# STELLAR POPULATIONS IN THE NUCLEI OF SPIRAL GALAXIES

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## 1. INTRODUCTION

Spiral galaxies are a composite of two dynamical population types: the spheroidal and disk populations. These can be studied in isolation in E and Irr galaxies, respectively. It is natural to expect that the combination in a spiral of a dense spheroidal population, having a deep central potential well, with a repository of interstellar gas and dust in the disk gives rise to special conditions not usually found in E or Irr galaxies. And in fact, we find spectacular concentrations of star forming regions in some spiral nuclei.

In this review, I will limit most of the discussion to later spiral types which are classified as "intermediate" in the Yerkes system (Morgan and Osterbrock 1969). Types earlier than Sbc usually have "k-nuclei," where the spheroidal population dominates; excellent reviews are available for these types (van den Bergh 1975, Faber 1977).

I take the operational definition of "nucleus" to be the innermost 10" of a galaxy, which corresponds to 1.2 Kpc at a distance of 25 Mpc. The Sc galaxy M33 is known to contain a compact, semi-stellar core which is distinct from both the spheroid and disk (Gallagher et al. 1982). In objects more than a few Mpc distant, however, this could not be resolved with current techniques, and the "nuclear" observations always contain a mixture of light from this core (if present), the spheroid, the inner disk, and whatever special structures are present by virtue of their interactions.

I follow King (1971) in regarding stellar populations as characterized by age, metallicity, and initial mass function (IMF), though there is very little information on this last parameter. For convenience, I usually discuss metallicity as though it were a single parameter, even though this is probably an oversimplification (see Sec. 3).

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## 2. POPULATION CRITERIA IN INTEGRATED LIGHT

Even where we are clearly dealing with a single generation, it has proven difficult to identify simple integrated light criteria which give an adequate description of population parameters over their full range. This partly reflects the fact that stellar energy distributions are not sufficiently independent in a mathematical sense, which is a consequence of the fact that the emergent spectrum of any atmosphere is itself a superposition of black body spectra modified by wavelength-dependent opacity.

Most studies of integrated light have concentrated on the k-nuclei (van den Bergh 1975, Faber 1977), which are dominated by an old ($\gtrsim$5 Gyr), metal-rich ($Z \gtrsim 0.02$) population. A number of important recent studies have extended such work to globular clusters, where we have independent information on age and metallicity through study of individual stars and CM diagrams. Galactic globulars represent old systems with a large range of metallicity (Aaronson et al. 1978, Zinn 1980). Magellanic Cloud globulars have a large range in both age and metallicity, which are probably correlated with one another (Rabin 1980, Searle et al. 1980, Hodge 1981, Cohen 1982, Aaronson and Mould 1982).

The globulars thus present an excellent opportunity for sharpening population criteria. But even here, where two photometric parameters should in principle suffice, it is evident that more are needed. For instance, the integrated spectrum in the 3400-6000 Å region appears to be insensitive to the mean color of the horizontal branch (Zinn 1980, Rabin 1980), and the M31 globulars (Rabin 1980, Burstein et al. 1981) are spectroscopically distinct from Galactic globulars, suggesting the importance of additional population parameters (also see Sec. 3). Further, convenient pairs of photometric indices, such as U-B and B-V or Q(ugr) and Q(vgr) exhibit "degeneracies," where crowding of isochrones and isoabundance loci prevents independent determination of age and metallicity. The best example is for age $\gtrsim$7 Gyr, $Z \sim 0.01$-$0.04$ in the U-B, B-V diagram, where constant age and constant Z loci converge within observational precision (e.g. Rabin 1980). Unfortunately, this is the region where E/S0 galaxies are located.

Where multiple generations are present, the need for an even larger number of criteria is obvious. If one wishes to determine the age and metallicity of each of N generations, a minimum of 3N-1 independent photometric criteria are required. Such systems frequently also exhibit internal reddening and line emission, demanding additional criteria. The usefulness of a given criterion can vary greatly with age and metallicity. Experience indicates that a number of high precision continuum colors and spectral line measures over a long wavelength baseline should be employed.

As expected if only a few colors are available, serious age/metallicity ambiguities occur for composite systems where hot and cool starlight is combined. For instance, the U-B, B-V locus of old, metal-rich galaxies with continuing star formation (e.g. Bruzual and Kron 1980) crosses through the region for old, metal-poor (OMP) systems (Rabin 1980). Only for U-B $\lesssim$ -0.1 does clear separation of younger from OMP systems occur.

## 3. AGE AND METALLICITY IN SPIRAL NUCLEI

The bulges of Sa/Sb spirals closely resemble E galaxies and S0 bulges, and though there are differences in dynamics (Kormendy and Illingworth 1982a) and color gradients (Wirth 1981), their stellar content is similar to those of E/S0's (e.g. Pagel and Edmunds 1981, Kormendy and Illingworth 1982b). The similarity extends to the well known spectrum-luminosity correlation in E/S0's (fainter galaxies are bluer and weaker-lined). Visvanathan and Griersmith (1977) and Griersmith (1980) have shown that the UBV-luminosity relation for Sa/Sb bulges has the same slope as for E/S0's. The accepted interpretation of this relation is that mean metallicity increases with galaxy mass, though more than one parameter is involved (Terlevich et al. 1981). The metallicity scale is uncertain but probably ranges from 0.2 to 2.0 $Z_\odot$ for $M_V$ = -15 to -23 (Pagel and Edmunds 1981).

Griersmith (1980) also found that there is a color-morphology relation for S0-Sb bulges (independent of the color-luminosity relation) in which later types are bluer. Because of the ambiguities noted in Sec. 2, he was unable to determine whether this was an age or metallicity effect. In types Sbc or later, one requires observations made with small apertures in order to avoid contamination by blue stars in the disk. It is well known that small aperture colors (de Vaucouleurs 1961, Tifft 1969) and spectra (Morgan and Mayall 1957, Heckman 1980) indicate the increasing prominence of a hot nuclear stellar population as types progress from Sb to Ir. This is paralleled by increasing frequency of nuclear line emission (Humason et al. 1956, Gisler 1978, Heckman 1980).

This striking continuity of properties from Sb to the irregular galaxies, where there is no doubt that active star formation occurs, has led most authors to the conclusion that later spiral nuclei have experienced recent star formation which is absent in the k-nuclei (Morgan and Osterbrock 1969, Sandage 1975, Heckman 1980). The increasing blueness is not regarded as a sign of decreasing metallicity. In view of the discussion above, however, it is clear that some caution is advisable; more precise criteria are desirable, and morphology and luminosity effects must be distinguished (Strom and Strom 1982, Visvanathan 1981). Also, the high metallicities found for gas near spiral nuclei (Pagel and Edmunds 1981) probably reflect abundances in the disk and not the nuclear stellar population.

Recent work by McClure et al. (1980) and Cowley et al. (1982, hereafter CCM) in fact argues that the spectral properties of later spiral nuclei reflect lower metallicity rather than youth. They find a good correlation between line strengths and bulge luminosity for S0-Sc nuclei, which they interpret as a metallicity sequence throughout. From their spectral resemblance to globular clusters, Sc nuclei are taken to be extremely metal deficient rather than young star rich. This would imply that Sc bulges, with $M_V \sim -15$, are much more metal-poor ($Z \lesssim 0.01\ Z_\odot$) than expected for their luminosities from the metals scale for E/S0's and that systems (bulges and globular clusters) which differ by a factor of over 100 in mass can experience the same nucleosynthetic history.

The single-parameter interpretation of all nuclei by CCM has an attractive simplicity; but there are difficulties. First is the fact that E/S0's lying near the Sc nuclei in the CCM line-luminosity diagram (NGC 185, 205, 3073, and 5102) are known to have unambiguous evidence for recent star formation (e.g. Hodge 1973, Burstein 1979, Heckman 1980, Gallagher and Mould 1981). Another is that detailed examination of colors (O'Connell 1982) and Balmer line profiles (Diaz et al. 1982) for Sc/Sd nuclei suggest a strong upper main sequence rather than an OMP population in at least some cases.

For a closer look at this problem, I plot in Figs 1-3 strengths for Mg I λ5175 and Ca II λ3933 for a selection of galaxies and globular clusters reduced to the photometric system of O'Connell (1980). To calibrate the diagrams, I have added calculations for $Z = Z_\odot$ star clusters with a range of ages from 0.005 to 25 Gyr; assumptions are as in O'Connell (1980). No SMR stars are included, and the age scale of Iben (1967) is adopted. One can readily estimate where composites formed from components in various proportions lie in these diagrams.

Because of the inhomogeneity of the data, conclusions from these figures must be drawn with caution. Relevant implications include:

i) The Galactic and M31 globular cluster systems exhibit different spectral behavior which does not seem to be explainable by reddening errors for M31. The k-nuclei do not form an extension of the globular sequences in the two diagrams involving Ca. Ca can be stronger in clusters than in any galaxy nucleus. Since the Ca feature is sensitive to the ionization equilibrium and local blanketing in the continuum, this does not necessarily imply Ca over-abundances in the clusters. However, Christensen (1972) could not find a combination of Pop I and II stars near the sun which could reproduce the Ca lines in the reddest clusters. This emphasizes again that stellar species distinct from local ones are important in other environments (cf. Faber 1977). Clusters and k-nuclei do not appear to form a continuum of systems which differ only in mean metal abundance. Multiple generations or selective abundance enhancements may be involved. Similar distinctions have been found in V-K, CN, and the Balmer series (Frogel et al. 1980, Rabin 1980, Burstein et al. 1981).

ii) The utility of a given pair of spectral criteria is a strong function of the population mixture involved. For instance, objects with admixtures of stars $\lesssim$0.05 Gyr old (e.g. NGC 205, 2903) are well segregated in the Mg-$(U-V)_0$ diagram (Burstein 1979), but if ~0.5 Gyr old generations are present (e.g. M51, NGC 4459) the Ca diagrams work

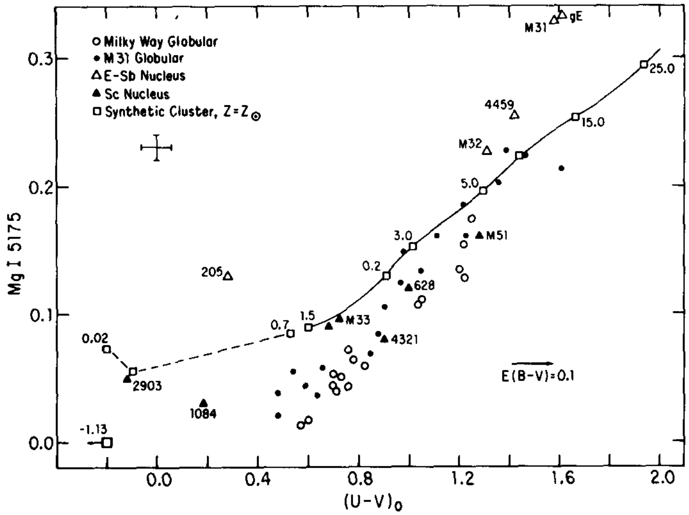

FIGURE 1: Mg index versus intrinsic broad-band U-V. Galaxy data from Turnrose (1976) and my observations are fully corrected for effects of line emission. Galactic and M31 globular cluster data from Zinn (1980), Rabin (1980), Christensen (1978), Frogel et al. (1980), and Burstein and Faber (private communication). Solid line connects synthetic clusters older than 1 Gyr; broken line connects younger synthetic clusters, where cool class I and II stars have important effects on colors (Harris 1976).

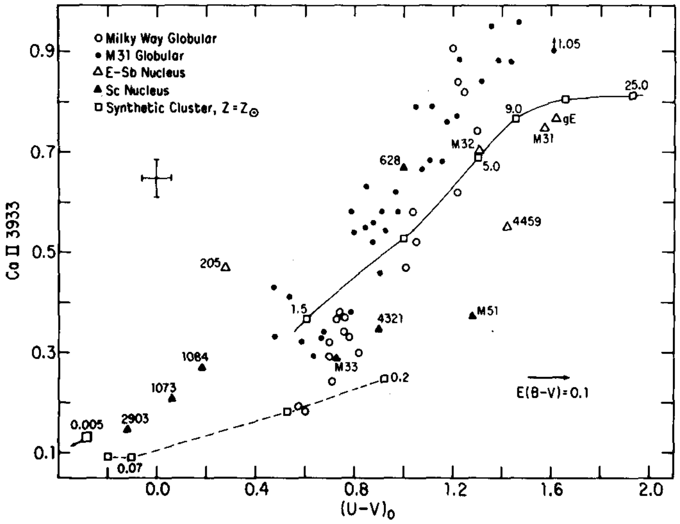

FIGURE 2: Similar to Fig. 1 but for Ca. Includes Searle Ca data from Frogel et al. (1980). Error bars in all figures are for the globulars. Note strength of Ca in globulars relative to E galaxies. For reference, M32 has $Z \sim Z_{\odot}$.

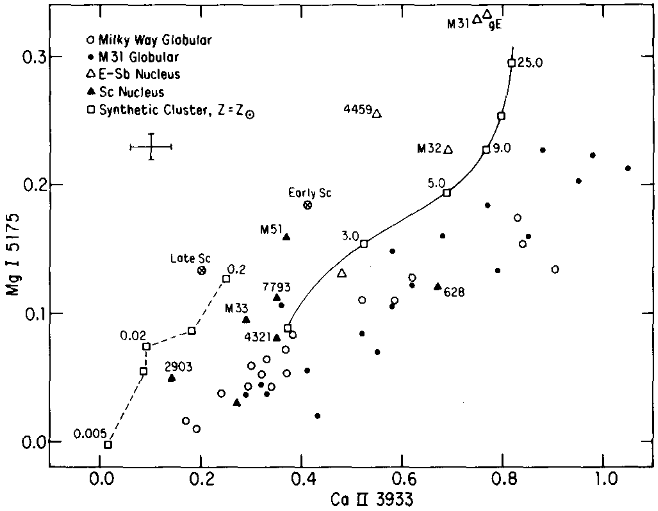

FIGURE 3: Ca index versus Mg index from previous diagrams. NGC 7793 data from Diaz et al. (1982). Note that E galaxies do not form an extension of the globulars. Circled crosses are Sc means from CCM; these positions cannot be reached by any combination of globular cluster-like populations.

better. Continuum indices like U-V are superior to line indices when very young generations are involved.

iii) Of the Sc nuclei plotted, only NGC 628 and 4321 could be regarded as superpositions of globular cluster populations, as suggested by CCM, on the basis of three criteria involved. The point is emphasized by the circled crosses in Fig. 3, which represent means for Sc nuclei as determined by CCM. These suggest not only that young generations are responsible for the early spectral types, but also that the background old population is relatively metal rich.

I conclude that the conventional interpretation of "intermediate" nuclei as mixtures of young and old populations is correct in most, if not all, cases and that the metallicity of spheroidal systems with $M_V \sim -15$ is probably above 0.1 $Z_\odot$. (For a different view of this problem, see the article by Crampton et al. in this volume.) CCM's work, however, emphasizes the insidious similarity of metal poor and composite populations and demonstrates the need for high precision data if an unambiguous result is to be achieved. This is a potential difficulty for galaxies at high redshifts, where even Space Telescope may not provide sufficient accuracy.

This conclusion then justifies the assumptions made in most spectral synthesis studies of intermediate nuclei (Wood 1965, Andrillat et al. 1972, Alloin 1973, Turnrose 1976, Pritchet 1977). These have shown that multiple generations of stars can successfully explain the absorption and emission line spectra of Sc nuclei. Turnrose's study is most complete.

He finds the Sc data imply histories ranging from continuous star formation to exponential decays with time constants of 3-6 Gyr, and he suggests a correlation between the presence of an inner Lindblad resonance (which would prevent density waves from propagating to the nucleus) and an absence of very recent star formation. My recent analysis of M33 suggests a continuous series of formation episodes separated by intervals of ~0.1 Gyr, which corresponds to the period during which Type II supernovae would sweep gas from the nucleus. Both studies find the data consistent with a normal IMF.

## 4. BURSTS OF STAR FORMATION IN SPIRAL NUCLEI

A rapidly increasing body of optical, infrared, radio, and X-ray data demonstrates that later spiral nuclei can be sites of remarkably intense bursts of recent star formation. These are much larger than found in disks and are perhaps miniature versions of the star formation events occurring during primordial infall of galaxies. The most dramatic instances, involving $L \sim 10^{11}$ $L_\odot$, are revealed by 2-100μ observations (Rieke and Lebofsky 1979, Telesco and Harper 1980). In some objects (e.g. M82, NGC 7714) the burst has probably been triggered by an interaction; but equally powerful bursts can occur in isolated objects (e.g. NGC 253, 6946). In many of these, the nucleus is a complex set of distributed "hot spots" (e.g. Morgan 1958, Sersic and Pastoriza 1967, Osmer et al. 1974, Alloin and Kunth 1979).

As one of the nearest examples, M82 affords a closeup view of a star burst. The star cluster M82A (O'Connell and Mangano 1978) may be regarded as a prototype hot spot. Comparison of optical (Kronberg et al. 1972, O'Connell and Mangano 1978) and infrared (Rieke et al. 1980) data indicates that M82A dominates the galaxy from 0.5 to 2.2μ. M82A has the following intrinsic properties: size = 150 x 45 pcs, $L_V$ = $1.1 \times 10^9$ $L_V(\odot)$, $L_{bol}$ = $3.7 \times 10^9$ $L_\odot$, $M = 8 \times 10^7$ $M_\odot$, $M/L_V = 0.07$, $L(H\beta) = 2.2 \times 10^{40}$ erg $s^{-1}$, age = 0.02 Gyr if the IMF is normal, indicative star formation rate = 4 $M_\odot$ $yr^{-1}$, and current supernova rate = 0.03 $yr^{-1}$. Dust is mixed with the stars in M82A, and the resulting correction for absorption is somewhat uncertain; the values adopted correspond to $A_V = 3$. The birth rate is 25 times higher than the mean for the brightest star forming regions of 15 Irr galaxies studied by Hunter et al. (1982).

The total infrared power of M82 is $3 \times 10^{10}$ $L_\odot$ (Telesco and Harper 1980) and corresponds to ~8 regions like M82A. A similar number of hot spots seems typical in other objects. For instance, the Hβ flux from the extremely bright, unresolved nucleus of NGC 7714 (Weedman et al. 1981) corresponds to 16 regions like M82A. As Weedman et al. (1981) point out, the resulting supernova rate, ~ 0.4 $yr^{-1}$, should produce readily detectable events. Laques et al. (1980) have in fact reported a Type II supernova in one of the hot spots of NGC 2903. There are probably strong interactions between supernova remnants, with new supernovae occurring in old remnants, implying a very different evolution than for isolated SNR's. Abundances in the ionized medium of hot spots do not appear peculiar (Pagel and Edmunds 1981).

In some cases, authors have claimed evidence for a truncated IMF which produces only high mass stars (Rieke et al. 1980, Kronberg et al. 1981, Kronberg and Biermann 1981). This is based on comparison of the massive star population (inferred from infrared or radio fluxes) to dynamical or HI masses. Given the complexity of these sources, particularly spatially variable extinction and interactions between SNR's, a definite conclusion here is probably premature. It does seem, however, that these objects are unusually efficient in converting gas to stars.

Only a few theoretical studies of star bursts exist (see Biermann 1980 for a review). It is important to understand the relationship between nuclear star formation and galaxy dynamics. Nearly all the hot spot galaxies have some signs of bar-like structure (Sersic and Pastoriza 1967); the extended potential well of the bar may explain the distribution of the hot spots, and circulation of gas streams induced by the bar (e.g. Sanders and Tubbs 1980) may provide the raw material for rapid star formation.

There is little evidence for a relationship between recent star formation and the Seyfert phenomenon although there are a number of interesting associations between active nuclei and star forming regions (see Balick and Heckman 1982 for a review). However, recent work has shown that the nuclei of outwardly normal galaxies like M81 and M51 exhibit evidence of Sy 1 activity at low levels (Peimbert and Torres-Peimbert 1981, Rose and Searle 1982). Since perhaps 30-50% of all spiral nuclei share the unusual [N II]/Hα ratios found in these cases, underactive Sy 1 nuclei may be common constituents of spiral galaxies.

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