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STRUCTURE AND EVOLUTION OF IRREGULAR GALAXIES

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INTRODUCTION

Irregular galaxies (Irrs) usually are smaller, less massive, and optically dimmer than commonly studied giant spirals, S0s, and classical ellipticals. At first glance they also appear to be rare objects that make up only a few percent of the major bright galaxy catalogs (87, 300). Is there then much reward in pursuing such faint and elusive galaxies? The answer to this question turns out to be a surprisingly strong "yes." An examination of more nearly complete samples of galaxies (213, 341, 366) reveals that Irrs account for a substantial (1/3–1/2) fraction of *all* galaxies, and that they certainly are dominant by number density among actively star-forming galaxies. A diversity of nearby examples therefore abound [including, of course, the Large and Small Magellanic Clouds (LMC and SMC)], making Irrs prime targets for detailed investigations of galactic stellar content and star formation processes. Recognition of their structural simplicity has provided an additional stimulus for recent interest in Irrs as tests for theories of galaxy structure and evolution. These galaxies also are comparatively unevolved, and thus they may yield further rewards by allowing conditions to be defined in the poorly understood realm of low-density extragalactic systems, which retain considerable information about galaxy formation (101, 327).

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In the broadest sense, the irregular galaxy class is loosely defined (e.g. see illustrations in 9, 23, 378, 379). Hubble (175, 176) originally built on earlier nebular classification schemes (e.g. 153) and considered galaxies to be "irregular" if they showed chaotic, nonsymmetrical blue-light distributions, in contrast with the axial symmetry of normal "regular" systems. Later classification systems subdivide irregular galaxies into two major groups: Magellanic systems (Irr I, Im), which resemble the Magellanic Clouds; and peculiar, often amorphous galaxies, which are classified as Irr II or I0 systems (72, 174, 290, 292).

Unfortunately, irregular structures may arise from a variety of physical causes, and as a result a wide range of physical types of irregular galaxies are known to exist: (*a*) There may be substantial chaos in the projected stellar mass distributions in galaxies, although such nonequilibrium structures are unlikely to survive for more than a few rotation periods ($\sim 10^9$ yr). Most currently known galaxies in disturbed states seem to be involved in galaxy-galaxy interactions (311, 358, 359, 384, 392, 393), although newly formed galaxies could also find themselves in this situation (45). Some galaxies classified as Irr II or I0 also belong in the category of interacting galaxies. (*b*) Similarly, unusual distributions of dense interstellar gas across the face of a galaxy may produce an optical image that is mottled by dark lanes. The dusty Irr II galaxies discussed by Krienke & Hodge (214) belong in this group. As these authors note, extended interstellar matter also can lead to emission filaments and reflection nebulae on galactic scales that give rise to abnormal optical morphologies (e.g. M82; 34, 67, 281, 332). The origins of peculiar global distributions of interstellar matter are not well understood, but some cases are caused by interactions between galaxies (65, 136, 373). (*c*) Young, massive stars have very low mass-to-light ratios, and thus sites of recent star formation stand out against even moderately high density projected stellar backgrounds. Furthermore, OB stars tend to form in spatially localized groups that are seen as OB associations or perhaps larger units with dimensions of up to 1 kpc ("constellations," 253; "star complexes," 91). Thus, in galaxies with low background stellar density levels and spatially incoherent star formation patterns, patches of young stars stand out against symmetrically distributed older stars and give rise to irregular optical brightness structures. This effect is beautifully illustrated in UV photographs of the Large Magellanic Cloud that were obtained from the lunar surface during the Apollo program (263, 264).

Most irregular galaxies belong in the third category, which includes Magellanic-type irregulars and spirals (70, 72, 78, 233, 290, 292, 365, 366, 368) as well as a smattering of genetically related systems such as intergalactic H II regions (304, 312), amorphous galaxies (defined by 294, 300; blue galaxies with relatively smooth optical light distributions; a subclass of Irr IIs or I0s: 174, 321; also "blue Es": 104), or luminous, clumpy Irr galaxies (50, 51, 149, 150, 302). Hereafter, we limit our scope to the Magellanic galaxy family (and mainly systems that are not involved in obvious galaxy-galaxy interactions), which we refer to simply as Irrs.

The Irrs blend from lower luminosities smoothly into the spirals, as emphasized by both G. de Vaucouleurs and A. Sandage, and thus can be viewed as an extension of actively star-forming disk galaxies to lower densities and luminosities. Luminous members of the Irr family overlap with spirals in optical luminosity and are often preferentially selected in surveys for blue or emission-line galaxies (e.g. the G. Haro and B. Markarian surveys; see 208). Thus Irrs probably now comprise the bulk of known galaxies with dominant hot stellar populations. We close this section with Figure 1, which illustrates NGC 4449, a classical nearby giant Irr. In the remainder of this article, we discuss specific physical characteristics of Irrs that are structurally related to NGC 4449, with an emphasis on exploiting the Irrs as probes of evolutionary processes in galaxies.

BASIC PROPERTIES

Light

Irrs exist over an extreme range in optical luminosity extending from clumpy irregulars with $M_B \lesssim -20$ to intrinsically faint dwarfs with $M_B > -13$. Usually, luminous systems have moderate-to-high optical surface brightnesses (blue SB $\sim 100\ L_\odot\ \mathrm{pc}^{-2}$ in an effective radius), while most dwarfs (i.e. galaxies with $M_B > -16$) are barely detectable above the night-sky background (blue SB $\sim 10\ L_\odot\ \mathrm{pc}^{-2}$). There are exceptions; for example, dwarf "blue compacts" can have high surface brightness (361), and luminous examples of low-surface-brightness Irrs also exist (231, 352). Most Irrs, however, are low-surface-brightness dwarfs, which accounts for their rarity in catalogs of bright galaxies.

Optical surface photometry is available for a number of Irrs, most of which are dwarfs (e.g. 2, 3, 32, 71, 73, 74, 79, 160, 165, 166, 323). The mean radial brightness profiles of these galaxies are well represented by exponential intensity distributions $I(R) = I(0)\exp(-\alpha R)$ with scale lengths $\alpha^{-1} \sim 1$–3 kpc. The light distributions in Irrs are therefore similar in form, but of lower surface brightness and shorter scale length, to those of spiral galaxy disks (117, 310). We thus infer that Irrs have lower mean projected stellar densities than typical spirals. The smooth profiles of Irrs are often disturbed by (*a*) star formation activity, which produces islands of high surface brightness, especially in the inner regions; (*b*) by bars, which are common in Irrs; and (*c*) by the effects of individual luminous stars in nearer systems (79). Deep images (172, 199) sometimes reveal that the actively star-forming cores of Irrs are embedded in smooth halos that qualitatively resemble diffuse dwarf elliptical galaxies. This has led several authors to suggest a close structural relationship between elliptical and Irr dwarfs (39, 125, 229, 386).

In terms of integrated optical colors, the Irrs are the bluest of the "normal" galaxy classes, with $(B-V) \sim 0.4$ and $(U-B) \sim -0.3$ (77, 177, 178). Standard models of stellar populations can yield such blue colors for galaxies of normal cosmological age only with some difficulty, which has

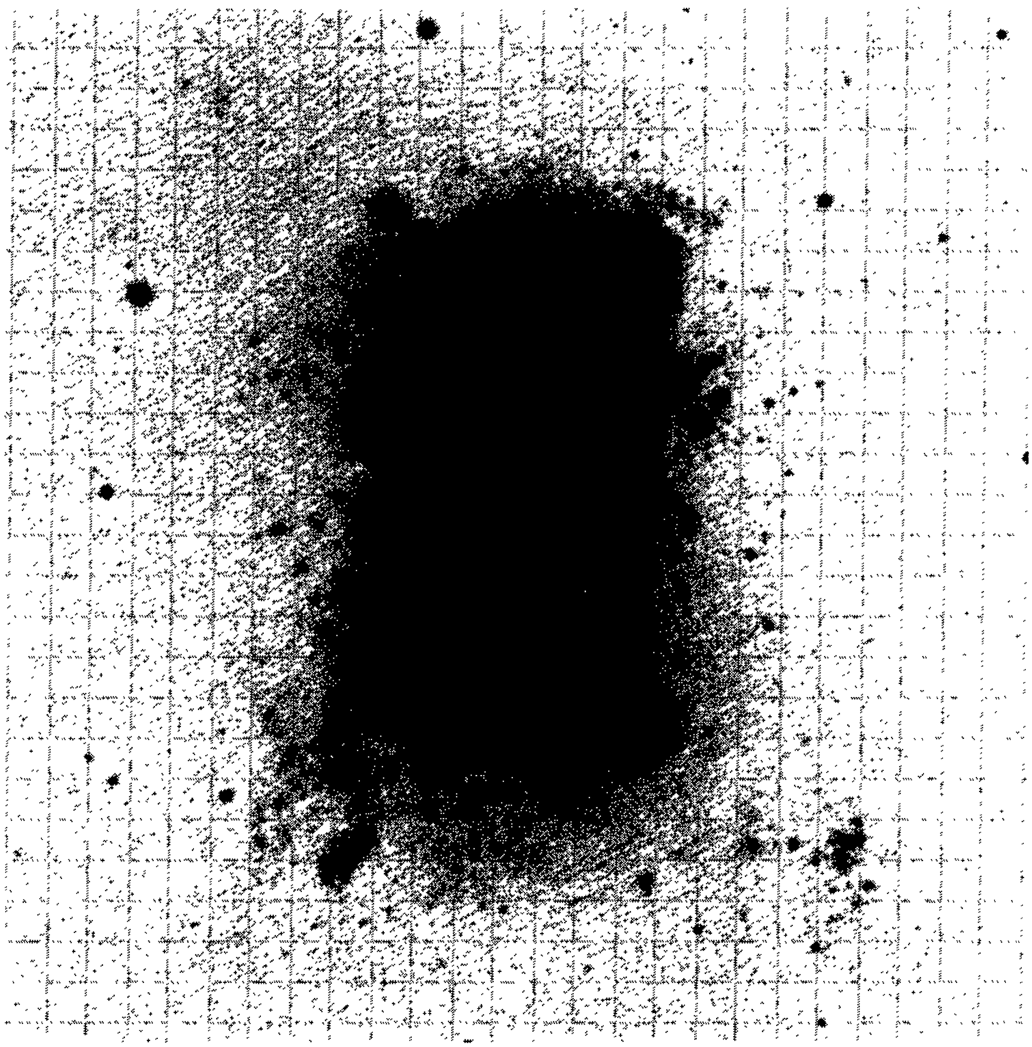

Figure 1 Blue photograph of the nearby ($D \sim 5$ Mpc), giant irregular galaxy NGC 4449, taken for the authors by G. Lelievre with the prime-focus camera on the Canada-France-Hawaii 3.6-m telescope. The scale of this print is approximately 3″ mm^{-1}; north is to the upper right corner, and east is counterclockwise. The chaotic structure of this galaxy largely results from many bright star-forming complexes superimposed on a strongly barred, amorphous, older stellar background. A few dark nebulae (light regions on this negative copy) are also visible.

fostered the idea that many Irrs have been detected in a stage of heightened star formation activity, i.e. very blue galaxies may be caused by star formation bursts (177, 178, 313). It also is possible that the colors could arise if the initial mass function (IMF) differed significantly from that deduced for stars in the Milky Way. Among intrinsically brighter Irrs, there is no strong trend between color and luminosity, but the fainter dwarfs in the David Dunlap Observatory (DDO) catalog of low surface brightness galaxies (365, 366) are systematically blue (82). This may be indicative of preferential selection of galaxies currently experiencing major star-forming events in samples of intrinsically small, faint galaxies. An example of the importance of star formation on the detectability of dwarf Irrs can be found by comparing VII Zw 403, a high surface brightness Local Group dwarf (361), with the low surface brightness Local Group Irr LSG 3 (363); the differences between these two galaxies stem from the presence of a small OB stellar complex in VII Zw 403.

Unlike spirals, Irrs often show a central bluing of optical color (81, 83). This implies a concentration of star-forming activity to the inner regions of the galaxy, which is consistent with observed steep radial falloffs in distributions of H II regions, supergiant stars, and other Pop I star indicators in the LMC (171) and other Irrs (165, 166, 188, 189, 291). Many years ago, de Vaucouleurs (72) remarked on the smooth transitions from the pure irregulars to true spiral galaxies. This in part involves a change in styles of OB star formation. Unlike Irrs, *relative* star formation rates in spirals are highest (and colors bluest) in the mid-to-outer optical disk. Thus, in spirals the young stellar component often has a *flatter* radial distribution than the overall light. The Sdm-Sm galaxies (the morphological transition between spiral galaxies and pure Magellanic irregulars) are intermediate cases in this regard, having extensive OB stellar components that extend well beyond the obvious older stellar amorphous backgrounds. This phenomenon does not seem to correlate with the form of the outer low-density H I distribution; for example, NGC 4449 has a very extensive H I envelope (376) but tight OB star distribution, while in NGC 4214 the H I profile is of more normal dimensions (7), even though far-flung OB stars abound.

Irr galaxies are only beginning to be extensively studied in the non-traditional X-ray, rocket ultraviolet, and infrared spectral regions, but interesting results have already appeared. Irrs may have high X-ray to optical flux ratios compared with nonactive spiral galaxies. This is consistent with the presence of binary X-ray sources in their large, young stellar population fractions (99, 100, 126, 333). Early OAO rocket-UV photometry revealed that Irr galaxies have integrated ultraviolet energy distributions somewhat like late B stars (59), a result that now has received support from a variety of UV observations (48, 49, 61, 239, 263). These energy distributions underscore the high-visibility, dominant role played by luminous OB stars in Irr galaxies, but they also clearly show the composite nature of the stellar populations in Irrs, since $m_{1550} - V \sim -1.5$ is redder than B stars.

Infrared *JHK* photometry of Irrs has been obtained by Aaronson (1), Thuan (349), and Hunter & Gallagher (in preparation). Most Irrs fall near globular clusters and star-burst nuclei in their *JHK* colors, and thus they contain cool, presumably evolved stars. Interpretation of these IR data is complicated by the important role of asymptotic giant branch stars in stellar populations of intermediate age and by uncertainties in red supergiant populations (193, 272, 279), but typical Irrs have IR colors near those expected on the basis of constant star formation rates (335; B. Tinsley, private communication, 1978). As emphasized by Thuan (349) and Huchra et al. (179), the blue $V-K$ colors ($\lesssim 1$) of some galaxies, however, could indicate a very large proportion of young stars or large-amplitude star formation bursts. Problems here include the sensitivity of young red star populations to low metallicities (24, 44) and the need to observe the entire old stellar component, which may be distributed across an underlying galaxy of low surface brightness and of larger angular size than the prominent young stellar complexes.

IR photometry is thus a potentially powerful tool in understanding recent star formation histories of galaxies (122, 123). Longer wavelength, thermal infrared emission from dust in Irrs has been detected in only a very few cases, but since large infrared luminosities (at wavelengths of > 10 μm and especially ~ 100 μm) are characteristic of high star formation rates in a variety of galactic environments, we can expect Irrs to begin to show up in this category as improvements are made in far-IR sensitivity (282, 345, 382). By providing information on IR luminosities and spectral characteristics as functions of readily determined gas metallicities and star formation rates, the Irrs play an important role in calibrating models for thermal IR emission from dust in "young," metal-poor galaxies.

Masses and Kinematics

Global dynamics for large samples of Irrs have been derived from H I 21-cm line surveys (53, 109, 110, 135, 231, 241, 350–352). These observations provide integrated Doppler line widths, and usually the full width at 20% of peak intensity is interpreted as a good estimate of $2V'_c \sin i$, where V'_c is a characteristic circular gas velocity in a galaxy disk of inclination *i*. The distribution of H I line velocity widths shown in Figure 2 demonstrates that the majority of Magellanic Irrs have peak orbital velocities of $V_c <$ 100 km s^{-1}, with $V_c \sim$ 50–70 km s^{-1} a representative value, in agreement with Brosche (41). Compared with spirals, for which $V_c \gtrsim 200$ km s^{-1} is typical (41, 102, 287, 374), Magellanic Irrs are slow rotators and have low specific angular momenta ($\lesssim 0.1$ of the solar neighborhood value).

Dynamical masses within the optical radii R_{opt} of galaxies are normally calculated on the basis of spherical mass distributions $M \approx (V_c^2 R_{opt}/G)$. This may lead to mass overestimates by a factor of two for Irr galaxies, which are disk dominated with low central mass concentrations. Since Magellanic Irrs have both smaller V_c and R_{opt} values than archetypal spirals, their masses are considerably smaller, with values of 10^8–10^{10} $M_\odot$ typical of survey results. Dynamical masses for individual galaxies are subject to a variety of uncertainties [e.g. inclinations are difficult to estimate for barred, chaotic galaxies (351, 352), velocity fields may be complex (376), and warps in the gas disk may not be uncommon (326)]. Even so, the mass range (but perhaps not the mass distribution function) derived from surveys of Magellanic Irrs should be reliable. Mass-to-blue-light ratios found from the H I surveys mainly scatter between 2 and 10 for $H_0 = 100$ km s^{-1} Mpc^{-1}. As a fiducial point, the LMC has a mass of $5 \pm 1 \times 10^9$ $M_\odot$ (105), which yields a value of $M/L_B = 1.6 \pm 0.2$. There is then some justification for believing that the M/L_B values based on H I survey results are systematically too high.

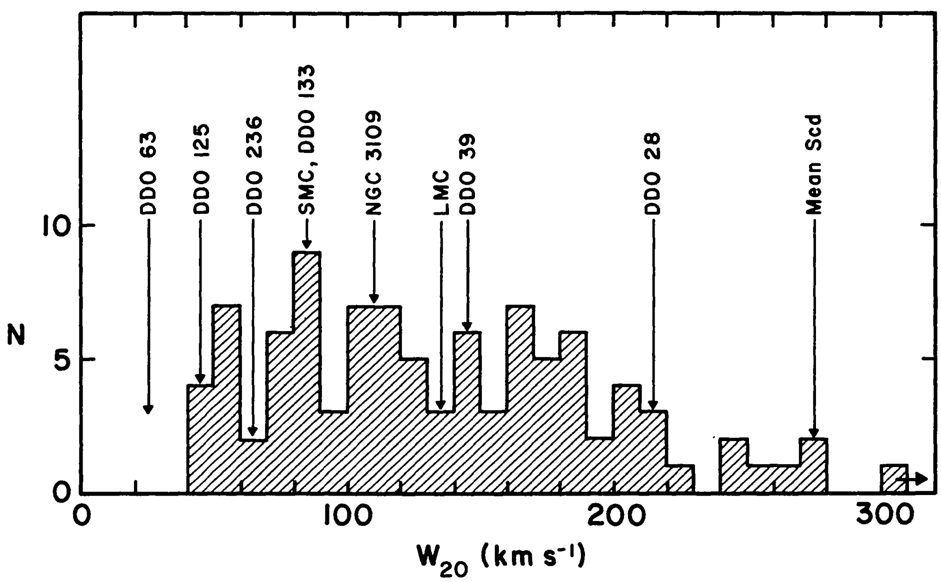

Figure 2 Distribution of H I line Doppler full widths at 20% of peak intensity for Im and Sm galaxies in the Fisher & Tully (110) survey that meet the conditions of (*a*) redshift velocity less than 1200 km s^{-1} and (*b*) estimated inclination of 50° or larger. Also shown are positions of several Irrs with known rotation curves based on references in the text (which are plotted at twice the maximum circular velocity) and the mean location of Scd galaxies [from Faber & Gallagher (102)]. Irr galaxies rotate more slowly than spirals, and virtually all systems with $W_{20} \gtrsim 180$ km s^{-1} are transition spirals, while for $W_{20} < 100$ km s^{-1} pure irregular morphologies greatly predominate.

Internal kinematics have been measured in several nearer Irrs using accurate H I velocity maps derived from pencil-beam observations (181–183, 286; earlier references in 374; rotation curve data are summarized in 18) and from H I aperture synthesis studies (5–7, 21, 67, 136, 137, 227, 303, 326, 360a, 373, 377). Both of these methods suffer to some degree from modest angular resolution. Velocities from optical emission lines can provide good spatial resolution and, in some cases, good velocity resolution but are sensitive to motions induced in the ionized gas by young stars (54, 78, 80, 105, 134, 188, 189, 236).

From these observations we can identify an underlying unity to the properties of Magellanic Irrs. Cool gas is located in uniformly rotating disks. The dispersion velocity of H I in the disks is typically $\sim 10 \pm 2$ km s^{-1}, a value that appears to be universal in H I disks of all galaxies (7, 182, 183, 375) and must therefore be an intrinsic property of interstellar matter rather than a property of specific galaxies. Rotation velocities within the gas disks, on the other hand, are quite sensitive to galaxy structure, with V_c declining from ~ 100 km s^{-1} in giant Irrs to virtually undetectable levels in extreme dwarfs and intergalactic H II regions. Among the very luminous clumpy Irrs and related blue compact galaxies, rotation velocities approach those of normal spirals (12, 53, 135), and thus these systems originate from a rather different state than the common Magellanic Irrs.

Mean rotation curves of Irrs also differ in form from those of spirals. Near-rigid-body rotation extends over most of the optical dimensions, with shallow velocity gradients of $dV/dr \sim$ 5–20 km s^{-1} kpc^{-1} that reach peak velocities near the optical peripheries of the systems. In spirals the rigid-body rotation region is often quite limited in radius and has a steep gradient of $dV/dr > 20$ km s^{-1} kpc^{-1} (134, 287) [often larger than 50–100 km s^{-1} kpc^{-1} in more massive spirals (62, 133, 212)]. The peak velocities in spirals are attained in a nearly flat rotation curve that extends over most of the optical galaxy (37, 38, 102). Thus Irrs exist in a state with minimal differential rotation in star-forming regions, while star formation in spiral disks suffers strong shear due to differential rotation.

The forms of the rotation curves thus strongly affect the optical appearances of galaxies and insure that low-density disk systems will be morphologically distinct from spirals. Strom (334) demonstrated that the degree of gas compression during passage of interstellar matter through a density-wave spiral arm depends upon the maximum V_c value, and that for typical arm inclinations, only galaxies with $V_c \gtrsim$ 50–100 km s^{-1} will produce spiral arm shocks. Thus, slowly rotating galaxies should not be capable of arm shock-induced star formation and thus will not appear as spirals. Similarly, patterns produced by propagating star formation will not distort into spirals in the absence of differential rotation (116, 315, 316), nor will shear amplification of small inhomogeneities lead to the creation of spiral armlets (357). So whatever the reader's favorite spiral arm theory may be, it probably will not directly stimulate star formation in slowly rotating Irrs (cf. 255). Star formation processes in Irrs are free from internal dynamical forcing and therefore appear in a free-wheeling, chaotic natural state. From this perspective, the luminous clumpy Irrs with their spirallike rotation properties will be more difficult to produce, which may explain their rarity and tendency to be found in interacting systems where star formation can be externally stimulated (50, 177, 201).

The kinematics of Irrs are qualitatively consistent with their exponential brightness distributions. Mass models based on exponential disks (117) or low central concentration, Gaussian density distributions (360a) reproduce observed Irr rotation curves for $M/L_B \lesssim 5$ in the central regions but fail in spirals (16, 17). A recent study of star cluster kinematics in the LMC similarly finds no evidence for a spheroidal component, even among old globular clusters (119). The Irrs thus have the expected character of pure disk galaxies containing (nearly) the observed amount of luminous mass, while spirals must be pinned on high-density central cores and also embedded in extensive stellar (and nonstellar?) halos. The lack of dense cores explains why Irrs rarely have optically identifiable nuclei and are not commonly sites for violent activity (20, 72; but see also 148a, 151). Evidently, a deep central gravitational potential well is a necessary ingredient for formation of massive, dense galactic nuclei and their associated fireworks.

When velocity fields in Irrs are observed with sufficient spatial and velocity resolution, numerous complexities appear. (*a*) H I is usually clumped into large clouds, which may not lie on the smooth rotation curves (as in the LMC; 241). (*b*) Irr galaxies are preferentially barred, and the bars primarily result from an enhanced density of older stars (75, 105, 188, 189), and usually do not lie on center [i.e. Irrs strangely prefer to be asymmetric rotators (78, 105)]. The presence of bars is to be expected if the Irrs are indeed dynamically cold systems that do not contain disk-stabilizing stellar or dark halos (93, 262, 318, 371). The combined impact of asymmetries and bars introduces significant perturbations into the velocity field (cf. 7, 236). Off-center bars remain theoretically poorly understood (63, 78, 106), which presents an impediment to construction of dynamical models for Irrs. (*c*) Injection of energy into the interstellar medium by massive stars can produce relatively large kinematic effects in slowly rotating Irrs. For example, giant H II regions expanding with velocities of ~ 20 km s^{-1} (124, 188, 347, 348) can significantly distort rotation properties as deduced from ionized gas. Blowouts in the cool interstellar medium due to stellar winds and supernovae lead to large-scale expanding gas shells (141, 243, 383) that are seen as "holes" in the H I distributions and can cause H I maps of Irrs to resemble Swiss cheese in both velocity and physical spaces (e.g. in the SMC; 19, 154, 331).

If one takes only optical light into account, then Irrs, like spirals (102, 255), must contain "dark" matter, but much of this is in the form of gas, including both easily detectable H I (and its associated helium) and elusive molecular material that nonetheless must be present at some level (197, 227, 390). Based on detections of CO emission in NGC 1569 and the LMC, the total mass of gas in inner regions of some Irrs may be as much as twice the H I value. The situation regarding dark mass, possibly nonnucleonic, that does not radiate detectable electromagnetic radiation is at present extremely unclear. Tinsley (354) and Lin & Faber (229) applied indirect arguments to conclude that dwarf Irrs probably have spirallike dark envelopes, but in both cases gas content, stellar population properties, and accuracy of dynamical masses introduce uncertainties. Feitzinger's (105) investigation of LMC dynamics, on the other hand, suggests there is little or no unaccounted mass, and a similar result was obtained by Gallagher et al. (126) for normal-mass Irrs ($M \lesssim 10^{10}\ M_{\odot}$) based on constant star formation rate models. Blue Irr galaxies of higher inferred dynamical mass, however, are found by Gallagher et al. to have excess mass for their optical luminosities; thus, two dynamical classes of Irr galaxies may exist, although the uncertainties are large.

The issue of spirallike dark envelopes in Irrs is relevant to fundamental points such as the necessity of dark matter for galaxy formation and whether the luminous baryon mass to total mass ratio could be nearly constant in all galaxies (cf. 101, 103, 229). Furthermore, the presence of dark envelopes in small systems would place useful constraints on relic elementary particle interpretations of dark matter [e.g. hot particles such as light neutrinos are unable to cluster on such small scales (68, 276, 360)]. We have seen that evidence for significant amounts of dark matter within Irrs is at best ambiguous. As in spirals, kinematic observations of Irrs at large galactocentric radii therefore must eventually play a crucial role, i.e. we should seek to identify dark envelopes from flat or rising rotation curves in regions exterior to most of the luminous mass. It does seem clear from the available data that single Irrs are unlikely to have rising rotation curves (but see 218), although the current observations of the gas kinematics of Irrs do not extend far enough or have sufficient spatial resolution to distinguish between flat and falling rotation curves. A new systematic high-resolution study of H I kinematics in inclined, noninteracting dwarf Irrs is needed to clarify the issue.

Abundances

The metallicities of the ionized gas (i.e. abundances of O, Ne, and N; for a review, see 268) have been determined from the emission-line ratios under the assumption of photoionization (4, 30) for a large number of high surface brightness Irrs (120, 191, 209, 216a, 226, 340, 381) and low surface brightness, dwarf Irrs (cf. 189, 226, 267, 270, 329, 340, 361). The abundances generally range from SMC-like to LMC-like, with no distinction between the high and low surface brightness systems. Only some of the dwarf blue compacts or "intergalactic H II regions" seem to be much more metal poor than the SMC (4, 120, 209, 216a, 226, 377), and no systems are known with emission spectra consistent with extreme metal-poor galactic Pop II abundances. The lower half of Figure 3 shows the number distribution of Irrs as a function of O/H for galaxies in the above references (including blue compact systems and intergalactic H II regions). Generally, O/H is $1–4 \times 10^{-4}$, where the solar value is $\sim 7.6 \times 10^{-4}$. Interestingly, several very luminous intergalactic H II regions have been observed at moderate redshifts and are found to have normal metallicities for Irrs; for example, B234 at redshift 0.06 (121) and B272 at redshift 0.04 (88) both have O/H $\sim 2 \times 10^{-4}$. Some very luminous blue compact galaxies and the unusual M82 system, however, may approach or even exceed solar metallicity levels in the gas (36, 132, 200, 257).

There are difficulties in measuring abundances of Irrs from emission lines. Often [O III] λ4363 is not strong enough to be accurately measured, so some other means must be found for determining the electron temperature, such as the empirical relationship between forbidden oxygen and hydrogen Balmer emission intensities developed by Pagel et al. (266). This can lead to an ambiguity in the derivation of O/H for low-abundance objects (189). For example, consider the very metal-poor object I Zw 18 (120). The [O III] λ4363 ratio gives a temperature of 16,300 K, whereas simple application of the relationship determined by Pagel et al. gives 6400 K. The former results in an O/H value of 0.2×10^{-4} and the latter in a value of 5×10^{-4}. A plot of [O II]/[O III] intensity vs O/H (189) appears to be able to resolve this ambiguity, since ionization levels and abundances are well correlated in H II regions; however, one must keep in mind that the errors in even routine emission-line abundance determinations can be large. For example, of the 45 overlapping observations in the references cited at the beginning of this section, 15 pairs agree within 20%, 5 within 50%, while 6 are off by factors of two or more.

A further complication in using emission lines as abundance indicators in more distant galaxies where individual H II regions are not resolved stems from anomalous inter-H II emission-line ratios found by Hunter (190). In nearby Irrs, the [O II]/[O III] intensity ratio from diffuse emission considerably exceeds the ratio for H II regions within the same galaxies. Thus, integral emission-line flux ratios will differ from those of typical H II regions. The origin of anomalous line ratios is unclear and could involve either shocks or some type of photoionization process. It is also uncertain whether these anomalous emission regions are similar to the diffuse Hα emission seen in late-type spirals (246) and the Milky Way (280).

Since Irrs do cover a range in gas metallicity, they have proven valuable in efforts to determine the pregalactic helium abundance level, which is an

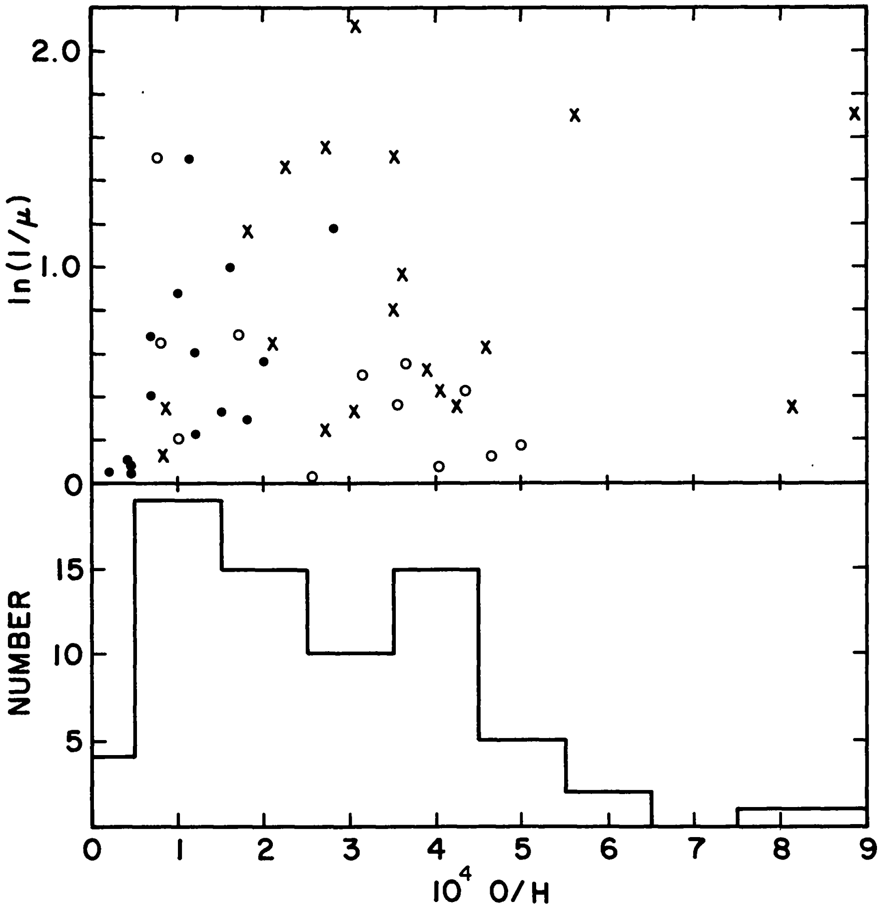

Figure 3 (*lower panel*) The distribution of Irr galaxies as a function of the oxygen abundance in H II regions is displayed. This sample includes low and high surface brightness Magellanic Irrs, luminous Irrs, blue compact systems, and intergalactic H II regions (see text for references). Gas abundances in Irrs, with few exceptions, are similar to the Magellanic Clouds. (*upper panel*) Dependence of oxygen H II abundances on gas mass fraction is shown in terms of $\mu = M_{gas}\ (M_{gas}+M_{stars})^{-1}$. Simple chemical evolution models predict a linear relationship between O/H and ln $(1/\mu)$, which is not found in this sample or in more traditional plots where $\mu = M_{gas}/M_{dyn}$ (238). All galaxies from the lower panel with sufficient data to enable μ to be estimated are included. Symbols are as follows: ×, high surface brightness normal Irrs; ○, low surface brightness dwarfs; ●, luminous and blue compact Irrs.

important constraint on cosmological models (see 14, 259, 268, 389). For example, an upper bound on the primordial helium abundance is provided by the most metal-poor intergalactic H II regions, and studies of larger samples of Irrs can yield insight into the variation of helium enrichment by stars as a function of metallicity, which allows an extrapolation to be made to zero metallicity (for excellent reviews, see 210, 216a, 265). Considerable effort therefore has been devoted to enlarging the sample of very metal deficient emission-line galaxies (cf. 215), but only limited success has been achieved thus far in that I Zw 18 remains the most metal-poor emission-line galaxy.

The metallicities of stars in Irrs seem to be consistent with the moderately metal-poor nature of the gas. Star clusters in the LMC have been found to have metallicities of 1/2 to 1/40 of the Sun (cf. 60, 168). The SMC, while on the average more metal poor than the LMC, is not known to contain objects as metal poor as the most metal-poor objects in the LMC or the Galaxy (127, 128), and thus it evidently has a smaller spread in abundances. Finally, *JHK* colors of Irrs are near those of several-billion-year-old intermediate metallicity systems (349). If gas captures from external sources are a common occurrence, e.g. among star-burst Irrs, then it is possible that gas and stellar metallicity levels may not mesh in some systems. This phenomenon has not to our knowledge been observed, but data on stellar abundances are still very sketchy.

The relatively low abundances of the Irrs tell us that these systems are less evolved than most spirals, in the sense that the interstellar gas is less processed. Less processing, however, does not mean that the returning metals are not mixed throughout the system. Spectrophotometry of individual H II regions (cf. 191, 266, 340, 381) shows that the O/H and N/S abundance ratios are remarkably constant throughout the disks of Irrs. By whatever process, the metals in these galaxies are fairly well mixed over at least the optically prominent regions.

Correlations between the gas abundances and other global parameters would be expected to give us some clue as to why this particular morphological type of galaxy (the Irrs) would be less evolved and better mixed than most spirals. As already mentioned, except for the intergalactic H II regions, which are the most metal poor, the abundances do not separate according to the luminosity of the systems. There also do not seem to be any compelling relationships between metallicity and current stellar birthrate or galaxian spatial dimensions, and thus our hopes for an obvious clue to evolutionary processes go unrewarded.

The closed-system model with the instantaneous recycling approximation provides the simplest and most widely used galaxy chemical evolution model (268, 312, 339, 353). In this model, the metallicity of the gas is given by

$Z_g = y \ln(1/\mu)$, where y is the stellar heavy element yield and μ is the gas fraction, i.e., mass in gas per unit total mass (stars plus gas); thus a correlation between Z_g and gas fraction should exist. Since the Irrs are evidently well approximated by a single zone, they provide a good test for the applicability of the basic chemical evolution model to real galaxies. The upper half of Figure 3 is a plot of $\ln(1/\mu)$ against the abundance parameter O/H for high surface brightness Irrs (189, 191, 226, 340), for low surface brightness Irrs (189, 226, 340), and for luminous Irrs and blue compact systems (4, 120, 209). The parameter μ is computed for all objects in the manner described by Hunter et al. (191), where the gas mass is taken to be 1.34 times the total hydrogen mass and the mass in stars is estimated using the *UBV* colors to determine the M_{star}/L_V ratio from Larson & Tinsley's (220) stellar population models. Thus, the total mass is the mass in gas plus stars, rather than the often-used dynamical mass, which could include contributions from matter that does not partake in the chemical evolution. Clearly, no correlation is evident in Figure 3, in agreement with the similar study by Matteucci & Chiosi (238). Thus we see that while simple chemical evolution models provide useful qualitative insights, they do not quantitatively fit the observations.

There are several possible ways to modify the basic model. For example, in using the closed-system model one must consider over what region does the galaxy really behave as a closed system. Complications along these lines could include gas infall from the outer parts of the galaxy (55, 126, 238), gas that does not actively participate in the galaxy's chemical evolution (188), or ejection of metals from star-forming regions (146). In loosely bound galaxies, material ejected due to supernovae could be lost from the system entirely or rain back down on other regions of the galaxy (115, 346). These types of processes may allow us to understand the empirical correlation that exists between metallicity and dynamical mass in dwarf Irrs and extragalactic H II regions (191, 226, 238, 340). Thus it may well be that total mass is equally or more important than relative gas fraction in controlling Z_g. In this case the simplest closed-system models would not apply, and more specific models will be needed instead.

Stellar Populations

The blue colors of Irrs are generally taken to mean that a proportionally larger component of the stellar population consists of early-type stars (247, 248). This is consistent with the fact that the high surface brightness Irrs are endowed with numerous H II regions and are actively forming stars. Bagnuolo (15) and Huchra (178), for example, have fit the colors of Irrs with a composite between old and young stellar populations, while continuous star formation models have been computed by Searle et al. (313), by Huchra (178) and by Code & Welch (59).

Specifics of the OB star populations have been explored through IUE spectra that are now available for a variety of high surface brightness Irr galaxy family members (27–29, 179, 180, 219, 377; see also 47, 196). Generally the $\lambda\lambda 1150$–2000 Å UV spectra of Irrs show features consistent with rich OB star clusters having near normal IMFs, but there are important exceptions. On the basis of UV spectra, a case was made for a very massive superstar ($\sim 2 \times 10^3\ M_{\odot}$) in the core of the giant 30 Doradus H II complex in the LMC (52, 107, 305) and more recently for the somewhat similar NGC 604 giant H II region in the nearby spiral M33 (237). Even if we do not accept the presence of superstars in these systems (245a), it is clear that extraordinary concentrations of high-mass stars ($\sim 10^2\ M_{\odot}$) must be present to meet the ionization requirements and to fit the observed spectral characteristics. Giant H II regions are common in Irrs (169), and their possible relationship to very massive stars is now receiving careful scrutiny.

The low surface brightness dwarf Irrs present more of a problem with regard to stellar content, since they are also fairly blue but do not have the many obvious star-forming regions that characterize the high surface brightness systems. In general, the dwarfs seem to have stellar population mixes similar to those of the larger Irrs (81, 82, 160, 189), but the numbers of luminous stars are down in a manner qualitatively consistent with a lower total star formation rate (173, 185, 228, 295). Some dwarf systems have extremely blue colors and high surface brightnesses, perhaps indicating that bursts of star formation have recently been completed (158, 177, 178, 232, 313); detailed population studies of a few resolved galaxies support these viewpoints (57, 288).

The Irrs, therefore, are correctly noted for their young stellar population, but they also contain older stars. Only a few of the extreme "intergalatic H II regions" seem to be without a possible older stellar component (cf. 179, 312, 349, 377), but the nature of this older population and the number of previous generations of stars are not so clear. In the dwarf Irr VII Zw 403, for example, the metallicity of the gas is sufficiently low and the level of current star formation sufficiently vigorous that one is forced to doubt whether the galaxy could have formed stars in this vigorous way at an earlier stage (361). Nevertheless, the existence of a diffuse stellar component implies that an older population is in fact present. (Star formation histories are discussed in a later section.)

Many Irr galaxies are close enough that they can be resolved into individual stars. The LMC and SMC are, in fact, the best systems outside our own for studying stellar populations and support the concept of a nearly constant IMF in disk galaxies (see below). Beyond the MC, only intermediate- to high-mass stars can be individually observed at present, and aside from very luminous supergiants, only colors and magnitudes are available (187, and references therein). In more luminous Irr dwarfs, observed color-magnitude diagrams are similar in form, with pronounced blue and red supergiant branches well separated by a Hertzsprung gap (184–186, 202, 295, 296, 301). Massive stars evidently are present with relatively constant properties in Irrs, and thus the door is open to modeling the light from young stellar populations in terms of fairly standard components (as in 76, 180, 189, 191, 225).

Differences in OB stellar content between galaxies are largely explainable in terms of statistical effects, which can be quite severe in faint dwarfs, where OB star formation probably involves a series of time-disconnected discrete events (172, 288, 313). At the upper extremes of stellar mass, the situation is, as we have seen, less well defined; for example, the presence of many Wolf-Rayet stars in a small galaxy like Tololo 3 (216) might be due either to statistics or to special processes (e.g. very massive stars) in very large star formation events that are seen as giant and supergiant H II regions (169, 237). Finally, we point out that intermediate-mass stars become very luminous during the AGB evolutionary phase (see 193) and may be seen as resolvable stars in the diffuse light of Irrs (140), as long-period variables of interest to the extragalactic distance scale (387), and as major contributors to the infrared luminosity (272).

Star clusters provide further important clues to stellar populations in galaxies (e.g. 56), and currently they can be detected to distances of several Mpc in Irrs as a result of the open structures of the parent galaxies (155, 188). While numbers, sizes, and richnesses of star clusters vary from galaxy to galaxy (160, 167, 369), the clusters themselves are found to be remarkably similar in their integral optical stellar properties within such diverse Irr systems as the LMC (370a), M82 (257), and NGC 6822 (165, 372). The main variables affecting integral cluster observables are well known to be IMF, age, and chemical composition, although stellar richness can also be a significant factor (279). From color-magnitude diagrams of individual Magellanic Cloud star clusters it has been possible to calibrate approximately variations in global cluster parameters as a function of age for metallicity levels appropriate to most Irrs. Unfortunately, some disturbing inconsistencies remain in the details of the age scales (170, 249), and subtle differences exist between clusters and stellar evolution model predictions (26, 112, 113). Still, the analysis of LMC cluster photometry in the classic work of Searle et al. (314), as well as Rabin's (277) investigations of individual cluster spectra, assures us that among younger clusters age is the major determinant of spectral properties, while in very old clusters metallicity is a primary factor. Star clusters thus are a comparatively reliable means for unraveling the stellar age/metallicity strata that hold the histories of galaxies.

Studies of the Magellanic Clouds and other nearby Irrs reveal star clusters covering a full range of age classes, and thus these galaxies have been actively producing stars for at least several billion years (162, 167). Recently photometry has been obtained by Stryker (336, see also 338) down to the main sequence turnoff in the red LMC halo cluster NGC 2257. As this cluster contains a well-defined horizontal branch and RR Lyrae variables, the preferred age calibration method, developed by Rood & Iben (284; see Iben 192) and based on the distance-independent luminosity difference between main sequence turnoff and horizontal branch, can be applied to show that NGC 2257 is as old as Galactic globulars. Evidently the LMC produced or obtained star clusters from the same early epoch as the Milky Way. In contrast to the Milky Way, however, the Magellanic Clouds are still making globularlike star clusters, the "populous blue clusters" or "blue globular clusters" (156). Although there has been some resistance to considering these as total parallels to young globular clusters, LMC blue globular cluster masses lie in the range of 10^4–10^5 $M_\odot$ and therefore overlap with true globulars (58, 114, 118, 148, 254). These clusters are not unique to the Magellanic Clouds, and the luminous, near-stellar knot seen in actively star-forming regions of Irrs such as NGC 1569 or NGC 5253 (2, 84, 188, 189, 367, 370) may be populous stellar clusters in early evolutionary phases when OB stars and circumstellar gas are still present. It is therefore not appropriate to attribute the production of globular star clusters only to unique conditions in the early Universe (e.g. 85), but rather there may be a variety of channels for the formation of dense, spheroidal star clusters.

Not all Irrs, however, display the same small-scale spatial patterns of star-forming activity. At one extreme, the low astration rate dwarfs often lack rich clusters and pronounced OB associations, even when massive stars are present (e.g. 288, 301, 369). At the other extreme, some rapidly star-forming amorphous Irrs are also quite smooth in their optical appearances (125, 294, 300) and are pervaded by diffuse optical emission lines from ionized gas (84, 157, 188). It is quite clear that these galaxies may contain large complements of massive young stars, as evidenced by their high Hα luminosities and hot IUE ultraviolet spectra (219). The optically distinct, large star-forming complexes (OB associations, H II regions, etc.), which are the hallmark of most Irrs, are, however, missing. Perhaps in these systems the individual star-forming sites are overlapping or the stars are forming via a different mechanism than in most Irrs. But in either case, the amorphous Irrs illustrate that kinematically similar galaxies do not necessarily follow identical evolutionary paths.

STAR FORMATION PROPERTIES

Current Global Star Formation Rates

Measures of Lyman continuum photon luminosities, e.g. as determined from the Hβ or Hα emission lines or radio thermal fluxes, can be used to estimate the current rate of formation of massive stars. When coupled with an IMF such as from Salpeter (289) or Miller & Scalo (245), this information can yield the total rate at which gas is condensing into stars of all masses (143a, 319). If the emission flux is that for the entire galaxy, then the global star formation rate is known. Galaxy-wide star formation rates for Irr galaxies have been estimated in this fashion by extrapolating from large-aperture spectrophotometry (191), from flux-calibrated Hα images (126), from Hα photometry (205, 206), from radio continuum observations (195), and from UV luminosities (29, 86). For one galaxy, NGC 1569, the number of Lyman continuum photons determined from the radio observations is about 3 times higher than the number found from Hα emission. This is probably due to extinction within H II complexes, and thus optical measurements will usually yield underestimates of star formation rates (205).

The star formation rates determined in this manner are found to cover a wide range, but the average rate per unit area in high surface brightness Irrs is comparable to the Milky Way disk ($\sim 5 \times 10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{pc}^{-2}$; 330, 353, 364). If we consider the total rate of star formation per unit gas mass, the average high surface brightness Irr is again comparable to a typical spiral, although some Irrs are overachievers in this regard. (NGC 1569, for example, has a rate 30 times that of our Galaxy; 390.) It is important to keep in mind that the samples chosen for star formation rate studies have been intentionally biased toward high surface brightness, rapidly star-forming galaxies, and that there do exist low surface brightness dwarf Irrs that have very little current star formation activity (e.g. 57, 189, 288). Nevertheless, these studies show that Irrs exist that are uninfluenced by interactions or other outside perturbations and yet are actively forming stars. We must conclude, therefore, that *spiral density waves are not necessary to a vigorous production of stars.*

In order to understand the star formation mechanisms and the galactic characteristics that govern them, a search has been made for correlations between star formation rates and various global parameters. One might expect, for example, a correspondence between stellar birthrate and gas density such as in the Schmidt (308) empirical model in which star formation rate varies as the gas density squared. The higher the mean volume density in the interstellar medium, the higher the star formation rate would be. In practice it is difficult to ascertain from the observed projected density of interstellar matter the fraction that is in a proper physical state to produce stars. Furthermore, it is both the fluctuations and mean gas density that are important in producing stars, so we may expect some problems with this type of approach. From a study of spiral and Irr galaxies, Lequeux (222) concluded that the star formation rate actually decreases with increasing average gas density, while Guibert (142) found that if the star formation rate is proportional to a power of the gas density, the proportionality constant decreases with increasing gas fraction. Young & Scoville (391), on the other hand, suggest that in spirals the production rate of stars per gas nucleon is constant. In their study of Irrs, Hunter et al. (191) found no relationship between star formation rates and average H I gas density or gas mass, although Donas & Deharveng (86) do find a correlation with gas mass. Low CO fluxes from actively star-forming Irrs (95, 390) further indicate that no simple relationship exists between measurable *global* gas characteristics and current stellar production rates.

A few studies (86, 191) have also searched for relationships between star formation rates and other integral galactic quantities such as metallicity, total mass, the ratio of mass in stars to dynamical mass, and the H I mass per unit luminosity. No convincing correlations have been found. From this it is concluded that local parameters are probably more important than global ones in determining star formation patterns in noninteracting Irrs.

The manner in which these local processes interact, then, must set the global states of Irrs. Unfortunately, the mechanisms that provide coupling between star formation sites are not known and may not include the traditional local moderators of star formation processes: gravitational and magnetic instabilities. Galactic-scale magnetic fields probably are present in Irrs, as evidenced by organized interstellar polarization in the Magellanic Clouds (198, 309), and potentially play an important, although as yet poorly defined, role in large-scale star formation processes (96, 250, 251). Gravitational instabilities against axisymmetric perturbations have also been proposed as drivers of global star formation in disk galaxies (see 143, 255). Both gas and stars in Irrs, however, have typical velocity dispersions of $\sigma \sim 10$ km s^{-1} (105, 119, 182, 183) and therefore by the usual criteria (356, 357) are safely stable unless the dispersions are highly anisotropic. The most probable mode of interaction in star-forming processes within Irrs is thus through modifications of conditions in the interstellar medium, which can be induced by the young stars themselves.

Distributions of Star-Forming Regions

Irregular galaxies, particularly high surface brightness Irrs, are noted for and defined by the rather chaotic spatial distributions of their star-forming regions (cf. 164). Correlations in the distributions and spacings of H II regions seem to be lacking, but there do seem to be a few significant chains of H II regions that are probably coeval (188). This indicates, as does the presence of ill-defined "spiral arms" in some systems, that the star formation mechanism is not entirely random. In Irrs with bars, for example, large star-forming regions often occur at one end of the bar, posing the possibility that gas flows due to the bar may be important there (98, 106).

In spite of the apparent chaos, star-forming regions are not uniformly distributed over the disks of the Irr galaxies; instead, they seem to be asymmetrical and clumped on large scales. Hodge (159) interpreted the clumping in terms of localized star formation bursts on a scale of ~ 1 kpc, and the major star-forming regions then must migrate around a galaxy with time. This effect can also be seen from the distributions of star clusters in NGC 6822 and IC 1613 (167) and of the Cepheids in the LMC (92, 269); the main star-forming centers of the recent past ($\sim 10^7$–10^8 yr) are in different locations than currently active regions. Large-aperture spectrophotometry centered on the most active areas of Irrs also shows that the star formation rates are too high and the metallicity and gas content too low for star formation to have always continued *in that region* at the current rate (191). Furthermore, in galaxies such as NGC 3738, NGC 4214, and NGC 4449, one can identify large complexes that obviously recently supported star formation but that are now in decline (188). In fact, the H II complexes typically cover less than 4% of the optical areas of Irrs; thus each position in a galaxy probably experiences a major star formation event once every 10^8–10^9 yr. This shifting of the major centers of star formation seems physically reasonable, since the star formation process must certainly deplete the local cool gas. But why star formation would necessarily clump on the observed scales and whether it migrates in a systematic manner are not known.

In addition, we do not find bright H II regions out to the optical "edges" of Irrs. That is, typically the current activity is within the inner 60% of the blue optical dimensions given in the Uppsala General Catalogue (UGC, 254a). A few extreme galaxies, such as NGC 5253, seem to be forming stars mostly in their central cores, although star formation obviously did occur in the outer parts of NGC 5253 at some time in the past (370). It is possible that areas outside of the active central zones no longer have gas above the critical density necessary for star formation, and so these galaxies will never form stars in their outer regions again (see below). However, an alternative possibility is that star formation in these less dense outer regions of Irrs is continuing but in a more diffuse manner. This is analogous to the problem of the dwarf Irrs, which also lack the giant H II complexes and large OB associations: Is star formation temporarily absent, or instead is the process of star formation different (i.e. higher mass stars and/or clusters are not formed)?

Star-Forming Complexes and the Interstellar Medium

The great star-forming complexes found in Irrs are very similar to those associated with giant H II regions in spirals, as in M33 or M101 (188, 189, 377). This includes their optical properties (225), ultraviolet spectra (180), sizes (188, 203, 204, 297–299), kinematics (compare 188 with 285), and morphology (Hunter & Gallagher, in preparation). These similarities indicate that once a gas cloud complex is stimulated or naturally reaches a stage where stars will condense, the region forgets what kind of galaxy it is in, and that the upper limit to star-forming cloud complex sizes is similar in spirals and Irrs. In addition, Hodge (169) has demonstrated that the distribution of sizes of all H II regions in a galaxy can be fit by an exponential law, although this fit steepens for less luminous parent galaxies. The giant H II regions in some Irrs are then found to be anomalously large relative to this distribution, and therefore they could result from special (but common) cloud formation processes (98).

There are also some differences between the interstellar mediums of Irrs and spirals. First, the Irrs appear to be deficient in large, dense interstellar clouds as judged from the low optical visibility of dark clouds, although a few dark nebulae are clearly present, especially on smaller spatial scales (161, 163, 165, 166, 188). Star-forming regions in the Galaxy and in spirals are most often adjacent to dusty areas that mark molecular clouds (97), so a dearth of dark clouds in star-forming galaxies is unexpected. An examination of blue and red passband images, Balmer decrements, and optical- and radio-determined star formation rates shows that even in and around star-forming sites, optical interstellar extinction in Irrs tends to be low [maximum $E(B-V) \lesssim 0.5$ (188, 191, 340); for the Magellanic Clouds, see, for example, 89, 111, 184, 186, 234, 271]. This may be in part a reflection of the underabundance of heavy elements, which certainly results in some modifications of dust properties (e.g. 283a, 306). In addition the low surface brightnesses and irregular light distributions could hinder the detection of dust in Irrs. A lack of extensive regions of high column density gas, however, is probably the main factor. The notable exception among Irrs is the peculiar galaxy M82, which is loaded with dust even as compared with spirals, although M82 is also relatively metal rich (257). Why some galaxies have optically obvious dust clouds and others do not and how the presence or lack of dark clouds affects the star formation processes are not known, since high and low star formation rate examples of both extremes are known to exist.

Furthermore, the high surface brightness Irrs are underluminous in CO molecular microwave emission relative to regions in spirals with similar luminosities and stellar content (95, 135a, 390). Although the global quantity of molecular matter evidently is down, the presence of vigorous star-forming regions in Irrs argues that on local scales the molecular clouds are normal. It is possible that the current star formation activity has disrupted most of the parent clouds, but then we should find systems with a reduced star formation rate that are full of CO clouds. An alternative is for diffuse molecular clouds to be comparatively short lived in Irrs, which is possibly related to the low specific angular momentum of Irr disks. If molecular clouds formed in low angular momentum environments in fact collapse more readily than in spirals, then in a *local* sense Irrs may be more efficient star-formers than spirals, despite the absence of dynamical forcing by arms. This could explain the anomalous presence of spectacular star-forming complexes (e.g. giant H II regions) in otherwise undistinguished galaxies (but see 35). Refueling from outer gaseous reservoirs (disks, halos; 126) or differences in the thermal structure of the interstellar medium are also important factors in determining the state of interstellar matter that potentially could differentiate Irrs from spirals.

The Initial Mass Function

The lack of understanding about the IMF (initial mass function) is a serious stumbling block in the study of galactic star formation histories (see 307 for a comprehensive review). The Magellanic Clouds are the only systems that are sufficiently near to check the IMF outside of the Galaxy, although as we noted earlier, massive star populations are relatively similar in most nearby Irrs. An inventory of Magellanic Cloud supergiants by Dennefeld & Tammann (69), for example, indicates that the stellar component of masses $\gtrsim 9\ M_\odot$ is not radically different from the Galaxy (see also 223, 224, 296). Deep luminosity functions measured in the LMC by Butcher (46) and Stryker & Butcher (337) extend this conclusion to $\sim$1–3 $M_\odot$ stars. The presence of classical Cepheids (269) and RR Lyrae variables (138, 139) in the Magellanic Clouds further shows that stars covering a range in mass from 1–10 $M_\odot$ have evolved off the main sequence. Cepheids also have been observed in several other Local Group and nearby Irrs, but only in IC 1613 are the numbers sufficient to probe the stellar content (291), which is found to be like the Magellanic Clouds (25, 240). Thus the stellar mixes of the Magellanic Clouds are surprisingly similar to those of the disks of spiral Local Group members (144, 145), although there are hints from the luminosity functions that the star formation rates are not smooth functions of time in either the LMC or SMC (147, 337).

If the IMF is to be different in the Irrs, we require that high surface brightness systems with extreme blue colors and strong emission lines be overabundant in high-mass stars, while the low surface brightness Irrs have fewer massive stars. In making such comparisons, however, one must distinguish between changes in the form (e.g. slope) of the IMF and statistical effects, i.e. very large star-forming events naturally will produce many massive stars. The similarities between the large H II complexes in Irrs and those in other types of galaxies give no reason to expect that local environments are sufficiently diverse that a different IMF would result. Hence, we are reluctant to invoke an unusual IMF when there is no compelling evidence for it. Terlevich & Melnick (347, 348) have argued that there is a systematic variation of the IMF with metal abundance, such that more metal-poor systems have flatter IMF slopes, but their approach to this problem is still controversial (cf. 124). Some effect of this type may, however, be necessary to explain the correlation between ionization level and metallicity that exists in H II regions. Below, we discuss further evidence that a normal IMF is at least consistent with the evolutionary histories of typical Irrs. However, we do not know over what time or spatial scales it is necessary to average the stellar populations in order to obtain the "normal" IMF. It is possible that during galaxy-wide bursts of star formation, conditions may be such that this spatial- or temporal-averaging process is disrupted, and a peculiar IMF results.

Usable Gas

In measuring star formation rates and other parameters that depend on the gas content, the gas mass used is the total mass *detected*. The proper value to consider is really the mass that has the potential to engage in star formation. Irrs often have halos of neutral hydrogen extending to several optical diameters. An extreme example is the dwarf Irr IC 10, which has a hydrogen envelope 20 times its optical diameter (326); however, this galaxy suffers heavy Galactic extinction, so it is possible that the optical size has been underestimated. It is not clear that this outer gas necessarily participates in the star formation process (an idea suggested for M33 in 235). If such is the case, our concept of the Irrs as systems that homogeneously evolve as a single spatial unit must be altered.

In a sample of 21 Irrs (mostly low surface brightness), Huchtmeier et al. (183) found that the FWHM of the H I distribution occurred at the Holmberg radius but that H I usually extended to several Holmberg radii at a density of $\geq 10^{19}$ atoms cm^{-2}. Spirals, on the other hand, can have H I values to 1.5 times the Holmberg dimension at 10^{20} atoms cm^{-2} (37, 38). However, there are important exceptions. NGC 4449 still has a column density $\sim 10^{20}$ atoms cm^{-2} at 4 times its Holmberg radius (376) and IC 10 at 2–3 times (326). Yet, in neither galaxy is there direct evidence for ongoing star formation at such large radii. All of this suggests that much of the gas in the outer parts of many Irrs may not be able to contribute to the star formation as effectively as the inner gas. This provides the empirical basis for our earlier assumption that condensation of at least detectably young OB stars is a threshold phenomenon that does not occur (or takes place with much lower frequency) in gas below a critical density (94, 244). Based on the data for spirals given by Bosma (37, 38) and the properties of Irrs, a rough empirical guess is that gas in H I disks is below the OB star formation threshold density when $\sigma_{\rm HI} \lesssim 5 \times 10^{20}$ atoms cm^{-2}.

STAR-FORMING HISTORIES

Constant Star Formation Rates

The localized bursts of star formation that characterize Irrs do not necessarily imply galaxy-wide bursts of activity; the global mean rates could still be constant while local variations are large (cf. 223). Gallagher et al. (126) have explored the star formation histories of a sample of high surface brightness Irrs chosen for their blue colors by considering parameters that measure the stellar birthrate over different time scales: The galaxian mass is a clue to the astration rates integrated over the galaxy's lifetime, the blue luminosity is dominated by stars formed over the last few billion years, and the ionizing photons give the current rate. They found that for most Irrs these parameters are consistent with a constant mean rate of star formation and IMF over the galaxy's lifetime, in agreement with results for the Magellanic Clouds (e.g. 283).

Few Irr systems seem to be undergoing honest global star formation bursts, i.e. only in unusual circumstances does the current global stellar production rate exceed the lifetime average rate (126, 191, 223, 283). In addition, Hunter (189) showed that the time scales to exhaust the present gas content at current astration rates and the metallicities were also consistent with constant stellar birthrates *if* all of the detected gas readily participates in the system's evolution. These results stand in contrast to studies based on colors and emission-line properties in which bursts and peculiar IMFs are found to be a normal feature of blue galaxies (see the following section). We are not currently able to reconcile these conclusions, although galaxy sample selections, data characteristics (i.e. local vs global measurements), and possible problems with stellar population models are all factors that may lead to differences.

If stars are formed at constant rates in Irrs, what does this imply about these galaxies? As we have seen, there is empirical evidence that gas densities must exceed some critical value for star formation to proceed at normal levels. A constant stellar birthrate then implies that a galaxy must maintain a constant amount of gas above this critical density, in a state suitable for starbirth, even as gas is continually being locked into new stars. How then does a galaxy manage to keep shuffling the same amount of gas into stars? We would expect that as more and more gas was turned into stars, the overall gas density would drop and the star formation rate would decrease. Thus the standard models predict that star formation should steeply decline with time in all galaxies (94, 126). This difficulty can be avoided either by postulating a continuous resupply of gas to star-forming regions, i.e. by maintaining constant average gas density (126, 221, 253), or by presuming the star formation rate is not solely dependent on mean gas density. Models of the former type require gas inflow from a halo or outer disk, which has never been confirmed by direct observation. In the latter class of models, the star formation rate must not depend on the total amount of gas. For example, the production of dense interstellar clouds from which stars are born could be the controlling factor and could be set by the OB stars themselves (e.g. 324).

A complementary question concerns the early stages of formation of an Irr. Given that the global star formation rates in the past might not have exceeded current levels by much, and that most Irrs probably formed as gravitationally bound entities at approximately the same time as other types of galaxies, then it seems that these systems managed to collapse into rotating "puddles of gas" before beginning serious star formation. Star formation in the earliest phases of galaxy evolution is still a heated issue with regard to all types of galaxies, and as Irrs represent the extreme end of the "late-bloomers," they should provide an important point for empirical comparisons with galaxy formation models.

Bursts of Star Formation

In spite of the previous section's tone, it is clear that a constant stellar production rate does not fit the evolution of all Irrs. Repeatedly in the literature, people find themselves forced to conclude that the current global astration rate in a system is much higher than it used to be. Bursts have been suggested for various high surface brightness Irrs from a comparison of evolutionary models of stellar populations with observed broadband colors for late-type galaxies (15, 220, 313, 333, 349), from colors and emission-line strengths in Markarian galaxies (177, 178), from population studies for the Magellanic Clouds (8, 43, 122, 168) and M82 (257), from metallicity enrichment rate arguments (4, 225, 226, 258, 361), from radio observations of Markarian galaxies (33, 148a), and from star cluster studies of NGC 5253 (370), to name a few examples. Similarly, amorphous galaxies such as NGC 1705, which appear to be involved in OB star formation at high rates over most of their optical dimensions, are likely to be in burst phases (22, 219), as are clumpy Irrs (66). It is also evident from the prevalence of very blue galaxies in binary systems that interactions affect star formation processes and may stimulate bursts (10, 11, 31, 201, 220).

It is not immediately obvious, however, how seriously one should take the evidence for star formation bursts as a *general* evolutionary feature of noninteracting Irrs. The formation of OB stars, after all, occurs via gravitational collapse in interstellar cloud complexes, a process that produces spatially compact OB associations and star clusters. Thus, as Searle et al. (313) explicitly recognized, star formation is an intrinsically grainy process, and in small galaxies the normal evolution should proceed as a series of "bursts" associated with the appearance and decay of individual star-forming complexes (cf. 86). These statistical effects will be most important in small galaxies, since the blue luminosities of single star-forming complexes probably do not much exceed $M_B \sim -15$ (388) and spatial sizes of ~1 kpc (170, 188). Star formation bursts in small galaxies therefore do not necessarily indicate any evolutionary anomalies. There are also some difficulties in interpreting the empirical evidence for bursts in any galaxies: With metallicity enrichment arguments, one can raise the questions of whether the system is closed and what volumes of gas must be considered (see previous discussions); and with colors, one can say that the evolutionary path to any set of optical colors is not unique. Despite these problems, it is still clear that even some nearby, noninteracting Irrs cannot be explained without global star formation bursts [e.g. NGC 2915 (320), Haro 22 (126)]. In NGC 1569, for example, OB stars are spread over an area of many kpc (84, 188, 191), the current star formation rate is 10 times higher than its average past rate (126), and the optical luminosity is more than 10 times the single event maximum. Alternatively, if galaxies like NGC 1569 are not bursting, then they must be peculiar in other ways, i.e. they must be young or have an unusual IMF that favors production of OB stars.

The existence of Irrs currently undergoing global bursts of star formation implies that (*a*) some mechanism must exist to organize star formation on large scales, and (*b*) there must be Irrs of the same basic types as bursters that are not now active. In fact, we should see systems in all phases of postburst decays. The low surface brightness, low star formation rate dwarf Irrs come immediately to mind as postburst candidates. These systems may have had higher star formation rates in the past, but spectrophotometric data indicate that the metallicities and the stellar populations are not consistent with the picture of their being the low star formation rate states of high surface brightness Irr galaxies (189).

High and low surface brightness Irrs, in fact, seem to have experienced parallel recent evolutionary histories that have produced similar integral properties, such as gas metallicities and stellar population mixes. These galaxies thus primarily differ as a result of stellar surface density, but it is also noteworthy that lower surface brightness Irrs rarely contain luminous star-forming complexes (and when exceptions occur, as in NGC 2366, they are obvious but do not change the overall surface brightness). Perhaps factors such as gas density prevent the low surface brightness dwarfs from forming gas clouds in the size and quantity necessary for large star-forming complexes, which are typical of high surface brightness Irrs. In NGC 6822, for example, many H II regions are small (211), and only a few H II regions require more than a single O star for their ionization (137). Based on the Hodge (170) study of H II region sizes in Irrs, this situation seems to be typical. Star formation in dwarfs evidently proceeds in an unspectacular manner due to the lack of giant star-forming complexes. This results in low surface brightness dwarfs having followed approximately the same evolutionary paths as giant Irrs, in agreement with the observations, but leaves the issue of descendants of global burst Irrs unresolved.

SSPSF: A Possible Model

Much work has been done on the theory of density-wave-induced star formation in spiral galaxies, but it is only recently that the first major theory of global star formation processes applicable to Irrs was developed. The stochastic self-propagating star formation (SSPSF) model is one in which star formation is continued through the energy dumped back into the interstellar medium by evolving massive stars through H II region expansions, stellar winds, and supernovae (for a review, see 316). Theoretical models of galaxian evolution with this mechanism were first computed by Mueller & Arnett (252) and have been developed extensively by Gerola, Seiden, and collaborators (130, 131, 315) as well as others (64, 116).

In the SSPSF models of Gerola & Seiden, a two-dimensional galaxy is divided into cells that represent the average size of distinct star-forming complexes; Comins (64) has extended this approach to three dimensions. The probability that a cell will form stars is greatly increased if an adjacent region formed stars in a previous time step, i.e. star formation stimulates further star formation as suggested by Öpik (256). Once a cell has formed stars, it is initially unable to produce any further stars, and the probability of further star formation thereafter increases as a function of time corresponding to the replenishment of cool gas supplies.

Models of low-mass galaxies with little or no differential rotation (64, 108, 131) produce systems with chaotic morphologies and properties (metallicity, stellar content, etc.) that depend primarily on the ratio of galaxy size to the size of star-forming cells. A smaller galaxy has a low average star formation rate, but the rate fluctuates widely between bursts and quiescent levels as cells individually and in small groups experience star formation. Larger systems exhibit a more constant and higher mean star formation rate and display more morphological structure as sites of current star formation activity move around the disk. Because of their higher mean star formation rates, the larger galaxies will be more evolved and hence have higher metallicities and lower fractional gas masses. Even in larger galaxies, however, collective effects can lead to significant nonrandom time variations in total stellar birthrates (317), which could explain the existence of luminous systems in apparent burst states.

Quantitative comparisons between the SSPSF models and observations are not easy. Measurements of the sizes of Hα complexes in nearby (<10 Mpc) high surface brightness Irrs indicate that the concept of an average "cell" size may not be entirely arbitrary (169, 188, 203, 204, 297). Therefore, the models predict that for a fixed cell size the gas fraction and average metallicity should correlate with galaxy size. In fact, no clean relationships are seen, although very small galaxies do tend to be the most metal poor and gas rich (189, 190, 238). Similarities between the mean colors of galaxies covering a considerable range in optical size also present a problem for basic SSPSF models. *Morphologically* the models reproduce reasonable Irrs. Star formation in many Irrs is *not* observed to be purely random, and any successful model must account for this fact. But SSPSF is not a unique answer. Ultimately the local gas characteristics, such as density, will determine when and where the star formation occurs. The origin of these density fluctuations could be associated with a variety of other mechanisms, such as the global velocity field, gas infall, magnetic field structures, etc., which could also act to organize star formation.

Direct evidence for propagation of star formation from one cloud complex or cell to a neighboring cell is lacking. The simplest version of SSPSF, in which star-forming events directly stimulate preexisting analogues to interstellar clouds, therefore may not apply to real galaxies. Sequential star formation within a cloud complex has been observed in the Galaxy (cf. 217), which *could* be interpreted as star-induced star formation, but again this is *within* a cell rather than between cells. Measurements of the energetics of H II regions show that considerable amounts of energy from massive stars are being dumped back into the interstellar medium (cf. 188). And we can see in nearby galaxies that the process of star formation does have a large effect on the interstellar medium; H I holes centered on NGC 206 in the M31 spiral (40) and the LMC's Constellation III (243, 383), as well as the supershells in our Galaxy (152), are examples. However, we still do not know what ultimate effects star formation may have on interstellar gas and whether these are sufficient to allow star formation to propagate on galactic scales. Until this problem is overcome, SSPSF will not be on a physically sound basis, although it should be emphasized that this theory provides a very general framework (316, 324, 325) in which the role of feedback (either positive or negative) in star formation processes can be readily examined.

EVOLUTIONARY STATUS

Even though Irrs are less evolved than most types of luminous galaxies, they are normally far from being in primordial states. Intermediate metallicity levels, modest gas-to-stellar-mass ratios, and strongly composite stellar populations found in the average Irr are indicative of maturity levels that have required billions of years to achieve. Similarly, stars and gas in all but the smallest dwarfs are in flattened disks and are largely supported by rotation. Thus considerable dissipation of energy has likely occurred since a purely gaseous protogalactic state, and sizes of present-day Irrs therefore reflect the angular momentum and density distributions as well as the extent and mean density of their pregalactic progenitors (101, 117, 327, 328). The smooth rotation properties in the outer disks of *many* (but not all) Irrs further indicate that a few rotation periods (which are in some cases $\sim 10^9$ yr) have elapsed since outer H I disk formation. Most irregulars therefore are probably old systems that formed as gravitationally bound entities $\sim 10^{10}$ yr ago, but we should be aware of possible exceptions. Metal-poor extragalactic H II regions are potential young galaxy candidates, and in some instances they have the disorganized, multiple gas cloud structures that are expected to characterize newly formed galaxies (21, 225, 227, 377). These small systems, however, could be old, but due to their low masses they have simply needed very long times to become dynamically organized and produce stars (cf. the multiple H I cloud structure of the SMC; 242).

Other exceptions to the above "late-bloomer" model are found primarily among the most luminous of the Irr family, i.e. giant blue compacts and clumpy irregulars. These systems have moderate-to-solar metallicities (36, 120, 342; Gallagher, Hunter & Bushouse, in preparation) and rotate at velocities similar to spirals, but they produce OB stars on incredible scales and in chaotic fashions that lead to Irr morphologies (66, 273, 274). The processes that cause such extreme (and probably transitory) evolutionary events in spirallike galaxies are not known, but they could include interactions with other galaxies or external agents (e.g. 220; many luminous Irrs are in binary pairs), major internal instabilities, such as relaxation of nonaligned gas disk components (90, 322), or delayed galaxy formation (e.g. 344). In any case, the existence of luminous Irrs and possibly related bursting Irr galaxies serves to remind us of the point stressed by van den Bergh (367): The evolution of galaxies may not be smooth in time, but instead may proceed by leaps and bounds in the form of postformation eruptions of star formation that dramatically and quickly alter the states of galaxies.

Most Irrs, however, are not in star formation burst phases, but rather they are evolving at nearly constant rates. Even though the mechanisms that produce such equilibrium behavior are not understood, it is clear that *local* processes play an extremely important role in the evolution of Irrs, probably through cumulative effects of many independent star-forming events or collective interactions between star-forming cells as envisioned in SSPSF theories. In the absence of strong differential rotation or dynamical forcing by spiral arms, these processes naturally lead to galaxies with Irr characteristics, i.e. astration is *globally* comparatively inefficient and star-forming complexes are distributed with a high degree of randomness. These features, furthermore, are not sensitive to details of galactic structure; it is then understandable that Irrs are found with remarkably uniform properties among slowly rotating galaxies over a range of $\sim 10^3$ in mass and that they predominate among low-mass disk galaxies.

The common dwarf Irr systems thus ultimately stem from the tendency for density and degree of central concentration to decrease in tandem with mass in disk galaxies, i.e. low-mass disk systems are slow, near-rigid-body rotators. A similar strong correlation between stellar mass and central density is found in diffuse dwarf elliptical galaxies (160, 293). Evidently the link between mass and density is nearly a universal property among galaxies with $M \lesssim 10^{10}\ M_{\odot}$, independent of morphological type, level of star-forming activity, or environmental factors (e.g. cluster vs field locations). This implies that initial conditions are crucial in determining fundamental properties of less massive galaxies, and that later environmentally induced modifications either have not been very common or have failed to produce major structural modifications.

Furthermore, as dwarf and luminous galaxies apparently have similar, clumpy spatial distributions within the Local Supercluster (362, 380), most regions of space must have produced a large range of galaxy masses, i.e. dwarfs do not originate from special initial conditions. Indeed, some would view the extreme dwarf Irrs as being representative of the types of individual bound fragments from which all galaxies initially arose (see 327). In this regard it is interesting that bound systems consisting only of cool gas (i.e. objects that contain H I but have undergone little or no evolution) are evidently extraordinarily rare (if they exist at all), even among the least massive galaxies (230). The characteristics of extreme dwarf Irrs may also provide useful tests for models in which galaxy formation is explosively induced (194, 260), since this mechanism naturally yields a lower cutoff mass for galaxies, which should be observationally accessible (261).

On the other hand, Irrs are fragile and thus easily influenced by external factors. Indeed, they are often observed to have been affected by close passages near giant galaxies. It is also possible that the seas of diffuse dwarf ellipticals that populate regular clusters of galaxies (278, 293, 385) represent systems that initially formed as dwarf Irrs but were later transformed into stellar fossils as a result of gas removal by the hot intracluster medium via processes such as stripping or thermal evaporation (see 39, 384). Alternatively, initial conditions at or near the time of formation may have separated low-mass galaxies over a spectrum of star formation rates (125, 293, 368), in which case initial conditions were simply not the same in regions destined to become regular clusters and in the much broader general field.

Interactions with the environment, however, need not always be destructive. Violent disruptions suffered by massive galaxies or their companions during deeply interpenetrating collisions or mergers yield sizable fragments that later can become independent dwarf galaxies, perhaps even gas-rich ones of the Irr type (129, 311). Populations and structural-type distributions of small galaxies therefore will be in a constant state of flux, and observational programs directed toward studies of Irrs in a wide range of settings are of considerable interest. The still unsolved problem of the relative importance of environment vs initial conditions ("genetics") in determining traits of galaxies thus extends to the Irrs. Since these galaxies are vulnerable and relatively uniform in their properties when in undisturbed states, comparative studies of Irrs in a range of environments have the potential to allow an empirical solution of this sticky issue.

By combining this information with an improved understanding of internal evolutionary processes, it should also prove possible to develop models for the initial states of Irrs. There are grounds for optimism about this task, since these low-density systems are probably closer to their protogalactic predecessors than are their dense spiral relatives. Thus somewhat paradoxically, Irr galaxies, which are dominated by young stars, are likely to be excellent stepping stones to the epochs of galaxy formation.

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