PART VI

GALAXIES AND MISCELLANEOUS SUBJECTS

Willem J. Luyten making a comment from the floor.

HR DIAGRAMS OF GALAXIES: AGES AND STAGES OF EVOLUTION

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1. HR DIAGRAMS AND STELLAR POPULATIONS

Baade (1944) based his concept of stellar populations in galaxies on the HR diagrams that he inferred from the magnitude at which their brightest stars could be resolved. His type I population had bright blue supergiants like those in the disk of the Milky Way, while the brightest stars in type II were the red giants found in globular clusters. He postulated that the Hubble sequence of galaxy types from irregulars to ellipticals contained increasing proportions of Population II relative to Population I, and that similar differences characterized nuclear bulges of spirals relative to their disks. A very important revision of this picture came with the discovery by Morgan and Mayall (1957; Morgan, 1956, 1959) that the integrated blue light of the nuclear bulges of M31 and the Galaxy is dominated by strong-lined CN giants, not by the weak-lined type found in globular clusters. On the basis of integrated spectra of galaxies, Morgan developed a revised population scheme, in which the extreme types are a young-star rich population, like Baade's extreme Population I, and a young-star deficient population, analogous to Population II but generally metal-rich. Different proportions of these two types are still thought to represent the main differences among stellar populations in different regions of galaxies.

This paper will discuss selected current ideas about stellar populations in galaxies, based on properties of their integrated light, with emphasis on the implications for galactic evolution. Related reviews are those of Roberts (1963), Morgan and Osterbrock (1969), King (1971), Sandage (1975), van den Bergh (1975), and several papers at a recent Yale conference (Tinsley and Larson,

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1977), as cited below.

Populations may be characterized by three functions: the stellar age distribution, chemical composition, and initial mass function (IMF). Many parameters are needed for an adequate description of these functions. For example, relative abundances of elements heavier than helium probably vary among populations (Faber, 1977), and the IMF varies within galaxies, at least on the scale of star clusters (Freeman, 1977). But, contrary to earlier claims (see King, 1971), there is no longer evidence that the *visible* part of any galaxy has an IMF with an unusually large proportion of red dwarfs, since spectroscopic data now show that late giants dominate the light at infrared wavelengths as well as in the blue (Baldwin et al., 1973; Frogel et al., 1977).

Spectra of galaxies show that, in general, individually bright stars are the main contributors to integrated light. Consequently, very little is known from direct observations about the lower part of the HR diagrams of galaxies - K and M dwarfs. Most of the light comes from luminous main sequence stars or red giants, with $M/L < 1$ (in solar units, and at any wavelength); yet rotation curves and velocity dispersions show that the visible bodies of galaxies have $M/L \sim 10$. At least 90% of their mass is therefore hidden, and the presence of late dwarfs is inferred not from their luminosity but from their weight. (This "hidden mass" problem is much less publicized than the further discrepancy of a factor ~ 10 between the "ordinary" M/L ratios of galaxies and the values ~ 100 derived from virial masses of clusters.) Luckily, the invisible stellar population is the least interesting, because K and M dwarfs hardly evolve in the lifetime of a galaxy. The stars that do show in integrated light give information on many aspects of stellar and galactic evolution, such as the following:

- The rate of evolution of the number of turnoff stars (and their descendent giants) in old populations governs the rate of luminosity evolution, which affects classical "lookback" tests in cosmology. This evolution can be predicted by analysis of the light of nearby galaxies and detected by bluer turnoffs in galaxies at large redshifts (Spinrad, 1977; Tinsley 1978a).

- Low-mass stars radiate a large fraction of their life's energy supply as very late red giants, which therefore contribute bolometrically most of the light from old populations. Their distribution by type can be estimated from galaxy spectra, and used to supplement theories of stellar evolution in stages where the complexities of envelope mixing and mass loss are unpredictable (Faber, 1977; Tinsley, 1978b).

- The color of the low-mass giant branch is sensitive to heavy-element abundances, so integrated colors of old populations give information about their compositions (see below).

- Upper main sequence stars and supergiants are making the oxygen and carbon responsible for the bulk of chemical enrichment. It would misleading, however, to claim to understand chemical abundances in a galaxy from its present enrichment rate by massive stars; as examples given later will illustrate, the compositions of stars in a system depend on relations between the past star formation rate, gas flows, and gas content.

- The relative numbers of upper main sequence stars and turnoff stars tell how fast stars are forming relative to the past average rate, and so indicate the time scale for star formation in a galaxy. This point will occupy most of the present paper.

We therefore turn to the first function mentioned as characterizing stellar populations: the age distribution. Its effect on HR diagrams can be visualized with Sandage and Eggen's (1969) composite diagram for open clusters. If the stars in a system were coeval, a single cluster diagram would represent its population - e.g. M67 for a metal-rich elliptical galaxy several billion years old (with an important addition of M giants that are missing from the cluster because of its small total population [Baum, 1959; Tinsley and Gunn, 1976]). Similarly, a system with continuous star formation would have the whole spread of clusters. Relative numbers of stars and their contributions to the light can be estimated from simple models: Let the main sequence be populated in accordance with the empirical local IMF (allowing for stellar evolution off the main sequence for stars above $\sim 1\ M_\odot$), and let evolving stars be represented according to the number of their progenitors and their rates of evolution. It is found that turnoff stars contribute at short wavelengths, and, if there is current star formation, B - F (especially B) main sequence stars are important; with increasing wavelength, giants become more dominant, until at 2.2μ (the K band), late M giants contribute most of the light. These results resemble observed spectral types of galaxies (e.g. de Vaucouleurs and de Vaucouleurs, 1959; Morgan and Osterbrock, 1969; Frogel et al., 1977). If the IMF were much steeper than the local function, a young-star rich population would have a later integrated blue spectral type than observed, and late dwarfs rather than the observed giants would dominate in the infrared.

It is useful to concentrate on two main components in the integrated light of galaxies: (1) The young component contributes light from upper main sequence stars and their descendent supergiants; their lifetimes are much shorter than the age of the galaxy, so their contributions are proportional to the present star formation rate (SFR). (2) The old component contributes light mainly from turnoff stars and their descendent red giants;

these stars have accumulated since star formation began, so their contributions depend on the total number formed. The spectrum and colors of a galaxy are sensitive to the ratio of these components, and hence to *the ratio of present SFR to total mass.* The exact age distribution of stars is not critical, because stars of intermediate age (e.g. F dwarfs) contribute less than the two groups mentioned, and because stars with lifetimes $> 10^9$ yr ($m \lesssim 2\ M_\odot$, A stars and later on the main sequence) have very similar giant branches. As a primary parameter available from integrated light, we therefore have the ratio SFR/mass, or its inverse which gives a *time scale for star formation.* Baade's postulate that the sequence of galaxy types is one of relative amounts of Populations I and II thus becomes a postulate that the time scale for star formation varies along the sequence: The latest types (Im, Sc) form stars over a long period of time, and the earliest (SO, E) made all their stars long ago.

2. STELLAR POPULATIONS FROM UBV COLORS

For stars, the UBV photometric system is closely tied to the two-dimensional classifications of positions in the HR diagram, as well as providing information on metallicity and reddening. UBV colors are also very useful in outlining several broad properties of galaxy populations, although the parameters available are not the same as for individual stars. Factors influencing the integrated UBV colors of galaxies include the ratio SFR/mass, the age of the system, metallicity, the IMF, interstellar reddening (galactic and internal), redshift, and nonstellar sources of light such as gaseous emission lines. Despite the length of this list, we can use evolutionary models, information from different sorts of data, and corrections for the more extraneous factors, to make interesting inferences about stellar populations in galaxies from their UBV colors.

An important fact is that morphologically normal galaxies define a narrow locus, barely wider than observational errors, in the UBV plane, if their colors are corrected for effects of redshift and reddening (e.g. Larson and Tinsley, 1978). Two sequences actually define this apparently one-dimensional distribution, a metallicity sequence and one of time scale for star formation. The near coincidence of these sequences in UBV is simply bad luck; they are separated by spectrophotometric studies, population models, and the absence of HII regions and other signs of star formation in galaxies defining the metallicity sequence.

The lower half of the "normal" UBV line is occupied in part by the central bulges of spirals and by ellipticals and SOs, in a sequence of increasing luminosity towards redder colors (Baum, 1959) that is almost certainly due to a correlation of heavy-element abundances with luminosity (Faber, 1973). On the assumption that all elements heavier than helium vary together, I have used models with different metallicities to estimate that the color-magnitude relation corresponds to $\Delta\log Z/\Delta M_V \simeq -0.1$ (Tinsley, 1978b). It is possible, however, that only a few elements are responsible for the trend (Faber, 1977), in which case a calibration must await new models for stellar interiors and atmospheres.

With a few exceptions (mainly extreme dwarfs), galaxies do not show orders-of-magnitude variations of mean metallicity among their stellar populations. This uniformity can be understood through very simple models for chemical evolution, on the assumption that the IMF is everywhere the same. Searle and Sargent (1972) pointed out that, if a galaxy evolves as a closed system, the gas acquires a metallicity $Z_g = y\ ln\ \mu^{-1}$, where the yield y is a constant for a given IMF and element and μ is the fractional gas mass; thus only modest variations in Z_g are expected despite huge variations in μ. For a different situation, where gas is accreted by a galaxy at approximately the SFR, Larson (1972) showed that $Z_g \rightarrow y$, independently of the gas content. Moreover, one can show that the mean *stellar* metallicity is about equal to the yield in both types of model. Since information on stellar metallicities is available for very few galaxies, it seems reasonable to neglect the effects of variations on UBV colors when other population parameters appear to be dominant.

Now we consider the UBV locus of normal giant galaxies, which is a narrow sequence running from blue for late spirals to red for giant ellipticals. The color sequence here is surely due mainly to a progression from richness to deficiency in young stars. Theoretical models for evolving stellar systems allow more detailed statements to be made. The sequence can be reproduced by series of models with the same IMF (approximately the local function) and the same age (about 10^{10} yr), and the narrow locus does not allow great variations in IMF or age. The quantity that *does* vary along the sequence is the time scale for star formation. Various authors have reached the above conclusions using different functions to define the time scales: the efficiency of converting gas to stars (Tinsley, 1968), exponential time constants (Searle et al., 1973), and dynamical models (Larson and Tinsley, 1974). Larson and Tinsley (1978) found a more general result, namely that a narrow locus close to the empirical one is occupied by all models with about the local IMF, solar composition, ages between 5 and 20 × 10^9 yr, and monotonically declining SFRs. Moreover, no matter what the detailed time dependence of its SFR, the position of such a model on the common UBV line depends on only one quantity: the ratio of present SFR to total mass of stars. Thus UBV colors pick out just the ratio of young and old population components discussed above.

3. DYNAMICAL ORIGINS

The color sequence of normal galaxies is, of course, closely related to their sequence of shapes. For example, there is a neat progression of mean colors, from blue to red, along the Revised Hubble Sequence (de Vaucouleurs, 1977). The areas of the UBV diagram occupied by sizeable samples of each type overlap rather widely, which is not surprising since the Hubble Sequence depends on several parameters (Sandage, 1975) that do not correlate perfectly. Van den Bergh (1976) finds that his two-dimensional classification of spirals, in which the strength of spiral arms decreases from "vigorous" spirals through "anemics" to SOs, gives a further correlation, in that the more vigorous types at a given disk/bulge ratio tend to be bluer. (This claim is disputed by de Vaucouleurs [1977], however.) Likewise, the Yerkes classification by central concentration of light also correlates with UBV colors, as expected from its close relation to nuclear spectral types (Morgan and Mayall, 1957), but again there is much overlap among categories. It would obviously be of great interest to understand both the main trends and the scatter in color-morphology relations, in terms of dynamics: Why do time scales for star formation correlate with forms of galaxies? Many studies of this question have led to a coherent working sketch for an answer; its details and even main outlines are often erased, and a definitive picture has by no means emerged! The following sketch is based on many papers, most of which are cited in reviews by King (1971, 1977) and Larson (1976, 1977).

The process of galaxy formation from primordial gas clouds may itself be responsible for the major correlations among morphology, mass, and stellar population; a graphic outline of this part of the picture was given long ago by Baum (1959). The spheroidal parts of galaxies - nuclear bulges of spirals and the entire bodies of ellipticals - must have formed their stars within a few free-fall times, so they contain almost entirely old stars. If the collapse is dissipative, the gas from which stars in the inner regions form will have been enriched in metals by massive stars that died further out; thus the observed metallicity gradients arise naturally. During the collapse and star formation, supernova heating can drive the remaining gas from the system, cutting off further star formation and chemical enrichment; this can occur at an earlier stage in less massive systems, which explains their relatively low metallicities.

Disks, on the other hand, may form very slowly as diffuse, outlying gas gradually dissipates its vertical motions; the less efficiently stars form from this gas, the flatter the system can become. Consequently, disks of galaxies tend to contain gas from which stars are still forming. Some spirals - including our own - may still be accreting gas at a significant rate; M83, with its warped outer HI that looks dynamically unstable on a short time scale, is suggested as an example (Rogstad <u>et al</u>., 1974). The present SFR in a disk may thus depend both on the efficiency with which gas is compressed to the point where stars form, and on the rate at which new gas is supplied from the outside. Some of the differences in colors among spirals with similar disk/bulge ratios could, in this picture, be due to differences in the ambient intergalactic gas density.

The environment of a galaxy may influence its SFR in other ways. The best-known case is the effect of intracluster gas in sweeping spirals clean of their interstellar matter, thereby turning them into SOs. A galaxy in the process of being stripped would look like the anemic spirals often found in clusters; and within a few billion years of the stripping, the victim would be hardly any bluer than an elliptical that had made all its stars in an initial burst. Conversely, swallowing an intergalactic gas cloud may suddenly enhance the SFR in a galaxy. M82 is the most famous example (Solinger <u>et al</u>., 1977), although its huge burst of star formation is buried in so much dust that the UBV colors are not unusually blue.

Violent interactions with other galaxies can also enhance the SFR, as illustrated by Larson and Tinsley (1978). The interacting systems in Arp's (1966) *Atlas of Peculiar Galaxies* have a very different distribution of UBV colors from the narrow locus of morphologically normal galaxies, and the peculiar colors correspond to population models in which bursts of star formation occurred up to a few times 10^8 years ago. There is even a correlation between time since the burst, indicated by the colors, and time since the interaction began, indicated by the presence or absence of tidal tails: In the dynamical models of Toomre and Toomre (1972), tails develop after the closest passage of the interacting pair, and indeed Arp pairs without tails have colors suggestive of bursts that occurred $\lesssim 10^8$ yr ago. Thus the abnormal color distribution of interacting galaxies can be understood if intense star formation is induced by violent dynamical interactions. Toomre (1977) remarks that ring galaxies are a fine example of this process. Peculiarities of morphology and colors are predicted to become negligible about 10^9 yr after a disturbance, so even so-called normal galaxies could have experienced very ragged histories of star formation in the more distant past.

Unusual distributions of stars in the HR diagram are responsible for the abnormal colors of galaxies with recent bursts (e.g. Searle <u>et al</u>., 1973; Larson and Tinsley, 1978), as follows. If a system has formed stars fairly uniformly for $\gtrsim 10^9$ yrs, the distribution of OB stars varies with both the IMF and their lifetimes (τ_m). But if the majority of massive stars were formed very recently, their distribution is not affected by evolution from the main sequence, so it is unusually rich in massive stars by a factor $\propto \tau_m^{-1} \sim m^2$. In such a case, the earliest B and O stars are the main contributors to U light, in contrast to the mid-B to F stars seen normally; the B and V bands are less affected, so the upshot is an ultraviolet excess relative to normal galaxies. Later, a second turnoff due to stars made in the burst can give an unusually red (U-B) for a given (B-V).

If the burst of star formation involves more than 10% of the mass in old stars, (B-V) also is so strongly affected that the UBV colors are practically indistinguishable from those of a truly young galaxy, made entirely of young stars. Some chaotic-looking galaxies do indeed have blue enough UBV colors to be young; examples are NGC 4485 and 4490 (Arp 269) and NGC 3395 and 3396 (Arp 270). But in each case, given only UBV colors, we cannot tell if 100% or only 10% of the stars are young, and the appearance and blueness could be due to interaction rather than to youth. Unusually blue (V-K) colors would give a less ambiguous test for the absence of old red giants, although unfortunately the converse conclusion cannot be drawn since there could be 2μ radiation from dust even in a young system (Struck-Marcell and Tinsley, 1978).

Younger galaxies must of course be present at large redshifts, because of the lookback time, which is roughly $\sim 10^{10} z/(1+z)$ yr. Observations and implications of cosmological aspects of galactic evolution have been reviewed recently by Spinrad (1977) and Tinsley (1978a). Among the expected effects of evolution over cosmological time scales are: systematic changes towards bluer colors, especially reflecting the earlier turnoffs of ellipticals at redshifts of a few tenths; much bluer colors among disk galaxies in clusters at times before the spirals have become S0s; and dramatic evidence for rapid star formation in primeval giant elliptical galaxies. The first two effects have almost certainly been found, and prospects for detecting giant primeval galaxies are promising.

4. CONCLUSION

It is obvious from the list given in § 1 of this paper that I have only scratched the surface of the mine of information provided by the integrated light of galaxies. One reason for the lasting value of Baade's original criterion for classifying stellar populations, the nature of individually bright stars in their HR diagrams, is that those same stars provide most of the integrated light from unresolved systems. The colors and spectra of galaxies are therefore sensitive to the presence of OB stars, red giants of the old-disk type, and/or metal-poor giants of the halo type. From their relative numbers comes information on the age and metallicity distribution of stars in different regions of galaxies, which in turn gives clues about galactic evolution. Despite decades of observational and theoretical work in this field, many interesting details are still out of reach. Several ubiquitous sources of difficulty include the following: the insensitivity of integrated light to details of stellar age distributions; the invisibility of stars comprising most of the mass of galaxies; and the fact that surface temperatures and compositions of the evolved stars depend not only on their original masses and compositions but also on stellar mixing and mass loss. I have concentrated in this brief paper on broad conclusions that can be drawn from fairly coarse indicators of stellar age distributions and metallicities. More detailed studies, referenced above, have suggested that chemical compositions and star formation histories differ in complicated ways, both within and among galaxies. A challenge for the future is to exploit further what *can* be seen in the integrated light, of systems whose HR diagrams cannot be drawn point by point, to obtain a fuller understanding of the evolution of stars and stellar systems.

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DISCUSSION

WEHLAU: Are you able to tell if the extreme colors occur over the entire galaxy or just in some regions? That is, in which parts of the interacting galaxy does the burst of star formation occur?

TINSLEY: I wish this were known. A few have been mapped. In particular, NGC 4038/9, with the long "antennae" tails, has recently been mapped by Schweizer (IAU Symposium No. 77 in press), and he finds H II regions right out to the ends of the tails. It should be done for more, but it isn't easy, because they are mostly faint galaxies.

PARTHASARATHY: Please make a comment on the position of cD galaxies in HR diagrams of galaxies.

TINSLEY: They are red, like giant elliptical galaxies, and of course they are the most luminous of galaxies. There is some suggestion that they may be a little blue for their luminosity, according to the idea that cD's are conglomerates of smaller galaxies.

PARTHASARATHY: With regard to interacting galaxies and cD galaxies, I would like to make a comment. Recently Dr. S.M. Alladin and I studied the problem of the tidal disruption and coalescence of double galaxies. We found that the coalescence rate is higher than the disruption rate. Coalescence of galaxies in clusters can produce supergiant systems like the cD galaxies.

KODAIRA: You have shown us color-color diagrams of galaxies. Could you give us any inferences you can make when you plot galaxies in color-magnitude diagrams?

TINSLEY: For the ellipticals and the SO's the smaller ones are bluer. They would appear in the HR diagram as metal-poor faint blue galaxies. The large ellipticals are red, and metal rich. They would be giants, by spectral type, in the HR diagram. And, of course, in the spiral sequence the smallest galaxies are the little irregulars, which would have a spectral type around B. You can't define a unique spectral type for galaxies, because the spectral type depends upon wavelength. The longer the wavelength you consider, the later the type you pick up. So an elliptical would look like a G8-giant at ultraviolet wavelengths and a very late M-giant in the infrared. A schematic plot of M_V versus (B-V) for galaxies has been given by van den Bergh (1977, The Evolution of Galaxies and Stellar Populations).

SCHOMMER: A comment on NGC 4921. Woody Sullivan, Paul Johnson and I are surveying the HI content of cluster galaxies using the Arecibo radio telescope. Preliminary results show that the spirals in Coma, for example, are hydrogen deficient by at least a factor of 5 or 10 compared to standard field sample and lower concentration clusters. NGC 4921 was one of the few galaxies actually detected initially in Coma, and it appears to be depleted in HI by about a factor of 5 compared to similar galaxies in a less concentrated cluster, (A 1367). Preliminary results will be submitted for publication in the near future.