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STELLAR POPULATIONS AND STAR FORMATION IN IRREGULAR GALAXIES*

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ABSTRACT

We review and intercompare data on various morphologically-chosen groups of irregular galaxies in order to understand the underlying physical mechanisms that differentiate these systems. We particularly discuss the observational clues to the stellar content, star-formation processes, and star-formation histories of these galaxies, with an emphasis on the uncertainties and the many unanswered questions.

Key words: irregular galaxies–star-formation rates–morphology of galaxies–stellar populations

I. Introduction

A perusal of the *Hubble Atlas of Galaxies* (Sandage 1961) can convince one that, even within the great family of normal spiral galaxies, there is a large variety of structures. As you glance from the Sa-type spirals to Sb to Sc, you can see the nucleus becoming less pronounced and from the Sc to Sm galaxies the spiral arms become increasingly ratty until eventually you reach the group of irregular galaxies which Hubble (1926) described as "lack[ing] both dominating nuclei and rotational symmetry." The irregular galaxies are the end of the galaxian line, at least in terms of the Hubble sequence. However, the transition from spiral to irregular morphology is a smooth one, and the noninteracting irregular galaxies that we will emphasize in this paper comprise a class of *normal* disk-like systems (cf. de Vaucouleurs 1959).

The irregular (Irr) galaxies then are defined by their lack of organized optical structure (cf. de Vaucouleurs and Freeman 1972). Compared to most spirals, they also tend to be smaller, less massive, less luminous, and bluer. The large fraction of their mass still in the form of neutral hydrogen gas and the moderately low metallicities of the gas suggest that Irr's are less evolved than most spiral galaxies. The Irr's therefore, provide a different sort of system in which to investigate processes of galaxian evolution. In addition, the lack of arms of organized star formation which so typify the spirals makes the Irr's much simpler systems in which to study the processes of star formation and the relationship of star formation to other properties of the galaxies (cf. Bok 1977). Furthermore, by restricting our attention to galaxies which are not engaged in interactions with companion systems and which are not part of a dense cluster of galaxies, we are assured that the processes we are investigating are internal to the Irr's.

In spite of the growing body of data on Irr galaxies it is clear that we are only just beginning to understand these systems. In this paper we review our current view of Irr galaxies in terms of their stellar populations and star-formation processes, the questions that they pose, and why these galaxies are so interesting. This is not intended as a comprehensive review of the literature or of all aspects of Irr's, but it is more of a summary of the data that we have gathered on various groups of Irr galaxies. For a more-detailed survey of the literature see Gallagher and Hunter (1984). In the next section we will discuss the selection of galaxies and in Section III summarize their basic global properties. Sections IV through VII then deal with as-

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pects of the stellar populations and star-formation processes.

II. Sample Selection and Complications

The term "irregular" has been used in the literature to describe a wide range of types of galaxies including peculiar and interacting systems. However, there is a group of normal, noninteracting, intrinsically irregular galaxies which form a surprisingly homogeneous family (with some complications; see also Hodge 1975). There are two basic morphological subdivisions of the Irr class: the Magellanic-type Im's which are noted for their resolution into stars and star-forming regions and the smoother, amorphous Irr's. The latter group, often called I0's, is actually a broad collection which includes diverse systems. We will consider here a subclass of this group defined by Sandage and Brucato (1979) which they refer to simply as "amorphous". This group is distinguished from the morphologically similar ellipticals by their blue colors, intense emission lines, and relatively steep radial intensity falloffs. The Im class is defined by the nearby Large and Small Magellanic Clouds (LMC and SMC). However, the Magellanic Clouds themselves are not full members of our sample because of their close proximity to each other and to the Milky Way and the possibility, therefore, for effects due to interactions. The Irr's are sometimes further subdivided, somewhat artificially, on the basis of stellar surface brightness. Generally speaking, the low surface brightness Im's are known as "dwarf" Irr's, and we will therefore call the high surface brightness Im's "giant" Irr's. Note, however, that "dwarf" is most used to refer to low-luminosity ($M_B > -16$) systems (Tammann 1980) which is not necessarily the same criterion as surface brightness which we will use in this paper.

Our intention is to divide the Irr's we have observed into various groups whose properties can then be compared with each other and with spiral galaxies. Understanding the underlying physical mechanisms that differentiate even closely related types of galaxies is important to our understanding of global galaxian processes in general. We have not always been careful about this in the past. In particular, the Hunter, Gallagher, and Rautenkranz (1982) study of giant Irr's also includes some peculiar spirals and interacting systems chosen because they were blue or morphologically interesting. However, for purposes of intercomparing properties of galaxies, it is important to attempt to start off with samples which are homogeneous according to some criterion so that one can see the intrinsic scatter in that type of system and the relationship between different types of galaxies.

The dwarf Irr sample comes from van den Bergh's (1959) survey of low surface brightness galaxies, and the systems were selected from Fisher and Tully's (1975) H I survey on the basis of their morphological classification as Irr. (Fig. 2(a) below shows the distribution of galaxies in our samples with surface brightness to emphasize this distinction.) Although this group was chosen solely on the grounds of stellar surface brightness rather than on their being in either the amorphous or Im subgroups, none can be said to truly belong to the amorphous subclass of Irr's.

Of the high surface brightness systems the majority in our sample are also Im rather than amorphous-type. Most morphological classifications of galaxies are made on the basis of broad-band images which include background stars and H II regions. Since we are particularly interested here in investigating star-formation properties of Irr's, we have emphasized the morphology of the ionized gas, which we take as a tracer of star-formation sites. Based purely on continuum images, for example, some of the amorphous Irr's would be classified as ellipticals. However, all four of what we have binned as amorphous Irr's in our sample (NGC 1140, NGC 1800, NGC 4670, NGC 5253) are characterized by a single, very large blob of ionized gas more or less at the center of the galaxy. NGC 1140 and NGC 1800 also have a little Hα "tail" coming out from the center. Although Hα images of the amorphous systems show very little resolution, on long-slit echelle spectrograms we can see kinematically distinct units of ionized gas in NGC 1800 although not in NGC 1140 and NGC 4670.

Sorting galaxies on the basis of morphology is obviously not without ambiguities and complications. The further away a galaxy is, for example, the less resolved its features will be. Emphasis has been placed in our samples on objects that are relatively nearby, i.e., within $\sim$10 Mpc, so that at least the larger star-forming regions should be resolved. However, we do include some galaxies in the giant Irr category that are more distant, up to 40 Mpc. NGC 4449, with its many star clusters and H II regions, serves as the archetype giant Im in our sample; and it is at a distance of about 5.4 Mpc. (We assume $H_0 = 50$ km s^{-1} Mpc^{-1} throughout.) In Figure 1 we show an Hα CCD image of this galaxy and compare it to the same image which has been smoothed to mimic the resolution of that galaxy at a distance 4 and 12 times further away. Clearly the star-forming regions begin to blend together, and the galaxy resembles more an amorphous-type Irr (see Fig. 5 and Hunter (1982*b*) for stellar continuum images of this and other giant Irr's). NGC 3738, a smaller Im at the same distance as NGC 4449, is also shown. It quickly loses all features, and resembles more a compact intergalactic H II region.

The main difficulty in binning galaxies from our data sets then lies with the high surface brightness Irr's which are moderately distant ($\geq$ 10 Mpc), appear relatively smooth in continuum images, and have only a few distinguishable H II regions. Are these poorly resolved or less active Im's or are they amorphous systems? Galaxies like NGC 1012 (at 22 Mpc) and NGC 3952 (at 30 Mpc), for example, contain only two big Hα clumps, but we have

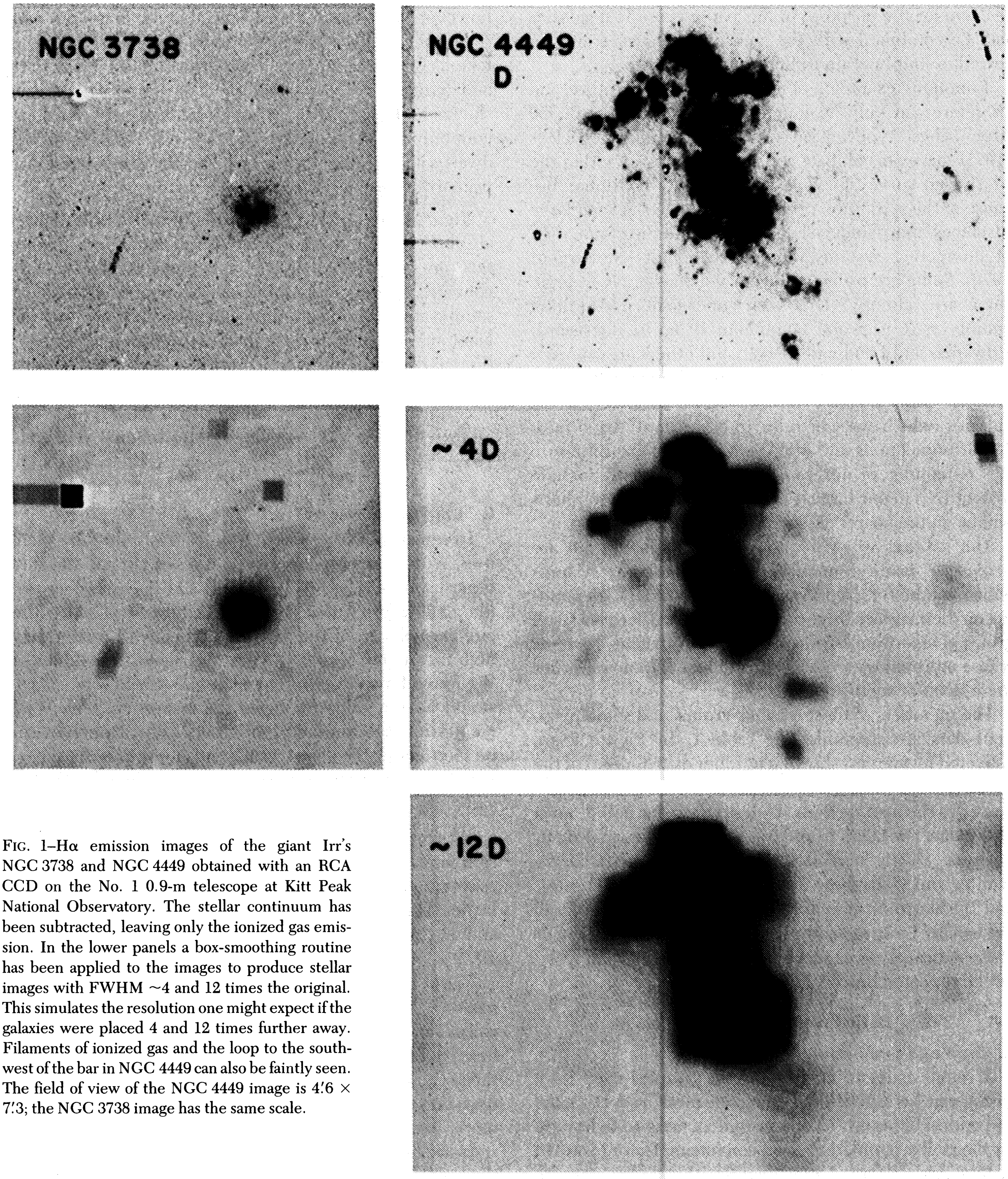

FIG. 1–Hα emission images of the giant Irr's NGC 3738 and NGC 4449 obtained with an RCA CCD on the No. 1 0.9-m telescope at Kitt Peak National Observatory. The stellar continuum has been subtracted, leaving only the ionized gas emission. In the lower panels a box-smoothing routine has been applied to the images to produce stellar images with FWHM ~4 and 12 times the original. This simulates the resolution one might expect if the galaxies were placed 4 and 12 times further away. Filaments of ionized gas and the loop to the southwest of the bar in NGC 4449 can also be faintly seen. The field of view of the NGC 4449 image is 4'.6 × 7'.3; the NGC 3738 image has the same scale.

chosen to include these galaxies in the giant Im group. The galaxies Haro 22 (at 28 Mpc) and Mrk 35 (at 20 Mpc), on the other hand, also contain only two big Hα clumps, but there seems to be less galaxy outside of these clumps than for other systems. These galaxies are more like the "intergalactic" H II-region system II Zw 40 (at 14 Mpc; cf. Baldwin, Spinrad, and Terlevich 1982; Sargent and Searle 1970; Searle and Sargent 1972). At least they resemble more the amorphous Irr's than the Im-type galaxies, and for the purposes of this paper these H II galaxies will be combined with the amorphous galaxies and referred to simply as amorphous Irr's.

Luminous examples of Irr-like galaxies are rare and therefore can only be found at larger distances ($\gtrsim 50$ Mpc). These types of galaxies are included in Zwicky's (1971) survey of compact and unusual galaxies and in the Markarian survey for galaxies with blue continua. Because of the resolution problems for objects at such large distances, morphological distinctions and the elimination of interacting systems are more difficult (cf. Sargent 1970). Some are probably bigger versions of NGC 4449, some are "clumpy" Irr's with supergiant star-forming complexes (Casini and Heidmann 1976*a,b*; Boesgaard, Edwards, and Heidmann 1982), and others are compact systems that may be giant versions of amorphous Irr's. Despite their intrinsic morphological diversity, these galaxies (which we will refer to as "distant" Irr's) have stellar populations and other features that are similar to the remainder of our sample. We, therefore, include distant Irr's in our discussion, even though our emphasis will be on the nearer galaxies.

The galaxies we will discuss in this paper then are *primarily* nearby, noninteracting, Im-type systems which will be referred to as dwarf or giant Irr's, depending on their surface brightness. In addition there is a small group of amorphous Irr's and a bin for "distant" systems whose morphology we really do not know. *In no sense are these samples complete.*

The members of these various groups and some pertinent data are assembled in Table I. In Figure 2 are collected histograms showing number distributions of the galaxies for various global properties which will be discussed in the next sections. Unless otherwise noted, most of the data are taken from Hunter, Gallagher, and Rautenkranz (1982; hereafter HGR); (Hunter 1982*a,b*); Hunter and Gallagher (1985*d*); and Gallagher, Hunter, and Bushouse (in preparation, hereafter GHB) and will not usually be specifically referenced in the text. Details of the data analysis are covered in these papers and will not be repeated here.

III. Basic Properties of the Galaxies

A. *Sizes and Luminosities*

A rough estimate of the mass in gas plus stars for a galaxy can be determined from the measured H I mass and optical luminosity if one assumes a mass-to-light ratio for the stellar population and a conversion factor from H I to total gas content. Unfortunately, the stellar mass-to-light ratios are very difficult to determine. We have used the models of Larson and Tinsley (1978) to give three very rough groups based on the $(B-V)$ color index corrected for metallicity effects: For $(B-V) = 0.1-0.3$, $\mathfrak{M}_*/L_B = 0.2$; for $(B-V) = 0.3-0.4$, the ratio is 0.5; and for $(B-V) \geq 0.4$, it is 1.1. These values are very approximate, however; and, in addition, note that we have not corrected the L_B for extinction internal to the galaxy. If we take $\mathfrak{M}_{gas} \simeq 1.34\ \mathfrak{M}_{H\,I}$ to account for helium gas (Kunth and Sargent 1985), we get the distribution of masses shown in Figure 2(b). Masses of the nearby Irr's are generally $< 10^{10}\ \mathfrak{M}_\odot$ and can be as low as $\sim 10^8\ \mathfrak{M}_\odot$ for the dwarf sample. The distant Irr's, on the other hand, are primarily more massive systems.

Figures 2(c) and 2(d), which show the distribution of absolute blue luminosity and optical Holmberg diameters, are consistent with the view that the dwarf sample contains smaller, less luminous systems, the distant Irr sample contains objects at the opposite extreme, and the giant and amorphous systems lie in between. However, there is considerable overlap between the various groups, and we see that Irr's of low surface brightness are not necessarily objects of low luminosity or mass (Thuan and Seitzer 1979; de Vaucouleurs, de Vaucouleurs, and Buta 1983).

B. *Kinematics*

Irregular galaxies generally have low rotation velocities, with characteristic values of less than half those of typical spirals. The width of the H I 21-cm emission profile at 20% intensity, W_{20}, is an estimate of twice the circular velocity of the gas for galaxies with moderately high inclination angles. Figure 2(e) shows the values of W_{20} found for galaxies in our samples. A typical Sc galaxy would have a value for twice the maximum velocity of $\sim$350 km s^{-1} (Rubin *et al.* 1985). Very little distinction can be seen among the dwarf, giant, and amorphous Irr types; however, the distant Irr's can have much higher rotation velocities.

A few rotation curves have been measured from emission lines (cf. Welch and Wallerstein 1969; de Vaucouleurs and Freeman 1972; Cheriguene 1975; Gallagher, Hunter, and Knapp 1981; Goad and Roberts 1981) and H I maps (cf. van Woerden, Bosma, and Mebold 1975; Cottrell 1976; Tully *et al.* 1978; Allsopp 1978, 1979*a,b*; Reakes 1980). Generally, if they show organized rotation, it is rigid body rotation over much of the optical galaxy; and a few rotation curves even turn over. Therefore, differential rotation will be greatly decreased in these galaxies. In addition, noncircular and random motions do seem to be significant in some galaxies. Furthermore, bar structures in the light distributions of the older stars are frequently present and do not necessarily lie at the center of rotation of the galaxy (cf. de Vaucouleurs and Freeman 1972; Feitzinger 1980). This adds additional pertubations to the velocity fields, and Elmegreen and Elmegreen (1980) have suggested that gas flows at the ends of the bars may enhance the formation of large star-forming complexes there.

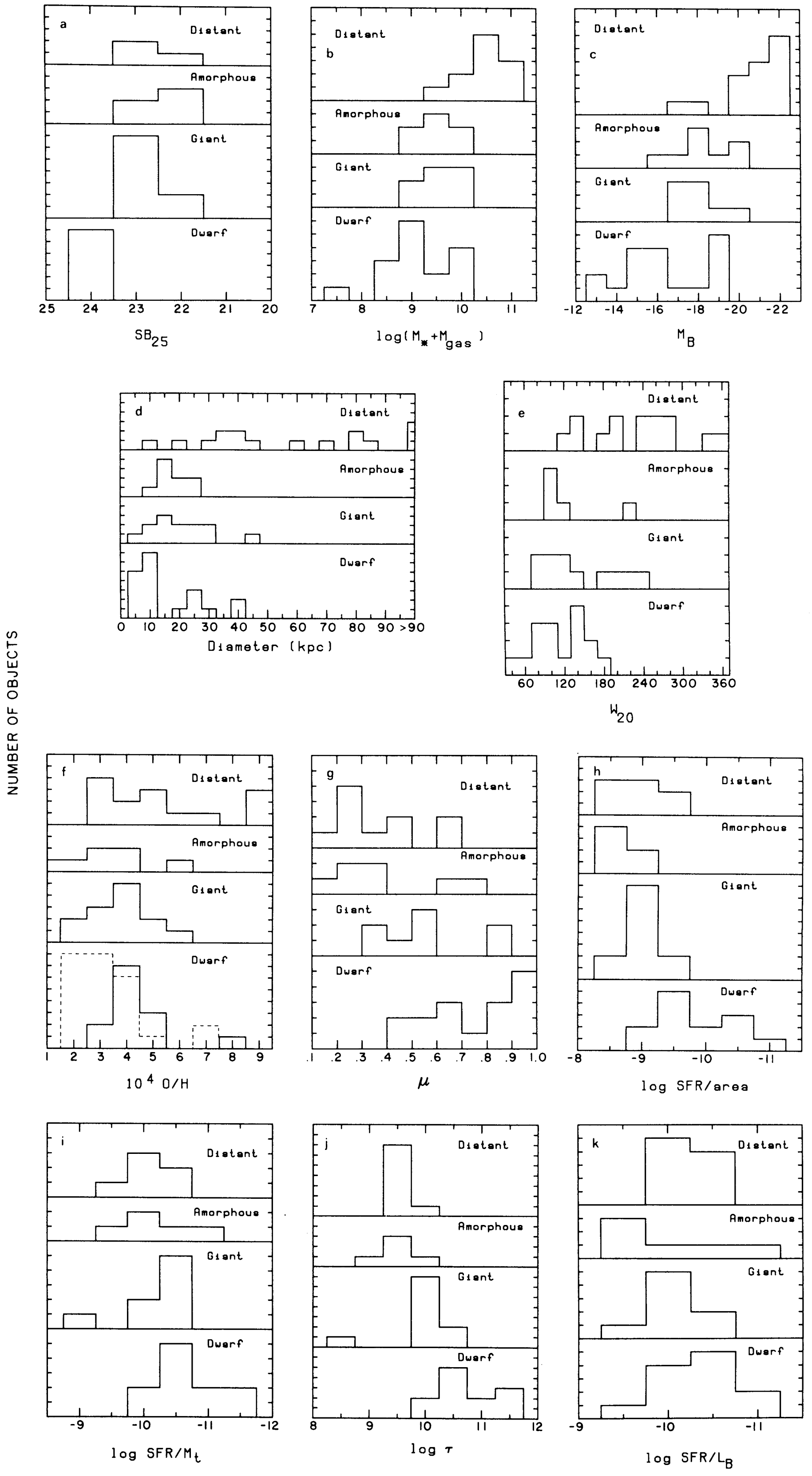

FIG. 2–Number distributions of the different galaxy groups for various global properties discussed in the text.

TABLE I

The Irregular Galaxy Groups and Some Basic Data

Galaxy	D	U-B	B-V	d_H	SB_{25}	M_B	O/H	L(Hα)	$\dot{M}$	$M_{H\,I}$	τ	$\dot{M}$/area	$\dot{M}/M_t$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Dwarf Irrs:													
DDO 8	0.9		0.59	6	24.1	-14.7							
DDO 26	23	0.00	0.33	23				>39.1	0.01	9.56	11.7	-10.6	
DDO 42	3.5	-0.41	0.23	10	23.7	-16.5	4.5	40.3	0.1	9.02	10.0	-8.8	-10.1
DDO 43	7.3	-0.22	0.33	6		-14.6		38.2	0.001	8.22	11.3	-10.5	-11.4
DDO 47	3.4	-0.11	0.44	8		-14.2		>37.5	0.0002	8.24	11.9	-10.4	-11.2
DDO 49	46	-0.33	0.34	39		-19.2	3.7	40.7	0.4	9.76	10.3	-9.5	-10.5
DDO 50	3.5	-0.35	0.30	11	24.2	-16.6	3.6	>39.7	0.04	9.05	10.6	-9.4	-10.6
DDO 53	3.5	-0.46	0.31	3		-13.3:	3.9	38.8	0.004			-9.3	
DDO 64	9.5	-0.58	0.17	9		-15.5	4.0	>39.2	0.01	8.62	10.7	-9.8	-10.7
DDO 68	9.0	-0.33	0.24	10		-15.0		>39.2	0.01	8.74	10.8	-9.8	-10.8
DDO 83	11	-0.45:	0.06:	10		-15.2	2.6	>38.7	0.004	8.65	11.2	-10.3	-11.2
DDO 94	30	-0.28	0.42	32		-18.8:	4.3			9.70			
DDO 140	41	-0.22	0.25	25		-18.7	4.7			9.47			
DDO 155	3.5	-0.52	0.29	2	23.5	-13.3	5.0			7.40			
DDO 168	5.5	-0.24	0.44	8		-16.0	8.2			8.35			
DDO 214	37	-0.10	0.39	39		-19.5		>40.6	0.3	9.72	10.5	-9.7	-10.7
DDO 218	32	-0.27	0.37	24		-18.6	3.2	40.8	0.5	9.49	10.0	-9.0	-10.1
IC 10	1.3	0.0	1.0	6	23.8	-15.5	5.3	>39.3	>0.01	8.27	10.3	-9.4	-10.5
NGC 2552	11	-0.23	0.56	18	23.6	-17.6	4.3			9.20			
Giant Irrs:													
NGC 1012	22			32			4.3	40.9	0.6	9.90	10.2	-9.1	
NGC 1156	9.7	-0.28	0.39	16	23.1	-18.4	4.5	>40.6	0.3	9.22	9.9	-8.8	-10.1
NGC 1569	4.7	-0.52	0.30	19	22.3	-18.4	1.8	41.2	1.1	8.59	8.7	-8.4	-9.0
NGC 3274	9.6	-0.11	0.39	10	22.9	-16.8	2.7	>40.0	0.08	9.31	10.5	-9.0	-10.6
NGC 3510	13	-0.23	0.38	23	23.4	-17.3	3.0	>40.2	0.1	9.43	10.5	-9.6	-10.6
NGC 3738	5.4	-0.17	0.43	7	22.6	-16.6	3.5	39.7	0.04	8.46	10.0	-9.0	-10.5
NGC 3952	30	-0.17	0.41	29	22.3		3.8	40.8	0.5			-9.1	
NGC 4214	5.4	-0.30	0.46	17	23.2	-18.5	3.6	40.4	0.2	9.16	10.0	-9.1	-10.5
NGC 4449	5.4	-0.30	0.41	16	22.8	-18.8	4.1	41.0	0.7	9.73	10.0	-8.4	-10.2
NGC 7292	24			26			5.8	40.9	0.6	9.57	9.9	-8.9	
NGC 7800	39	0.0	0.4	44		-20.0	3.8	41.0	0.7	9.89	10.2	-9.4	-10.4
DDO 236	3.5			18	23.4		5.4			9.44			
A1004+10	7.9	-0.36	0.29	8			2.1	39.9	0.06			-9.0	
Amorphous Irrs:													
NGC 1140	30	-0.33	0.35	22	21.8	-19.7	3.9	>41.4	1.9	9.87	9.7	-8.3	-9.9
NGC 1800	12	-0.23	0.48	12	22.3	-17.5	5.6	>40.1	0.09	8.54	9.7	-9.1	-10.4
NGC 4670	21	-0.49	0.38	21	22.8	-18.6	4.0	41.2	1.2			-8.5	
NGC 5253	6.9	-0.23	0.40	15	21.8	-18.3	2.2	41.1	0.9	8.70	8.9	-8.3	-9.4
Haro 22	28	-0.32	0.32	15		-20.0	3.1	40.3	0.1	8.81	9.8	-9.1	-10.8
Mrk 35	20	-0.30	0.50	15		-18.4	2.7	41.1	0.8	9.07	9.3	-8.3	-9.8
II Zw 40	14	-0.34	0.37	24		-16.4	1.2			8.89			
Distant Irrs:													
Mrk 14	63			46			5.7						
Mrk 303	160	-0.16	0.48	86		-21.4				10.06			
Mrk 314	45	-0.38	0.39	35		-19.9	3.0			9.92			
Mrk 390	150	-0.21	0.42	71		-21.3	5.1			10.17			
Haro 15	130	-0.49	0.13	98	22.6	-22.1	3.0			10.10			
Haro 20	36	-0.35	0.45	20	22.5	-18.3	3.4	(40.4)	0.2	8.98	9.7	-9.3	-10.4
0049.4-00	33	-0.12	0.61	8		-17.3	3.3	(39.8)	0.04				
II Zw 23	165	-0.24	0.41	130		-22.2	7.0	>42.1	9.4	10.59	9.7	-9.2	-10.3
II Zw 33	54	-0.41	0.37	33		-20.2	3.9	>41.3	1.3	9.59	9.6	-8.8	-10.0
II Zw 168	170			39		-20.9	9	>41.5	2.5	9.77	9.5	-8.7	
II Zw 185	150			78		-21.9	9			10.44			
III Zw 12	120	-0.37	0.33	28		-20.6	5.4	(41.5)	2.3	9.83	9.5	-8.4	-10.0
III Zw 33	160	-0.30	0.28	62		-21.5	5.0	>41.7	3.3	10.27	9.9	-9.0	-10.0
III Zw 42	160			110		-21.5		>41.5	2.5	9.56	9.3	-9.6	
III Zw 43	71	-0.02	0.43	39		-20.2	9			9.36			
IV Zw 149	74	-0.22	0.25	80	21.9	-21.7	4.4	42.2	10.2	10.36	9.5	-8.7	-9.6

Notes to Table I

Explanation of column headings:

(2) Distances in Mpc are taken from Kraan-Korteweg and Tammann (1979) or determined from radial velocities and $H_0 = 50$ km s^{-1} Mpc^{-1}.

(3) and (4) Integrated *UBV* colors are taken from de Vaucouleurs, de Vaucouleurs, and Corwin (1976) (RC2); de Vaucouleurs, de Vaucouleurs, and Buta (1981); Gordon and Gottesman (1981); or Gallagher and Hunter, unpublished. Colors are corrected only for Galactic reddening using Burstein and Heiles (1984). Measurements for IC 10 use A_B from RC2 and are highly uncertain due to heavy Galactic reddening and contamination by foreground stars.

(5) Holmberg diameters in kpc are determined using the method described by Fisher and Tully (1981). Apparent diameter measurements come from RC2 and Gordon and Gottesman (1981).

(6) Surface brightness, the magnitude of one square arc sec, is determined from m_{25} in RC2.

(7) The absolute blue luminosity. Data come from RC2, Kinman and Hintzen (1981); Gordon and Gottesman (1981); Gallagher and Hunter, unpublished. The luminosities are based on a solar *blue* magnitude of 5.41.

(8) 10^4 O/H, the oxygen abundance of the ionized gas determined from large-aperture spectrophotometry. For measurements of individual H II regions see Hunter and Gallagher (1985*d*) and references therein. The method used to determine O/H (see text) becomes highly inaccurate at high values. Therefore, for three distant Irr's with calculated values much greater than solar, 10^4 O/H is set equal to 9.

(9) The log of the Hα luminosities in ergs sec^{-1}, corrected only for Galactic reddening. The Hα fluxes have been summed from narrow-band images and corrected for the inclusion of [N II] in the filter bandpass. Values marked with a > sign were observed through thin clouds or the galaxy was larger than the field of view; so, the Hα luminosities are lower limits and the quantities in columns (10), (12), (13), and (14) which are derived from L(Hα) are uncertain. Values in parentheses are 2.86 L(Hβ) which come from large-aperture (22″ and 10″.3) spectrophotometry. They are corrected for underlying stellar absorption using population synthesis techniques (GHB). Based on galaxies with both imaging and spectrophotometric data we have included measurements from the spectrophotometric sample only if the galaxian diameter d_{25} (from RC2) is less than twice the aperture size. Note that the Hα measurement of DDO 47 differs from that in Hunter and Gallagher (1985*d*); because diffuse emission is faint, their large-aperture measurement is very uncertain and we feel that the value given here is a better estimate.

(10) The star-formation rate in $\mathfrak{M}_\odot$ yr^{-1} determined from the Hα luminosity with a Salpeter IMF, using equation (1) in the text.

(11) The log of the H I mass in $\mathfrak{M}_\odot$ from 21-cm observations. Data are taken from Fisher and Tully (1975, 1981), HGR, and Hunter and Gallagher (1985*c*).

(12) The log of the time scale in years to exhaust the current gas supply (1.34 $\mathfrak{M}_{\rm H\,I}$) at the current star-formation rate.

(13) The star-formation rate per unit area in $\mathfrak{M}_\odot$ yr^{-1} pc^{-2}. The area has been taken to be $\pi d_{\rm H}^2/4$ where $d_{\rm H}$ is from column (5).

(14) The star-formation rate per unit total mass of the galaxy in units of yr^{-1}. The total mass is taken to be 1.34 $\mathfrak{M}_{\rm H\,I} + a\,L_B$, as discussed in the text.

C. *Emission-Line Ratios*

The abundances of heavy elements determined from emission-line ratios of the ionized gas are a clue to how much the gas has been processed through stars. The relative oxygen abundances that we have measured from large- and small-aperture spectrophotometry are shown in Figure 2(f). For the Irr's in our sample, O/H varies between the solar value of $\sim 7.6 \times 10^{-4}$ and 1/4 of solar, with the average being around half of solar. Thus, the Irr's are generally moderately metal poor, but none of the objects in these samples are found to be extremely metal poor (but see Kunth and Sargent 1985).

There are considerable uncertainties, however, in our approach to measuring oxygen abundances. First, Hβ must be corrected for underlying stellar absorption, especially for large-aperture data. We have done this using population synthesis model fits to the spectra. Second, rarely is [O III] λ4363 measured accurately enough to determine the electron temperature, and so an empirical relationship of the type determined by Pagel *et al.* (1979) based on ([O II] λ3727 + [O III] $\lambda\lambda$4959, 5007)/Hβ must be used. The scatter is fairly large for this relationship, and there is an ambiguity in O/H for low-abundance objects. A plot of [O III]/[O II] vs. the predicted O/H appears to help resolve this ambiguity (see Fig. 3 and discussion of Hunter and Gallagher 1985*d*), but uncertainties of 25% should be expected.

Third, large-aperture spectrophotometry includes contributions from diffuse ionized gas or filaments as well as from the H II regions proper. Hunter (1984) discovered that oxygen emission-line ratios of the filamentary gas near major star-forming regions are different from those measured for the H II regions themselves. Hunter and Gallagher (1985*d*) also found that O/H measurements from large-aperture spectrophotometry were systematically high by a factor of $\sim$40% compared to small-aperture

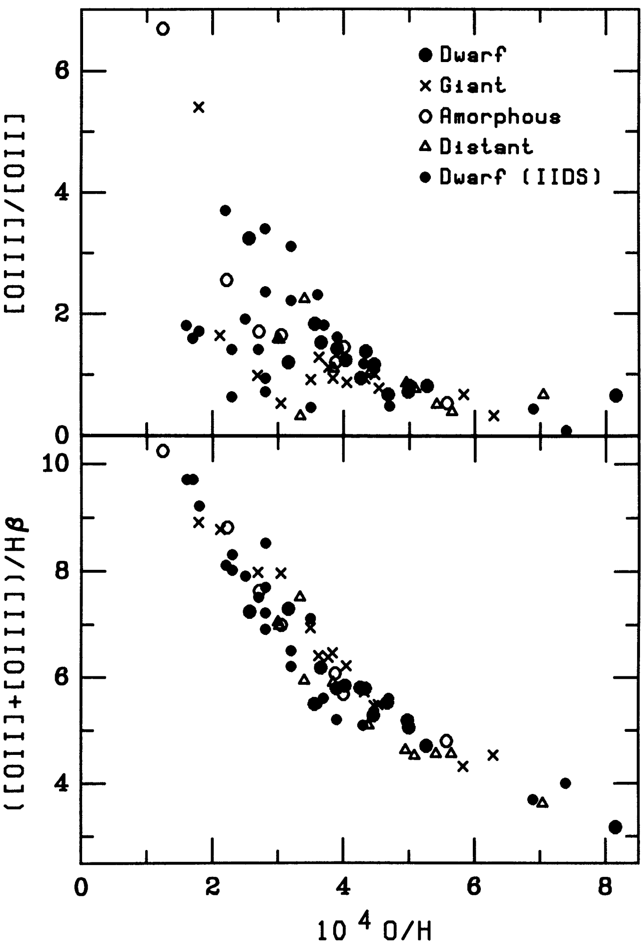

FIG. 3–The sums and ratios of the [O II] λ3727 and [O III] λλ4959,5007 emission-lines as a function of the calculated O/H abundances. Any object improperly assigned an O/H on the bottom curve would appear discrepant in the top curve. The small filled circles are IIDS data of individual H II regions (Hunter and Gallagher 1985*d*); the other data were obtained from large-aperture spectrophotometry.

observations of specific H II regions in dwarf Irr's. Thus it is possible that abundances derived from measurements that integrate over several H II regions and diffuse gas are on a different scale than the individual H II region data.

Another diagnostic emission ratio comes from nitrogen and sulfur. Sulfur is produced only in massive stars while nitrogen is probably produced to some extent in all stars. As a result, this ratio should be able to serve as a clue to the evolutionary history of a galaxy (cf. Edmunds and Pagel 1978). Observed ratios of [N II]/[S II] for the Irr's cover a rather narrow range of values (0.25–1.5); and no correlation is seen with the oxygen abundance or with the [O III] λ5007/Hβ ratio.

Nevertheless, these galaxies do approximately follow the relationship found by Rubin, Ford, and Whitmore (1985) in which the mean [N II]/[S II] ratio increases with increasing galaxian luminosity (see their Fig. 5). They interpret this in terms of the role of the gravitational potential in metal enrichment processes. The potential, as they suggest, might also be related then to observed differences in abundance distributions within the galaxies. Studies of individual H II regions in Irr's (cf. Pagel *et al.* 1978; Pagel, Edmunds, and Smith 1980; Talent 1980) show that the heavy elements in these galaxies are fairly well mixed over the disks. Spirals, on the other hand, often have radial abundance gradients, with their outer parts being more metal poor than their centers (cf. Searle 1971; Shields and Searle 1978).

Thus, we find that Irr's are moderately less evolved chemically than typical spiral galaxies and that the different Irr groups are chemically quite similar. What effect metallicity has on the star-formation processes is not well known. For example, theoretical studies suggest that the star-formation efficiency could be lower for lower gas metallicities (Talbot 1974). Therefore, Irr's should be locally less efficient than spirals in forming stars. It has also been suggested that lower heavy-element abundances result in enhanced formation of massive stars (cf. Viallefond, Goss, and Allen 1982). However, other factors may be more important than metallicity in controlling the star-formation process (Jura 1976) and an unusual IMF may not necessarily result from variations in metallicity (Palla, Salpeter, and Stahler 1983).

IV. Stellar Populations

A. *Resolved Galaxies*

With few exceptions, the Irr galaxies in our sample are too distant for measurements of any but the most luminous individual stars. There are, however, a number of nearby dwarf Irr's for which optical color-magnitude diagrams have been obtained (e.g., see Hoessel and Danielson 1984; Sandage and Carlson 1985, and references therein); and the extensive investigations of the stellar content of the Large Magellanic Cloud provide insight into the situation in giant Irr galaxies. The important point to note from these studies is the similarity of the luminous stellar content. All of these systems show pronounced blue supergiant and more sparsely populated red supergiant branches on their color-magnitude diagrams. Thus we immediately see that evolved massive stars are an important component of the stellar population in both giant and dwarf Irr galaxies.

The normal and comparatively uniform properties of young, luminous stars in Irr's is demonstrated by other types of measurements:

(1) The optical stellar luminosity functions for Irr's are similar to one another (Freedman 1984). While the observations by Hoessel and collaborators show there are differences in the absolute luminosity functions in dwarf Irr's, it is not yet clear whether these reflect varying levels of star-forming activity or are due to minor intrinsic differences in the nature of the young stellar populations.

(2) Wolf-Rayet stars provide a tracer for the presence of

very massive stars ($\mathfrak{M} \geq 30\ \mathfrak{M}_\odot$) in galaxies (see Massey 1985). Wolf-Rayet stars are common in the LMC and are also found in the Local Group dwarf Irr NGC 6822 (Armandroff and Massey 1985) as well as in the integrated spectra of star-forming complexes in a few giant Irr's. Thus, very massive stars exist in Irr's covering a wide range in luminosity and optical surface brightness.

(3) Finally, ultraviolet spectroscopy of luminous star clusters in both giant and amorphous Irr's reveal normal mixes of hot OB stars (Huchra *et al.* 1983; Lamb *et al.* 1985).

In the nearest Irr's the luminous OB stars are often seen to be superimposed on a spatially more extended, partially resolved sheet of red stars (e.g., Graham 1982; Hoessel and Danielson 1983). The spatial smoothness of this sheet is consistent with an older stellar population in which the effects of individual star-forming events have been averaged out (see Sandage 1971). Precise ages, however, are very difficult to determine since both intermediate- and low-mass stars can produce evolved red stars with similar bulk properties. For the present we can only roughly estimate that smooth sheets of red stars originate from stellar populations having ages of $\gtrsim$ 1 Gyr.

B. *Colors and Spectrophotometry*

A rough idea of the integrated stellar content of more distant Irr's can be obtained from large-aperture spectrophotometry and photometry. This approach becomes necessary even at the intermediate distances of many of the Irr's in our sample since a variety of factors complicates the construction of H-R diagrams for D $\gtrsim$ 3–5 Mpc. A traditional integrated *UBV* color-color diagram is shown in Figure 4 for the Irr's. As a group, the Irr's are generally the bluest of the normal galaxies, having an average $(U-B) \simeq -0\overset{m}{.}3$ and $(B-V) \simeq 0\overset{m}{.}4$. There is,

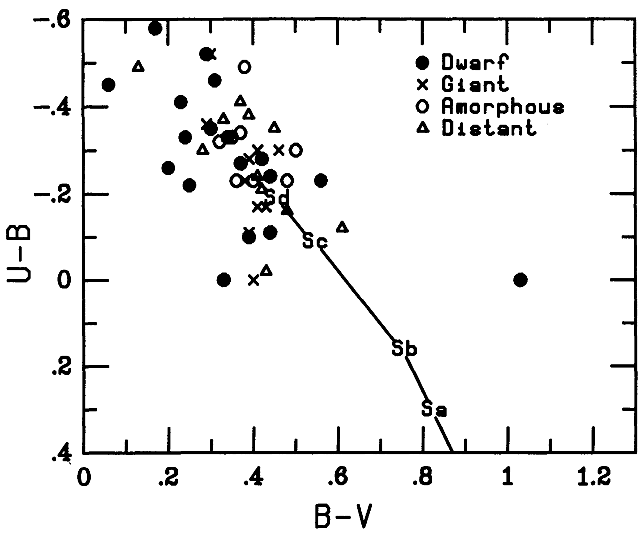

FIG. 4–The *UBV* color-color distribution of the Irr galaxies. The color indices are integrated values and are corrected for Galactic reddening only. See Table I for references.

however, a continuum of normal Irr's from $(U-B) \leq -0.6$ to ~ 0 (Huchra 1977). Although the groups of Irr's are fairly well mixed in terms of *UBV* colors, the very bluest objects tend to be dwarf or distant Irr's. Since our sample contains few H II-region-like Irr's, which often are omitted from morphological catalogs, we may have systematically excluded the intrinsically bluest systems from our studies (Hazard 1985).

The blue $(U-B)$ color indices of Irr's correlate well with other indicators of young stellar populations and are therefore primarily indicative of massive star content. For example, NGC 1569, NGC 4449, and NGC 3738 form a sequence of decreasing young stellar content as judged by Hα emission strength and the prominence of young OB associations seen on direct images (cf. Fig. 5), and these galaxies also follow a sequence of declining $(U-B)$ color index (see Table I). The dominant young stellar components in many Irr's combined with their relatively high degree of interstellar transparency also make Irr's bright and blue in the rocket ultraviolet spectral regions (Code and Welch 1982).

$(B-V)$ color indices cover a smaller range than is seen in $(U-B)$, as is expected from theoretical models where B and V light are primarily contributed by intermediate- and older-age stellar populations (e.g., Larson and Tinsley 1978). This also explains the lower degree of correlation between $(B-V)$ and current levels of star-forming activity. Infrared *JHK* colors of Irr's are even more homogeneous, with mean values of $(J-H) \simeq 0.6$ and $(H-K) \simeq 0.2$ (Hunter and Gallagher 1985*b*). These color indices are nearly the same as the averages of all types of spirals and ellipticals, which probably reflects the basic similarities in old- and intermediate-age red-star populations. We have also obtained $(V-K)$ color indices for the most actively star-forming zones in a few Irr's, and yet in most instances $(V-K) \gtrsim 2$, which implies by comparison with LMC star clusters that the young stars are not the main source of infrared light (cf. Persson *et al.* 1983).

C. *The Initial Mass Function*

Unfortunately, the strongest statement that we can make concerning the relative numbers of stars of a given mass (the initial mass function, IMF) in Irr's is based only on the similar luminosity functions for their OB stellar populations. A common luminosity function can then be translated into evidence for a roughly constant form for the massive star end of the IMF in Irr's (cf. Lequeux 1979; Freedman 1984; Massey 1985). The uncertainties, however, are large, and at best we can say that there are no large differences. Furthermore, this does not tell us about the lower mass stars.

If we look at the LMC, however, which has an approximately normal upper IMF, then we can extend our statement regarding luminosity functions down to $\sim 1\ \mathfrak{M}_\odot$. The analysis of LMC data by Stryker (1983, 1984) suggests

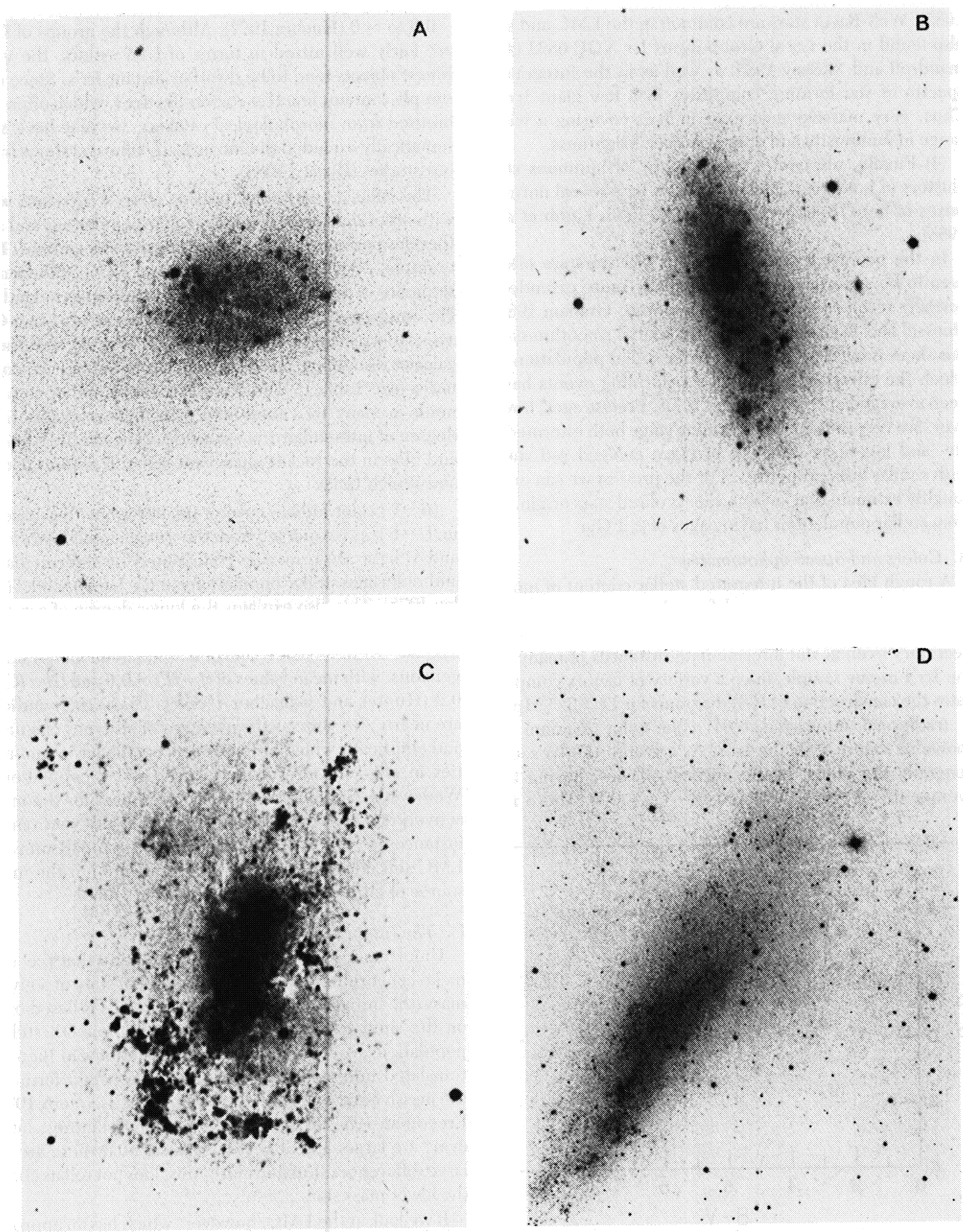

FIG. 5–Images in blue light of two giant Irr's (NGC 3738 [A] and NGC 4449 [C]) and two dwarf Irr's (NGC 3109 [D] and DDO 168 [B]) show the variety of star-forming region distributions. The plates were obtained for us at the prime focus of the Canada-France-Hawaii Telescope during June 1983. Images "A" and "C" have been printed using the KPNO unsharp masking technique to bring out details.

that the IMF for stars with $\mathfrak{M} \geq 1\ \mathfrak{M}_\odot$ is close to that deduced for the Milky Way although this result depends on the adopted LMC distance and the model for the LMC star-formation history. We do not have any direct information for the IMF at masses below $1\ \mathfrak{M}_\odot$ in *any* Irr galaxy.

We therefore adopt as a working hypothesis a Salpeter (1955) representation for the form of the IMF in Irr galaxies, i.e., $dN = A\ \mathfrak{m}^{-2.35}\ d\mathfrak{m}$ gives the distribution of number of stars dN between mass $\mathfrak{m}$ and $\mathfrak{m} + d\mathfrak{m}$ for $\mathfrak{m} \geq 0.1\ \mathfrak{M}_\odot$. This seems to provide a better fit to the most recent determinations of the Galactic upper IMF than our earlier choice for a Miller-Scalo (1979) IMF (e.g., see Humphreys and McElroy 1984). However, we emphasize that the physical concepts underlying the IMF are not understood (Scalo 1985). While one can, with some disagreements, derive a mass distribution function for stars, we must recognize that this derivation involves averages over as yet undefined time and spatial scales, while we are applying the concept of an IMF to instantaneous snapshots of sometimes sparse young stellar populations in Irr's.

V. Star Formation

A. *The Interstellar Medium*

1. *Neutral Hydrogen*. Irregular galaxies are the most H I-rich of the normal structural classes of galaxies (Fisher and Tully 1975, 1981). Using the total mass estimates of Section III.A., we can determine the fraction μ of the total mass which is in gas (taken to be $1.34\ \mathfrak{M}_{\rm H\,I}$, a minimum value). The distributions are shown in Figure 2(g); and we find that dwarf and giant Irr's have about half or more of their mass in gas while amorphous and distant Irr's generally have somewhat less. Thus, the Irr's still have a large reservoir of materials with which to build stars.

Although these gas masses do not include the unknown molecular mass, they do include all of the *detected* H I associated with each galaxy. For many Irr's the H I distribution is quite extended relative to the optical galaxy and to the places where stars are currently forming in the galaxy (cf. Roberts 1970; Tully *et al.* 1978; Huchtmeier, Seiradakis, and Materne 1981; Krumm and Burstein 1984; Hunter and Gallagher 1985*c*). In NGC 4449, for example, H I has been mapped out to 10 times the optical diameter (van Woerden *et al.* 1975). Many spiral galaxies also have some H I extending beyond the optical Holmberg radius (cf. Bosma 1981*a*,*b*; Briggs *et al.* 1980), but the Irr's are more commonly extreme in this regard. In IC 10, for example, over 60% of the H I mass lies outside of the Holmberg radius (Huchtmeier 1979) while for spirals this is usually less than 20% (Rogstad and Shostak 1972; see also Hewitt, Haynes, and Giovanelli 1983).

One wonders then what part this extended gas is playing in the evolution of the galaxy. It would seem that, if this gas is to participate in the star formation of the galaxy, it must come in toward the center. Infall of the gas has been suggested theoretically; and the free-fall time for gas in the outer parts of NGC 4449, for example, is approximately a few million years, less than a Hubble time. Although turbulent velocities have been observed in the H I envelopes of IC 10 and NGC 4449 (Huchtmeier 1979; van Woerden *et al.* 1975), we really have no observational evidence that infall of gas is actually taking place. Until we do, the possibility remains that a portion of the gas associated with Irr's is inactive in star-formation and chemical evolutionary processes (see also Madore, van den Bergh, and Rogstad 1974; Alloin, Bergeron, and Pelat 1978).

Why are stars not forming further out in the H I gas distribution? Bosma (1981*a*,*b*) obtained H I synthesis maps of a small sample of spiral galaxies and found that the gas reaches a column density of $\sim 1.8 \times 10^{20}$ atoms $\rm cm^{-2}$ at a distance of about 1.5 ± 0.5 times the Holmberg radius. Low-resolution maps of six dwarf and giant Irr's give a similar result (1.3 ± 0.4). Alternatively, we can ask what the column density of gas in galaxies is at their optically defined Holmberg radius. From Bosma (1981*a*) and Rogstad and Shostak (1972) we obtain a column density of $\sim 4 \pm 2 \times 10^{20}$ atoms $\rm cm^{-2}$ for spirals at their Holmberg radii. The six Irr's give $3 \pm 2 \times 10^{20}$ atoms $\rm cm^{-2}$. Although the measurements for the Irr's are quite rough, these results suggest a critical density of gas for all types of star-forming galaxies below which star formation cannot proceed (cf. Mouschovias 1981). One cannot be sure, of course, how column densities translate into volume densities in a given galaxy. Observations of spirals suggest that gas disks become thicker with radius by factors of 5 or 10, so that volume densities decrease (Sancisi 1981) and gas clouds may be harder to form (van der Kruit 1981).

There are still a few problems, however. The agreement of column densities is far from tight, and differences of factors of 2 are still puzzling. Furthermore, the relationship between the optical galaxy and the *global* H I gas distribution is not a simple one (see also Kennicutt and Kent 1983). NGC 4449, for example, with its far-flung H I distribution has an OB star distribution which ends rather abruptly (see Fig. 4). By comparison the very similar Irr NGC 4214 has H I out to only ~ 1.4 times its Holmberg diameter (Allsopp 1979*b*) even though the number of OB stars appears to decline slowly with radius.

However, the global gas properties do not tell us about the characteristics of the individual gas clouds out of which the stars will form. From H I maps we see that the gas is lumpy, as one expects, and even dwarf Irr's can accumulate gas into large 10^6–$10^7\ \mathfrak{M}_\odot$ clumps (cf. Cottrell 1976; Gottesman and Weliachew 1977; Tully *et al.* 1978). Furthermore, gas peaks are not necessarily near the current star-formation activity. For example, in NGC 6822 the three largest H II regions do roughly sit on a ridge of H I, and in the SMC and LMC there is good agreement between H I and H II regions (McGee and Milton 1966; Smith and Weedman 1973). But, in NGC 4449 (van Gorkom, unpublished) and Ho II (Cottrell 1976), for example, many of the H I peaks are seemingly completely unrelated to the current activity. Overall the hydrogen surface density in Irr's, like that in spirals, does not necessarily fall off smoothly, and there can be clumps of gas further out in the galaxy that do not coincide with notable optical features (Bosma 1981*a*; Viallefond, Allen, and Goss 1981). Thus, the relationship between H I density enhancements and the current star-forming sites is also not obvious (see also Madore 1981).

2. *Molecular Clouds*. In the Milky Way the formation of molecular clouds seems to be a prerequisite to star formation; at least the earliest stages of forming protostars are always found embedded in molecular material and the H II regions of young massive stars are always associated with molecular clouds. Furthermore, in the Milky Way the less abundant but more easily observable CO molecule has been found to be a good indicator of the presence and mass of the molecular (primarily) H_2 clouds. Observations of ^{12}CO show that CO luminosities of Irr's, on the other hand, are considerably lower than those of spirals relative to their star-formation activity (Elmegreen, Elmegreen, and Morris 1980; Israel *et al.* 1982; Cohen, Montani, and Rubio 1984; Young, Gallagher, and Hunter 1984; Tacconi and Young 1985). Young and Scoville (1982) have found that the star-formation activity as measured by the blue luminosity is proportional to the CO luminosity for Sc-type spirals. This does not seem to extend to Irr galaxies.

That the CO fluxes of Irr's is different from spirals seems clear, but what these observations imply about the molecular content and star-formation process is not as clear. There are several possibilities: (1) The molecular H_2 content is higher than the CO observations indicate (cf. Crawford *et al.* 1985); (2) The individual clouds are different in size, density, or temperature (cf. Elmegreen *et al.* 1980); (3) The cloud lifetimes are much shorter than those in spirals; and (4) The star-formation process proceeds without preexisting molecular clouds (Palla *et al.* 1983).

The physical conditions in the clouds may be important, for example, to the IMF of stars formed. According to models, increased internal turbulence or temperature could favor higher mass stars (Fleck 1982; Larson 1982, 1985*a*). Larson (1985*b*) has suggested that low- and high-mass stars may form under different conditions. Diffuse clouds, like those in the Taurus dark-cloud complex, for example, may preferentially form low-mass stars, and the maximum mass may increase with the mass of the associated molecular cloud.

Larson (1983) has also suggested that differential rotation plays a key role in the star-formation process since the differential rotation itself can enhance the growth of gravitational instabilities. Galaxies with low differential rotation, such as the Irr's, then should form stars more slowly over their lifetimes. In addition, he suggests that less shear favors larger clouds which in turn favor massive stars. These basic points are consistent with the observed properties of Irr's, but a full test would require comparisons between rotation curve forms and star formation over a wide range of galaxy structural classes.

It has also been suggested (cf. Fleck (1980) and review by Turner (1984)) that turbulence caused by differential rotation of a galaxy is important in supporting molecular clouds against collapse. This is used to explain the existence of the many clouds in the Milky Way which should be gravitationally unstable. Irr galaxies, however, have little or no differential rotation. Hence, if this mechanism is indeed important in spirals, it implies that Irr's will not be as effective in preventing the immediate collapse of dense molecular clouds (cf. Blitz and Glassgold 1982); and this might help explain why CO fluxes are so much lower in Irr's compared to spirals. It would imply that Irr's are locally more efficient star formers than spirals which is contrary to theoretical expectations based on the metallicity (cf. Talbot 1974).

The activity associated with star formation itself, such as supernovae explosions and stellar winds from massive stars, could also be a source of turbulence in the interstellar medium and clouds could be supported by internal processes such as heating by protostars. In that case, Irr's would be no better off than spirals, and in fact there is evidence that the dispersion velocity of H I in Irr's is the same as that in spirals (cf. Allsopp 1979; Huchtmeier, Seiradakis, and Materne 1980, 1981).

3. *Dust*. Another component of the interstellar medium often associated with regions of star formation in spirals is dust (cf. Elmegreen 1980). Again, however, Irr's seem to differ from spirals. Optical images of Irr's reveal only a few dark nebulae (Hodge 1972, 1974; van den Bergh 1974; Hunter 1982*b*), implying that the high column density clouds of large extent and the dust lanes of spirals are missing, although smaller more diffuse clouds would be harder to detect against the irregular background light. In addition the internal reddening of star-forming regions seems to be low. The mean Balmer emission-line decrement of H II regions in NGC 4449 is $E(B-V) \simeq 0.3$ (Talent 1980) while in the Sc galaxy M 83 it is roughly $E(B-V) \simeq 0.5$ (Brand, Coulson, and Zealey 1981; Dufour *et al.* 1980). A comparison of optical and ultraviolet fluxes for three Irr's gives $E(B-V) \simeq 0.2$ (Huchra *et al.* 1983; Lamb *et al.* 1985) while a comparison of optical and radio data, which can yield very high measures of extinction in Galactic H II regions, gives $E(B-V) \simeq 0.7$ in NGC 1569 (Israel 1980).

IRAS infrared data at wavelengths of 12 to 100 μm have been used to explore the properties of the dust in a small sample of dwarf and giant Irr's (Hunter *et al.* 1985 and unpublished). Generally Irr's do not stand out as extremely different from spirals in terms of their *IRAS* properties; although they are generally at the hot end of the far-IR color-temperature distribution and have on average higher L_{IR}/L_B ratios. Although there is a large range in star-formation rates among the sample Irr's, ratios of infrared to Hα luminosities are fairly similar (ranging over a factor of 3) and are roughly near the expected value if both luminosities are measuring the OB stellar power output. This implies again that normal, nearby Irr's are relatively transparent systems optically. The same arguments, when applied to several distant Irr's, however, yield the opposite results (see section V.C. below), and this group of Irr's therefore potentially suffers from substantial amounts of dust obscuration at optical wavelengths.

Global dust-to-gas ratios determined from *IRAS* data may also be lower in Irr's relative to spirals. In addition studies of local ratios for a few large star-forming regions in the LMC indicate relatively lower values (cf. Viallefond *et al.* 1982; Viallefond, Donas, and Goss 1983; references in Israel (1984) and Koornneef (1984)). This would be consistent with the decreased metal abundance of these galaxies (cf. van den Bergh 1974; Clayton and Martin 1984).

Basic physical properties of the dust grains, such as composition and size distributions, are still unknown for Irr's. Optical and ultraviolet studies of reddening laws in the LMC indicate that there may be differences in the properties of dust in Irr's compared to average grains in the Milky Way. It has been suggested that there is an enhancement of graphite over silicate forms in the LMC (cf. Bromage and Nandy 1983; Lequeux *et al.* 1984; Nandy 1984) although anomalous enrichments in small-sized grains are not entirely ruled out (cf. Rocca-Volmerange *et al.* 1981).

What are the consequences to the star-formation processes? Dust is often associated with molecular clouds in the Milky Way. H_2 molecules may form on dust grains (cf. Savage and Mathis 1979), and the dust to some extent shields molecular clouds from destruction by ultraviolet radiation. Thus, the low dust and low CO luminosities in Irr's could be related (cf. Israel 1984, 1985). Van den Bergh (1981*b*), for example, has suggested that clouds may form more easily if metals and dust are present to act as coolants (see also Palla *et al.* 1983). Theoretical studies have suggested that dust affects the IMF (cf. Reddish 1975; Sarazin 1977; Savage and Mathis 1979; Palla *et al.* 1983). It is possible, however, that the need for dust for "normal" star formation is a threshold phenomenon, and the Irr's have the necessary amount.

However, observations of a protostar in the LMC (Gatley *et al.* 1981) and one in the SMC (Gatley, Hyland, and Jones 1982) indicate that large optical depths due to dust are found at those sites (see also Aitken *et al.* 1982). This suggests that, at least on the smallest scale, star formation is proceeding in those galaxies in a manner which is very similar to that in the Milky Way. Yet optically we see a large difference between galaxies which have heavy internal extinction, like M 82, and those which do not, like the Irr's; but why these differences exist and the actual consequences to the star-formation processes are not yet known.

B. *Star-Forming Regions*

1. *Distribution*. Giant Irr's are noted for their chaotic distributions of H II regions. In Figure 1 and 5 one can see the distributions of stars and ionized gas regions for four rather different Irr's. Although chaotic, the star-forming (i.e., H II) regions are not uniformly distributed over the galaxies. First, on a local scale ($\lesssim$ 0.5 kpc) there are occasional chain or hook-like structures of apparently *coeval* H II regions. Second, on a larger scale there is some clumping of H II regions. Hodge (1969, 1980), in a study of star clusters and H II regions in several dwarf and giant Irr's, concluded that star-forming regions are clumped on kpc-type scales (see also Hamajima and Tosa 1975; Hunter 1982*b*).

The distributions of H II regions then suggest that the locations of star-forming centers vary over time. Payne-Gaposchkin's work (1974) on Cepheid stars in the LMC directly indicates that the major concentration of star-formation activity has changed with time in that galaxy. This implies that star formation must move around the galaxy with time (Hodge 1969). Like a pot of oatmeal bubbling on the stove, the star formation bubbles around a galaxy. A given region will form stars, the star-formation activity will die down, and later that region will be ready for more star formation.

In addition Irr's tend to be bluer toward the central regions of the galaxy. By contrast spirals are bluest toward the outer parts of their disks, implying a flatter overall radial distribution of young stars, although Hodge and Kennicutt (1983; see also Kennicutt and Hodge 1984) show that the radial distribution of star-forming regions in spirals approximately follows the integrated light of the stellar disk. Hunter and Gallagher (1985*d*) concluded that this was also approximately true over most of the optical disks in the Irr galaxies they looked at. This implies that star-formation rates in normal disk galaxies have been approximately constant as a function of radius over the past few million years.

2. *Sizes*. There is a distribution in sizes of H II regions in any galaxy, and the smaller regions are usually more numerous. Van den Bergh (1981*a*) and Hodge (1983) have fit the H II size distribution in Irr's with an exponential law with the less luminous galaxies having steeper slopes (fewer large regions). Hodge (1977, 1978) has also demon-

strated that the mean masses of OB associations in four rather different galaxies—the Milky Way, LMC, NGC 6822, and IC 1613—are approximately the same, indicating that different types of galaxies can make stars in similar types of units.

There are difficulties, however, in measuring the diameters of H II regions in galaxies outside of the Local Group. First, in galaxies with many H II regions there can be crowding so that individual, especially smaller, H II regions are hard to distinguish. This becomes more severe the more distant the galaxy is, as illustrated by Figure 1. Furthermore, very small regions, such as the Orion nebula in our Galaxy, or low surface brightness regions would not be detectable in all but the closest galaxies.

Second, ideally one would like to measure all H II regions out to a predetermined surface-brightness level. The giant Irr's have a background from diffuse ionized gas, and thus one cannot follow an H II region brightness profile out to very low limits before running into the background.

Third, in the dwarf Irr's, which are low surface brightness and have fewer crowding problems, H II regions can be measured more easily to low light levels. In these cases one runs into statistical problems. Because the dwarfs have fewer H II regions, a very large complex is not as likely to be present at any given instant of time. In the dwarf Irr NGC 6822 (at 0.7 Mpc), for example, today there happen to be three respectably large regions, and numerous stellar clusters indicate that moderately large star-forming events are not uncommon (Hodge 1977). In addition, however, Killen and Dufour (1982) have cataloged several dozen smaller nebulae and about a dozen stellar-like H II regions.

A comparison of sizes of H II regions measured to the same surface brightness level in nearby (< 10 Mpc) giant and dwarf Irr's shows that dwarf Irr's *can* make big H II regions. The size distributions of regions in dwarf and giant Irr's cover the same range. NGC 2366, for example, contains an H II complex of hundreds of O stars as well as numerous small H II regions that are typical for a dwarf Irr. In fact, Hodge (1983) found that in six Irr's the largest H II region was anomalously large for the galaxy's overall distribution of H II region sizes. This raises the question of what sets the limits to the size of an H II region in any galaxian environment and to the number of such very large star-forming regions that a given galaxy can support (see below).

Our data on H II region size distributions do show that on average the regions we measure in the dwarf Irr's are smaller than those in the giant Irr's which is consistent with the findings of Hodge (1983). If this difference is real, one must worry about how star formation in smaller units might differ from that in large H II complexes. Larson (1982), for example, has suggested that the very small regions in the Milky Way can only form low-mass O or high-mass B stars; the higher mass O stars must be found in bigger complexes. In addition Kennicutt (1984) has suggested that low-luminosity galaxies preferentially contain diffuse H II regions; and the star formation in such regions, as discussed in a previous section, could give preference to lower mass stars (Larson 1982). The consequences of such local differences to the global galaxy and its evolution could be large if such regions play a dominant role in the star formation of dwarf galaxies.

3. *Giant H II Regions*. Giant H II regions (≥ 200 pc in size) are often found in actively star-forming late-type galaxies, including Irr's. The closest and best-known example is the great 30 Doradus nebula in the LMC in which a large cluster of massive stars appears to be forming (cf. Weigelt and Baier 1985). Other examples include NGC 595 and NGC 604 in the spiral M 33; the complex CM 12, 16, 18 in the giant Irr NGC 4449; and NGC 2363 in the dwarf Irr NGC 2366. The giant H II regions are generally characterized by the presence of many OB stars and probably one or more stellar clusters or associations. Studies of 30 Doradus (McGregor and Hyland 1981) suggest that these objects contain multiple generations of stars and have lifetimes $\geq 10^7$ yrs. Although there are variations, particularly between early and late-type spirals (cf. Kennicutt 1984), examples of similarities in the apparent morphology of the ionized gas do exist among the giant H II regions of gas-rich galaxies (cf. Hunter and Gallagher 1985*a*). Similarities in stellar content, structure, and kinematics (discussed below) of giant H II regions in late-type spirals as well as giant and dwarf Irr's suggest that the evolution of giant H II regions is relatively independent of the global galaxian characteristics (see also Viallefond *et al.* 1983; McCall, Rybsky, and Shields 1985). That is, once a giant H II region is started local processes are dominant and these processes are independent of galaxian type, at least among the gas-rich Sc to Irr-type systems (see also Kennicutt 1984).

Some distant Irr's have the unique property that they seem to contain several *supergiant* H II complexes which are closely packed and produce much of the total optical light from the galaxies (e.g., the clumpy Irr galaxies: Coupinot, Hecquet, and Heidmann 1982; Heidmann, Klein, and Wielebinski 1982). Each supergiant complex produces an energy output equivalent to many 30 Doradus-like giant H II regions. In most instances we lack the spatial resolution which would allow us to tell whether the supergiant H II complexes are made up of individual giant H II complexes or are indeed single physical entities. In either case, the concentration of star formation into a few centers of such intense activity cannot be understood in terms of statistical variations, but rather represents a different star-forming pattern than is seen in either more common Irr's or normal spirals (cf. Boesgaard *et al.* 1982).

Giant H II regions are often characterized by supersonic motions of the ionized gas (Rosa and Solf 1984). High-resolution spectra of the Hα emission line of regions in giant Irr's show that the mass-weighted average velocity of the gas is $\sim$18 km s^{-1}. Such velocities are typical of giant H II regions regardless of their parent galaxies (e.g., 30 Doradus: Meaburn 1981; M 101 and M 33: Smith and Weedman 1970; NGC 3603 in the Milky Way: Balick, Boeshaar, and Gull 1980), but they are large compared to the internal motions of smaller H II regions (Smith and Weedman 1971). Furthermore, there is gas at velocities greater than the average, up to nearly 100 km s^{-1}. Velocities in the individual supergiant H II complexes in clumpy Irr's and the intergalactic H II region II Zw 40 are even higher, with full widths of $>$ 100 km s^{-1} being common at low intensities (Gallagher and Hunter 1983; Gallagher and Anderson, in preparation). Obviously, such motions cannot be provided by ionization processes alone. Stellar winds from the massive stars and "champagne" flows (Tenorio-Tagle 1979) are probably important contributors to the observed kinematics.

A considerable amount of energy is connected with these motions of the gas. Typical masses of ionized gas of "single" giant H II regions are $\sim 10^5\ \mathfrak{M}_\odot$ (ranging from 10^4 to $5 \times 10^6\ \mathfrak{M}_\odot$), giving kinetic energies of $\sim 5 \times 10^{50}$ ergs (10^{49} to 10^{52} ergs) which are being dumped back into the interstellar medium. In the end, holes are often blown in the neutral hydrogen, like those found around the star cluster NGC 206 in M 31 (Brinks 1981) and Constellation III in the LMC (McGee and Milton 1966; Meaburn 1980). Clearly, star formation can be a rather traumatic event for the surrounding gas. The longer-term consequences to the interstellar medium are not certain. It is likely that the gas will take some time to recover, and it has been suggested that the star-formation process itself through the disruption of the interstellar medium provides negative feedback on the production of stars (Hoyle 1953; Reddish 1975; Cox 1983; Franco and Shore 1984). Alternatively, the energy returned by stars could trigger further star formation in neighboring regions by compressing the gas and causing either gas cloud formation or stellar precipitation from existing clouds (cf. Gerola, Seiden, and Schulman 1980; Seiden and Gerola 1982; Seiden, Schulman, and Feitzinger 1982; Comins 1983, 1984). The H I hole blown by the cluster NGC 206 M 31 has star-forming regions along one edge (Brinks 1981). The implication is that the current star formation was induced by the energy associated with the NGC 206 event. Direct evidence that star-induced star formation may take place on a moderately large spatial scale is rare, although for smaller scales the evidence appears to be greater (cf. Herbst and Assousa 1977; but see also Lada, Blitz, and Elmegreen 1978). The problem is difficult observationally, though, since the time delay between the triggering event and the subsequent star formation could be long (cf. Seiden 1983); and clues to the causal relationship between regions would be easily lost.

4. *Filaments*. Extensive filaments of ionized gas ($\sim$0.8 kpc) have been observed in several giant Irr's, e.g., NGC 3738, NGC 4214, and NGC 4449. Usually these are associated with large or multiple-center star-forming regions. For example, there is a loop of ionized gas to the north of regions 1, 2, 3 in NGC 3738 (see Hunter (1982*b*) for Hα images and numbering system); a filament between the large region 5,6 and the small hook 1,2 in NGC 4449; and intricate webs of Hα to the west of 1,2,3 in NGC 4214 and between the bar and the northern-most H II regions in NGC 4449 (see also NGC 604 in M 33, Hunter and Gallagher 1985*a*; the LMC, Meaburn 1981).

Not all filamentary structures can be associated with particular star-forming regions. In NGC 4449, for example, one also finds a coherent three-sided loop to the southwest of regions 5,6 (just visible in Fig. 1) and filaments to the west of and perpendicular to the bar. Similar filaments are also seen in NGC 5253 (Hodge 1975; Graham 1981).

The physical nature of these ionized filaments is not clear. Some filaments could mark the edges of bubbles blown in the interstellar medium by supernovae and stellar winds (cf. LMC supershells, Meaburn 1980; NGC 55, Graham and Lawrie 1982). Many filaments, however, extend outside of regions of young stars, and thus the bubble explanation cannot apply to all filaments. Magnetic structuring of interstellar matter is another possibility (cf. Parker 1966, 1979). Blue spectra of some of these filaments yield high [O II] λ3727/[O III] λ5007 emission-line ratios relative to the normal H II regions (Hunter 1984). These emission-line ratios could be indicative of either shock-heating, photoionization due to leakage from major H II complexes, or low-excitation photoionization by numerous cooler B stars. Red spectra have failed to turn up the high [N II], [S II]/Hα ratios one might expect for shocked gas (Hunter, Gallagher, and Mathis, unpublished). However, our high-dispersion Hα spectra reveal an unusual velocity structure around one of the filaments perpendicular to the bar in NGC 4449.

It is possible that these filaments are involved in energy transport from actively star-forming areas of the galaxy, as discussed in the previous section. As a result, the filaments may be important in the mixing of metals throughout the gas disk of a galaxy. They could also be important sources of pressure in the interstellar medium. Jura (1976), for example, has suggested that star formation could be particularly rapid in regions where the external pressure is high. Certainly they are an interesting clue to large-scale processes in the interstellar medium of these systems.

C. *Star-Formation Rates*

Global star-formation rates (SFR) given in Table I have been determined primarily from Hα emission fluxes which were summed from flux-calibrated digital images or (for some distant Irr's) derived from Hβ fluxes measured from large-aperture spectrophotometry which have been corrected for underlying stellar absorption using population synthesis techniques. Following the prescription of Gallagher, Hunter, and Tutukov (1984; see also Güsten and Mezger 1982), the Hα luminosity of a galaxy is converted to the total number of ionizing photons. This is then compared to the integrated number of photons expected from massive stars for a Salpeter (1955) IMF, taking into account main-sequence lifetimes of the stars. We then have the formation rate of hot stars in the galaxy. Extrapolating the Salpeter IMF down to stars of mass 0.1 $\mathfrak{M}_{\odot}$, we can determine the formation rate of all stars (0.1 to 100 $\mathfrak{M}_{\odot}$), which is given by

$$\mathfrak{M} = 7.07 \times 10^{-42} L(\mathrm{H}\alpha)\, \mathfrak{M}_{\odot}\, \mathrm{yr}^{-1} \quad . \qquad (1)$$

For this choice of IMF most of the ionizing photons are produced by 30–60 $\mathfrak{M}_{\odot}$ stars with lifetimes $\sim 3 \times 10^{6}$ yrs; so equation (1) is a measure of the current instantaneous SFR (see also Lequeux 1980). (Note that eq. (1) yields rates 60% higher than the formula used by HGR.)

Obviously there are uncertainties here. First, although the Irr's are relatively transparent systems, a typical internal reddening would be $E(B-V) \simeq 0.2$. We have chosen to not correct the $L(\mathrm{H}\alpha)$ given in Table I and hence also the SFR's for internal extinction; these numbers should probably be multiplied by ~ 1.6 to correct (on average) for the reddening. In principle SFR's can also be, and have been for some systems, estimated from radio observations of the continuum emission of H II regions. This method minimizes the extinction problem, but diffuse emission is more easily missed and one must deconvolve the thermal from the nonthermal components of the signal. For NGC 1569 the SFR thus determined by Israel (1980) is three times higher than the Hα-determined rate.

Another method of determining the hot stellar component of a galaxy which avoids some of the extinction problem is to measure the far-infrared flux which arises from heating of interstellar dust, usually preferentially that dust which is associated with star-forming regions. A basic difference with this method is that it measures energies while the Hα method counts photons. For a small sample of dwarf, giant, and amorphous Irr's it seems that the two methods agree to factors of 2 or 3 (cf. Hunter *et al.* 1986). A preliminary survey of distant Irr's suggests that members of this group often have very high ratios of far-infrared to Hα flux as compared with other Irr's. As a result SFR's deduced from the *IRAS* observations may exceed the values estimated here from uncorrected Hα measurements by as much as a factor of ten. Optical observations of distant Irr's thus do not in general provide a complete picture of the levels of star-forming activity.

Second, the SFR depends considerably on the IMF chosen. Using the formulas of Güsten and Mezger (1982), which are nearly on the same system as equation (1), we find that a Miller and Scalo (1979) IMF with the same mass limits yields a SFR which is ~3 times higher than that derived with the Salpeter IMF. Changing the upper mass cutoff of a Salpeter IMF to 50 $\mathfrak{M}_{\odot}$ increases the rate by a factor of 2 while an upper mass limit of 200 $\mathfrak{M}_{\odot}$ decreases the derived rates by 30% (see also Kennicutt 1983). Super-massive stars have, in fact, been postulated to be present in star-forming regions like 30 Doradus in the LMC (cf. Cassinelli, Mathis, and Savage 1981). Although their nature is controversial (Weigelt and Baier 1985), if they indeed exist with > 100 $\mathfrak{M}_{\odot}$, our choice of the upper-mass cutoff would lead to an overestimate of the SFR.

There is, in addition, another statistical problem with the use of a universal IMF. In galaxies, such as the dwarf Irr's, with low total numbers of massive stars, we could find ourselves in the absurd situation of counting a fraction of a very massive star. Furthermore, if, as Larson (1982) suggested, the maximum stellar mass is tied to the size of the star-forming site, then the dwarf Irr's may not always contain stars up to the mass limit. We would then be underestimating the SFR's of these systems. The extrapolation of a universal IMF to lower stellar masses is also uncertain (Poveda and Allen 1985; Larson 1985*b*). All we can do at this point is choose what seems to be a reasonable, approximately universal, IMF.

Third, since our SFR's are tied to $L(\mathrm{H}\alpha)$, we cannot account for any star formation which is occuring without the presence of massive stars to ionize the gas. Larson, for example, has suggested that the formation of low-mass and of high-mass stars may not be coupled in either time or space. In addition, extended low surface brightness H II regions may be missed, although very deep long slit red spectra for several dwarf Irr's obtained at KPNO with the Cryogenic camera failed to reveal low surface brightness line emission (Gallagher, Hunter, and Mould, unpublished).

Star-formation rates determined using equation (1) range from 0.0006 $\mathfrak{M}_{\odot}\, \mathrm{yr}^{-1}$ for a dwarf Irr up to 10 $\mathfrak{M}_{\odot}\, \mathrm{yr}^{-1}$ for a distant Irr. These rates need to be normalized to some sort of measure of the size of a galaxy before they can be intercompared. In Figure 2 (h,i,j) we show the distributions for three different normalizations: (1) per unit area, (2) per unit total mass of the galaxy in stars and gas, and (3) the inverse of the SFR per unit gas mass (1.34 $\mathfrak{M}_{\mathrm{H\,I}}$). The latter is a measure of the time τ that the current gas supplies in a galaxy would last at the current rate of consumption by star formation. All three normalizations have difficulties. The uncertainties in determining the total mass in stars and in gas other than H I have already been discussed. For normalization to the area of a galaxy, we have chosen to use the Holmberg dimensions. Obviously, if the star-formation activity is highly peaked, the SFR per unit area will decline with the size of the region sampled. This can be particularly a problem in dwarf Irr's with only a few H II regions. Also, note that the Holmberg diameter, which is derived from statistical relationships (Fisher and Tully 1981), is very uncertain for the distant Irr's.

One can see from these measurements of SFR's that Irr's can be quite successful at forming stars. In fact, many Irr's have rates of star formation which are comparable to those of spiral galaxies. Kennicutt (1983) has measured SFR's for a large sample of spirals (multiply his rates by 0.79 to obtain rates on our system). His sample has SFR's per unit area that range from 6×10^{-8} to 5×10^{-10} with an average $\sim 5 \times 10^{-9}$ $\mathfrak{M}_{\odot}$ yr^{-1} pc^{-2}. The giant and amorphous Irr's in our sample range from 5×10^{-9} to 3×10^{-10} with an average of 2×10^{-9}. For comparison, the global SFR's of the Milky Way and Magellanic Clouds, which have been determined using different methods, have rates $\sim$3–5 $\times 10^{-9}$ $\mathfrak{M}_{\odot}$ yr^{-1} pc^{-2} (see references in HGR). Another way to compare SFR's is through the ratio SFR/L_B. The spirals and the Irr's cover the same range with the same average of SFR/L_B $\sim 10^{-10}$ $\mathfrak{M}_{\odot}$ yr^{-1} $L_{\odot}^{-1}$, independent of the luminosity (see Fig. 2(k)).

In spiral galaxies spiral density waves are believed to play a key role in the star-formation processes. Irr galaxies, on the other hand, do not have spiral arms and cannot have density waves; and yet they can be quite successful at forming stars. Thus, we conclude that spiral density waves are not *necessary* to a vigorous production of stars. That is why Irr galaxies are so important to our understanding of star-formation processes (cf. Bok 1977). And in fact, the role of density waves in spiral galaxies has been questioned in recent years (Gerola and Seiden 1978; Smith, Elmegreen, and Elmegreen 1984).

However, there is a considerable range in SFR's and some dwarf Irr's have rates as much as 100 times smaller than the average giant. Yet we have already seen that many of the global properties of the dwarfs and giants in our sample are similar. This leads us to a key question: What properties of a galaxy does the overall level of star-formation activity depend on?

Obviously there must be plenty of gas, but both giants and dwarfs satisfy that criterion. Plots of the star-formation rate against various global parameters are shown in Figure 6; at best only suggestions of very poor correlations are seen. This is also true if one plots μ vs. $\dot{\mathfrak{M}}/\mathfrak{M}_{tot}$ or $\dot{\mathfrak{M}}$ vs. $\mathfrak{M}_{tot}\sigma_{gas}$ as suggested by Dopita (1985, see his Figs. 1 and 2); these Irr's increase the scatter even on log-log plots. That is, no single global parameter is clearly connected to the level of star-formation activity (see also Kennicutt and Kent 1983) except those, like surface brightness, which would be a result rather than a cause of the SFR. Perhaps then local conditions are more important than large-scale galactic properties and the local conditions interact to give the global picture we see. For example, the SFR could depend more on the gas density distribution rather than on the total mass of gas or global average density in the galaxy. Or, as Talbot (1980) has suggested, the surface density of H_2 could be more important than that of H I.

VI. Star-Formation Histories

A. *Empirical Methods*

Determining the star-formation history of a galaxy is fundamental to our understanding of how galaxies evolve. The dominant role of young stellar populations in setting the optical properties of Irr's clearly establishes that these systems are still very actively evolving. But, do Irr's evolve smoothly over time, or do these galaxies "flash" and accomplish much of their evolution in short bursts of star formation? Are Irr's all ancient systems that formed into stars $\sim 10^{10}$ yrs ago, or are some Irr's just now condensing into stars?

The processes in a galaxy which has a steady SFR could be quite different from those in a galaxy which undergoes periodic bursts of star formation. By "burst" of star formation here we mean that a galaxy experiences long periods of inactivity interspersed with intense episodes of *global* star formation. This is not the same as local bursts of star formation in which a particular region in a galaxy begins making stars for a short period of time. Galaxies are expected to be bursty on a local scale because of the episodic nature of the local star-formation process. Furthermore, even on a global scale fluctuations in the total SFR may occur as individual, especially large, star-forming complexes come and go. These fluctuations due to the grainy nature of star formation will be more severe in galaxies, such as the dwarf Irr's, with lower total SFR's and hence fewer H II regions (cf. Searle, Sargent, and Bagnuolo 1973; Fisher and Tully 1979). A single moderately-sized H II region coming on-line could change the SFR in some dwarfs by a factor of two, for example; but this would not be a "burst" in the sense we mean here.

Unfortunately, the star-formation history of a galaxy is not an easily isolated variable (cf. review by Lequeux 1980). The historical records are certainly present, e.g., in the stars born over the galaxy's lifetime, but it is hard to access this information. In particular, knowledge of the IMF as a function of time is needed to untangle stellar masses and ages. Fortunately, the LMC provides direct evidence that in at least one Irr the IMF has followed approximately a Salpeter form over its lifetime. So, we again adopt a time-independent Salpeter IMF as the simplest possible first model to use in our explorations.

Keeping this problem in mind, we can investigate various clues to the evolutionary history of a galaxy. First, the time scale τ discussed in the previous section tells us how long a galaxy could continue forming stars at its current

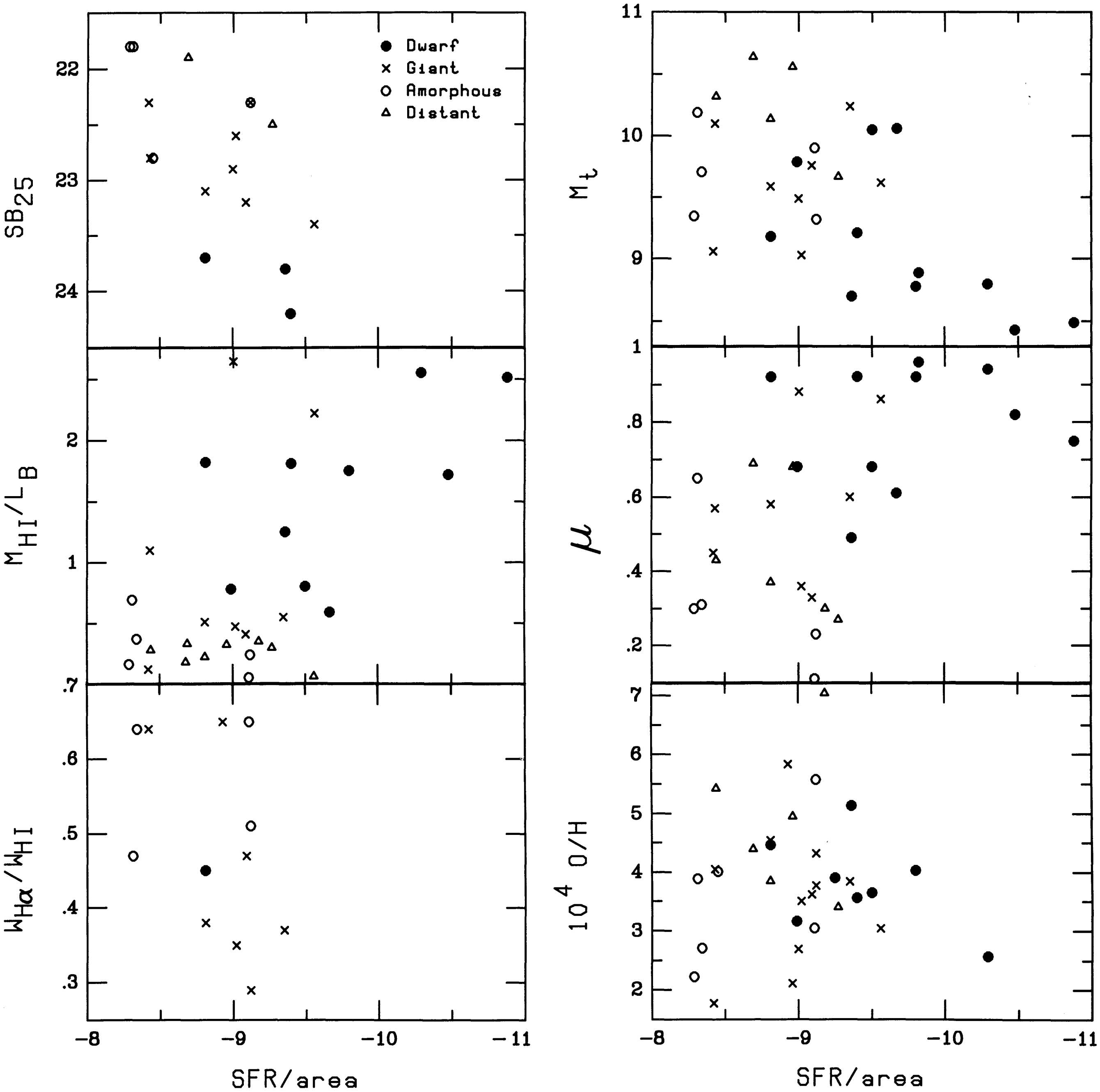

FIG. 6—SFR per unit (Holmberg) area plotted against various global galaxian properties: $\mathfrak{M}_t = \mathfrak{M}_{gas} + \mathfrak{M}_{stars}$ as discussed in the text; $\mu = \mathfrak{M}_{gas}/\mathfrak{M}_t$; $W_{H\,I}$ = average velocity FWHM of the H II regions divided by the full width at 20% of the global H I profile velocity width (see Hunter 1982*b*).

rate. Some τ's are upper limits because the SFR's could be somewhat higher (see Table I), so these values are only approximate. We see in Figure 2(j) that most Irr's have enough gas to last at least another Hubble time. Compared to normal spirals, however, these time scales are moderately long. The spirals in Kennicutt's (1983) sample range from 10^9 to 10^{10} yrs with a median of $\sim 3 \times 10^9$ yrs. Our giant Irr's range from 10^9 to 6×10^{10} yrs with a median $\sim 10^{10}$ yrs, while dwarf Irr's can have time scales as high as 10^{12} yrs.

This shows that constant SFR's over roughly a Hubble time are at least feasible for many Irr's. Only a few galaxies in our normal Irr sample—NGC 1569, Mrk 35, and NGC 5253—have noticeably shorter τ's. Of course, these time scales assume that all of the detected gas of a galaxy will be used by it. As discussed in a previous section, we do not know for sure that this is the case; and if some of the gas is not usable, then the τ's would have to be revised downward by factors of ≤ 2. In addition, the distant Irr's tend to have τ values that are significantly less than a

Hubble time (median value $\sim 3 \times 10^9$ yrs, and recall that optical SFR's are probably substantial underestimates in many distant Irr's). This suggests that distant Irr's are more likely to be in transitory evolutionary phases than the more common dwarf and giant Irr's.

Second, colors can also be used to probe the development of galaxies since they provide approximate measures of the relative contributions to the galaxian light of stars in different age groups. For example, *UBV* colors are most sensitive to star-formation histories in blue galaxies over the past $\sim 10^9$ yrs (Larson and Tinsley 1978). Several models suggest that galaxies with $(U-B) \geq 0.3$ and $(B-V) \sim 0.4$ are experiencing near constant SFR's with a Salpeter IMF, while bluer systems may be in a burst or unevolved state (Searle *et al.* 1973; Huchra 1977). These conclusions are not unambiguous, however, since they depend on a convolution of many factors, including the form of the SFR with time, stellar metallicities, and the IMF. In addition there is growing evidence that colors do not separate stellar age groups as cleanly as once was thought; e.g., red stellar populations show remarkably similar IR colors over an age range of $\sim 10^9$–10^{10} yrs (cf. Persson *et al.* 1983). Still, it is interesting that the majority of Irr's in Figure 4 lie in the color regime expected for near constant SFR's. There are, however, some Irr's, such as NGC 1569, which are far too blue and at least moderate bursts may be going on in these systems.

The approach behind color diagnostics can be extended by taking more information into account. Balmer emission-line equivalent widths depend on the luminosity ratios of massive main-sequence stars which provide ionizing photons to (typically) intermediate and low-mass stars which provide most of the optical light. This "color" is then a good diagnostic of the very recent star-forming history and was used by Huchra (1977) to search for bursting galaxies, although he lacked global equivalent-width measurements needed to make full use of the method. These are now becoming available from aperture photometry (Kennicutt and Kent 1983); and again, the data suggest approximately constant SFR's in normal Irr's. Furthermore, Donas and Deharveng (1984) came to the same conclusion for a sample of spiral and Irr galaxies by combining ultraviolet $\lambda 1910$ with *B*- and *V*-passband photometry.

Third, Gallagher *et al.* (1984) explored three different time scales in SFR estimates: The stellar mass of the galaxy provides a SFR estimate α_m integrated over a galaxy's lifetime, the blue luminosity depends on the SFR integrated over the past $\sim 10^9$ yrs. (α_L), and the current SFR α_c is derived from the numbers of OB stars calculated from Hα luminosities. The different mass ranges are linked to one another in the models by a Salpeter IMF. They found that the majority of Irr's and spirals in their sample have $\alpha_c \simeq \alpha_L$ and thus have produced stars at rates that are constant to within factors of 2–3 over the past $\sim 10^9$ yrs. Low-mass Irr galaxies typically appear to have constant SFR's over longer time scales (i.e., $\alpha_m \sim \alpha_L$) and massive Irr's and spirals have excess mass in lower mass stars ($\alpha_m > \alpha_L$), which could either indicate a declining SFR over a Hubble time, that the lower mass limit of the assumed IMF is incorrect (see, however, Kennicutt (1983) who concluded that spirals have experienced approximately constant SFR's with a Salpeter IMF), or the presence of dark matter. This approach unfortunately suffers from the low accuracy with which stellar masses can be estimated from the available kinematic data on Irr's, and thus long-term star-formation histories of Irr's remain uncertain.

Fourth, the metallicity of the gas is a record of how much the gas has been processed in stars and, hence, of the cumulative star-formation history. We can ask, therefore, whether the current SFR's acting over a Hubble time are consistent with the enrichment of the gas. As pointed out by Kunth and Sargent (1985), things are complicated by the fact that we are determining the abundances from emission-lines in H II regions which have probably already been polluted by the massive stars doing the ionizing. The global metallicity of the system may, therefore, be somewhat lower than indicated by the H II regions.

The closed-system model with instantaneous recycling is the simplest galaxian chemical evolution model (Searle and Sargent 1972). Although galaxies are far more complicated than this (cf. HGR), it can provide a first look at the enrichment of the gas expected in a galaxy. In this model $z = y \ln(1/\mu)$ where z is the gas metallicity and y is the heavy element yield factor determined empirically by Lequeux *et al.* (1979) to be 0.004. Differentiating with respect to time and multiplying by a Hubble time t_H, we obtain the metallicity expected if the SFR has been constant, $z = y\, t_H/\tau$. The observed oxygen abundances give metallicities ($z \simeq 26$ O/H), which are higher than those predicted for both high- and low-surface brightness Irr's. If the current SFR represented a burst, we would expect the opposite. Higher observed metallicities can be understood from Kunth and Sargent's argument and from the possibility that the outer gas content of the Irr's may not be as active in the evolution of the galaxy as the central regions. The three exceptions are the galaxies, NGC 1569, Mrk 35, and NGC 5253, which we found above to have unusually low τ's. For most of the Irr's there is no inconsistency between a constant SFR and the moderately low abundances, primarily because the Irr's have plenty of gas with which to dilute the pollutants.

Thus, we find that a variety of techniques yield similar results for a first look at star-forming histories of Irr's. These galaxies have evolved at roughly (to factors of 3) constant rates over a fair fraction of a Hubble time and their observed properties are reasonably well fit by a time-independent Salpeter IMF. The majority of Irr's also seem to be old systems with star-forming lifetimes that cover a substantial fraction of a Hubble time.

B. *Star-Formation Bursts and Young Galaxies*

Despite the basic picture developed above, Irr galaxies cannot have precisely constant SFR's. For example, there is considerable scatter in Hα equivalent widths, $(U-B)$ color indices, and the α_L/α_c ratio for Irr's of fixed $(B-V)$ color index. It is particularly the range in colors which does not fit with our simple picture of Irr galaxies. This implies that there are observable fluctuations in the ratios of current to recent past SFR's or modest random fluctuations in the IMF. As discussed above, these variations are likely to be statistical in many instances and result naturally from a tendancy for star formation to occur in spatially distinct, local episodes. Statistical effects in small galaxies may account for much of the wide color distribution of dwarf Irr's seen in Figure 4 (see also Lequeux 1980).

There are, however, also galaxies which exhibit evidence for nonstatistical variations from a constant SFR. These objects appear to be involved in enhanced star formation on a global scale; i.e., there are too many centers of star-forming activity for a feasible statistical explanation. NGC 1569, NGC 4670, and Mrk 35 are the galaxies in our samples which seem to be likely candidates for such systems; and there is a large population of H II-region galaxies not represented in our sample. Two interpretations have been advanced for these types of galaxies: (1) they are young objects which only recently began to form stars, or (2) global star-formation bursts are taking place in a previously existing galaxy (e.g., see Searle and Sargent 1972; Huchra 1977). (By "young" we mean that the bulk of the star formation has occurred considerably less than a Hubble time ago. This implies nothing about the formation of the initial protogalactic gas cloud.)

We cannot yet readily distinguish between these two options although we see hints that both types of events occur. In a bursting galaxy we may be able to detect an underlying older population, either through its spatial extent outside of the actively star-forming area or by its (primarily red) light contribution. For example, on the basis of infrared and optical color measurements of LMC star clusters, we can empirically guess that a galaxy with a roughly constant SFR and an age of $\geq 10^9$ yrs will have $(V-K) \geq 2$. On the other hand, young galaxies will have blue colors and a deficiency of old stars that also may be revealed in a low total stellar mass. These latter circumstances occur, for example, in NGC 1569 which Gallagher *et al.* (1984) suggest is a good candidate for a young galaxy.

Sometimes the criteria for young galaxies yield conflicting results. One case is II Zw 23 for which Keel (1985) has assembled several arguments for extreme youth, including the strength of the Hα emission, unusual morphology, and nonequilibrium gas kinematics in the outer regions. From a stellar-population viewpoint, however, our optical data suggest that II Zw 23 has the properties of a burst in an evolved galaxy with a substantial component of older stars. This can be seen in its reddish *UBV* colors, moderately high oxygen abundance (Table I), $(V-K) = 2.7$ (Hunter and Gallagher 1985*b*), relatively cool stellar population mix, and only modest Hβ emission equivalent width (GHB). Additional interpretive uncertainties are introduced by the very high ($\sim 70\ \mathfrak{M}_\odot\ \text{yr}^{-1}$) star-formation rate required to provide the far-infrared luminosity of II Zw 23 derived from the fluxes given in *Cataloged Galaxies and Quasars Observed in the IRAS Survey* (Jet Propulsion Laboratory Preprint, 1985). II Zw 23 could, therefore, either be young or undergoing a major burst which was triggered by a nearby, also peculiar, companion galaxy.

If there are galaxies undergoing true bursts of star formation, we should be able to find examples of these systems in their quiescent phase. If the star formation in NGC 1569, for example, which now has a SFR ≥ 10 times a past average over a Hubble time, were to end and the galaxy to decay we might expect its surface brightness to decline to ~ 23.6 mag arc sec^{-2}, its absolute luminosity to ~ -17, and its color indices to $(U-B) \geq -0.2$ on a time scale of $\sim 2\text{–}3 \times 10^8$ yrs for reasonable choices of model parameters (Searle *et al.* 1973; Larson and Tinsley 1978). Models with a wide variety of characteristics are possible, but the quiescent state of NGC 1569 could be consistent with the properties of a red-dwarf Irr.

There is a group of moderately red ($(U-B) \simeq -0.1$ to 0.2) dwarf Irr's in the photometric catalog of de Vaucouleurs, de Vaucouleurs, and Buta (1981) with surface brightnesses, luminosities, and hydrogen contents (Fisher and Tully 1975) which would be consistent with these properties. As the uncertainties in the color indices are large ~ 0.15), these must be considered only as "candidate" red Irr's. Furthermore, the number of red systems is not as large as one might expect if the burst phase is truly short lived. We might expect that, if any of these are postburst systems, they should have spectra which are dominated by late-B or A stars which have main-sequence lifetimes of $\sim 10^8$ to 10^9 yrs. Since we never see normal Irr's with $(B-V) \sim 0$, then if bursts do take place, the burst SFR's are less than ~ 20 times the past average rates (Searle *et al.* 1973).

VII. Comparison of Irregular Groups, Summary, and Questions for the Future

A. *Normal Irregulars*

In this category we include dwarfs, giants, and amorphous systems, which comprise the majority of common, actively star-forming galaxies of low-to-moderate optical luminosity. The normal Irr's appear as a single family in terms of ranges in optical colors, characteristic internal rotational velocities, oxygen abundances, and relative Hα emission-line strengths. From this latter property we deduce that SFR/L_B ratios are independent of structural details and luminosity. Differences that are seen in the SFR/area, time scales τ, and gas mass fraction μ are correlated with absolute levels of star-forming activity, which are lowest in the dwarf Irr's. We then found in Section VI that the properties of all but a few normal Irr's are consistent with near constant (to within factors of ~ 3) SFR's over significant fractions of a Hubble time. The normal Irr's, therefore, are galaxies that have experienced similar evolutionary histories. It also then follows that Irr galaxies do not form a simple one-parameter family in which mass or optical luminosity are closely correlated with stellar content, colors, or surface brightnesses.

There are, nevertheless, several problem areas. Deviations from constant evolutionary rates in some Irr's exceed those expected from statistical effects alone, and may be providing us with clues regarding the as yet unknown physical mechanism(s) which regulate star-formation processes in simple galaxies. In a few normal Irr's these deviations are sufficiently pronounced that a special event is involved, and we are either seeing star-formation bursts or young galaxies. Since the collapse of low galactic-mass clouds to densities that can readily support star formation may be very slow, we should not be surprised to find "young" galaxies (in the stellar population sense) among the less luminous normal Irr's.

Amorphous Irr's are distinguished from other members of the normal group by their smooth optical appearances. The presence of ionized gas which is associated with H II regions and *IUE* ultraviolet spectra show that our sample of amorphous galaxies contain near normal complements of young, massive stars, and yet we do not see the many spatially distinct star clusters and associations which so typify young stellar populations in the more numerous Magellanic and dwarf Irr's. These amorphous galaxies do not stand out in terms of levels of star-forming activity or in terms of global parameters, including those that are distance-dependent and those that are distance-independent. Evidently different global star-forming patterns in these Irr's have not led to radical variations in stellar content, but we do not understand why this occurs or what its physical significance might be.

B. *What Are the Distant Irr's?*

Our distant Irr sample consists of luminous, optically blue galaxies that do not show obvious spiral structure. While these galaxies resemble normal Irr's in terms of global stellar population and star-formation characteristics that are derived from *optical* observations (see Figs. 2 and 6), they stand out from normal Irr's when other characteristics, including distance-independent parameters, are considered. Distant Irr's are large, massive, and rotate rapidly. They contain relatively smaller amounts of H I. In many instances their star-forming processes are concentrated into a few amazing supergiant H II complexes, which J. Heidmann properly describes as "hyperactive" when compared with the largest normal star-forming centers in giant H II regions. Preliminary estimates of SFR's from *IRAS* far-infrared photometry further suggest that optical Hα fluxes which are uncorrected for internal extinction underestimate levels of star-forming activity by factors of ~ 10 in several systems. The only possible trend in our data is for lower density galaxies to have lower mean SFR's, and this may be either a cause or an effect.

Many of these differences can be understood if the distant Irr's include spiral-like galaxies that are experiencing star-formation bursts. Such galaxies are more likely to contain dense concentrations of dust and gas that would obscure star-forming centers. Furthermore, in our deep CCD imaging studies of luminous Irr's, we have found, in agreement with earlier work, a number of examples of interactions. These provide a feasible trigger for star-formation bursts. Not all distant Irr's can be understood in this way, however, and some systems (e.g., II Zw 33) may well represent high-luminosity versions of normal giant Irr's. In any case, it is clear that the distant Irr's are not a physically homogeneous group, and that optical observations of stellar population characteristics alone are insufficient to distinguish between the various physical categories of luminous blue galaxies.

C. *Star-Formation Processes*

Normal, noninteracting Irr galaxies can be quite succesful at forming stars. Therefore, spiral density waves are not necessary to a vigorous production of stars. Nevertheless, there is a large range in SFR's among Irr galaxies. Irr's with common characteristics can have different overall levels of star-formation activity, so that the level of activity does not seem to be simply related to observable global properties of irregular systems.

The constant SFR's of most normal Irr galaxies implies the existence of regulatory processes acting in the galaxy to keep gas shuffling into stars at a steady pace. It has been suggested that the star-formation process itself may provide a negative feedback as recently formed massive stars churn up the interstellar medium, making subsequent star-formation more difficult (Hoyle 1953; Reddish 1975; Cox 1983; Ikeuchi, Habe, and Tanaka 1984; Franco and Shore 1984; see, however, Jura 1976). The giant star-forming regions do return a lot of energy to the interstellar medium, and the huge filaments of ionized gas seen in several Irr's could be important symptoms of this process. The consequences of this energy input to the interstellar medium, whether in regulating or promoting star formation, are issues of current interest where Irr's can provide us with clues to evolutionary processes in galaxies.

The existence of galaxies undergoing bursts of star formation, on the other hand, is puzzling. Certainly the physical conditions for star formation will be altered, and the conditions implied by the very high star-formation activity in small volumes of space in some "clumpy" Irr's can be extreme indeed (cf. Boesgaard *et al.* 1982). Scalo and Struck-Marcell (1985) have suggested that bursts can occur when the time delay between massive cloud formation and their subsequent disruption is greater than the collision time between clouds. They predict that in the aftermath of the burst the clouds will be broken up into many small clouds such as are observed in M 82. Why the regulatory processes initially break down and how the star-formation processes are affected are outstanding questions in understanding star-formation bursts.

Irr galaxies have ample gas with which to form stars although the role or the extended outer gas is not known. There may be a critical density of gas below which star formation cannot proceed and which prevents the extended envelopes of gas from forming stars. Also, the relationship between the H I distribution and the current star-forming sites is not clear; in some cases they seem to be unrelated. We then may also ask whether all galaxies once had extended gas components and whether these are ever stable over long times.

There is a range in sizes of star-forming regions in Irr's, as in any galaxy. Furthermore, the H II regions in dwarf and in giant Irr's cover the same range of sizes; dwarfs can make large H II complexes. What factors determine the limit to the size of a star-forming region and to the size and number that a given galaxy can support? Theoretical studies also suggest that star formation might vary in clouds of different characteristics; thus, if a galaxy preferentially makes smaller or more diffuse clouds, we might expect global consequences.

Compared to spirals, Irr's are more metal poor, have lower relative CO luminosities, lower apparent dust contents, and fewer high-column-density, optically dark clouds. Theoretical models suggest that star-formation efficiencies and the IMF could be affected by any or all of these interrelated conditions. This would imply that star formation in Irr's might be locally different from that in spirals or in dusty galaxies like M 82. Yet, normal dust color-temperatures, the normal stellar products, and similarities in at least giant star-forming region characteristics argue that star formation is a local process and that in normal Irr's it is not very different from that in other morphological classes of normal galaxies.

Clearly, there is much that we still do not understand about star-formation processes and the factors which control them. The Irr's, therefore, are important laboratories to study how different galaxies form stars.

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