — but the velocities must be maintained or else the spatial extent will not be.

The collapse occurs because an extended mass of gas will rapidly lose its velocities. If the internal motions are thermal, then collisions will excite atoms and they will lose energy through radiation. If the motions are systematic motions of gas clouds, then the clouds will collide and thermalize their motions, after which the process goes just as in the gaseous case.

The energy loss rates are fast compared to the characteristic time that a star — or a gas cloud — needs to move about in a galaxy. Hence the velocities do not persist long enough to give any support at all, and a gaseous halo can last only for as long as it takes to collapse. For the present extent of the halo of the Milky Way, this free-fall time is a few times 10^8 years, but for a larger original extent the time could approach 10^9 years.

There is little doubt that the foregoing argument is correct, and it is quite generally accepted; but I have been unable to find a calculation of rates-of-energy loss that applies directly to this case of a pregalactic halo. A number of calculations apply to related problems (Spitzer 1942, 1956; Hoyle 1953) or are quoted in summary only (Schwarzschild 1958), but there does not seem to be anywhere a direct discussion of energy losses in a hydrogen-helium mixture.

The results of the collapse are easy to see. The gas radiates away its energy but cannot get rid of its angular momentum. Its ultimate state, if it loses all the energy that it possibly can, would be a completely flattened disk in which all motions are circular; there are then no random motions, and there is thus no source of excitation to cause the gas to radiate further energy. In the real world, however, a disk of gas will never reach this extreme state, because there will be energy inputs of one sort or another to keep it stirred up, giving it both random motions and finite thickness.

If, on the other hand, the gas condenses into stars before a collapse can take place, the stars will retain their original dynamical energy without any dissipation such as the gas undergoes. In this case it is important whether the original motions in the prestellar gas were thermal or turbulent, because each star will have only the mean *systematic* velocity of the material that went to make it up. Thus thermal velocity is lost, as far as the motion of the star is concerned; but the velocity of a cloud persists in the stars that it forms.

Let us now apply these ideas to the early history of a galaxy. Suppose that in its prestellar stage the galaxy consists of a large cloud of gas, rotating slowly — since the total angular momentum is unlikely to be exactly zero — and only slightly flattened on account of its rotation. If it does not turn its gas into stars immediately — that is, in less than the free-fall time of the system — the galaxy will collapse into a disk, and later formation of stars can produce only a disk-shaped galaxy. If, on the other hand, the gas does condense immediately into stars, there are still two possibilities. If there are no large-scale systematic motions, the stars will have nearly zero velocities and a collapse will take place; the kinetic energy has disappeared from the dynamical picture just as effectively as if it had been radiated by the gas. Only if the protogalaxy was in a turbulent state will the stars have velocities that can completely prevent the collapse. Thus a round galaxy — or equally, a round subsystem in a flattened galaxy — must have turned its material into stars immediately; and furthermore the original size must now be greatly reduced, or else the material must have been in a turbulent condition prior to star formation. Notice, however, that a partial collapse may have taken place even in a relatively round system; the only safe conclusion is that in a round system star formation took place before the collapse could become complete. For the Milky Way, Eggen, Lynden-Bell, and Sandage (1962) have argued that the angular momenta of halo stars prove that a collapse took place, involving both halo and disk; their arguments for collapse of the halo stars are not clear, however, and newer data (Bond 1970) may put this latter question in a different light. For other galaxies, note that the argument that collapse will produce a disk does not in itself show that all disks were formed by collapse — but such a conclusion would nevertheless seem likely because of the coexistence of a round halo and a flattened disk in systems like the Milky Way and in other galaxies that show a round distribution of globular clusters.

Thus according to the collapse argument any galaxy that does not quickly turn its material into stars must take on a flattened shape. It is possible, however, that all the material forms stars shortly after completion of the collapse; such a system would then be a disk containing only an old population — an S0 galaxy. If, on the other hand, some material is retained in interstellar form, then the galaxy can go on forming new stars as long as such material is available. The spiral galaxies and the irregulars are systems that have behaved in this way.

We can also understand the differences in form along the flattened sequence of galaxy types from S0 to irregular, in terms of the amount of material that has been retained in interstellar form. The key to this particular understanding is the difference between the dynamical behavior of stars and that of gas. In a system the size of a galaxy, stars do not interact with each other dynamically on a one-to-one basis. Close encounters between pairs of stars are extremely rare, and each star therefore moves in the smooth gravitational field of all the remaining members of the system. As a result there is a kind of phase mixing, in which the differing velocities of neighboring stars wash out any irregularities that may exist; and a stellar system soon finds itself with an extremely smooth density distribution. Hence the high degree of symmetry in systems that have little or no interstellar material. Gas, on the other hand, interacts with neighboring gas in the strongest possible way. Shocks, turbulence, and magnetic interaction all produce irregularities, while radiation losses cool the gas to the point of gravitational instability. The degree of the resulting irregularity depends on the extent to which the gas itself contributes to the overall dynamics of the galaxy. It is tempting to suggest that when gas irregularities operate only within a dominant gravitational field due to a symmetrical distribution of stars the result is a spiral pattern, but that when the gas itself contributes a large fraction of the gravitational field, the result is an irregular galaxy. In any case there is a clear correlation between the proportion of gas and the form of a galaxy.

If the foregoing picture is correct, the form of a galaxy is determined in a perfectly straightforward way by the promptness with which it turns its material into stars. It is by no means so easy, however, to see why one galaxy should form stars faster than another. It may have something to do with the angular momentum itself; elliptical galaxies, in which star formation took place in an immediate burst, have a lower angular momentum per unit mass than spirals, in which star formation was delayed. Theories of how stars form are still quite uncertain in their details, but perhaps regularities like this will eventually serve as a guide for them.

The interpretation of spiral and irregular galaxies as systems that have formed stars at a slower rate seems to raise one paradox. The prominence of young Population I in those galaxies suggests the very opposite — that they are the locations of the most vigorous star formation. The paradox can be resolved only by quantitative comparison: how fast are these systems turning interstellar material into stars, *relative* to the amount of potential star-forming material that they contain? The answer (Roberts 1963; Epstein 1964) is reassuring; star production in spiral and irregular galaxies is indeed conservative enough to allow them a time scale of 10^{10} years for the process. They give the opposite appearance only because young Population I is inherently so spectacular.

In addition to the differences in forms of galaxies there are also differences in chemical composition. As we have seen, these differences are prominent among the elliptical galaxies, where the dwarfs contain only a metal-poor population. Such a difference may reflect a different history of star formation and chemical evolution in galaxies of different sizes. It seems very likely — as will be discussed in the following section — that the heavy elements in stars of Population I are the result of an enrichment process carried out by evolving stars of an earlier generation. Galaxies of small mass may well have been, for one reason or another, unable to hold onto the enriched interstellar material from which a later generation of Population I stars could be made. An obvious danger is that in systems of low escape velocity, material ejected from the surfaces of evolving stars is able to escape completely from the galaxy. Another possibility is that the dwarf systems had their enriched interstellar material swept out by the intergalactic gas whose existence many astronomers postulate; this seems less likely, however, because of the rapidity with which this would have to have been done. In systems that contain an old Population I, that population seems to have formed almost immediately after the Population II — if indeed the hypothesis is correct that the formation of Population I was at all later. In connection with this problem of chemical abundances it will be extremely interesting to find out what the metal abundances are in extreme dwarf irregular galaxies.

VI. Enrichment

One of the most fascinating problems of stellar populations is to understand how differences in chemical abundances have come about. The theories of nucleosynthesis show so many successes of detail that there can be little doubt about their basic premise: that the heavy elements were made in the interiors of stars. The difficulties occur in connecting this idea quantitatively with what is known about stellar populations. The populations now play a double role; on the one hand they show what the chemical abundances were at various places and at various times, while at the same time they must provide the mechanism for producing those very abundances. Here again our perception of the picture has changed with time. Fifteen years ago it seemed very reasonable that the universe started as hydrogen and that in each galaxy the abundances of helium and the heavier elements were built up in a regular way by the return to the interstellar medium of material thrown out of evolved stars. Today most astronomers would agree that the basic idea of enrichment is correct — but it now appears that the details in the earlier picture were wrong. First, it is now clear that much of Population I is nearly as old as the Population II that supposedly provided its enrichment. Second, it is now generally agreed that the helium content of the two populations is practically the same and that this helium is primeval rather than produced in stars. Since most of the normal evolution of a star burns hydrogen to helium, this is a double embarassment; stellar evolution must produce appreciable quantities of the heavy elements, and at the same time it must avoid increasing the abundance of helium by more than a few percent.

There are obviously serious difficulties with the time scale too. There is a painfully short interval between the formation of the metal-poor Population II and the appearance of the metal-rich stars of Population I. To make it worse, after that very rapid rise, the metal abundance of Population I seems to have leveled off almost completely.

And what about the hyper-strong-line stars? If these are really super-metal-rich, this would imply that enrichment really did continue for some time — but only near the centers of galaxies. Furthermore, the super-metal-rich material seems to have used itself up in star formation long ago, leaving no such material for formation of stars around the present epoch.

A further difficulty arises in processing a sufficient quantity of material. The Population I stars of the galactic disk make up at least 90 percent of the mass of the Milky Way (Oort 1965); hence it would appear that the remaining small minority population had an overwhelming effect on this great majority. Perhaps this is not too difficult to imagine, since the more massive stars of the halo population, which are now all gone, may have contained considerably more total mass than the remaining stars of lower luminosity that we now find in the halo. Furthermore, this problem is less serious than it appeared when the helium of type I stars was believed to come from enrichment. Helium is about 30 percent of the mass of type I stars, but the heavy elements are only a few percent and thus add up to a smaller total mass. Even so, considerable stellar mass must have been involved in the enrichment, and this probably implies a luminosity function richer in high-mass stars than the Salpeter function that seems to describe present-day births.

There is a stronger reason for believing that the enriching population had a very high proportion of stars of high mass — the seeming absence of low-mass stars with metal abundances even lower than those of the globular clusters. This has always been a sore point, since any conventional luminosity function would put a considerable fraction of the total mass into dwarf stars that would still be present in an unevolved state. It may be that we do not know how to recognize such stars, but it seems much more likely that they simply do not exist in appreciable numbers. Yet some earlier generation must have provided the heavy elements that are now in stars of Population II, since the original cosmological events seem incapable of producing anything heavier than helium. If this reasoning is correct, then the real first generation must have consisted almost completely of high-mass stars, which lived extremely brief lives and are now completely gone. Such a conclusion is consistent with theories of star formation and of nucleosynthesis (Truran and Cameron 1970). If material has a very low abundance of heavy elements, there are reasons for believing it will fragment into large masses, and the resulting high-mass stars are of just the sort that can produce heavy elements with a high efficiency. Truran and Cameron suggest a bizarre by-product of this development: that a considerable fraction of the total mass of a present-day galaxy might consist of a population of collapsed gravitational singularities that are the final stage of the most massive stars.

Problems of stellar populations and nucleosynthesis have recently been discussed by Greenstein (1970), Pagel (1970), Burbidge and Burbidge (1970), and Cameron (1970).

The foregoing discussion indicates many of the difficulties in developing a quantitative picture of the development of chemical abundances in a galaxy, but it does little toward really solving the problems. Earlier attempts to build up a quantitative picture (Schmidt 1959, 1963; Mathis 1959; Salpeter 1959) are unfortunately no longer valid, because they all build up the helium abundance of Population I through nucleosynthesis. A modern study would have to concentrate on the build-up of heavier elements relative to both hydrogen and helium, and the point has been reached where different groups of elements should be followed separately. For example, Cameron and Truran (1971; Truran and Cameron 1971) predict a much slower build-up of nitrogen; observational data on this question would be most interesting.

On a galactic scale this subject has received little attention until quite recently. A study of galaxy populations by Tinsley (1968) gives some abundance changes as a weak by-product, but Cameron and Truran (1971; Truran and Cameron 1971) have now begun a fundamental study of the enrichment problem. This problem certainly does deserve reexamination in the light of present-day knowledge of stellar populations.

VII. A Synthesis

Our knowledge of stellar populations is extensive but often fragmentary, and the facts are puzzling as often as they are logical. Taken together, however, they give a picture of the development of galaxies which can serve as a working model for exploration of the many unknown questions. Not all astronomers would agree with all of the details in the following summary, but I believe that the majority would agree with most of the details and nearly everyone would accept the general picture.

When, in the early stages of the expansion of the universe, matter decoupled from radiation, the proportions of hydrogen and helium were approximately as they are in most stars today, with helium accounting for about one-quarter by weight. It seems unlikely that heavier elements were present at that time in any appreciable quantity. At some later stage some of the material—perhaps only a small fraction of it—separated into protogalaxies. Each protogalaxy soon turned an appreciable fraction of its mass into a first generation of stars, nearly all of which had large masses and therefore short lifetimes.

As the most massive stars of the first generation died, they enriched the remaining gas to a level of about 10^{-4}, by mass, in elements heavier than helium. Star formation then began anew; the result was Population II. The enrichment process continued, either from the remaining stars of the first generation or from the shortest-lived stars of the newly formed Population II, and star formation continued. Meanwhile, however, the gas constituting the major part of the mass of the galaxy was in a dynamical collapse. The stars formed at each stage of this collapse retained the degree of flattening that the galaxy had at the time of their formation. Material that did not form into stars during this period ended up as a flattened, rotating disk of gas.

This stage of star formation took place shortly after that of the Population II but had the benefit of nearly all the heavy-element enrichment that was ever to take place. It resulted in the old Population I. For some reason, which may be connected with the initial angular momentum, the formation of the oldest Population I took place at different rates in different galaxies, relative to the collapse time of the gas. Some galaxies formed their Population I quickly and retained their unflattened shape; these are the ellipticals. Others formed their Population I after the collapse was complete and thus became S0's. Some galaxies, on the other hand, carried the collapse to completion and still retained an appreciable fraction of their material in interstellar form; these are the spirals and irregulars. In spirals of intermediate type, star formation was quickly completed in the central region but did not go to completion farther out in the disk.

Subsequent star formation has been very much slower, and a considerable fraction of gas still remains in irregular galaxies and in the outer parts of spirals. Its pattern of distribution is probably governed by the nature of the gravitational field; in systems where most of the mass is stellar and strongly concentrated to the center the gas forms a spiral pattern, while in larger proportions the gas is less regularly distributed.

There has been little change in chemical abundances since the time of formation of the old Population I. It is possible, however, that some overly enriched material was either retained or produced near the centers of giant galaxies and gave rise to a super-metal-rich population that is similarly concentrated to the center.

Dwarf elliptical galaxies did not follow the same evolutionary process. For one reason or another, they were unable to hold onto the later enriching materials and never formed a Population I. For dwarf spirals and irregulars the situation is not clear.

It is my view that later explosive events in the nuclei of galaxies, as important as they may be for their own sake, have no significant influence on this picture. Many astronomers would dispute this statement, however.

This oversimplified picture leaves countless questions unanswered. It is intended to be stimulating rather than satisfying. There is, however, some satisfaction in recognizing the progress that has been made in a few decades. Thirty years ago hardly a sentence in this article could have been conceived. It is equally stimulating to wonder how the picture will look in 2001.

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