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THE BIRTH OF STARS IN GALAXIES

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THE BIRTH OF STARS IN GALAXIES

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Abstract. Our empirical understanding of galaxy formation and evolution rests on a combination of observations of the stellar populations in the nearest galaxies, direct observations of galaxies at cosmological lookback times, and integrated measurements of galaxies at the present epoch. This review describes several examples of recent observations which offer important clues about the history of star formation in galaxies.

1. Introduction

The conference organizers have asked me to combine a talk on the evolution of nearby galaxies with a review of conference highlights relating to galaxy evolution in general (Jill Bechtold will review quasars and the intergalactic medium). Rather than attempt a comprehensive conference review, I will discuss what recent observations of nearby galaxies reveal about the history of star formation in galaxies, and integrate that with some of the results presented at this meeting, most of them pertaining to more distant galaxies.

Several approaches can be used to study the evolutionary histories of galaxies. One is to study the resolved stellar populations in our own Galaxy and Local Group, where in principle detailed fossil records of galaxy formation and evolution can be reconstructed. The stellar age and abundance distributions in the Galactic neighborhood offer the ultimate tests of galaxy formation and evolution theories. Since this area was discussed only briefly this week, I will discuss a few of the most interesting recent results here.

Another direct approach is to observe galaxies at successive cosmological lookback times, and reconstruct the history of the stellar birthrate directly. This exciting field has been discussed extensively by several speakers, and was the sole subject of the panel discussion. Consequently I will limit my own discussion to summarizing the main conclusions, and drawing parallels to what we see in nearby galaxies.

A third approach is to measure the star formation properties, stellar populations, and star formation histories of nearby galaxies ($z \leq 0.1$). This approach is less direct than the others, since we only observe galaxies at the present epoch, and we obtain only rudimentary information on the birthrate history of any single object. However these observations provide several important pieces of the puzzle. They enable us to delineate the evolutionary nature of the Hubble sequence, study the systematic effects of galactic environment on evolution, and identify local analogs to primeval galaxies of different types. Perhaps most important, these data provide information on the physical relationships between the stellar birthrate and the physical properties of galaxies and their interstellar media. Such observations offer

the hope, at least over the long term, of understanding not only how galaxies evolve, but *why* they evolve as they do, in the context of an empirically based, physically deterministic model of galactic evolution.

My approach in this review will be to present a sampling of recent results from each of these subfields, in Sections 3–5. My objective is not to provide a detailed review of any individual area, but rather to illustrate by example the broad range of observational constraints which are available to us. The results will also illustrate how these nearly independent approaches often point to similar pictures of galaxy formation and evolution.

2. Theoretical Background and Expectations

At this school we were blessed with a comprehensive review of current theoretical ideas on galaxy formation and evolution, in talks by Mitch Begelman, Ed Bertschinger, Dick Bond, Gustavo Bruzual, Marc Davis, Gus Evrard, Lars Hernquist, and Rosemary Wyse. Before proceeding to the observations of star formation in galaxies, it is useful to review what the star formation rates and histories of galaxies are predicted to be in the different galaxy formation/evolution scenarios.

As recently as a few years ago, many searches for primeval galaxies and starburst galaxies were predicated on a much simpler collapse model for galaxy formation. In this model, similar to the 'ELS' scenario outlined in the famous paper by Eggen, Lynden-Bell, and Sandage (1962), the formation of galactic spheroids was a rapid process, with the bulk of the star formation occurring on a dynamical time scale (order 10^8 yr). From a theoretical point of view the model offers an elegant simplicity, as all of the principal steps involved in galaxy formation— the accretion of mass, the accretion of gas, star formation, metal enrichment— occur almost simultaneously, over the brief free-fall collapse time scale. From an observer's point of view, the collapse model generates glorious protogalaxies. If we consider, as an example, an M^* proto-spheroid with a gaseous mass of $2 \times 10^{11} M_\odot$, a characteristic star formation rate (SFR) during the formation phase would be of order:

$$SFR \sim \frac{2 \times 10^{11}\ M_\odot}{2 \times 10^8\ yr} \sim 1000\ M_\odot\ yr^{-1}$$

It is easy to demonstrate, using models of the type discussed by Bruzual, that such a protogalaxy would have luminosities of $L_{bol} \sim 10^{13} L_\odot$, $M_B \sim -25$, and $L(H\alpha) \sim 10^{43}\ erg\ s^{-1}$. The possibility of such protogalactic mega-starbursts motivated an entire generation of searches for primeval galaxies in the 1970's and early 1980's. The failure to detect them implies either that galaxies do not form so rapidly, or that the collapses occur beyond the limiting redshifts of current surveys.

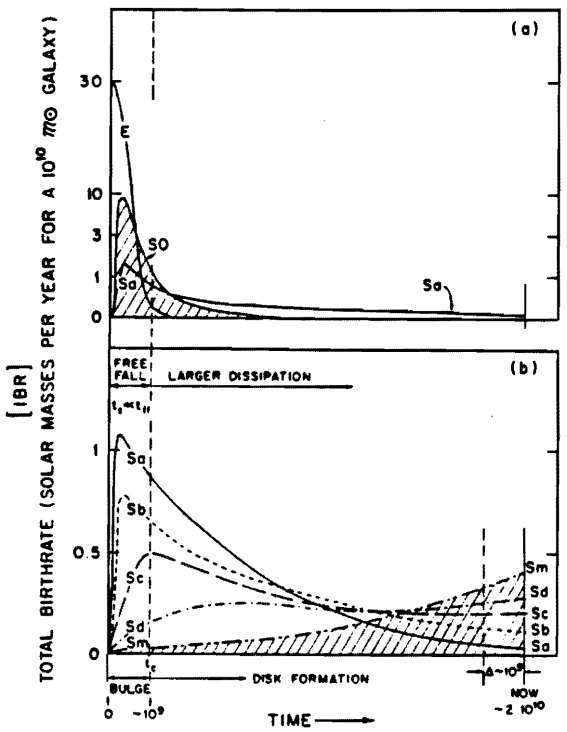

Fig. 1. Schematic depiction of the evolution of the stellar birthrate, from Sandage (1986). Note the contrast in time scales and star formation rates for the spheroid and disk components, and the changes in star formation history with Hubble type.

A more detailed depiction of the star formation histories predicted in this picture, including later disk star formation and the variation with Hubble type, is shown in Figure 1, taken from Sandage (1986). On an absolute scale, one expects peak SFRs of order 100–1000 $M_\odot\ yr^{-1}$ in the largest protospheroids, and mean rates of order 1–10 $M_\odot\ yr^{-1}$ in spiral disks. (Throughout this discussion I will reference the SFRs to a roughly L* galaxy; for lower mass galaxies the SFRs will scale down proportionally.) In the simplest form of this scenario, at least, the transition between a rapidly collapsing spheroid and a steadily evolving disk is quite distinct, and distinguishing between these different stages of galactic evolution at high redshift should be relatively straightforward.

This collapse picture contrasts markedly, however, with what is expected in the hiearchical "bottom-up" picture of galaxy formation presented at this conference. In that scenario galaxy formation consists of several physically and temporally distinct steps: First the protogalactic mass fragments, mostly dark matter, must condense; then the gas must cool and condense further;

finally stars can form, either from the collapse of clouds within individual fragments, or in mergers of fragments. These complications have important consequences for observing star formation in primeval galaxies. In many cases the major epoch of star formation may be delayed to late cosmological times and consequently lower redshifts. The formation of galactic spheroids, rather than involving a single starburst of order 100–1000 $M_\odot\ yr^{-1}$, may consist of several smaller collapse and merger events, occuring over a span of billions of years. In such cases the peak SFR associated with spheroid formation will be of order the fragment mass (in stars) divided by its formation time scale, perhaps of order:

$$SFR_{peak} \sim \frac{10^9 - 10^{10}\ M_\odot}{10^8 - 10^9\ yr} \sim 10 - 100\ M_\odot\ yr^{-1}$$

This may be barely distinguishable with the steady-state SFRs in disks (order several $M_\odot\ yr^{-1}$), especially when extrapolated back to early lookback times. For example, in the recent numerical simulations of galaxy formation by Katz (1992), a typical spiral does not reach peak luminosity until the disk forms, at $z \sim 2$. For more detailed discussions of the observable properties of protogalaxies in this picture see Baron and White (1988) and Katz (1992).

The point of this admittedly sketchy comparison is to demonstrate the wide range of star formation properties of galaxies expected in these different theoretical scenarios. I have deliberately chosen two extreme versions of the collapse and merger pictures to illustrate the range of possibilities; the truth may well lie somewhere between these extremes. As observers we are interested in testing to what extent these scenarios apply to our universe, and isolating examples or analogs to the various galaxy formation and evolution stages.

3. Resolved Stellar Populations in the Local Group ($z \leq 0.001$)

As was emphasized by Rosemary Wyse in her review, observations of the ages, kinematics, and abundances of individual stars in the Milky Way (or other galaxies) should allow us to construct the most complete picture possible for the formation and evolution of these galaxies. Several recent instrumental developments, most significantly the availability of CCD detectors, multi-object spectrographs, and sophisticated PSF-fitting reduction software have led to major advances in our ability to probe the fossil record in the Galaxy and other Local Group members. Here I mention just a sampling of recent results, to illustrate the variety of observations which are being used, and to emphasize the fundamental character of the questions that are being raised.

3.1. The Galaxy

Probably the most exciting (and controversial) work in the last few years concerns the distribution of stellar ages in the Galactic bulge and halo. State-of-the-art CCD photometry now makes it possible to obtain color-magnitude diagrams for globular clusters with internal precision of 0.01 mag or better, sufficient in principle to measure *relative* cluster ages with an accuracy of $\sim$1 Gyr. This makes it possible to test whether the Galactic globular clusters form a coeval system, and if not to measure the time scale for the formation of the spheroid.

Several recent investigations show evidence for significant age differences among the globular clusters. The most convincing results are based on measurements of pairs of clusters with nearly identical compositions but strikingly different horizontal branch morphologies— examples of the famous 'second parameter problem.' Figure 2 shows an example from one such pair, NGC 288 and NGC 362, from Green and Norris (1990). The striking difference near the main sequence turnoff (both clusters are fitted to the same ridge line in Fig. 2) corresponds to an age difference of 2–3 Gyr. Age differences of 2–5 Gyr are seen in other cluster pairs (e.g., Buonanno et al. 1990). Relative ages can also be measured from the turnoff vs red giant branch color difference, or by fitting the horizontal branch luminosities (e.g., VandenBerg et al. 1990, Chaboyer et al. 1992). These yield age ranges of up to 5 Gyr, though some subsamples appear to be coeval. There are some reports of systematic correlations of age with metallicity and galactocentric radius (e.g., Chaboyer et al. 1992).

Taken at face value these results suggest that there is a young tail to the globular cluster age distribution, extending to 3–5 Gyr younger than the oldest clusters, or perhaps even a dispersion in the formation time of the entire cluster system. This would be consistent with the extended formation picture for the outer halo by Searle and Zinn (1978). As emphasized by Bolte (1992), however, there are several important caveats which must be addressed. Most recent studies have concentrated on the most extreme examples of second parameter effect clusters, and these may not be representative of the entire cluster ensemble. Age comparisons for clusters with widely differing compositions are subject to errors from variations in other parameters or uncertainties in the theoretical models. It may be premature to conclude from the existing data that "the spheriod formed over a period of several Gyr," but it seems likely that observations over the next several years will resolve this question once and for all. For a more detailed (and competent) review of this field, I refer the reader to Bolte (1992).

Chemical nucleosynthesis offers an entirely independent constraint on the formation time scales for the Galaxy. As an illustration, Figure 3 shows the differential abundance distributions of oxygen and iron in nearby field stars,

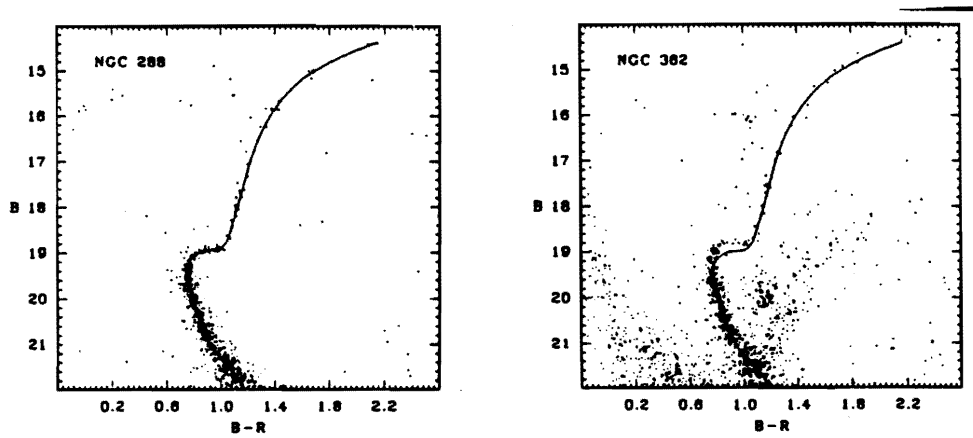

Fig. 2. Color-magnitude diagrams for the Galactic globular clusters NGC 288 and NGC 362. The empirical fit to the NGC 288 ridge line, shifted slightly in color and magnitude to account for the differences in reddening and distance to the clusters, is superimposed on both diagrams. The diagrams also illustrate the precision which can be obtained with current CCD photometry and PSF fitting techniques. Figure taken from Green and Norris (1990).

from a review by Wheeler et al. (1989). If O and Fe were formed together in the Galaxy we would expect the [Fe/O] ratio to be identically zero (i.e., the solar value) everywhere. Instead Fig. 3 shows a distinct transition near [O/H] = -0.5 (or [Fe/H] = -1). Below that level iron is consistently underabundant with respect to the solar Fe/O ratio, but above [O/H] = -0.5, [Fe/O] increases smoothly toward the solar value. The same trend is seen when the abundances of the "alpha" addition elements Mg, Si, Ca, and Ti are compared to iron. Similar abundance patterns are also seen in the Galactic globular cluster system (Minniti et al. 1993).

Oxygen and the alpha elements are thought to arise predominantly from Type II supernovae, with massive and shortlived progenitors, while iron is preferentially produced in older Type Ia supernovae. Consequently the transition in [Fe/O] vs [O/H] may represent the delayed Fe enrichment of the Galaxy from the Type Ia supernovae, at [Fe/H] $\simeq$-1. If this interpretation is correct, then the lifetimes of the supernova progenitors provide an independent clock for the enrichment time scale for the metal-poor halo. This time is sensitive to the nature and masses of the supernova progenitors, as well as the nucleosynthetic yields of the different supernova types. Analyses by Wyse and Gilmore (1988) and Smecker-Hane and Wyse (this meeting) suggest a time scale of $\leq$1 Gyr. This could imply that the bulk of the metal-poor component of the spheroid formed within a few dynamical time scales, or it may be tracing the enrichment times within individual protogalactic

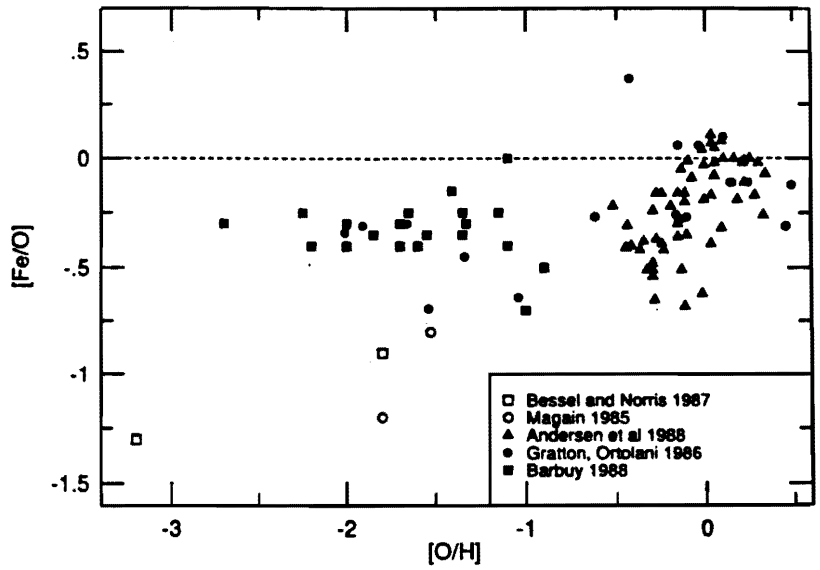

Fig. 3. Comparison of oxygen and iron abundances in field stars, with oxygen taken as the independent metallicity indicator. Figure is taken from Wheeler, Sneden, and Truran (1989).

fragments. Regardless of the final interpretation, the example serves to illustrate how chemical abundance constraints can provide crucial clues to galactic formation and evolution.

Observations of several stellar age tracers in the Galactic disk provide a fairly self-consistent history. The most detailed histories come from isochrone fitting of F dwarfs (Twarog 1980, Carlberg et al. 1985) and from chromospheric dating of K giants (Barry 1988). Both data sets indicate that the stellar birthrate in the disk, when averaged over 1 Gyr time scales, has been nearly constant over its age, probably varying by no more than a factor of 2–3 from its current value. Other less direct age tracers, including the white dwarf luminosity function, lithium dating, and the continuity of the local IMF near the main sequence turnoff also indicate a relatively constant disk birthrate. Important questions which remain unresolved include the constancy of the disk birthrate over time scales shorter than a Gyr, and the age of the oldest disk stars relative to the spheroid. See Scalo (1986) and Kennicutt (1992c) for complete discussions of these observations.

3.2. Other Local Group Galaxies

It is now possible to extend the same types of stellar population studies to the other galaxies in the Local Group. To date the most complete studies

have been made of the Magellanic Clouds and several dwarf spheroidal galaxies. These observations reveal star formation histories which are strikingly different from either the spheroid or disk of our own Galaxy.

The LMC has been the object of several investigations, as summarized in Stryker (1984). Photometry of field stars in the main body of the LMC indicate that most of the stars lie in the age range 0–5 Gyr. The stars in the outer halo of the LMC appear to have a much broader distribution in age, with a peak age of several Gyr, but with both older and younger stars present as well. The LMC bar is a relatively young structure; star formation was initiated there in the past 3 Gyr, and continues to the present (Hardy et al. 1984). Taken together, these studies indicate that star formation in the LMC commenced at times which are comparable (but not necessarily identical) to the formation of the Pop II component of the Galaxy, but the subsequent star formation was quite different from the Galaxy, peaking only in the past few Gyr.

The LMC contains a population of massive star clusters ranging in age from a few million years to over 12 Gyr, and these can be used to construct an independent picture of the star formation and chemical enrichment history of the LMC. Figure 4 shows the age and abundance distributions for the populous clusters, as compiled by Da Costa (1991). Both distributions are remarkably bimodal. There is a distinct population of old, metal-poor globular clusters which resemble in most respects Galactic globulars, and a second population of clusters with ages less than about 3 Gyr, and abundances at least an order of magnitude higher than the old clusters. Only one cluster in Fig. 4 (and no more than a handful of other candidates in the LMC) lie in the gap between 3 and $\sim$15 Gyr.

The striking bimodality in Fig. 4 could reflect a peculiarity that is unique to the LMC population, for example a collision with the Galaxy 3 Gyr ago, which disrupted all but the most massive halo clusters. It is interesting that the SMC clusters do not show such a strong bimodality in age or composition (Da Costa 1991). However the correspondence of the LMC cluster age distribution with the results of the field star studies suggests that the 3–15 Gyr age gap is at least partly real. Whatever the interpretation, it is clear that the LMC experienced a star formation history that was different from any of the components of the Milky Way.

The dwarf spheroidal galaxies in the Local Group tell yet a different story, as reviewed recently by Da Costa (1992). Studies of the Sculptor, Fornax, Ursa Minor, Carina, and Andromeda II galaxies show evidence (excepting perhaps And II) for a composite stellar population, with both a very old ($\tau \geq$ 13 Gyr) metal-poor component, and an intermediate age (roughly 5–10 Gyr) population. In the best studied system to date, Carina, the intermediate age component comprises over 80% of the entire stellar population (Mighell 1990). Yet none of these galaxies is forming stars today, and none appears to

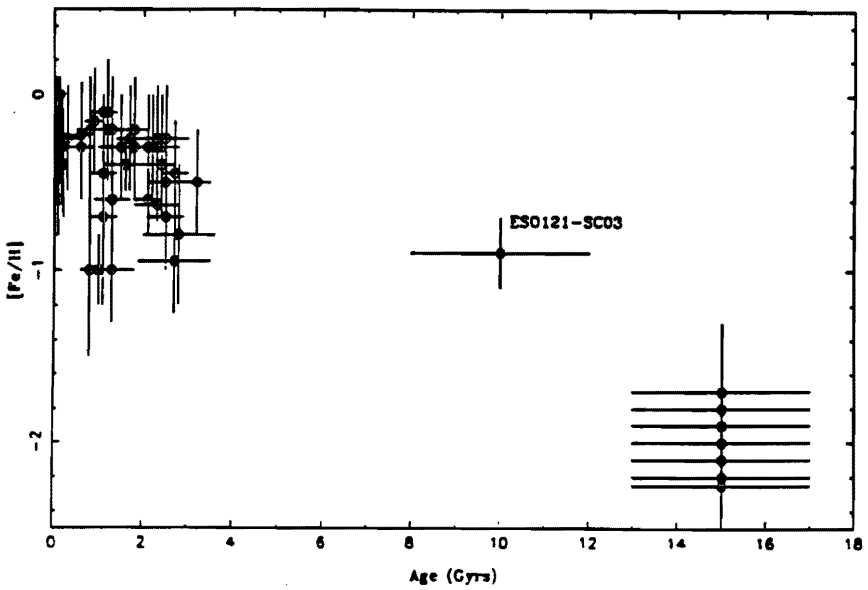

Fig. 4. Age-metallicity relation for populous clusters in the LMC. Sample is restricted to clusters with ages determined from main sequence turnoff photometry. The ages of the oldest clusters have been arbitrarily set to a constant value of 15±2 Gyr. Figure reproduced from a review by Da Costa (1991).

possess enough interstellar gas to form stars anyway. Again we see evidence for a dramatic change in the stellar birthrate over the past ~5 Gyr.

With such a variation between the star formation histories of the individual members of the Local Group— it is probably a fair statement that no two systems studied to date have the same history— one must be cautious about drawing general inferences, but some important trends are apparent. While the schematic evolutionary picture illustrated in Fig. 1 appears to provide a realistic description of the history of our own Galaxy (and presumably M31 and M33), it bears little resemblence to the evolution of the lower mass members of the Local Group. Galaxy mass appears to be at least as important a variable as Hubble type in dictating evolution. This is nowhere more apparent than in the dwarf spheroidal galaxies. These systems, formerly classified as 'dwarf ellipticals,' share more in common with dwarf irregulars than with giant elliptical galaxies. In addition to having distinct histories on long time scales, there is indirect evidence for starbursts being a more important factor in the evolution of the low-mass systems.

It is tempting to associate the rapid evolution of the Local Group dwarfs over the past 5 Gyr with the evolution that is seen in faint galaxy counts and redshift surveys, as has been suggested recently by van den Bergh (1992). The high space densities of the faint blue galaxies are difficult to associate

with any present-day population (e.g., Cowie et al. 1992), but the parallels between the fossil histories revealed in many the Local Group galaxies and what is seen at cosmological lookback times of a few Gyr are unlikely to be entirely coincidental. As discussed later, present-day Magellanic irregulars are spectroscopically indistinguishable from the z=0.4 blue galaxies, and it seems likely that many nearby low-mass galaxies comprise the fossil remnants of *part* of this extraordinary blue galaxy population. Applying modern observing techniques to galaxies like the Magellanic Clouds (much of the work cited above was based on photographic plates!) could clarify the relationship, if any, between these populations.

4. Distant Galaxies and Clusters ($z \geq 0.3$)

The current excitement in this field was reflected at this meeting, with talks by Ellis, Heckman, Lilly, and Spinrad at Monday's panel discussion, reviews of distant clusters by Donahue and Mushotzsky, and roughly 20 posters devoted to studies of distant galaxies. I will restrict my discussion to those results which are most relevant to understanding the star formation histories of galaxies. For proper reviews by the leading players in this field, see those by Cowie and Lilly, Dressler and Gunn, and Ellis in Kron (1990).

Much of the discussion at this conference has focussed on the ongoing multi-object spectroscopic surveys of faint (B=20–25) galaxies, and the remarkable intermediate-redshift "blue dwarf" population revealed by these surveys. Figure 5 shows a dated but nevertheless instructive example, the redshift distribution at B=20–22.5 from Colless et al. (1990). See Ellis' paper in this volume and Colless et al. (1992) for the most recent work by this group.

Figure 5 is dominated by the enigmatic blue dwarf population, but from the perspective of understanding star formation histories, what we *don't* see in Fig. 5 is nearly as significant as what we do see. For example, we do not see a high redshift tail of galaxies extending beyond the "no evolution model" fit. If most massive (L^* and brighter) galaxies were significantly brighter at z=0.5–1, their apparent magnitudes would fall into the B=20–22.5 window, and they would show up in Fig. 5. Their absence rules out rapid luminosity evolution of massive galaxies over the past several Gyr (Colless et al. 1992). Nor do we see, among the hundreds of galaxies that have been detected in these field surveys to date, even a single example of a high-redshift mega-starburst galaxy, of the sort envisioned in the rapid collapse galaxy formation scenarios. Given the large volume over which a 1000 $M_\odot\ yr^{-1}$ starburst should be visible, this result suggests that such starbursts are either very rare at $z \leq 3$, or they are highly obscurred in the rest frame blue and UV. At the other extreme, the absence of very low-redshift galaxies at B=22 and fainter constrains the nature and subsequent

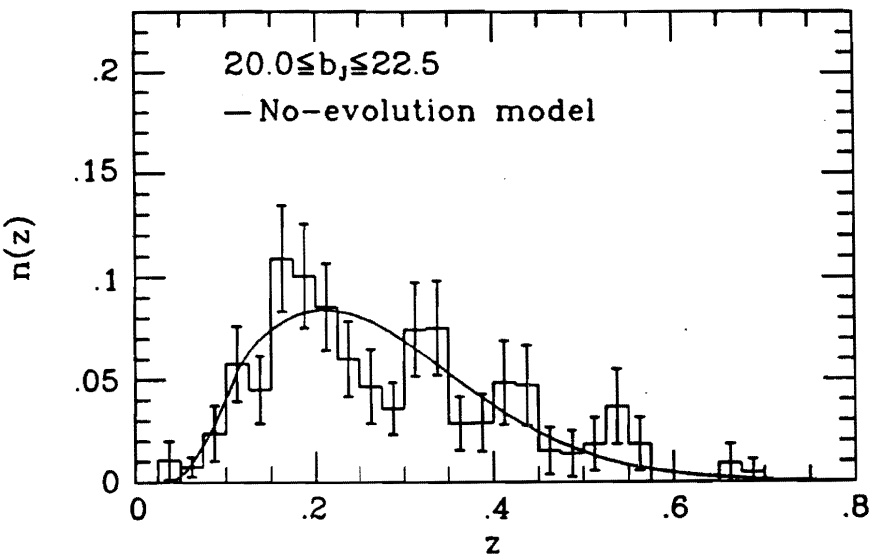

Fig. 5. Redshift distribution of galaxies in a spectroscopically complete sample at B=20–22.5, Colless et al. (1990).

evolution of the z=0.3–.4 population.

The galaxies which *do* appear in Fig. 5 are comprised of the infamous blue dwarfs, relatively unevolved normal galaxies, AGNe, and some spectroscopically peculiar objects, including flat-spectrum galaxies and post-burst 'E+A' galaxies. The blue galaxies are remarkable in terms of both their space density, roughly 2–5 times the unevolving density for B≃21–24, and their photometric properties, which appear to be roughly comparable to nearby Markarian galaxies. Speculation about the nature of the faint blue galaxies appeared in several talks and posters during the meeting. Producing objects which are so bright, blue, and numerous as recently as z=0.3–0.5, yet evolve to obscurity by z=0–0.1, without leaving much of a trace in light or heavy elements, is utterly problematic. The list of possibilities includes mergers (e.g., Guiderdoni and Rocca-Volmerange 1990, Broadhurst et al. 1992), bursting dwarf galaxies (e.g., Babul and Rees 1992), or an entirely new population of galaxies which evaporate at very recent epochs (e.g., Cowie et al. 1991, 1992). Adopting an open cosmology (or worse) helps reduce the space densities at high redshift. I refer the reader to the reviews cited above for more detailed discussions. As emphasized by Cowie et al. (1992) these objects may well dominate the global star formation, light, and metal production in the universe, so understanding their relationship to present-day galaxies is a crucial prerequisite to understanding galaxy formation and evolution in a

broader context.

In many of the scenarios cited above, the faint blue galaxies have little or no evolutionary connection to today's dominant population of giant galaxies. If that proves to be the case, then how do we penetrate this clutter of low-redshift dwarfs to study galaxies like our own at large lookback times? Several approaches were discussed during the meeting. Infrared-selected field surveys (e.g., Elston et al. 1991, Glazebrook 1991, Cowie et al. 1992) are effective probes for red galaxies out to at least $z=1$, though at faint magnitudes even the K counts appear to become dominated by the blue dwarf clutter. Studying distant galaxy clusters is another powerful approach (e.g., Dressler and Gunn 1990), at least for understanding the evolution of present-day cluster members. Mg II absorber selected samples, as reviewed here by Steidel, appear to offer a powerful probe of L^* field spirals. Optical and infrared identification of distant radio source fields, as discussed here by Spinrad, provide a virtually unique probe at very high redshifts. Gravitationally lensed galaxies may provide another window to $z \gg 1$.

The enigma presented by the faint blue dwarf population illustrates what is perhaps the singular limitation of distant galaxy surveys for unraveling galaxy evolution. In principle there should be nothing more direct than surveying the universe at successive redshifts, and tracking the evolution of galaxy populations with increasing lookback time. However this approach relies on our being able to connect an individual galaxy at each redshift (or photometric class of galaxies) to its evolutionary counterpart at other epochs. This is proving to be very difficult, even over the modest range of lookback time between $z=0$–0.3. The availability of expanded spectroscopic data sets, combined with high-resolution images from HST may eventually resolve this particular difficulty, but we should not be surprised to encounter similar ambiguities at higher redshift. The long-term solution may require integrating the statistical information on high-redshift galaxy populations with the more detailed data for nearby galaxies, along with theoretical constraints on photometric and chemical evolution.

5. Star Formation Properties of Nearby Galaxies ($z < 0.1$)

The development of observational techniques for measuring star formation rates (SFRs) in galaxies has made it possible to characterize the evolutionary nature of the Hubble sequence, and to begin probing the physical and environmental parameters which regulate the SFR. This subject was reviewed at length at the Second Teton Conference (Kennicutt 1990), and I will not repeat that discussion here. Instead I discuss three specific areas which are especially relevant to galactic evolution in a broader context, the statistics of global star formation rates and histories in nearby galaxies, the physical nature of the star formation law, and local analogs to primeval galaxies.

5.1. Global Star Formation Properties

As noted earlier, several empirical techniques for measuring SFRs in galaxies have been developed over the past decade. These include calibrations of the UV continuum fluxes (1500–2500 Å), far-infrared fluxes (20–300 μm), Balmer emission-line fluxes, and population synthesis modelling of the UV and visible colors. See Kennicutt (1990) for a details and references to the relevant literature. The most complete surveys to date come from Hα emission line fluxes (e.g., Kennicutt 1983, Romanishin 1990, Gavazzi et al. 1991), and balloon or satellite-based UV fluxes (e.g., Donas et al. 1987, Buat 1992). Data are currently available for some 300–400 galaxies, spanning types S0 to Irr, and luminosities of M_B = -12 to -22. Intercomparison of these studies shows that the SFRs for galaxies in common reproduce to ±25% when a common set of extinction corrections and IMFs are adopted. Variations in extinction and the IMF remain as the largest sources of systematic error in these global SFR determinations.

The publication of full optical emission-line spectra for nearby galaxies has made it possible to calibrate the [OII]λ3727 emission line as a quantitative star formation tracer (Gallagher et al. 1989, Kennicutt 1992a). Variations in excitation and reddening make [OII] a less precise SFR tracer than Hα, but its flux or equivalent width can provide a useful substitute, at least for comparisons of large samples. This is especially valuable for high-redshift galaxies, where Hα is unobservable. Applying [OII] in this way, either alone or in conjunction with blue–UV continuum fluxes, makes it possible to extent the techniques developed for nearby galaxies to $z \geq 1$.

The total SFR, normalized to unit luminosity or area, is a very strong function of Hubble type. For a galaxy of constant blue luminosity ($M_B = -21$), the total SFRs integrated over all stellar masses range from about 0.1–1 $M_\odot\ yr^{-1}$ in S0/a-Sa galaxies to an average of about 10 $M_\odot\ yr^{-1}$ in Sc-Irr galaxies (Kennicutt 1983, Caldwell et al. 1991). Overall, the total SFRs can range from below 0.001 $M_\odot\ yr^-1$ in extreme dwarf galaxies to over 100 $M_\odot\ yr^{-1}$ in luminous starburst galaxies. Spatially resolved Hα observations show that this trend in total SFR is due to both an increase in the number of star forming regions per unit area, and an increase in the characteristic masses and luminosities of the individual regions (Kennicutt et al. 1989). Note that the total SFR *per galaxy* is not necessarily a monotonic function of type. As pointed out by Devereux and Young (1991), the mean FIR luminosity (and probably the total SFR) per galaxy peaks at intermediate Hubble types, decreasing for both very early (i.e., S0) and very late (Sd–Irr) galaxies. The distinction appears to be mainly due to the systematic change in mean galaxy mass along the Hubble sequence, but other factors, such as a systematic change in extinction or IMF with galaxy type, cannot be entirely ruled out.

The changes in current SFRs along the Hubble sequence imply similar changes in star formation histories. Kennicutt (1983), Gallagher et al. (1984), Sandage (1986), and Larson (1991) have investigated the systematic behavior of the birthrate history for spirals and irregulars, where reliable global SFRs can be obtained. A useful parametrization is the ratio of the current SFR to the average past SFR, often denoted as the birthrate parameter b. This parameter is a strong function of type, increasing from ≤ 0.05 in Sa–Sab galaxies to ~ 1 in Sc galaxies. Note that these results are consistent with the measurements of the Galactic disk (Section 3.1), where $b \sim 1$ as well. Irregular galaxies are characterized by $b \sim 1$ on average (Gallagher et al. 1984), but with a considerable dispersion among individual objects. In many Sc and Irr galaxies $b >> 1$, i.e., their current SFRs are much higher than in the past. Since these high SFRs cannot be sustained indefinitely, these galaxies must be experiencing large bursts of star formation.

The observed trends in birthrate parameter with type form the basis of the evolutionary picture of the Hubble sequence first outlined by Roberts (1963), and which is illustrated schematically in Fig. 1. While this general trend has been quite firmly established, several other important questions remain unanswered. These include the radial variation, if any, in the star formation history, the temporal variation of the SFR in early-type disks, and the role of starbursts in the evolution of galaxies of different masses. For elliptical galaxies and bulges, which have not been discussed at all here, the most fundamental questions about the duration and variation in the star formation histories remain to be addressed (see Bruzual's review in this volume).

5.2. The Star Formation Law

As Judy Young emphasized in her review, one of the most fundamental contributions that these kinds of observations can offer is a better understanding of the physical mechanisms which regulate the global stellar birthrate in a galaxy. There has been considerable progress in this area in the past few years, which was reviewed in detail in Kennicutt (1990). Here I summarize and update that discussion.

Gas content must be a fundamental parameter which determines the SFR, and since the seminal paper by Schmidt (1959) several dozen papers have been written which attempt to parametrize the SFR as a power-law function of the gas density. Recent work indicates that the form of the SFR vs gas density law is more complicated than a single Schmidt power law, and its form depends on the physical scale one considers, and the dynamical properties of the gas, independent of its absolute density. This should not be surprising, because the physical mechanisms which regulate the gas/star conversion rate on the scale, say, of individual molecular clouds are likely

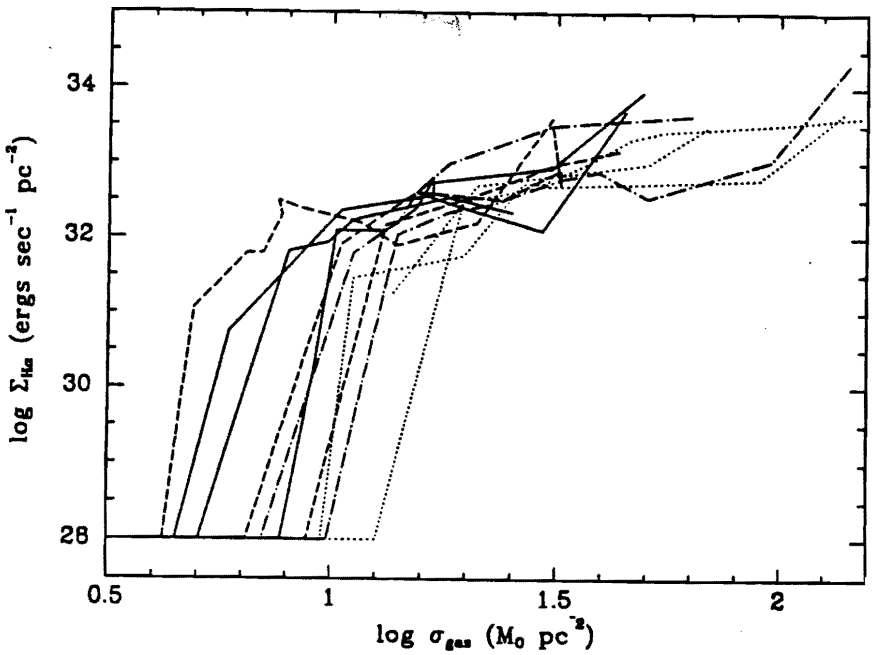

Fig. 6. Spatially resolved relations between Hα surface brightness and gas surface density for selected galaxies. Lowest values at bottom of plot represent zero Hα emission.

to be quite different from those which regulate the formation of interstellar clouds on galactic scales.

The form of the star formation law on kiloparsec scales is illustrated in Fig. 6. The plots show the relationships between Hα surface brightness (assumed to scale with the SFR) and total gas density (atomic and molecular) within several spirals in the Virgo cluster, from Kennicutt and Martin (in preparation). Similar relations, covering both field and Virgo galaxies, can be found in Kennicutt (1989). These observations show that the star formation law possesses three distinct physical regimes. At high gas densities the SFR follows a Schmidt law, but below a critical threshold density the relation becomes much steeper, and the SFR drops to very low values at densities well below the threshold. The thresholds are often quite sharp, as illustrated in Fig. 6. The thresholds are observed over the full range of galaxy types (e.g., Skillman 1986, Guiderdoni 1987, Kennicutt 1989, Taylor et al. 1992). They occur at column densities of order $10^{21} H\ cm^{-2}$ or 1 $M_\odot\ pc^{-2}$, but the variation from object to object is real (Kennicutt 1989).

The observed thresholds appears to be physically associated with the gravitational stability of the gas. Application of the Toomre (1964) stability

criterion for an isothermal gas disk reproduces the threshold densities and radii in spiral with excellent accuracy (Kennicutt 1989). The observation that the gas lies near the stability limit at all radii ($Q \sim 1$) is also consistent with the gravitational model (Quirk 1972, Kennicutt 1989, Zasov and Simikov 1989). The criterion outlined in Kennicutt (1989) has been applied subsequently to several other types of objects, including S0 and Sa disks, low surface brightness galaxies, ring galaxies, and spiral arms within galaxies. I refer the reader to papers at this meeting by Hogg and Roberts, Struck-Marcell, Taylor et al., van der Hulst, and van Gorkom for more details. The physical connection between the stability criterion, which is relevant only to the large-scale gas component, and the star formation, which ultimately is a local phenomenon, is not completely clear. I suspect that the stability criterion actually regulates the formation of gravitationally bound clouds (either atomic or molecular), but it is conceivable that we are actually seeing a atomic/molecular threshold in some cases, which should occur at column densities of the same order as the Q=1 gravitational threshold. Further observations, extending to lower CO limits than are currently available, are needed for a empirical test of these hypotheses.

For gas densities above the threshold, the star formation laws in different galaxies are remarkably coincident (see Fig. 6 and Kennicutt 1989), and this suggests that some other physical mechanism may control the SFR in that regime. Self-regulating models, in which pressure and energy input from stellar winds and supernovae limit the SFR, predict a Schmidt law similar to that seen in Fig. 6 (e.g., Silk 1987, Dopita 1990). Models of density-wave induced star formation may also be able to account for the observed gas and SFR distributions (e.g., Wyse and Silk 1989). So far we have found no direct empirical support for these models, in so far as they fit the data no better than a pure Schmidt law, but this may reflect the limited range of physical conditions that we can probe with our current data. Further observational tests of the self-regulating models are currently under way, both by our group and by B. Wang (private communication).

5.3. Local Analogs to Primeval Galaxies

There are several approaches to isolating potential analogs to primeval galaxies. One is to identify nearby galaxies with the most extreme star formation bursts, as evidenced by their ultraviolet, infrared, or emission-line spectra. Another is to search for local examples of genuinely young galaxies, i.e., those which are forming stars for the first time, and thus can be regarded as *bona fide* primeval galaxies themselves. Yet another approach is to identify objects which by some peculiar circumstance are analogs to a particular stage in galaxy formation, e.g., mergers or galaxies with cooling flows. In this section I describe examples of each type.

5.3.1. Blue Emission-Line Galaxies

The most common type of nearby starburst galaxy is characterized by blue colors and strong nebular emission lines. Figures 7a and b show the integrated optical spectra for two examples, NGC 1569 and NGC 4449, from a recently published spectrophotometric atlas of galaxies (Kennicutt 1992b). These data were obtained by drift scanning the galaxies across a long slit, so that an integrated spectrum could be obtained. NGC 1569 is a true starburst galaxy, with a dominant young stellar population and an SFR which is several times its average rate. NGC 4449 represents a milder level of star formation, and it was chosen because its luminosity and integrated spectrum is similar to the intermediate-redshift 'blue dwarf' galaxies.

At visible wavelengths these galaxies are dominated by a blue continuum, with Balmer absorption lines and strong nebular emission lines. In many intermediate-luminosity systems, including NGC 4449, [OII]λ3727 is the strongest spectral feature, rivaling even Hα in flux. The anomalous strength of [OII] appears to be due to a combination of an intermediate metal abundance, which increases forbidden line strengths in general, and a strong contribution from diffuse interstellar gas, which is ionized by a dilute radiation field and thereby has an abnormally high [OII]/Hβ ratio (Kennicutt 1992a). This is relevant to the spectra of distant galaxies, which are also characterized by strong [OII] equivalent widths. The abnormal excitation may lead to a modest overestimate of the SFR if only the [OII] flux is used, but this does not alter the qualitative interpretation of the distant blue galaxies as starbursting objects (Kennicutt 1992a).

Figure 8a shows the integrated energy distribution of NGC 1569 over the UV–FIR spectral range, as measured by Israel (1988). The peak in the energy distribution extends well into the ultraviolet, so such galaxies should be detectable to quite high redshifts. Identifying such galaxies beyond $z \sim 1$ can be difficult, however, because their UV spectra consist of a flat-spectrum continuum with only weak emission or absorption features (e.g., Hartmann et al. 1988). Even Lyman-α emission is weak or absent in all but the most metal-poor galaxies. Hartmann et al. attribute the Ly-α quenching to absorption/scattering from surrounding neutral gas, as well as trapping by dust in the HII regions themselves. Work presented at this meeting by Valls-Gaboud indicates that superimposed stellar Lyα absorption may be a more important effect, especially during the late stages of the starburst. If this is the case, the detectability of Ly-α may depend more on the age of the burst than on metallicity, and the line may be a more useful diagnostic at high redshift than was previously believed.

Many dwarf emission-line galaxies are characterized by very large gas fractions and low metal abundances, so it is legitimate to ask whether any of these might be genuinely young galaxies, i.e., those for which we are

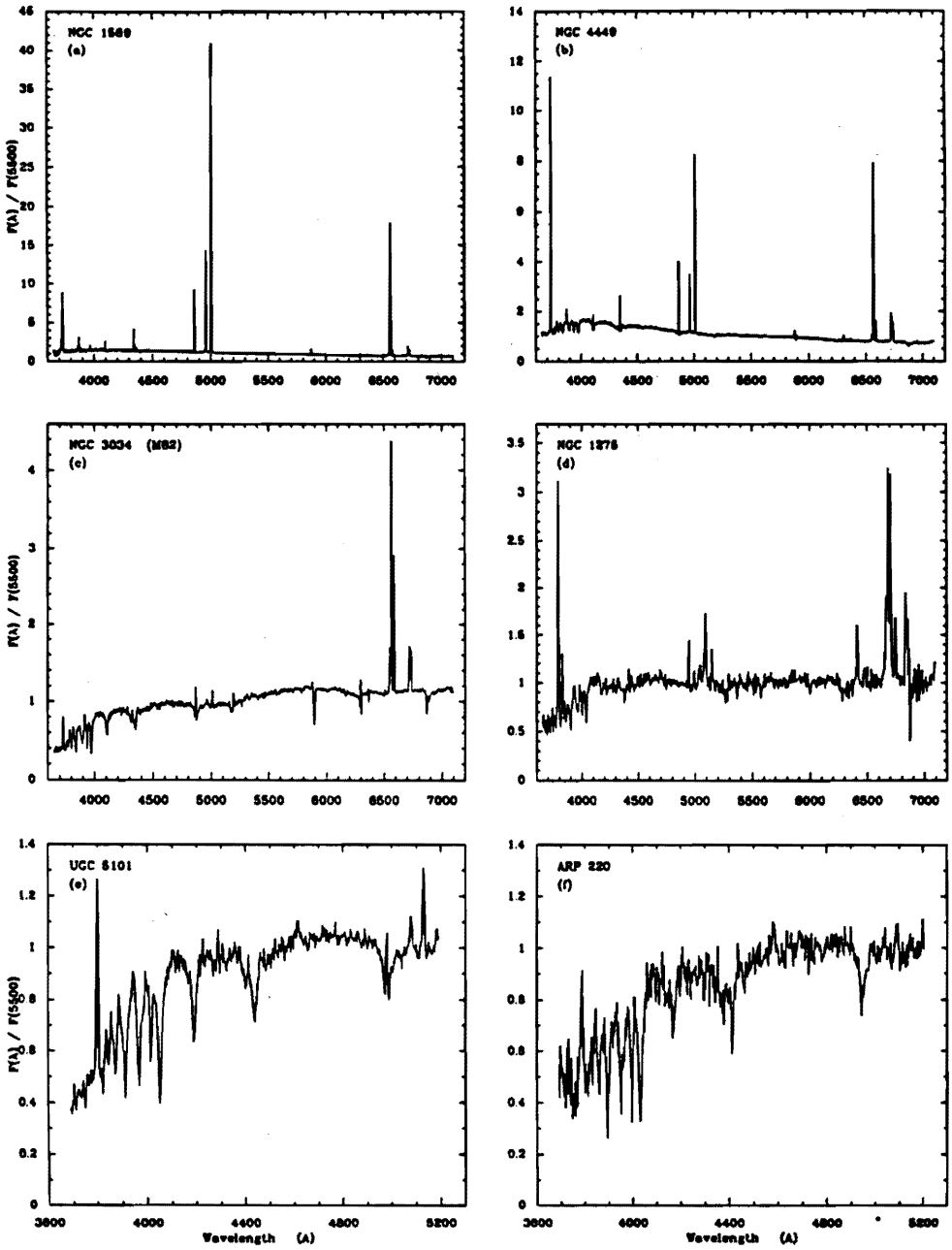

Fig. 7. Spectra for nearby galaxies, as described in the text. Note the different wavelength scales for the bottom two spectra.

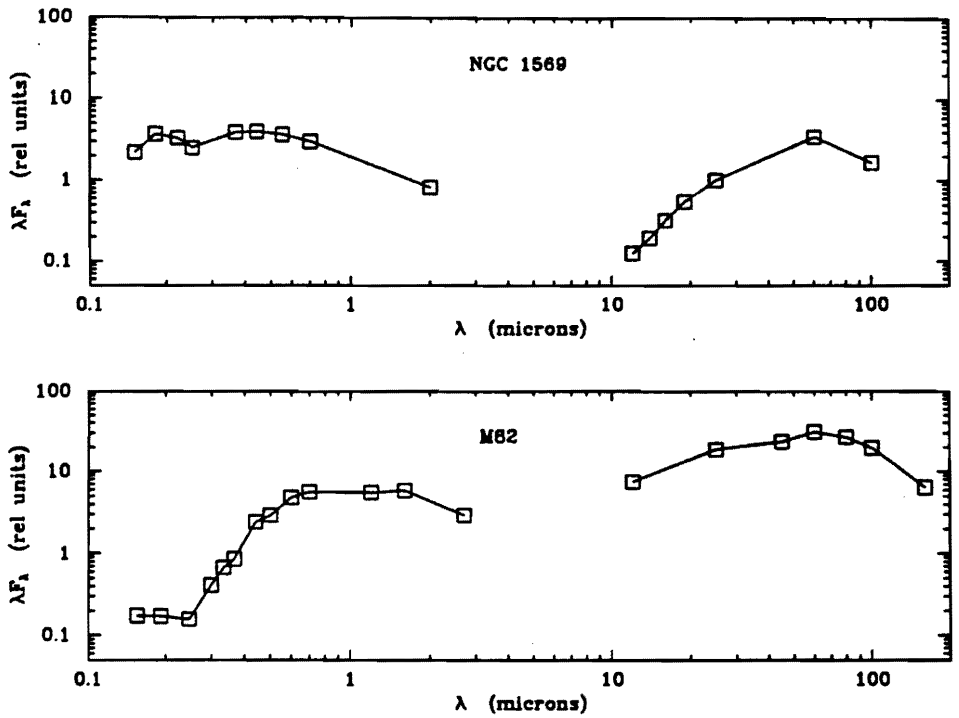

Fig. 8. Spectral energy distributions for NGC 1569, a blue emission-line galaxy, and M82, a prototype infrared starburst galaxy. The ordinate is λF_λ, to better indicate the relative contributions to the bolometric luminosity.

seeing the first generation of stars? The question has been debated since this class of galaxies was first identified, and it still is not firmly settled. Infrared photometry and imagery shows that most blue compact dwarfs contain smooth extended red envelopes, which presumably represent an older underlying stellar population (e.g., Loose and Thuan 1986, Kunth et al. 1988, Salzer and Elston 1991). Among the possible exceptions are I Zw 18 and the optical counterpart to the Virgo HI cloud (Salzer and Elston 1991, Salzer et al. 1991). For a review of the subject see Thuan (1991).

5.3.2. Far-Infrared Starburst Galaxies

Many starburst galaxies emit the bulk of their radiation at far-infrared wavelengths (e.g., Soifer et al. 1987, Telesco 1988). The prototype of this class is M82, and its integrated spectrum (Kennicutt 1992b) and energy distribution (Telesco 1988) are shown in Figures 7c and 8b, respectively. The differences which are most immediately apparent are the strong reddening in the optical

spectrum of M82, and the vastly increased fraction of bolometric luminosity in the far-infrared. If such objects are common at high redshift, they will be most readily detectable at FIR and submillimeter wavelengths, either in the continuum or in fine structure nebular lines.

Despite the high FIR luminosities and large optical depths in these objects, many appear quite blue at visible wavelengths. Charles Liu and I recently obtained spectra for a complete sample of ultraluminous IRAS galaxies, and two examples are shown in Figures 7e and f. The blue spectra are usually quite flat, and early-type stars dominate the absorption spectra; they are recognizable as starburst or post-starburst galaxies even without information in the infrared. This combination of high extinction and relatively low reddening can be understood if the dust is clumpy, and significant star formation occurs in regions of low extinction. These observations also confirm that star formation is responsible for at least a part of the extraordinary infrared luminosities of these objects.

While some of the IR-luminous starburst galaxies may be nothing more than dusty versions of the blue galaxies discussed earlier, several lines of evidence suggest that the most extreme cases represent a physically distinct phenomenon. The bolometric luminosities of the most luminous objects, if powered predominantly by star formation, imply SFRs of up to several hundred solar masses per year, comparable to the primordial starbursts in rapid collapse models of galaxy formation. Many objects possess unusually massive central gas complexes (e.g., Scoville et al. 1991, Solomon et al. 1992). Several authors have demonstrated a strong statistical link between the most luminous IR starbursts and very close interactions or mergers of galaxies (e.g., Sanders et al. 1988, Melnick and Mirabel 1990). It is conceivable that these objects represent sites where galactic nuclei and/or spheroids are forming today (e.g., Sanders et al. 1988), hence their relevance to more distant protogalaxies. Modelling of M82 and similar galaxies also suggests that the local properties of the starburst, such as the IMF and star formation efficiency, may be different from those in normal disks (e.g., Rieke 1991).

5.3.3. Star Formation in Cooling Flows

Yet another star formation environment occurs in the dominant central galaxies of cooling flow clusters (see Mushotsky's review in this volume). Figure 7d shows the integrated optical spectrum of one of the best known examples, NGC 1275 in the Perseus cluster (Kennicutt 1992b). This is easily the most peculiar spectrum in the atlas. The famous double-velocity emission line system is readily apparent; this emission arises from a combination of gas associated with the cooling flow itself, and nuclear activity in NGC 1275 itself.

The X-ray inferred mass deposition rates for typical cooling flows are of

order 10–1000 $M_\odot\ yr^{-1}$, which implies utterly enormous SFRs, if this gas is converted into stars at this rate. This issue has stimulated several extensive surveys of the stellar populations and emission-line gas in cooling flow cluster dominant galaxies (e.g., Romanishin 1986, 1987; McNamara and O'Connell 1989, Heckman 1989, Caulet et al. 1992). Evidence for young stars is seen in ~60% of the galaxies studied to date, but the mean inferred SFR is only 7% of the mass deposition rate (20% in NGC 1275), if a normal IMF is assumed (McNamara and O'Connell 1989). The discrepancy suggests that either the mass accretion rates are in error, or if the stellar IMF in the cooling flows is abnormally enriched in low-mass stars. Note that the latter is quite the opposite of what is alleged to occur in IR-luminous starburst galaxies. It is quite possible, but not yet firmly established, that the cooling flows contain an entirely distinct mode of star formation from what is observed to other types of starburst galaxies.

5.3.4. Young Analogs to Globular Clusters

A prominent signature of galactic spheroid formation should be the formation of globular star clusters. If objects comparable to our Galaxy's globular clusters formed in regions with a normal IMF, they would have initial luminosities of order M_B = -15, and ionization rates of order 10^{53} photons s^{-1} (Kennicutt and Chu 1988). In the past year there have been claims of detection of such clusters with the Hubble Space Telescope, in NGC 1275 (Holtzman et al. 1992) and the infrared starburst galaxy Arp 220 (Dowling and Shaya 1992).

The observation of massive, compact young clusters is not new. The Magellanic Clouds contain a large population of blue populous clusters with ages of order 10^7–10^9 yr; these clusters are structurally similar to Galactic globular clusters, though their masses are typically an order of magnitude lower. Other examples of luminous, unresolved clusters with ages of order 10^7 yr are seen in NGC 1569, NGC 1705, NGC 3597, NGC 5253, and possibly NGC 5128 (references in Kennicutt and Chu 1988 and next section). Compact core clusters are also observed in several nearby giant HII regions, including 30 Doradus. There seems to be a strong correlation between those galaxies which possess giant HII regions and those which contain populous blue star clusters (Kennicutt and Chu 1988).

Whether these compact young clusters are destined to evolve into true globular clusters is still open to question, in my view. Even with HST, the spatial resolution at the distance of NGC 1275 or Arp 220 is tens of parsecs at best, and this is insufficient to resolve a true globular cluster from a more weakly bound open cluster or compact association. The starlight in these objects is dominated by O, B, and early A-type stars, so it is nearly impossible to detect a low-mass stellar population, even in nearby clusters.

Probably the strongest circumstantial evidence in favor of the formation of at least some young globular clusters is the existence of intermediate age objects ($\sim 10^{7-8}$ yr) in the LMC, which have roughly Salpeter IMFs ranging from below 1 $M_\odot$ to nearly 10 $M_\odot$. However the formation rate of such clusters is at least an order of magnitude below the formation rate of of giant HII regions of the same primordial luminosity (Kennicutt and Chu 1988). This suggests that bound globular clusters, if they form at all in such HII regions, only form under rare circumstances.

5.3.5. Interacting Galaxies and Mergers

Up to now we have only considered galaxies which bear some photometric signature of a starburst. An alternative approach to identifying analogs to primeval galaxies is to select objects which dynamically resemble protogalaxies, independent of their photometric properties. By studying the star formation properties of these objects, one can avoid the selection biases which are inherent in studies of starburst galaxies. Here I discuss an example of how this approach can be applied to the study of interacting and merging galaxies.

The link between galaxy-galaxy interactions and star formation bursts is now well established. Close pairs of galaxies are known to have average mean disk star formation rates (e.g., Bushouse 1987, Kennicutt et al. 1987), stronger FIR emission (Bushouse et al. 1988), and elevated levels of nuclear star formation and nonthermal activity (e.g., Cutri and McAlary 1985, Keel et al. 1985). N-body simulations of interacting systems can reproduce the large-scale gas compression and angular momentum transport that is needed to fuel this disk and nuclear activity, respectively (e.g., Barnes and Hernquist 1991, Mihos et al. 1991).

The most spectacular activities appear to be associated with galactic mergers. Observations of a few prototype mergers, such as NGC 7252 and NGC 3597, show evidence for large fossil starbursts, in some cases with spheroid-like $r^{1/4}$ luminosity profiles (Schweizer 1990, Lutz 1991). Lutz identifies several bright compact blue knots in NGC 3597, which he suggests may be young globular clusters. Ashman and Zepf (1992) discuss the cluster formation in mergers in general, and suggest that similar clusters have formed in Cen A (NGC 5128). Recently I began a more comprehensive spectrophotometric and imaging survey of ~40 systems, in collaboration with Charles Liu and Pat Hall. Two examples of these objects (which also happen to be ultraluminous IR galaxies) are shown in Fig. 7e and f. Our preliminary results show that the mergers display the full range of SFRs, ranging from completely old stellar populations, to ultraluminous starbursts. The most common spectrum is that of a postburst population (UGC 5101, Fig. 7e), often mixed with an older underlying population (Arp 220, Fig. 7f). A few

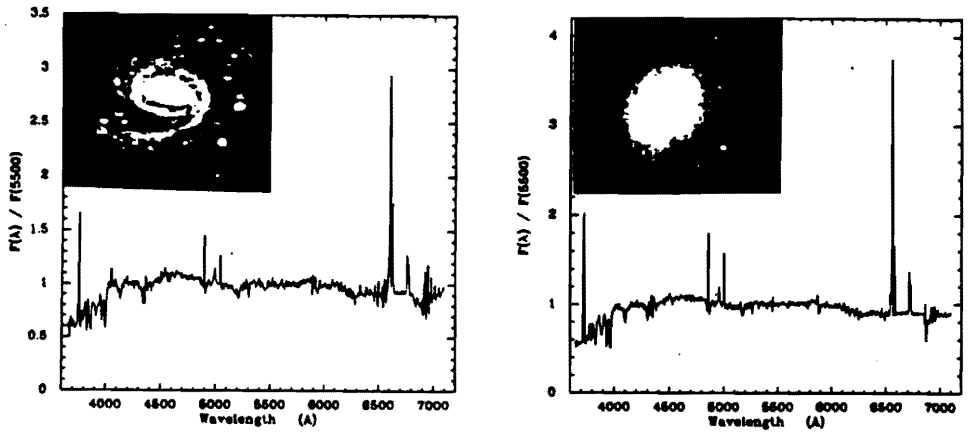

Fig. 9. Integrated spectra of NGC 1832 and NGC 3077, from Kennicutt (1992). Insets are blue images of the galaxies.

of the latter resemble the 'E+A' galaxies seen frequently in distant clusters, though true analogs appear to be rare. Quantitative analysis of the star formation rates and histories is under way.

6. Concluding Remarks

Observations of nearby galaxies offer a wide range of constraints on galaxy formation and evolution, which in many respects complement the information that is obtained from observations of cosmologically distant objects. In all three of the areas discussed, local stellar populations, nearby galaxies, and distant galaxies, recent advances in instrumentation have led to significant progress in our ability to reconstruct the stellar birthrate history of the universe. The advent of new large telescopes promises to continue this progress. Galactic evolution has become an observation-driven science, and it is an exciting time to work in the field.

As a final illustration of the value of close-up observations, Fig. 9 shows integrated spectra of two nearby galaxies, NGC 1832 and NGC 3077 from Kennicutt (1992b). These galaxies are as close to being spectroscopic twins, at least at visible wavelengths, as any I encountered during the survey (except that NGC 1832 is about 3 magnitudes brighter). If these galaxies were observed at high redshift, one might reasonably conclude that they have similar stellar populations and star formation histories. The insets show blue photographs of NGC 1832 (SBb) and NGC 3077 (Irr II). *Caveat emptor!*

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