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THE AGES OF ELLIPTICAL GALAXIES

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Abstract: We describe evidence supporting the view that the evolution of elliptical galaxies and spiral bulges was more complex and heterogeneous than formerly supposed. They appear to have prolonged, episodic star formation histories, and their dominant stellar populations can range in age from $\sim$ 1 to $\sim$ 15 Gyr.

Key words: Stellar populations, galaxy evolution, ages of galaxies

1. Introduction

Elliptical galaxies are deceptively simple in appearance. They are highly symmetrical in morphology. Outwardly, they lack the multicomponent character of spiral galaxies, which includes distinct dynamical subsystems, red and blue stellar populations, gas, and dust. The large bulges of early-type spirals (S0–Sb) are superficially similar to ellipticals. It is therefore usually assumed that large bulges and ellipticals have had similar evolutionary histories, and they are often grouped together under the title "spheroidal populations".

Since the introduction of the concept of stellar populations by Walter Baade in 1944, spheroidal systems have also been supposed to have experienced simple evolutionary histories. They were believed to contain *uniformly old* populations, formed in a rapid burst ($\delta t \lesssim 1$ Gyr) at early times with virtually no subsequent star formation. Their mean ages were taken to be comparable to those of globular star clusters ($t \sim 15$ Gyr).

This "classical" interpretation of the history of spheroidal systems has been remarkably tenacious, especially considering how dramatically the rest of extragalactic astronomy has changed since the 1940's. Its continuing influence is testimony to the unifying power, beauty, and simplicity of Baade's formulation. The classical properties assigned to spheroidal systems have tremendous appeal. For cosmologists, they mean that spheroidal systems are reliable "standard candles" and that they were among the earliest structures to form in the universe. For galaxy modelers, they mean that only a few parameters need be employed. The classical interpretation consequently became an almost subconscious element of the fabric of extragalactic astrophysics.

This familiar and widely accepted picture is now unraveling. Most workers are coming to accept that the histories of elliptical galaxies and spiral bulges were considerably more complex and heterogeneous. Although much of the evidence that demonstrates the inadequacy of the classical picture is new, some of it has existed for over thirty years. In this paper I want to review this evidence, focusing on what can be deduced from the *stellar populations* of spheroidal systems. Related areas, including dynamics, nuclear star formation, and the incidence of active nuclei, are covered in other papers at this conference (e.g. Binney, Gerhard, Kormendy, Rieke, and Sargent).

2. The Classical Concept of Stellar Populations

Baade (1944a) was the first to resolve stars in the outer parts of the Local Group elliptical galaxy M32 and in the bulge of the Sb spiral M31, and he showed they were identical in color and (estimated) luminosity to the giants found in globular clusters. This became the final link in the chain of inference which led to Baade's concept of the two major stellar population groups (for complete reviews, see Sandage 1986 and Baade 1963). Baade classified ellipticals, spiral bulges, and globular clusters together as *Population II*, to be distinguished from the Population I regions of spiral disks, which contained massive blue stars and a rich interstellar medium. Although only the brightest stars had been resolved in the galaxies, the working hypothesis was that the entire populations of ellipticals and globulars were identical. Globulars are nearby and suitable for deep imaging studies, and in the 1950's they were demonstrated to be the oldest known stellar aggregates (Sandage 1986). The ages of the clusters are now estimated to be 16 ± 3 Gyr (Hesser 1993).

By the 1970's, these fundamental results, together with a large body of supporting observational and theoretical work, had become translated into what was called the "standard scenario" by Beatrice Tinsley at IAU Symposium 77 (1978; see also Tinsley 1980):

> "...the integrated [broad-band UBV] colors of galaxies are consistent with the following hypothesis: Normal galaxies have the same age and stellar initial mass function (IMF), and have monotonically decreasing star formation rates, but the time scale for star formation to decline varies along the sequence of morphological types. "

More specifically, the standard scenario was taken to imply: *(i)* that there was a unique formation epoch for galaxies $\sim$ 15 Gyr ago; *(ii)* that star formation subsequent to this epoch declined exponentially with a time scale (τ) which depended on morphology, yielding a one-parameter sequence of morphology/mean age (the Hubble sequence); and *(iii)* that chemical composition could be specified by a single metal abundance parameter (Z), which varies with a galaxy's mass. In the standard scenario, spheroidal populations were thought to have $\tau \sim 1$ Gyr and hence to be uniformly old. They were assumed to differ only in their mean Z's.

3. A New Consensus

If one took a survey of the stellar populations community as little as 5 years ago, I expect that most people would have subscribed to the standard scenario. Although it had certainly been challenged from various sides, this had not swayed the majority. Now, I think, a new consensus is emerging. This was most obvious at IAU Symposium 149 on Stellar Populations (Barbuy and Renzini 1992) and also figured prominently at IAU Symposium 153 on Galactic Bulges (Habing and Dejonghe 1993). The elements of this consensus are these:

1. *Spheroidal systems are not coeval, and their stellar populations can have a range of ages from $\sim$1 to $\sim$15 Gyr.*

   This statement refers to those populations which dominate the *light* of galaxies, not necessarily their masses or underlying dynamical structure. Star formation processes may have begun coevally, and long ago, but they evidently continued for different periods in different systems. The oldest populations in galaxies, as exemplified by globular clusters, may be ancient and roughly coeval, but they are not normally very important in the integrated light.

2. *Environmental processes are important in the evolution of most spheroidal systems.*

   The kind of rapid collapse and evolution of an isolated structure which was envisioned by Eggen et al. (1962) probably applies to only a minority of spheroidal systems. Strong interactions with the environment are more common. Important effects can include galaxy mergers, tidal interactions, infall, stripping, subcluster collapse, and accretion flows. The combined effects of the environment imply:

3. *Star formation in spheroidal systems can be prolonged and episodic, with large excursions in amplitude.*

What has happened to the standard scenario? Put most simply, it is that we have begun to actually look at elliptical galaxies and spiral bulges. This is not a facetious remark, since it is very difficult to study these faint systems at the resolution (both spatial and spectral) and signal-to-noise ratios appropriate to the task. In imaging, Baade's 1944 observations of M31 and M32 (acquired under superb observing conditions) were in fact not superseded until the last 10 years with CCD and infrared detectors. In spectroscopy, the state of the art for galaxies is now $S/N \sim$ 50–200 with resolutions of $\lambda/\delta\lambda \sim 1500$.

Simultaneously, we have refined our interpretational tools, especially for galaxy colors and spectra. The period of interest is the age range 1–20 Gyr. An important development was the recognition of the inadequacy of many population diagnostics for that range. In particular, broad-band colors, which Tinsley (1978) cited as strong evidence in support of the standard scenario, have limited usefulness for two reasons. First, they *evolve slowly* for large ages (O'Connell 1988), with $\Delta(\text{color}) \lesssim \Delta \log t$. Second, there is a serious *metallicity/age ambiguity*, because

$$\partial(\text{color})/\partial \log Z \sim \partial(\text{color})/\partial \log t,$$

(cf. O'Connell 1986, Renzini 1986, Worthey 1992). One must have enough information to determine age and metal abundance simultaneously.

The upshot is that integrated UBVRIJK colors are not very useful in constraining evolutionary histories for $t \gtrsim 3$ Gyr. Systems which formed at 15 Gyr, which formed at 8 Gyr, or which experienced a series of star formation bursts lasting until 5 Gyr ago, can all have nearly indistinguishable broad-band colors. Two recent sets of models nicely illustrate this fact (Schweizer & Seitzer 1992, Fritze-v. Alvensleben & Gerhard 1993). The first of these states, "... the relatively small scatter of the UBV colors of E+S0 galaxies...(often cited as evidence for uniformly high ages) is fully compatible with [them] having formed through major mergers over at least 1/3 to 2/3 the age of the universe". The general agreement between UBV colors and the expectations of the standard scenario is therefore not sufficient to demonstrate its validity, since they cannot exclude alternative histories.

An example of the problems of dating old populations is given in Figure 1. Here we see two isochrones, separated by 12 Gyr in age. These would be trivial to distinguish if one could resolve individual stars to the bottom of the diagram. Unfortunately, that cannot be done even in nearby galaxies like M31, where the working HST limit is currently brighter than the turnoff of the younger population. The resolvable parts of the giant branches do not provide good age discrimination, except at the very tips, where the younger one has an "extended asymptotic giant branch" (AGB) which reaches 1–2 mags brighter than the older one (e.g. Iben & Renzini 1983, Aaronson & Mould 1985). These AGB objects are very

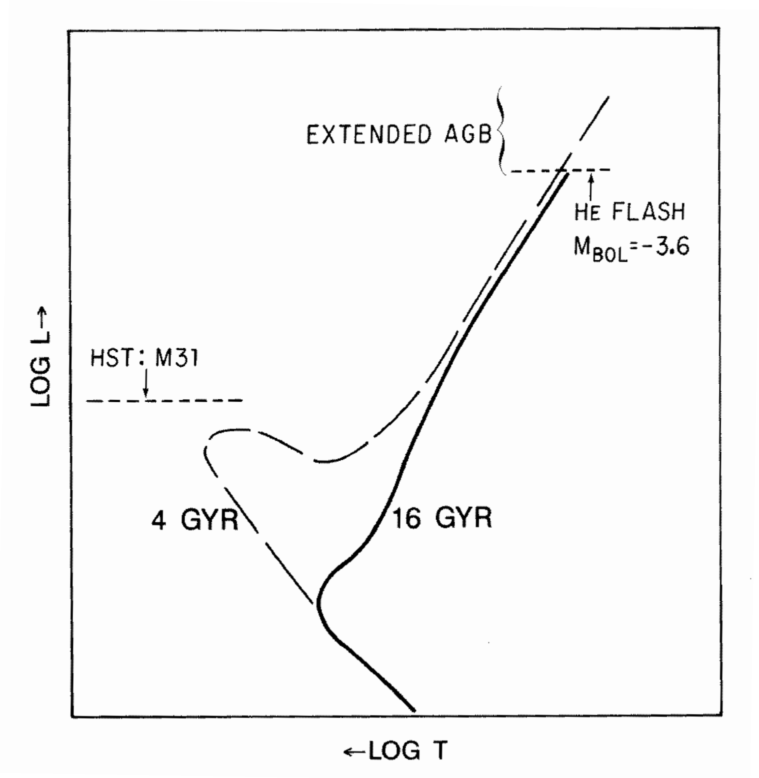

FIGURE 1: A schematic HR diagram, showing two old isochrones. The younger is distinguishable mainly by its warmer turnoff stars and its extended AGB. The limiting magnitude of the HST for detection of point sources in M31 is indicated.

cool, so long-wavelength imaging is called for. Until the advent of optical-band CCD's and more recently panoramic infrared arrays ($\lambda > 1\mu$), this was not feasible.

Integrated light photometry or spectroscopy sums all the stars in the isochrones together. Since information on stellar temperature is retained, this is like adding the diagram vertically in temperature bins whose sizes depend on the technique used. The net integrated properties of the two isochrones will differ mainly by virtue of the presence of warm turnoff objects in the younger one, which will affect the short-wavelength (ultraviolet-blue) spectral region. The UBV system covers only part of this region, and with only two filters, yielding too little information to be effective in measuring age and abundance effects. Spectral resolutions of $\lambda/\delta\lambda \gtrsim 100$ are more appropriate. The most sensitive spectroscopic system so far developed for dating old populations is that of Rose (1985, 1993), which employs a resolution of 1500 for selected absorption features in the near-UV/blue.

Thus, the most promising means of dating older populations involve either IR imaging or UV-blue integrated light spectroscopy.

4. The Evidence

In this section I describe several of the lines of evidence which support the new consensus and give examples of highlights or recent results. The list is not meant to be exhaustive, and it is not possible to include complete citations. The list is in chronological order to emphasize the fact that some of the clues are quite venerable.

1944–: *Population I components in spheroidal systems*. In a companion paper to the announcement of the resolution of M31 and M32, Baade (1944b) reported the presence of a dust cloud in NGC 185, one of the peculiar dwarf elliptical companions to M31. Subsequent observations also located massive OB stars in both NGC 185 and 205 (Baade 1951). These were the first hints that "pure Pop II" systems, thought to be devoid of interstellar matter or young stars, were really often more complex. More recent work has confirmed that these systems have experienced recent bursts of star formation, possibly induced by interactions with M31 (Wilcots et al. 1990, Davidge 1992, Lee et al. 1993). Radio, infrared and X-ray observations in the 1980's demonstrated that E and S0 galaxies often contain a massive interstellar medium, though this may exist in forms (very hot gas; cool distributed dust) which are difficult to detect at optical wavelengths (see the catalog of Roberts et al. 1991). Examples of HST detections of dust in Virgo elliptical galaxies are shown in Figure 2.

In a related development, Morgan and his collaborators (Morgan & Mayall 1957, Morgan & Osterbrock 1969) showed spectroscopically that the bulges of later type spirals (Sbc-Sd) often contained stellar populations with ages $\lesssim 1$ Gyr. It was not widely appreciated that if they were only 3-5 Gyr older (still much younger than globular clusters) such populations would not be distinguishable with low-resolution techniques. With more sensitive methods, King (1986) was able to find such intermediate age populations in over 40% of the (mostly) Sa-Sb bulges in his sample (see also Kormendy 1993). It is likely that gas transfer from the spiral disks fuels the birth of these populations, long after the initial burst of star formation.

1956–: *Integrated light differences between galaxies and globular clusters*. The first test of the hypothesis that the entire populations of globulars and spheroidal systems were identical was made by Morgan in 1956. He obtained low dispersion spectra of the bulge of M31 and immediately found that the galaxy had much stronger absorption lines than the clusters. It was now clear that the stars which Baade had resolved in M31 and M32 were only a trace population, not representative of the whole. This ought to have forced a reevaluation of the age issue. Instead, the community adopted the view that the metal abundances of spheroidal systems may differ from those of clusters but that the ages were identical. It was assumed that the globulars and elliptical galaxies were a one-parameter continuum in metal abundance, with the latter at the metal rich end.

Later work with increasing resolution and precision demonstrated that spheroidal populations were neither identical to nor a simple extension of the globular clusters (e.g. Baum 1959, Frogel et al. 1980, O'Connell 1983, Burstein et al. 1984, Rose 1985, Brodie & Huchra 1991). A recent study by Rose (1993) is the most exhaustive. He uses high resolution spectra to show that the metal rich globular cluster 47 Tuc and the elliptical galaxy M32, which are nearly indistinguishable in low resolution spectroscopy and photometry, differ at over the 5σ level in those near-UV/blue absorption features which are most sensitive to the structure of their color-magnitude diagrams. The populations of these two systems are not closely related and cannot differ only in metal abundance.

The differences between these two types of objects are model-independent, and they remove the original basis for the presumption that globular clusters and galaxies are coeval.

1971–: *Integrated spectrophotometry of spheroidal populations.* The first important quantitative step beyond broad-band colors was the high S/N, moderate-resolution spectropho-

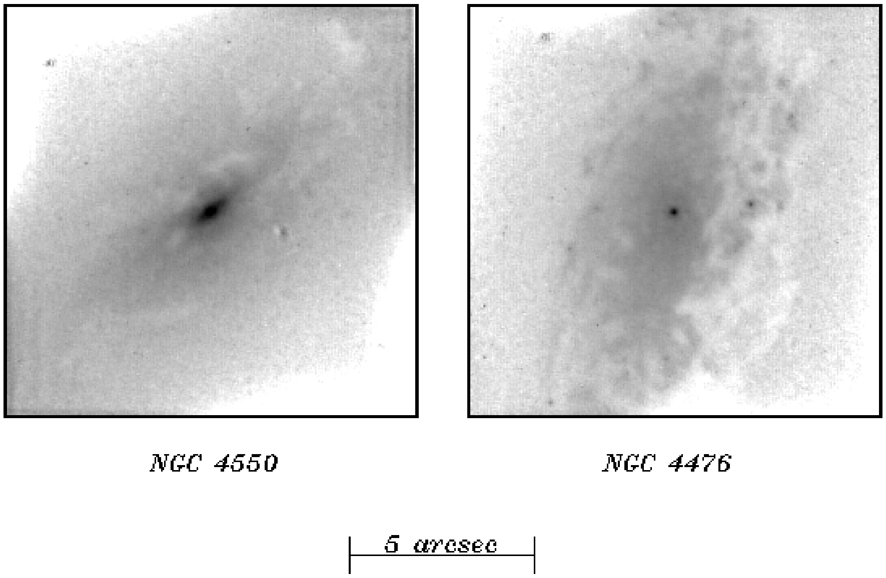

FIGURE 2: Examples of a cold ISM in E galaxies, taken from an HST/PC survey of bright Virgo E's by Jaffe et al. (1993). Deconvolved V-band images. Complex, spiral-like dust lanes are present in both. NGC 4550 has a flattened nuclear light distribution, consisting of co-spatial, counter-rotating stellar disks (Rubin et al. 1992).

tometry pioneered by Spinrad and Taylor (1971). Elaborations of the method included studies by Faber (1972), O'Connell (1976), Gunn et al. (1981), Pickles (1985), Rose (1985), Bica & Alloin (1987), Gregg (1989) and many others. The most immediate result was that the stars in luminous spheroids had significantly higher metal abundances than the sun. For a given integrated color, or inferred main sequence turnoff, the estimated age of a population decreases as its metal abundance increases. Most modeling therefore suggested that ages of 12–15 Gyr would yield redder energy distributions than observed.

The situation was clouded by questions about the nature of the "super metal rich" (SMR) components (e.g. Taylor 1982, Faber et al. 1985). It was possible that the strong lines of SMR stars and galaxies were enhanced by mechanisms other than abundance, and there was evidence that the light and heavy metals were decoupled in galaxy spectra (O'Connell 1976, Pritchet & Campbell 1980). The importance of metallicity mixtures was also debated (e.g. Renzini 1986), though it is not obvious that a dispersion in abundance in a given system would necessarily *bias* an age determination even if it might reduce its precision.

M32 became an important test case when O'Connell (1980) showed that its near-UV/IR spectrum could be fit to 2% accuracy by a solar-abundance model of age 5 Gyr, only 1/3 the age of the globular clusters. The problems of SMR-ness were less important here. These conclusions were supported by a variety of later integrated light studies of M32 from UV to IR wavelengths (Burstein et al. 1984, Rose 1985, Kjærgaard 1987, Rocca-Volmerange & Guiderdoni 1987, Boulade et al. 1988, Bica et al. 1990, Davidge 1990, Magris & Bruzual

1993, Rose 1993).

The largest database of elliptical galaxy digital spectra is the Lick Observatory survey of Faber et al. (1992). Detailed modeling of line strengths from the survey (Worthey 1992, Worthey et al. 1992), has recently yielded two conclusions: first, that the ratio of light to heavy elements does change with mass among the galaxies, suggesting variable nucleosynthetic histories; and second, that the colors and line strengths of many objects are not consistent with ages $\gtrsim$12 Gyr. The Hβ–Mg diagram, which offers the best age-abundance separation, is shown in Figure 3.

The direct spectral evidence therefore indicates a considerable range in light-weighted ages and evolutionary histories. Spheroidal systems appear to be sensitive to three population parameters (not one, as in the standard scenario): age, heavy metal abundance, and light metal abundance (Worthey 1992).

1972–: *Interactions and mergers.* Individual examples of interacting galaxies had been known for many years, mainly through the work of Zwicky, Vortonsov-Velyaminov, and Arp, before the Toomres (Toomre & Toomre 1972, Toomre 1977) suggested that interactions might be a common feature of galaxy evolution and that, in the right circumstances, the merged product of an encounter might resemble an E galaxy. A large body of observational and theoretical work followed, reviewed in Barnes & Hernquist (1992). Recently, dynamical evidence of multiple accretion events has been found in a number of nearby elliptical galaxies (e.g. Kormendy 1984, Franx & Illingworth 1988, Bender 1988, Bender & Nieto 1990; Rubin et al. 1992). One of the more dramatic examples of a likely merger remnant is the double nucleus of M31 (Lauer et al. 1993). Correlations between dynamical disturbances and population youth in E galaxies have been found by Schweizer et al. (1990) and Schweizer & Seitzer (1992). About half of the field E's in the latter study may have been formed through mergers during the last $\sim$ 7 Gyr. A related spectral study of E/S0 galaxies by Bower et al. (1990) indicates that star formation was completed earlier in the denser environments of rich clusters of galaxies than in the field or poorer clusters.

In a study of all types of "dynamically hot" galaxies (E's, bulges, compacts, and dwarfs), Bender et al. (1992, 1993) find that structural properties are consistent with a hierarchy of mergers which involve a systematically smaller proportion of gas as the total mass increases. Mg line strengths also indicate that the mean abundance and age of a population are closely linked to a galaxy's dynamics. The mechanisms which might closely couple dynamics to the stellar populations are not clear yet.

1978–: *Late evolution of cluster galaxies*. According to the standard scenario, luminous E/S0 galaxies should not show appreciable changes in their rest-frame colors until lookback times comparable to their ages, i.e. $\Delta t \gtrsim 12$ Gyr, implying $z > 1.5$. The discovery by Butcher & Oemler (1978, 1984) that evolutionary effects could be detected in rich clusters in the form of an excess of blue galaxies at redshifts as low as $z \sim 0.2$ was therefore unexpected. Spectroscopy by Dressler & Gunn (1983) and others revealed that many of the blue objects appeared to be in a post-starburst phase. The mechanisms responsible have not been positively identified (see the reviews by Gunn & Dressler 1988 and Oemler 1992), but interactions/mergers are important in many cases (e.g. Lavery et al. 1992), and ram-pressure induced star formation may play a role in others.

Milder forms of the "Butcher-Oemler effect" have also been detected in nearby clusters,

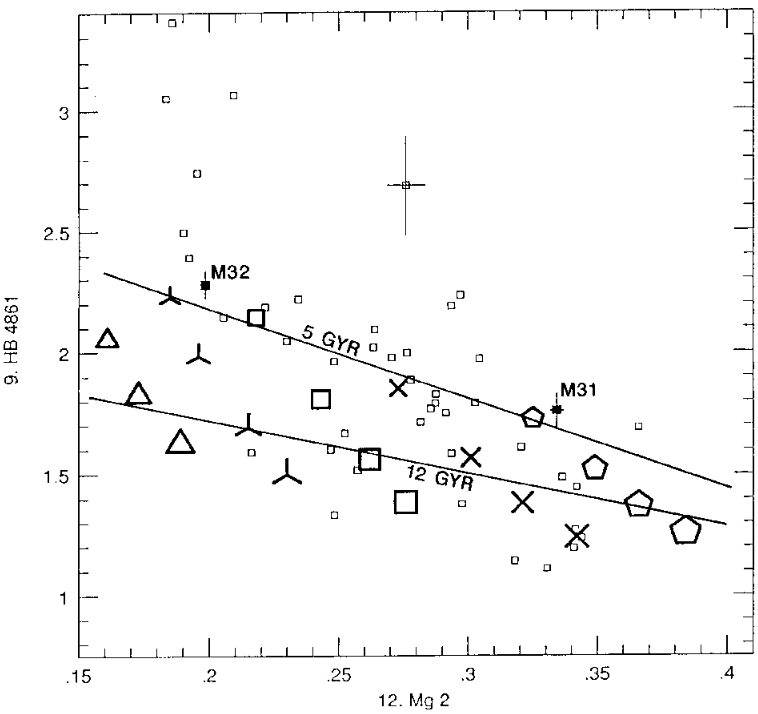

FIGURE 3: Line strengths (Hβ and Mg I λ5175) in the Lick survey of E galaxies. Small open squares are observations for E nuclei; M31 and M32 are marked. Large symbols are models by Worthey (1992) for 5 different log $Z/Z_\odot$ values between -0.5 (triangles) and +0.5 (pentagons). Four ages from 5 to 17 Gyr are included; the approximate isochrones for 5 and 12 Gyr are drawn in. According to the standard scenario, all objects should lie below the 12 Gyr isochrone. Most are clearly younger, according to this calibration.

including Virgo (van den Bergh et al. 1990) and Pegasus I (Vigroux et al. 1989). The Coma cluster presents an interesting case. E/S0 galaxies in the core show little scatter about the mean luminosity-color relation, implying uniform star formation histories (e.g. Sandage & Visvanathan 1978, Bower et al. 1992). However, 1/3 of the E/S0 cluster galaxies in a field 40$'$ from the center have enhanced Balmer absorption or emission lines indicative of recent star formation (Caldwell et al. 1993), possibly induced by a subcluster merger.

1980–: *Extended AGB stars in Local Group spheroidal systems.* As noted in Sec. 3, stars on the "extended" AGB can be used as tracers of intermediate age (1–10 Gyr) populations. AGB stars of older ($>$ 12 Gyr), populations can rise $\lesssim 1$ mag above the helium flash, but only more massive (and therefore younger) stars can survive to higher luminosities (Aaronson & Mould 1985, Mould 1992). During the 1980's, Aaronson and Mould carried out an extensive program to detect luminous, cool AGB stars in spheroidal populations throughout the Local Group, with great success. They found that, with only four exceptions, all of the dwarf spheroidal galaxies studied contained intermediate age populations with ages $\sim$2–10 Gyr. It was possible to confirm the age estimates by direct observations of the main sequence turnoffs in several cases. The most thoroughly studied is the Carina dwarf (Mighell 1990), in which about 80% of the stars are only $\sim$ 7.5 Gyr old.

Since the dwarf spheroidals had long been considered prototypical examples of "pure Pop II" galaxies, these results were unsettling for the standard scenario. However, it could be argued that such small systems were easily disturbed by interactions and gas exchange with their larger neighbors. The same is true of the larger dwarf systems NGC 185 and 205, which contain both very young blue stars and intermediate age components (Davidge 1992, Lee et al. 1993) and of the LMC, where there is evidence of a major star formation episode beginning only 3 Gyr ago (Butcher 1977, van den Bergh 1991). The key test of the classical interpretation was therefore to obtain IR imaging of the more massive systems M31, M32, and M33 which would rival Baade's original probe of these populations.

All three objects have now been found to contain intermediate age spheroidal populations. Recent H-band imaging of the faint bulge of M33 has identified luminous AGB stars corresponding to ages $\lesssim 1$ Gyr (Minniti et al. 1993). In the bulge of M31, Rich & Mould (1991) detected AGB stars up to 2 mags brighter than the He flash using J,K imaging. DePoy et al. (1993) suggested that image blending might bias the luminosity function in M31, but recent HST imaging (Rich & Mighell 1993) appears to remove this objection. The AGB stars in M31's bulge probably have ages $\lesssim 8$–10 Gyr.

In M32, four infrared imaging studies have found luminous AGB stars with probable ages of $\sim 4 \pm 3$ Gyr (Freedman 1989, 1992; Davidge & Nieto 1992; Elston & Silva 1992). The IR color-magnitude diagram from the latter work is shown in Fig. 4 and reveals a strong population of stars brighter and cooler than those found in the bulge of the Milky Way. Baade missed these luminous stars in M31 and M32 because they were too cool to detect in his B&R bands; they are revealed only with infrared imaging. Freedman (1992) discusses the various alternative interpretations of these objects—e.g. as merged binaries or SMR stars (Renzini 1993)—but concludes that an intermediate age population is most plausible.

5. The Bulge of the Milky Way

The bulge of our Galaxy is the nearest spheroidal system. In an ideal world, it would also be the best to study. Instead, it is afflicted with several unique problems: it lies in the Galactic plane and therefore suffers large and variable extinction; there is bad contamination by foreground field stars; and it is significantly extended in depth, probably with a bar-like shape. All three effects make inferences regarding its stellar population troublesome, and it may not be surprising that interpretation of the Galactic bulge has been particularly controversial. There are two main schools of thought: evidence supporting the classical interpretation is reviewed by Frogel (1988) while that supporting a more complex and extended evolutionary history is reviewed by Rich (1992). The most recent debates over these scenarios are in Habing & Dejonghe (1993). The strongest evidence for the revisionist interpretation is the luminous AGB star population in the bulge, which includes many long-period Mira variables, with probable ages $\lesssim$ 4 Gyr.

6. Conclusion

There is strong and growing evidence that many spheroidal systems experienced prolonged, episodic star formation histories, probably greatly influenced by their environments. Stars are still the best tracers of the evolution of galaxies, the best "clocks", as Renzini characterizes them, so it is important that stellar population studies have now validated the other less direct pointers to this picture which were anticipated by studies of AGN's, starburst galaxies, and high redshift galaxies.

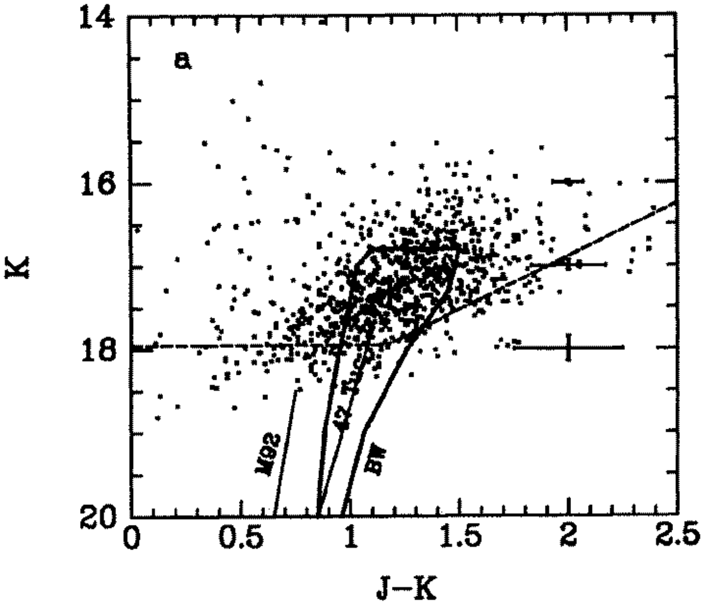

FIGURE 4: An infrared color-magnitude diagram for M32 from Elston & Silva (1992). The giant branches of two globular clusters are shown, as is the region occupied in the bulge of our Galaxy ("BW"). The extended AGB stars in M32 are up to 1-2 mags brighter and appear to have ages $\sim$ 4 Gyr.

This revised interpretation of spheroidal populations is now favored by all of the varieties of evidence originally marshaled in support of the "standard scenario". It is not surprising that increased observational sensitivity has changed our outlook. What is surprising is how long it took—especially given such telltale clues as the young populations in M32's sibling, NGC 205, or Morgan's spectra of the bulge of M31.

This newer evolutionary picture predicts that most galaxies are mixtures of disparate subsystems. It suggests that the term "galaxy formation" is obsolete, or at least inaccurate, and that it may be better to speak of galaxy "assembly" instead. A good analogue might be the way in which mountain ranges are assembled from both fresh and ancient materials in plate tectonic geology.

What are the implications for the nature of the nucleus of our Galaxy, which is the principal subject of this conference? I am impressed by the fact that the Local Group as a whole appears to have experienced a very turbulent history during the past 12 Gyr, with major episodes of star formation traceable in all but a handful of objects, regardless of whether they are spheroidal or disk populations. It seems unlikely that our Galactic bulge could have avoided the melee, and the direct evidence for intermediate age populations there is growing. Although much of the radio, infrared, and high-energy activity in the nucleus of the Milky Way is related to star formation of very recent vintage, I think it should be viewed as only a near-term example of a long history of activity, probably often induced by external agents.

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