

GIANT H II REGIONS AND THE FORMATION OF POPULOUS STAR CLUSTERS

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ABSTRACT

We critically examine the hypothesis, previously suggested by several authors, that populous "blue globular" star clusters may be forming in 30 Doradus and other nearby giant H II regions. A simple cluster evolution and photoionization model has been used to estimate the initial ionizing luminosities of the populous clusters in the LMC, and the results have been compared to the actual luminosities of giant H II regions. We have also compiled the available data on H II region and star cluster populations in galaxies, in order to compare the systematic trends in the populations with Hubble type, and to compare formation rates for the two types of objects. We have re-examined the structure of the stellar cores of 30 Doradus and other nearby giant H II regions, and compared their properties to the LMC clusters. Our results suggest that populous clusters may be forming in giant H II regions, but only a small fraction of giant H II regions are likely to contain such clusters. The apparent absence of both giant H II regions and populous clusters in early-type galaxies may be caused by a deficiency of massive interstellar clouds in these systems.

I. INTRODUCTION

Many late-type galaxies possess giant H II regions that are much larger and brighter than any in our own galaxy. The 30 Doradus complex in the Large Magellanic Cloud is the nearest and best-known member of this class of "giant" or "super-giant" H II regions; why they are absent from the Milky Way is not understood. The unusually large ionization requirements of these nebulae, typically 10^{51} – 10^{53} ionizing photons s^{-1} (e.g., Israel 1980; Lequeux *et al.* 1981; Kennicutt 1984), combined with the presence of unusually compact and luminous central objects, such as R136a in 30 Doradus, have led several workers to speculate that normal OB stellar associations may not be the predominant exciting sources for the H II regions. The suggested alternatives include supermassive stars (e.g., Schmidt-Kaler and Feitzinger 1981; Cassinelli, Mathis, and Savage 1981; Savage *et al.* 1983; Massey and Hutchings 1983), and accretion disks around massive black holes (e.g., Bath 1979; Lacey and Ostriker 1985). The resolution of R136a into normal stars has removed a principal motivation for these exotic scenarios, and recent evidence favors the argument that unusually luminous H II regions are ionized by unusually luminous stellar associations or clusters (e.g., Walker and O'Donoghue 1984; Weigelt and Baier 1985; Moffat, Seggewiss, and Shara 1985; Walborn 1986). As pointed out by Hodge (1983), however, the statistical properties of the giant H II regions in late-type galaxies are still difficult to explain if normal OB associations are the sole ionizing sources.

One intriguing possibility is that the giant H II regions may be ionized by progenitors of the populous "blue globu-

lar" clusters, which are common in the Magellanic Clouds and other late-type galaxies but appear to be absent in the Milky Way. Several authors have called attention to the structural similarity between the central stellar core of 30 Doradus and the populous blue clusters in the LMC, and have suggested that such a cluster may be forming in 30 Dor (e.g., McGregor and Hyland 1981; van den Bergh 1984; Moffat, Seggewiss, and Shara 1985). This hypothesis, though quite speculative itself, is attractive for several reasons, and deserves further examination. The populations of both star clusters and H II regions appear to differ markedly in different types of galaxies, and it would be useful to establish whether these differences are physically related. Massive protoclusters could also account for the high ionizing luminosities of the largest giant H II regions, without need for nonstellar objects. Finally, identifying the formation sites of populous clusters would provide the closest observable analogs to forming globular clusters.

In this paper, we critically examine the hypothesis that the formation of giant H II regions and blue globular clusters are related. In Sec. II, we use a simple model for the luminosity evolution and initial ionization of a star cluster to compare the extrapolated initial ionizing luminosities of the LMC clusters with the actual ionization requirements of giant H II regions. In Sec. III we compile the available data on H II regions and star clusters in nearby galaxies, and compare their formation rates in different types of galaxies. In Sec. IV, we use data on the distribution of stars in the core of 30 Doradus and other nearby H II regions to re-examine the evidence for compact central star clusters. The results and implications of these tests are discussed in Sec. V.

II. IONIZING LUMINOSITIES OF YOUNG POPULOUS STAR CLUSTERS

The populous clusters (hereafter referred to as PCs) or blue globular star clusters in the LMC possess masses and structures that are similar to globular clusters in the Milky Way, but with ages in the range 10^7 – 10^{10} yr (e.g., Freeman 1980; Hodge 1981). If their IMFs extended to OB stars at

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birth, they would have produced quite luminous H II regions. In this section, we use a simple cluster evolution model to place quantitative limits on the initial ionizing luminosities of the PCs in the LMC, for different assumed IMFs. Although this extrapolation is subject to considerable uncertainty, the results provide some interesting constraints on the formation of the clusters and their relationship with giant H II regions.

a) Cluster Evolution and Photoionization Model

The exercise of evolving a cluster “backwards” in time to estimate its initial photoionizing flux requires two steps. A cluster evolution model is used to estimate the initial luminosity of a cluster, given its present brightness and age. Then a zero-age model for the composite ultraviolet–visual continuum is applied to derive the initial Lyman photon luminosity of the cluster.

The luminosity evolution of a star cluster in the *UBVR* passbands was modeled using the techniques described by Searle, Sargent, and Bagnuolo (1973) and Larson and Tinsley (1978). Published evolution tracks were combined with stellar energy distributions from the Kurucz (1979) atmosphere models to synthesize the luminosities and colors of stars over a mass range of $0.7\text{--}200 M_{\odot}$, and ages of $0\text{--}10$ Gyr. Model star clusters were then constructed from sums of the stellar models, weighted with various choices for the IMF (discussed below). The models are similar to those discussed in Kennicutt (1983), except that we have adopted more up-to-date evolutionary tracks for low- and intermediate-mass stars from Demarque and Gisler (1975), Sweigart and Gross (1978), Mengel *et al.* (1979), Becker and Iben (1979, 1980), and Becker (1981). To simplify computations, a fixed (solar) composition was used. The most relevant result of the models is a theoretical cluster (*V*) luminosity–age relationship, which enables one to estimate the initial luminosity of any cluster of known age and (present) absolute magnitude. Our results are very similar to the widely used “single-burst” models of Searle, Sargent, and Bagnuolo (1973), Larson and Tinsley (1978), and Struck-Marcell and Tinsley (1978).

The initial Lyman-continuum luminosities of the clusters were computed in similar fashion, using evolution tracks for massive stars undergoing moderate degrees of mass loss (Chiosi, Nasi, and Sreenivasan 1978; Stothers and Chin 1979; Maeder 1980), Lyman-continuum fluxes from stellar-atmosphere models (Hummer and Mihalas 1970; Kurucz 1979), and the IMFs discussed below. Again, the reader is referred to Kennicutt (1983) for details. The most relevant parameter for the present application is the total Lyman-continuum photon flux of the cluster, normalized to the integrated Johnson *V* luminosity.

Since we are using the evolution models to extrapolate the initial stellar contents of clusters at early ages, the results are very sensitive to the form of the IMF, both its slope and upper mass limit. We calculated models for several power law IMFs:

$$\psi(m) = am^{\alpha} m < M_u,$$

with slopes $\alpha = -3$, -2.35 (Salpeter), and -1.8 , and upper mass limits M_u of 30, 60, 100, and $150 M_{\odot}$. It is not clear which slopes are most appropriate for the PCs; Freeman (1977) measured slopes $\alpha = -1.5$ to -3 for several intermediate-age clusters in the LMC, while Mateo (1987) derives $\alpha = -2.9$ for three old LMC clusters. Given the

sensitivity of the extrapolated ionizing fluxes to the IMF, we have chosen to present models for a large range of mass functions, partly as an illustration of the large uncertainties in the exercise.

Another parameter of secondary importance is the age spread of stars in a cluster. The ionizing luminosity of a coeval population of OB stars begins to drop rapidly after $2\text{--}3$ Myr, as the most massive stars evolve off the main sequence, and as stellar mass loss causes the position of the upper main sequence itself to shift to cooler temperatures (e.g., Chiosi and Maeder 1986). If the massive stars form over a period that is longer than this lifetime, the peak ionizing luminosity of the cluster will be depressed and spread over a longer period. The coexistence of massive main-sequence stars with more evolved supergiants, Wolf–Rayet stars, and supernova remnants in many giant H II regions (e.g., Searle 1971; McGregor and Hyland 1981; D’Odorico, Rosa, and Wampler 1983; McCall, Rybski, and Shields 1985; Chu and Kennicutt 1987) suggests that the ionizing stars have a range in ages of at least a few million years. Likewise, there is evidence for an age spread of up to 5 Myr in some PCs in the LMC (Becker and Mathews 1983). We have incorporated this effect by calculating fluxes for one set of clusters which form instantaneously, and another set which form over an interval of 5 Myr.

An illustration of the application of these models is given in Fig. 1, which shows the extrapolated initial ionizing luminosity of a star cluster with absolute magnitude $M_V = -9$ and age 10^8 yr, values that are similar to the intermediate-age cluster NGC 1866 in the LMC. Ionizing flux is plotted as a

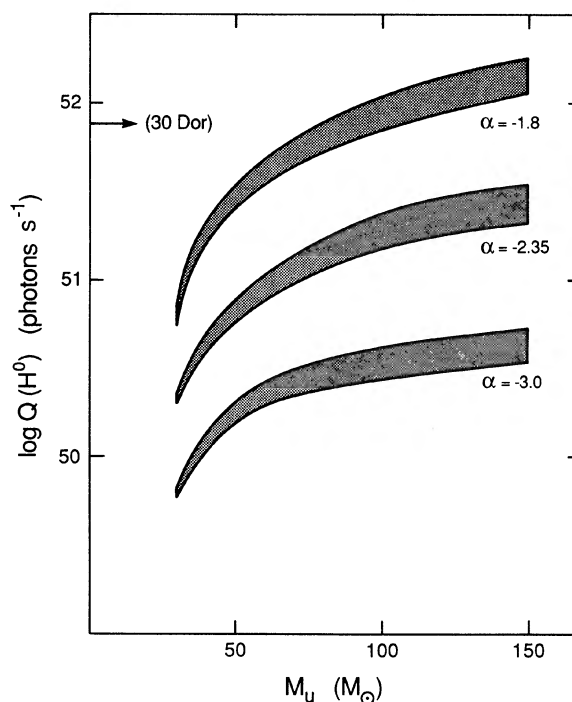


FIG. 1. Initial ionizing luminosity for a cluster with $M_V = -9$ at age 10^8 Myr, for different initial mass functions. Ionizing luminosity is plotted as a function of the upper stellar mass limit, and the curves correspond to the three power law slopes adopted. The shading reflects the effect of a finite age spread for the stars in the cluster.

function of the upper stellar mass limit, with the three curves corresponding to the different IMF slopes, and shading indicating the effect of varying the age spread in the cluster from 0 to 5 Myr. For comparison, we have denoted with an arrow the actual ionization requirement of the 30 Doradus H II region (Kennicutt 1984).

Figure 1 illustrates above all the sensitivity of our extrapolation to the presumed mass functions of the clusters at early ages; varying either the IMF slope or the upper mass limit within reasonable limits can change the derived initial ionizing luminosities by 1–2 orders of magnitude. Nevertheless, it is interesting to note that the range of luminosities spanned by the models in Fig. 1 encompasses the actual luminosities of giant H II regions.

b) Application to LMC Clusters

We have applied these models to a sample of 45 LMC clusters with age estimates compiled by Hodge (1981). Although Hodge's sample is by no means complete, it includes most of the brightest clusters in the galaxy. The estimated ages were combined with photometry from van den Bergh (1981), including an average aperture correction of -0.35 mag, following Mateo (1987), and an assumed distance modulus of 18.5 to the LMC. Figure 2 shows histograms of the extrapolated initial ionizing luminosities, one for an intermediate IMF with $\alpha = -2.35$ (Salpeter slope), $M_u = 100 M_\odot$, and age spread 5 Myr, and for an IMF deliberately enriched in massive stars, with $\alpha = -1.8$, $M_u = 150 M_\odot$, and zero age spread. Again, we indicate the actual luminosity of 30 Dor for comparison. We have subdivided the clusters into two classes by age, with a dividing line of 1 Gyr; the oldest are red clusters, which are more similar to the Milky Way globular clusters, and for which the evolutionary extrapolations are especially uncertain. There is a strong segregation between the extrapolated luminosities of the young and old clusters in Fig. 2. Much of the difference reflects the fact that the most massive old clusters in the LMC have no younger analogs, combined with an observational bias against old, low-mass clusters in the magnitude-

limited cluster surveys. Part of the difference could represent a systematic error in the extrapolation for the oldest clusters, however; for example, an unrealistic choice for the IMF.

Figure 2 demonstrates that if the richest LMC clusters formed with anything resembling a Salpeter IMF, they would have produced impressively bright H II regions, comparable to the brightest in the Milky Way. On the other hand, very few clusters, almost none of those formed in the LMC over the past 1 Gyr, could have produced giant H II regions comparable to 30 Doradus, unless their IMFs were very heavily enriched in OB stars. The formation of bound clusters with very shallow IMFs is unlikely on dynamical grounds (see Sec. V), but it is possible that the additional OB stars could form as part of an unbound association surrounding the PC. As will be discussed in Sec. III, there are a few examples of extremely luminous young PCs in nearby galaxies which could single-handedly ionize a giant H II region, but such clusters are rare.

On one final amusing, if hardly meaningful note, we could not resist applying the models to the old Galactic globular clusters. Extrapolating the same models to massive clusters such as ω Cen and 47 Tuc yields initial Lyman fluxes of order $10^{54} - 10^{55}$ photons s^{-1} . These luminosities are an order of magnitude higher than the brightest single H II regions known, and larger than the integrated ionizing luminosities of most galaxies! Such protoclusters, if they existed, would be detectable in emission lines at cosmological distances. We reiterate, however, that the large extrapolation to higher stellar masses makes the computation little more than a speculative exercise.

III. POPULATIONS OF STAR CLUSTERS AND H II REGIONS IN GALAXIES

It is well known that both blue globular clusters and giant H II regions are relatively deficient (if not altogether absent) in the Galaxy relative to the LMC, but is this simply a coincidence or are the differences physically related? In this section, we compile the published data on the populations of clusters and H II regions in other nearby galaxies, in order to

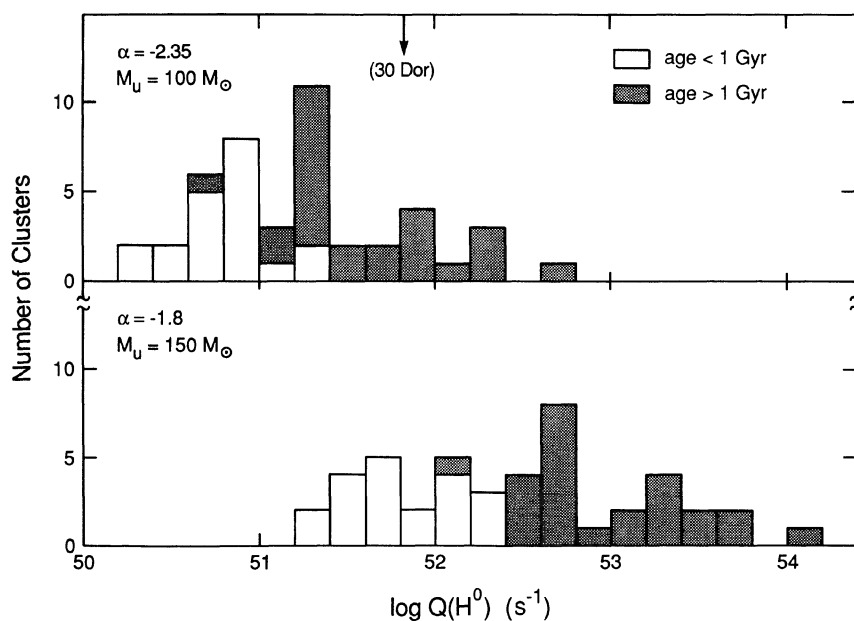


FIG. 2. Extrapolated initial ionizing luminosities for the populous star clusters in the LMC, for two assumed IMFs. The cluster populations have been divided into two age classes. The reasons for the differences between the two age classes are discussed in the text.

determine whether the distinctions between the LMC and the Galaxy are representative of more general trends along the Hubble sequence. We then compare the absolute formation rates of clusters and giant H II regions, and thereby constrain the fraction of H II regions that could contain PCs.

a) Parent Galaxies of Giant H II Regions

Homogeneous data on the luminosities of H II regions in spiral and irregular galaxies are available from Kennicutt (1979, 1981, 1988), Hunter and Gallagher (1985a), and Kennicutt, Edgar, and Hodge (1988). We have combined these data sets, reduced to a common distance scale with $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, in order to investigate the behavior of the luminosities of the first-ranked H II region in each galaxy. As demonstrated in Fig. 3, the luminosities of the brightest H II regions are strongly correlated with both the Hubble type and absolute magnitude of the parent galaxy. The dependence on galaxy luminosity among galaxies of the same type is mainly due to a simple size-of-sample statistical effect (as discussed by Kennicutt and Hodge (1980) and Kennicutt (1988)). The pronounced dependence on Hubble type is partly caused by a similar selection effect (late-type galaxies have more H II regions than early-type galaxies of the same brightness), but much of it is due to a physical change in the nebular luminosity function (Kennicutt, Edgar, and Hodge 1988). H II region diameters exhibit a similar dependence on morphological type (Sersic 1960; Hodge 1987).

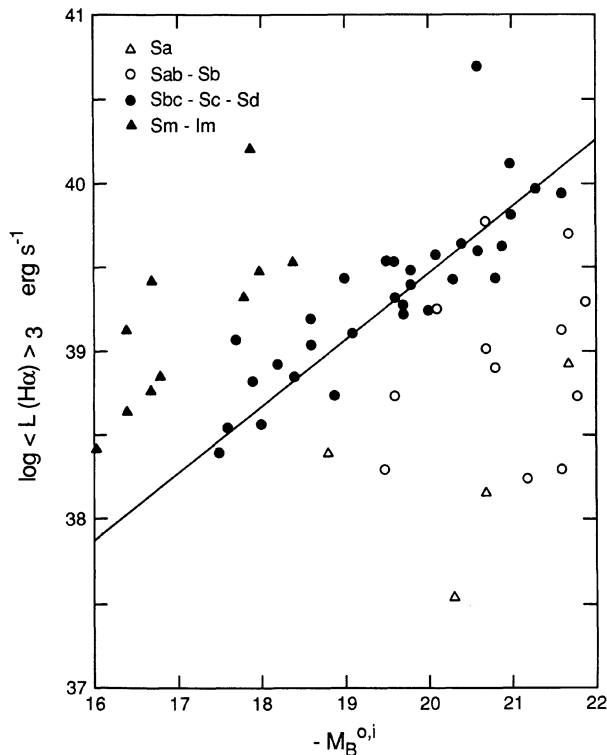


FIG. 3. Average luminosity of the three brightest H II regions in galaxies, plotted as a function of absolute magnitude. The line indicates the slope of a linear relation between nebular and galaxian luminosity, as would be expected from statistical effects alone for an inverse-square H II region luminosity function (see the text).

The differences in H II region populations are especially pronounced for the very luminous 30 Doradus class H II regions of most immediate interest here. To illustrate this point, we have compiled the data on H II region luminosity functions from Hunter and Gallagher (1985a) and Kennicutt, Edgar, and Hodge (1988), in order to derive the average number of "giant" H II regions as a function of Hubble type, as summarized in Table I. For this purpose, "giant H II regions" have been arbitrarily defined to be those with total observed $H\alpha$ luminosities greater than $3 \times 10^{39} \text{ erg s}^{-1}$ (or $\sim 2 \times 10^{51}$ ionizing photons s^{-1}), the approximate brightness of NGC 604 in M33 or 30 Doradus in the LMC (adopting a different threshold luminosity does not significantly alter the relative number of H II regions versus type). Listed in Table I are the total number of galaxies of each type, the total number of such giant H II regions, the total blue luminosity of the galaxies (normalized to unit luminosity at $L_B = 10^{10} L_\odot$ or $M_B = -19.5$), and the average number of giant H II regions per unit blue luminosity. The normalization to fixed absolute magnitude removes the size-of-sample bias mentioned earlier. Thus an irregular galaxy with $M_B = -19.5$ contains, on average, roughly two H II regions comparable in brightness to 30 Doradus, while fewer than one in 40 Sb galaxies of the same luminosity will contain one such H II region.

The results in Fig. 3 and Table I demonstrate that the apparent differences between the giant H II region populations of the Galaxy and the LMC are representative of a strong general dependence of the formation rate of large H II regions on Hubble type. Before discussing this result further we examine the behavior of star cluster populations in galaxies.

b) Parent Galaxies of Populous Star Clusters

Much less is known about the star cluster populations in external galaxies. A search of the literature revealed at least partial information on 14 galaxies that have been searched for blue PCs, and a summary of these results is given in Table II. Tabulated are the estimated number of PCs, as identified by the original investigators, and for comparison the number of identified old globular clusters. Objects identified as open clusters or stellar associations were excluded. The reader is cautioned against overinterpreting the absolute numbers of clusters listed in Table II, because the completeness and selection criteria in the different surveys vary enormously, as discussed below.

Compiling a homogeneous set of data on PCs in external galaxies is extremely difficult, partly owing to the widely variable completeness of the surveys themselves, and moreover from the ambiguity in the definition of a populous blue cluster. Although the brightest blue globular clusters in the

TABLE I. Average frequency of giant H II regions in galaxies.

Hubble type	Number of galaxies	Number of giant H II regions	$L(B)$ ($M = -19.5$)	$N(\text{H II})$ $L(B)$
Sa	4	0	13.2	0.00
Sb	10	1	43.1	0.023
Sc	15	25	22.9	1.09
Irr	22	7	3.1	2.28

TABLE II. Populous clusters in nearby galaxies.

Galaxy	Type	Distance (Mpc)	Number of blue PCs (identified)	Number old globular clusters	Reference
Milky Way	Sbc	—	0:	150	
LMC	Irr	0.05	20:	10:	1,2,3
SMC	Irr	0.07	0-7	10:	1,2,3
M31	Sb	0.7	<70:	400	4,5
M33	Sc	0.8	50:	12-25	6
NGC 6822	Irr	0.6	0-4	3	7
IC 1613	Irr	0.8	0:	0	8
NGC 55	Sc	3	1	—	9
NGC 1569	Irr	3	2	—	10
NGC 1705	IO	6	1	—	11
NGC 2403	Sc	3.5	1-3	—	12
NGC 3034 (M82)	IO	3.5	20-50	—	13
NGC 4449	Irr	4	6	(11:)	14
NGC 5253	IO	5	0-50	—	15

References to TABLE II

(1) Hodge (1981), (2) van den Bergh (1981), (3) Elson and Fall (1985), (4) Sharov and Lyuty (1983), (5) Crampton *et al.* (1985), (6) Christian and Schommer (1988), (7) Hodge (1977), (8) Hodge (1978), (9) Da Costa and Graham (1982), (10) Arp and Sandage (1985), (11) Melnick, Moles, and Terlevich (1985), (12) Tammann and Sandage (1968), (13) O'Connell and Mangano (1978), (14) Bothun (1986), (15) van den Bergh (1980).

LMC are easily distinguished from any in the Galaxy, the clusters in the Magellanic Clouds span a continuous range in mass and luminosity between those of rich open clusters and globular clusters in the Milky Way. It is not clear at all whether intermediate objects such as $h + x$ Persei in the Galaxy, the fainter populous clusters in the LMC, or any of the blue clusters in the SMC should be considered as blue globular clusters or simply large open clusters (Hodge 1981). This ambiguity becomes even more severe in more distant galaxies, because the clusters are less resolved.

For the purposes of Table II, and most of the following discussion, we shall arbitrarily count a cluster as a "blue PC" if it has a color $(B - V) < 0.5$, and a mass above $10^4 M_{\odot}$, which corresponds roughly to $M_V \leq -7$ for an age of 100 Myr. For the Local Group galaxies in the top half of Table II, where relatively complete multicolor photometry is available, we applied this simple luminosity discriminator, corrected approximately for age effects using the published colors, to estimate the total number of PCs in each galaxy. This admittedly is an arbitrary definition, but since we are mainly interested in the *relative* numbers of clusters in different types of galaxies, the precise definition should not be critical.

The galaxies listed in Table II fall into two categories. Several Local Group members have been systematically searched for clusters (LMC, SMC, M31, M33, NGC 6822, IC 1613), and relatively complete information is available:

Galaxy: We include the Milky Way in this sample, and list it as containing no populous blue clusters. Although the Galaxy contains a few clusters with luminosities that are comparable to the PCs in the Magellanic Clouds, the brightest Galactic open clusters are still considerably fainter and less dense than the largest PCs in the LMC (Freeman 1980; Hodge 1984). It is possible that several bona fide PCs lie in obscured regions of the Galactic disk, but in any case the relative number of such clusters is much lower than in the LMC or M33.

Magellanic Clouds: The estimate for the LMC was derived from the compilations of Hodge (1981) and van den Bergh (1981). The SMC contains several clusters near our threshold luminosity (e.g., NGC 176, 330, 419), and it is not clear whether these are bona fide PCs (Hodge 1981). We estimated the number of old globular clusters in both galax-

ies by using the age calibration of Elson and Fall (1985), and counting clusters for which their age parameter $S \geq 45$.

M33: The numbers listed are derived from the survey data of Christian and Schommer (1982, 1988). The bright clusters are not well resolved, so we have operationally defined blue PCs to be those clusters with $B - V < 0.5$ and luminosities as described above.

M31: Searches for globular clusters in this galaxy have revealed a considerable number of blue ($B - V < 0.3-0.5$) clusters, but it is not clear whether these are PCs, bright open clusters, or old globular clusters with erroneous colors (Sharov and Lyuty 1983; Crampton *et al.* 1985; Zinn 1986). The possible range is listed in Table II, but in any case the fractional number of PCs relative to old globular clusters is relatively small in M31.

NGC 6822, IC 1613: The cluster populations of these galaxies have been studied by Hodge (1977, 1978). NGC 6822 possesses four bright clusters, but as with the SMC, their luminosities are close to our arbitrary threshold for a PC. IC 1613 appears to possess only open clusters.

The remainder of Table II lists more distant galaxies in which candidate PCs have been identified; in these cases, we only list the number of clusters detected, and not necessarily the total number. Of special interest are a number of galaxies (M82, NGC 1569, 1705, 5253) that appear to contain very luminous ($M_V < 10$) and young ($< 2-3 \times 10^7$ yr) PCs. As pointed out by Melnick, Moles, and Terlevich (1985), these luminous blue clusters may represent the intermediate evolutionary "missing link" between the bright clusters in giant H II regions (e.g., NGC 2070 in 30 Dor) and the older PCs. The brightest of these clusters are considerably more luminous than the brightest LMC clusters, even taking into account their age differences, and could have been capable of ionizing a bright 30 Doradus class H II region at birth.

The cluster data are too sparse and nonuniform to allow us to draw any strong general conclusions about the dependence of cluster populations on galaxy type. The results summarized in Table II do indicate that luminous blue PCs are preferentially found in late-type, active star-forming galaxies, and that PCs are noticeably absent or deficient in the two early-type spirals (Milky Way and M31) for which data are available. This is consistent with a trend which roughly par-

allels the change in H II region populations along the Hubble sequence.

c) Formation Rates of Clusters and H II Regions

Another important constraint on the relationship between PCs and giant H II regions can be imposed by comparing the absolute numbers (or formation rates) of the objects in the same galaxies. Table I lists the average number of giant H II regions at any one time in different types of galaxies, and these numbers can be combined with an estimate for the lifetime of individual H II regions to derive the total number of H II regions formed over the lifetime of a galaxy. If we assume an average lifetime of 5 Myr for giant H II regions, an Sc galaxy with $M_B = -19.5$ forms about one 30 Doradus class H II region every 5 Myr on average, and an irregular galaxy of the same luminosity forms once every 3 Myr. If the average lifetimes are longer than 5 Myr, then the estimated number of H II regions will be reduced proportionally. (On the other hand, a larger cluster will be required to ionize the H II regions over these longer lifetimes.)

As a direct illustration of these results, we list in Table III the corresponding total number of giant H II regions which should have formed over the past 1 Gyr and 10 Gyr in three nearby galaxies, the LMC, M33, and M101 (these estimates are based on the average number of H II regions in Sc-Irr galaxies listed in Table I). The larger figure is appropriate if the PCs are not disrupted over timescales comparable to the age of the disk, but if disruption is important, the expected number of PCs will probably lie between the limits. The calculation is made under the assumption that the global star-formation rate is roughly constant with time in the galaxies (Kennicutt 1986); if the average birthrate in Sc-Irr galaxies was actually higher in the past, the numbers in Table III will be lower limits.

The results in Table III strain any hypothesis that attributes most of the ionization of giant H II regions to populous star clusters. If massive clusters formed within every giant H II region, we would expect between 100 and 1000 such clusters to remain in the LMC, depending on the rate at which they were disrupted. The total number of clusters of all types in the LMC probably exceeds this number (e.g., Hodge 1984), but recall from the models in Sec. II that only the most massive LMC clusters were able to ionize a 30 Doradus at birth; the number of such clusters is 1–2 orders of magnitude smaller than required to account for the number of giant H II regions. We thus tentatively conclude that PCs provide the dominant ionization for, at most, a small fraction ($\leq 20\%$) of the brightest giant H II regions. Note that it is still quite possible that most or all of the PCs form in giant H II regions, but the bulk of the ionization of most of the H II regions must come from (unbound) OB associations, not the PCs.

TABLE III. Examples of total number of "giant" H II regions formed.

	LMC	M33	M101
Type	Irr	Sc	Sc
M_B	-18.4	-19.1	-21.0
Total number (1 Gyr)	170	150	900
Total number (10 Gyr)	1700	1500	9000

IV. STRUCTURE OF STELLAR CORES OF GIANT H II REGIONS

Most previous discussions of PCs in giant H II regions have centered on the resemblance of the stellar core of 30 Doradus to the PCs in the LMC (e.g., McGregor and Hyland 1981; Moffat, Seggewiss, and Shara 1985). In this section, we re-examine the evidence for a dense massive cluster in 30 Dor, and discuss the central star clusters in more distant H II regions.

a) 30 Doradus

Figure 4 [Plate 31] shows the structure of the 30 Doradus H II region and its central star cluster, NGC 2070. The top two panels show the large-scale structure of the region in H α and red stellar continuum, over a field of 23'. The two bottom panels, printed from prime-focus plates obtained with the CTIO 4 m telescope at 4765 Å, show expanded images of the central cluster. The bright composite object at the center is R136. The lower left-hand panel was reproduced from a print which was kindly provided by Nolan Walborn.

Moffat and Seggewiss (1983) and Moffat, Seggewiss, and Shara (1985) have measured the surface-brightness profile of NGC 2070, and have discussed the structure of the region around R136. In order to investigate the structure of the cluster itself in more detail, we independently measured the profile of NGC 2070 using both CCD surface photometry and star counts. Our surface photometry is based on two 5 min exposures obtained with a GEC CCD detector on the CTIO 0.9 m telescope, using a 400 Å FWHM filter at 6000 Å to exclude nebular line emission. The radial profile was measured by integrating the surface brightness in concentric 0.72" (2 pixels) rings around R136a, after subtracting a sky background determined at the east and west edges of the CCD field (3.5' $\times$ 2.3'). The resulting profile is shown in Fig. 5(a). As discussed by Moffat, Seggewiss, and Shara (1985), the profile in the outer regions of the cluster is sensitive to the background determination, and the error bars in Fig. 5(a) show the effect of adopting two extreme limits, a resolved stellar background to zero (i.e., only a sky-brightness correction), and a background set equal to the average brightness (including resolved stars) at the edges of the CCD field. The complex structure of the surrounding stellar association makes it difficult to apply an accurate stellar background correction, and the true profile should lie between these extremes.

Figure 5(b) shows the radial distribution of 750 stars in the central 3' of NGC 2070. These were derived from *BVR* exposures obtained with an RCA CCD camera at the prime focus of the CTIO 4 m telescope, as described in Chu, Seitzer, and Walborn (1986), and kindly provided to us by P. Seitzer. The program DAOPHOT was used to identify the stars on a composite *B* exposure (average of five consecutive 5 s exposures), and measure their positions and approximate blue magnitudes. The instrumental magnitudes were tied to photoelectric photometry of the field by Rousseau *et al.* (1978). For the central 5" region around R136, we used the high-resolution photometry of Walker and O'Donoghue (1984). Figure 5(b) shows the distribution of (unweighted) star counts, with error bars indicating the effect of changing the stellar background correction as before. The error bar at the very center reflects the uncertainty in the number of components in R136a (e.g., Walker and O'Donoghue 1984; Weigelt and Baier 1985).

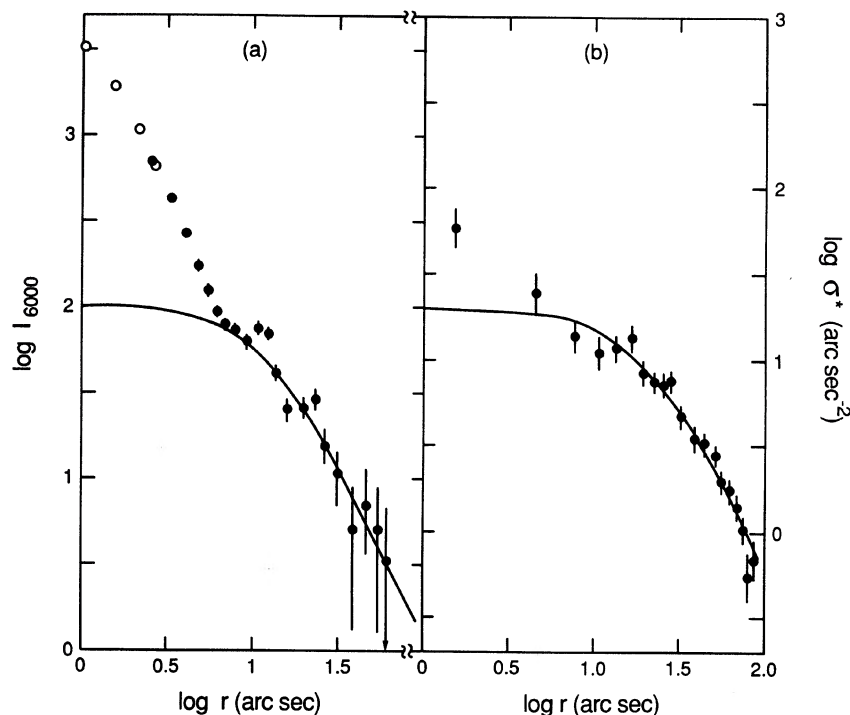


FIG. 5. Radial distribution of starlight and stars in NGC 2070. (a) Red luminosity profile; error bars indicate uncertainty due to the background correction. The curve is an isothermal profile with core radius $11'' = 2.8$ pc. (b) Distribution of star counts; error bars indicate uncertainties from Poisson statistics. The curve is an isothermal profile with core radius $18'' = 4.5$ pc. The unresolved central feature in both profiles is R136.

The profile of NGC 2070 is dominated by two components, a central unresolved core dominated by R136a, and a more extended structure corresponding to the remainder of the cluster. Moffat, Seggewiss, and Shara (1985) discuss the structure of the core in detail, and argue that its light distribution can be fitted to a King (1962) profile. This component, however, is much more compact (core radius ≤ 0.2 pc) than the typical core radii of Galactic globular clusters or the PCs in the LMC (Chun 1978; Mateo 1987). It seems more reasonable to us to compare the structure of the larger feature in Fig. 5 to the PCs. This feature is at least qualitatively similar, in both structure and radius, to the populous clusters. To illustrate this point, we have superimposed isothermal profiles with core radii $11''$ and $18''$ on the data in Figs. 5(a) and 5(b), respectively. (The difference in fitted core radii probably is not significant, given the uncertainties due to the small number of stars in the center and the contribution of the unresolved central component.) Although these theoretical profiles have little physical relevance to a cluster as young as NGC 2070, they do provide good fits to the observations. The distribution of light in this component also resembles the radial profiles measured by Elson, Fall, and Freeman (1987) for several PCs in the LMC, though our data do not extend to large enough radii to permit a thorough comparison.

Although our measurements confirm the resemblance between NGC 2070 and globular clusters, which was previously reported by Moffat, Seggewiss, and Shara (1985), we are inclined to attach less significance to the result. The profile of the cluster also resembles those of rich open clusters, and it is doubtful whether such a young cluster could have thermalized into the configuration of a globular cluster; stars are still forming (Walborn and Blades 1987), and most of the stars plotted in Fig. 5 presumably will disappear over the next 10 Myr. The qualitative structural similarity

between NGC 2070 and older populous clusters is interesting, but its physical significance is questionable.

We have also combined the *UBV* photometry with information on the spectral types of the brightest stars in NGC 2070 in order to derive a crude estimate of the mass of the cluster. For the brightest members of the cluster (exclusive of R136), spectral types from Melnick (1985) and Walborn (1986) were combined with the spectral-type-mass relation of Dorland, Montmerle, and Doom (1986). This yielded a mass of $5300 \pm 1500 M_{\odot}$ for the 59 stars with spectra, including an estimated $1500 M_{\odot}$ for the stars in R136a (e.g., Chu, Cassinelli, and Wolfire 1984). For the other members of the cluster, we used our *BVR* photometry, combined with the photometry of Walker and O'Donoghue (1985) for the core region around R136, to construct the upper luminosity function, and combined this with the mass-luminosity relation of Scalo (1986) to derive a mass of $8100 \pm 2000 M_{\odot}$ for 447 unclassified stars brighter than $M_V < -2.5$ in the cluster. This assumes an average extinction $A_V = 1.2$ mag and a distance modulus of 18.5 mag to the LMC. The estimated mass in stars above $10 M_{\odot}$ only in NGC 2070 is $13\,500 \pm 3000 M_{\odot}$. Note that this mass applies to the central 10 pc (radius) in 30 Doradus; considerably more stars are scattered over a larger region of the nebula. It is also likely that several hot, massive stars in the core have not yet been identified (Walborn and Blades 1987).

This result, combined with the compact structure of NGC 2070, may strengthen the case for the formation of a populous cluster in 30 Doradus. Although the mass derived above is only comparable to the smaller PCs in the Magellanic Clouds, which have masses of 10^4 – $2 \times 10^5 M_{\odot}$ (Chun 1978), our estimate for NGC 2070 does not include stars fainter than $M_V = -2.5$, or $M < 10 M_{\odot}$. For the range of IMFs considered in this paper, stars above $10 M_{\odot}$ contrib-

ute approximately 10%–20% to the total stellar mass, and hence even if the cluster IMF were abnormally shallow it is likely that several times $10^4 M_{\odot}$ will form in lower-mass stars, a mass that is comparable to those of the young and intermediate-age PCs in the LMC, and much larger than those of Galactic open clusters.

b) H II Regions in Other Galaxies

The nearest giant H II regions beyond 30 Doradus are over 10 times more distant, and their embedded clusters are only partially resolved into individual stars. We can use measurements of the integrated properties of the clusters, however, to determine whether the core of 30 Doradus is representative of most giant H II regions, and to compare the properties of H II region core clusters to those of PCs in nearby galaxies.

We have obtained spectrophotometry and CCD imagery for several giant H II regions in the Local, M81, and M101 groups, in order to derive the integrated continuum luminosities and structural properties of their embedded star clusters. Figure 6 [Plates 32 and 33] shows H α and continuum (6000 Å) images of selected H II regions in M33, M101, and NGC 2403. The data were obtained using CCD direct cameras (Texas Instruments and Tektronix chips) on the Kitt Peak National Observatory (KPNO) 2.1 m and No. 1 0.92 m telescopes. The fields were imaged in line-free continuum bandpasses at 4500 and 6000 Å, in order to isolate the central stars, and in the H α emission line. We also obtained absolute spectrophotometry (emission line and continuum) of the H II regions in M33, NGC 2366, and M101, using the IIDS scanner on the KPNO 2.1 m telescope, the IRS scanner on the KPNO No. 2 0.91 m telescope, and the IDS scanner on the UM/UCSD 1.5 m telescope on Mount Lemmon. The CCD data were used to map the structure of the embedded stellar associations and clusters, while the spectrophotometry was used to derive integrated magnitudes.

The next nearest giant H II region after 30 Doradus is NGC 604 in M33. The visually brightest stars are resolved in this H II region (see Figs. 6(a) and 6(b)), and have been studied in detail by Conti and Massey (1981), D'Odorico, Rosa, and Wampler (1983), Massey and Hutchings (1983), and Hunter and Gallagher (1985b). The stellar population in NGC 604 is similar to that in 30 Doradus, but the structures of the two clusters are significantly different in two respects. NGC 604 does not contain a dominant central core like R136 (though Massey and Hutchings have identified at least one composite semiresolved UV-bright object), and the cluster appears to be more extended and irregular than NGC 2070. This is illustrated in Fig. 7, which shows the radial profile of the central cluster in NGC 604 as measured from the 6000 Å CCD data, along with the average fitted profile for NGC 2070 (not including R136).

Hence while 30 Doradus appears to be ionized by a composite of a compact cluster within a more extended association, NGC 604 appears to be an example of a bright H II region that is entirely ionized by a luminous stellar association, with perhaps one or more bright open clusters. In this respect, the stellar component of NGC 604 strongly resembles the core of the Carina nebula (including the open cluster Tr 16 and η Car) in the Milky Way. The Carina nebula is one of the most luminous H II regions in the Galaxy (e.g., Kennicutt 1984), so the resemblance with NGC 604 is not coincidental.

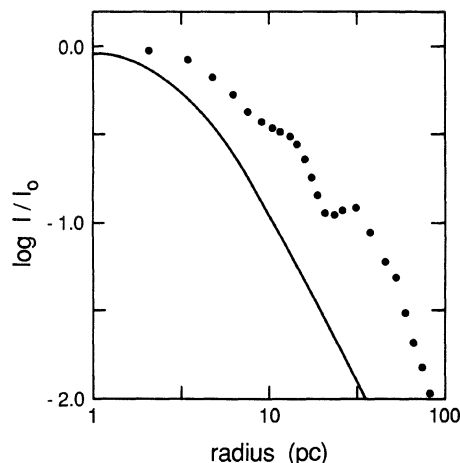


FIG. 7. The points indicate the radial luminosity profile (at 6000 Å) for the central star cluster in NGC 604. The solid curve is the average best-fitting isothermal profile (core radius 3.5 pc) for NGC 2070, exclusive of the bright central object R136.

The next nearest giant H II regions are in members of the Sculptor, M81, CVn I, and M101 groups. At these distances (2.5–8 Mpc), a compact cluster like NGC 2070 would be essentially unresolved. Such semistellar core clusters are observed in several giant H II regions in NGC 2403, NGC 2366, and M101. NGC 2366 and NGC 2403 contain five giant H II regions (using the arbitrary threshold of 10^{51} ionizing photons s^{-1}), and all five regions contain compact core clusters, though it must be noted that the spatial resolution at these distances is so poor ($1'' = 15$ – 20 pc) that some of the cores may be nothing more than very luminous open clusters. The giant spiral M101 contains over a dozen 30 Dor class H II regions, and several of these also contain compact core clusters (e.g., NGC 5461 in Figs. 6(e) and 6(f)), but several others appear to contain only loose associations and/or faint clusters (e.g., NGC 5462 in Figs. 6(c) and 6(d)). These results tend to confirm the earlier statistical analysis, which indicated that only a fraction of the giant H II regions are likely to form bright PCs.

Table IV lists the integrated magnitudes of star clusters in several nearby giant H II regions. The magnitudes were derived from our continuum spectrophotometry (NGC 604, NGC 2363, M101), the published spectrophotometry of NGC 2403 by Fierro, Torres-Peimbert, and Peimbert (1986), observations of CM-16 in NGC 4449 by Hunter and Gallagher (1985b), and our CCD photometry of NGC 2070 in 30 Doradus. Reddening corrections were estimated from the Balmer decrement of the nebular spectrum. We attempted to measure the radii for the clusters as well, but except for 30 Dor and NGC 604 the cluster cores were unresolved at the $1''$ (15–30 pc) scale. Table IV also lists for comparison data for luminous PCs in the LMC, NGC 1569, and NGC 1705.

Table IV demonstrates that the embedded star clusters in giant H II regions are among the most luminous stellar aggregates found in galaxies. The core clusters in NGC 5461 (M101) and CM-16 (NGC 4449) are even comparable to the “super” star clusters in NGC 1569, NGC 1705, and M82. Perhaps the most interesting object in the sample is the

TABLE IV(a). Core clusters/associations in H II regions.

Galaxy	H II Region/Cluster	M_B (cluster)
LMC	30 Dor	< -12.6
M33	NGC 604	-12.6
NGC 2366	NGC 2363	-12.2
NGC 2403	VS 44	-12.9
NGC 2403	VS 24	-13.2
M101	NGC 5461	-14.1
NGC 4449	CM-16	-15.2

TABLE IV(b). Comparison blue populous clusters.

Galaxy	Cluster	M_B	Age (Myr)
LMC	NGC 1866	-9.3	100
LMC	NGC 2100	-10.1	10
NGC 1569	—	-13.3	10
NGC 1569	—	-14.9	10

cluster in CM-16, which has been studied in detail by Hunter and Gallagher (1985b). This cluster is located inside a bright H II region, but its spectrum shows an unusually strong stellar continuum, with an absorption-line spectrum that is very similar to the 10^7 -yr-old "superclusters" in NGC 1569 and 1705. It seems likely that the clusters in NGC 5461, CM-16, NGC 1705, and NGC 1569 represent (in rough sequence) the early evolutionary stages of unusually massive PCs, which would later evolve into clusters comparable to the most massive intermediate-age clusters in the LMC. A serious caveat in this scenario, however, is the limited spatial resolution of the observations of these distant clusters. Imagery with resolution comparable to that of the *Hubble Space Telescope* will be required to confirm whether these very luminous young core clusters are compact enough to form bound, permanent PCs.

V. DISCUSSION AND SUMMARY

The results of our study are mixed, and in many cases inconclusive. We have found several pieces of circumstantial evidence which are consistent with the hypothesis that populous blue globular clusters may be forming in the centers of some giant H II regions, but the observed properties of PCs and giant H II regions also impose strong limits on the number of H II regions that may harbor such clusters. Here we summarize and combine the results of the previous three sections, and briefly discuss their implications for the information of rich clusters and giant H II regions.

Our models indicate that blue globular clusters would have produced impressively luminous H II regions at birth, provided that their IMFs extended to OB stars. The latter is likely, because the youngest PCs in the LMC have well-populated present-day mass functions that extend as high as $20 M_{\odot}$, and very bright PCs are observed in at least four other galaxies. On the other hand, only the most massive (and rare) PCs would have been capable of ionizing a supergiant H II region like 30 Doradus, unless their IMFs were enriched in OB stars by at least a factor of 2–3 over a Salpeter function.

The additional OB stars required to account for the ionization of giant H II regions may not have formed as bound members of the PCs themselves. Numerical simulations of open clusters by E. Terlevich (1987) indicate that clusters with shallow (in this case $\alpha = -1.1$) IMFs are disrupted

over timescales of a few times 10^7 yr, mainly due to the high rate of mass loss from advanced stages of stellar evolution in such a population. It is questionable whether tightly bound PCs could survive if they formed with such shallow IMFs. It is possible that the additional ionizing stars form not in the PCs themselves but rather in surrounding OB associations. The stellar population in 30 Doradus, with a dense core cluster and a more extended OB association which provides a major fraction of the ionization, may be an example of such a composite system.

An IMF heavily enriched in massive stars is also needed to avoid uncomfortably high star-formation rates and efficiencies in the H II regions. For example, if the 30 Doradus H II region were ionized by a stellar population with a normal Salpeter or extended Miller–Scalo IMF, simple photoionization models (e.g., Kennicutt 1983; Gallagher, Hunter, and Tutukov 1984) predict a total mass in formed stars of $3\text{--}5 \times 10^5 M_{\odot}$. A composite ionization model, with both a compact central star cluster and a surrounding association of predominantly massive stars, avoids this problem in a way that is consistent with the observed properties of the H II region.

The statistics of giant H II regions and PCs in external galaxies suggest that both kinds of objects occur primarily in late-type spiral (Sc–Sm) and irregular (Magellanic and amorphous) galaxies. Both are conspicuously deficient, if not altogether absent, in the Galaxy, M31, and (in the case of giant H II regions) most other early-type galaxies.

It is tempting to attribute the apparent deficiencies of both giant H II regions and massive star clusters in early-type galaxies to a deficiency of massive interstellar clouds in these galaxies. The PCs in late-type galaxies have masses ranging from a few times 10^4 to $10^6 M_{\odot}$ (Chun 1978; Elson, Fall, and Freeman 1987), and if we assume the clusters form in regions with star-formation efficiencies of a few to a few tens of percent (e.g., Elmegreen 1983; Mathieu 1983; Wilking and Lada 1985; Myers *et al.* 1986), interstellar clouds with masses of at least $10^6\text{--}10^7 M_{\odot}$ would be required to form PCs. The gas complexes associated with giant H II regions in nearby galaxies do have masses of this order (e.g., Israel *et al.* 1982; Kennicutt 1984; Melnick and Rubio 1985), while the largest molecular clouds in the Milky Way lie close to the limit (e.g., Scoville *et al.* 1987; Waller *et al.* 1987). As discussed earlier, the largest H II regions in early-type spirals are 1–2 orders of magnitude fainter (and less massive) than the giant H II regions in Sc–Irr galaxies, and unless the efficiency of star formation is orders of magnitude lower in the early-type spirals (an unlikely possibility), the differences in H II region populations probably mimic similar underlying differences in the mass spectra of cold interstellar clouds.

Hence we speculate that the absence of massive star clusters in early-type galaxies may be caused in part by an absence of massive interstellar clouds, as reflected by the H II region statistics. This would not solve the problem of why giant clouds (or PCs) do not form in early-type galaxies, but it at least would reduce two problems into one. Another possible explanation, discussed by Elmegreen (1983), is that lower metallicities in late-type galaxies are responsible for the increased cluster masses. This theory also predicts that bound clusters form in relatively low-mass clouds, and if it is correct it would contradict our hypothesis.

The structure of the central star clusters in 30 Doradus and other nearby H II regions is consistent with the possible formation of PCs in their cores, but the results are inconclu-

sive. A major shortcoming in the available data is the lack of information on the low-mass stars in giant H II regions. The well-studied stars in 30 Doradus are all above $10 M_{\odot}$, and hence there is virtually no overlap with the stellar mass range, which is observed in the PCs. Even if this information becomes available, we should not expect to observe a compact, relaxed globular cluster embedded in an H II region, because the formation time for such a cluster is probably comparable to the lifetime of the H II region.

Perhaps the most direct evidence for the existence of very young PCs with massive stars are the observations of "super-luminous" compact clusters in NGC 1569, NGC 1705, and possibly M82 and NGC 5253. These clusters, invariably found in galaxies containing bright H II regions and widespread star-formation bursts, demonstrate that massive clusters can form with stellar mass functions that extend to at least $20 M_{\odot}$.

Finally, several pieces of evidence indicate that while blue globular clusters may be forming and ionizing some giant H II regions, unbound stellar associations are probably the most important ionization source for most bright H II regions. This evidence comes from the ionization models discussed earlier, comparisons of the numbers of PCs and giant H II regions in nearby galaxies, and from the observed absence of compact stellar cores in many giant H II regions, for example, NGC 604 in M33.

In summary, we have found several strong suggestions,

but no hard proof, that some giant H II regions are the birth sites of the populous star clusters. Nevertheless, we remain intrigued by the possibility that we may be observing the formation of blue globular clusters in some extragalactic H II regions. Several additional observations could help to clarify the questions raised here. Especially valuable would be more observations of the star cluster populations in nearby galaxies, especially early-type systems, and observations of the stellar luminosity and mass functions in NGC 2070 and the youngest PCs in the Magellanic Clouds. High-resolution observations of the mass distributions of atomic and molecular clouds in nearby galaxies would test whether the strong gradients in H II region properties along the Hubble sequence extend to the interstellar cloud spectrum in general; if this is the case, we may be able to explain the systematic properties of both the star clusters and H II regions in different types of galaxies.

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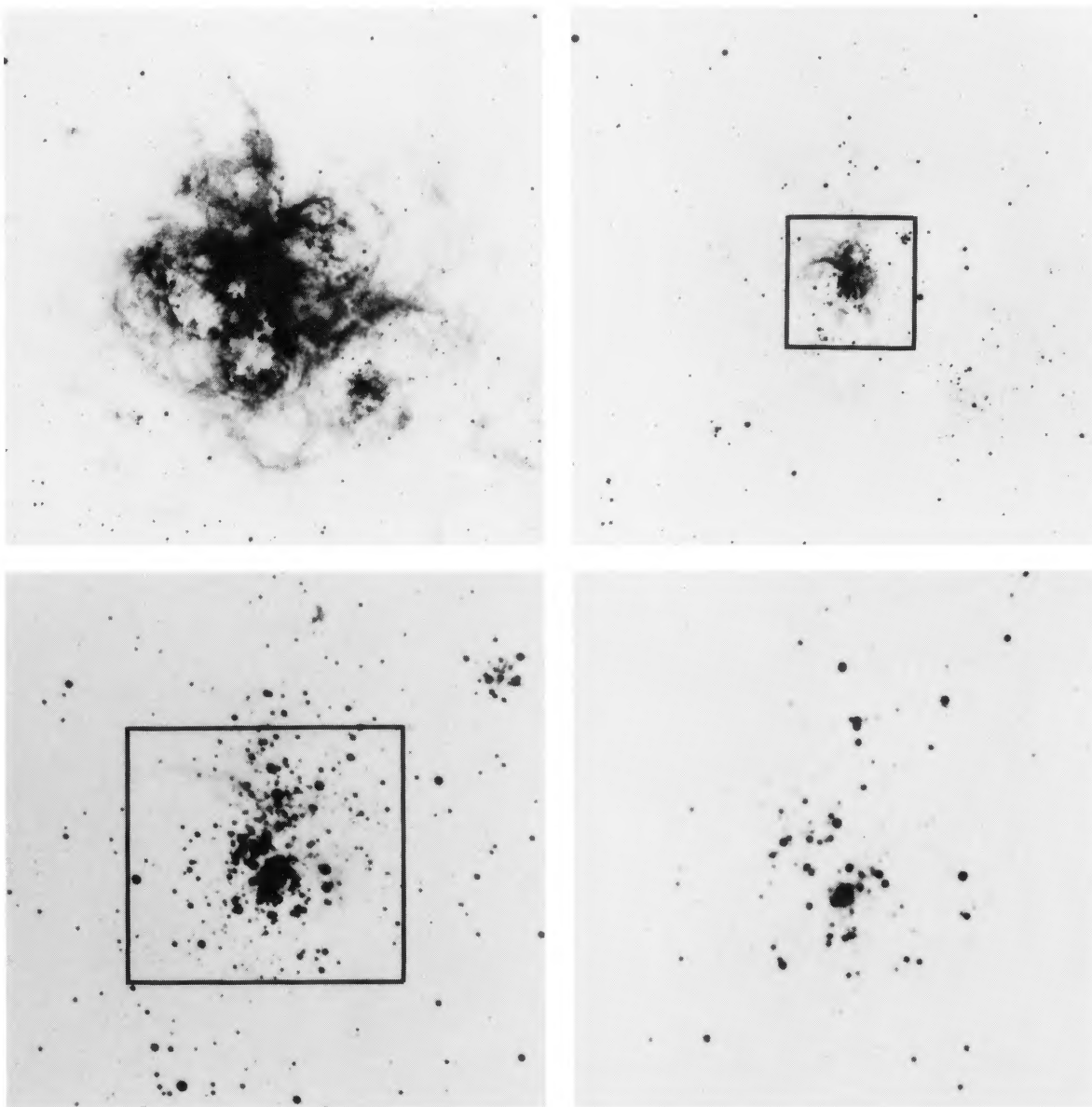


FIG. 4. The 30 Doradus H II region in the LMC and its central star cluster, NGC 2070. The top panels show the entire H II region (panel size = 23') in H α and the red continuum. The bottom panels show expanded views (indicated by the boxes) of NGC 2070.

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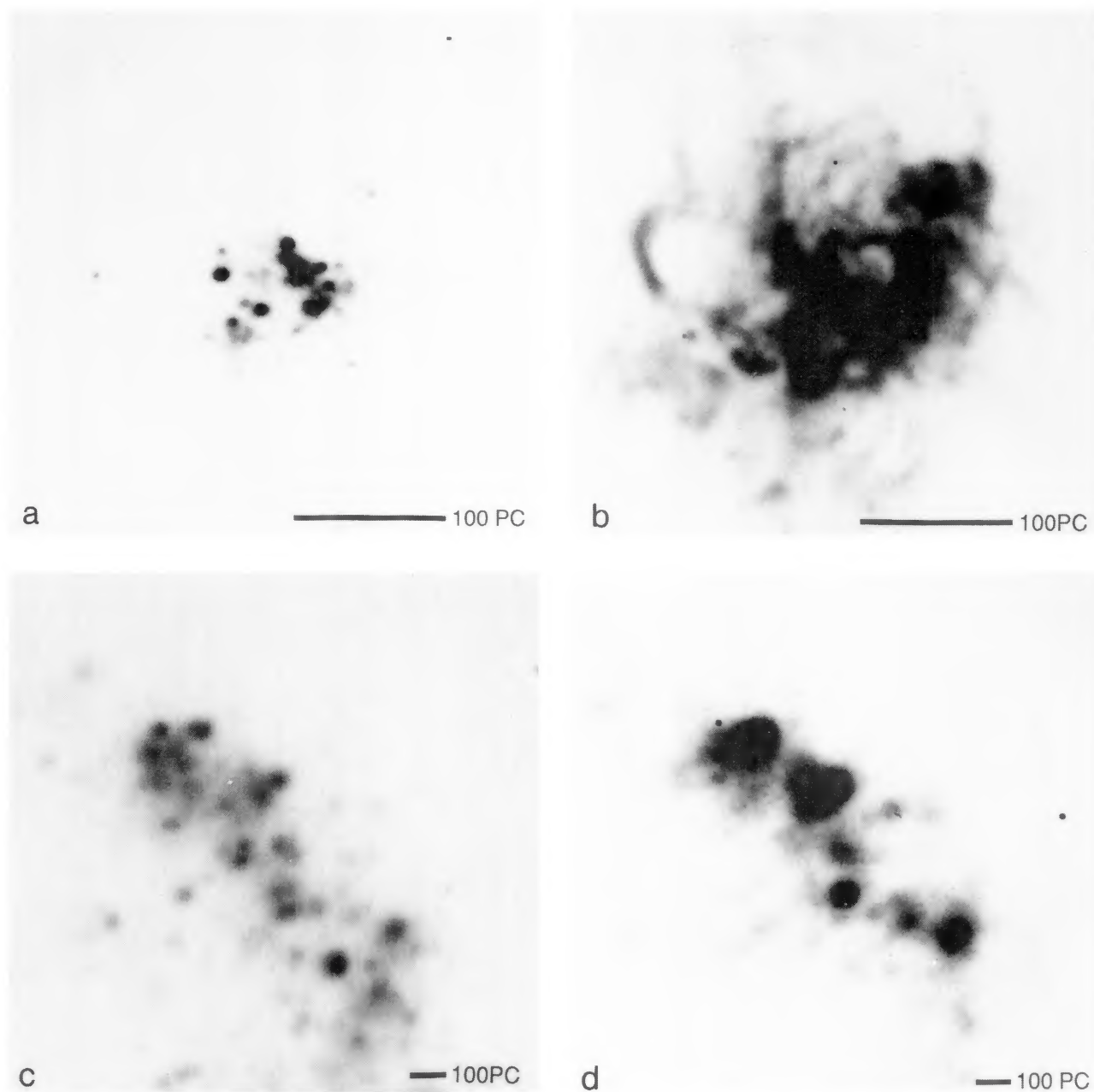


FIG. 6. Examples of other nearby giant H II regions and their ionizing stars. The left-hand image in each pair is an exposure in the stellar continuum at 6000 Å, while the right-hand image is an H α exposure at the same scale. (a) and (b) NGC 604 in M33; (c) and (d) NGC 5462 in M101. These are examples of giant H II regions without strong central stellar concentrations.

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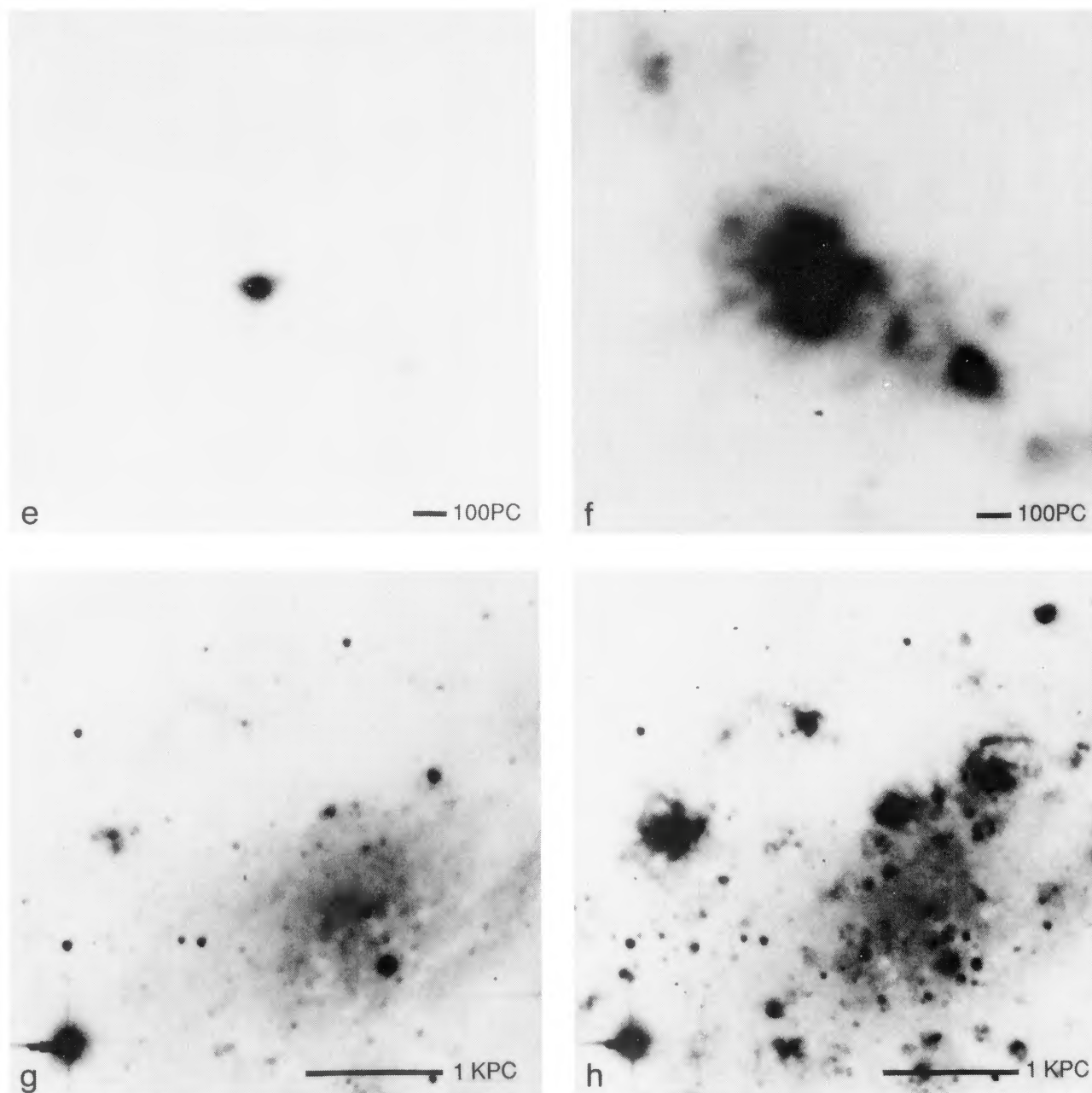


FIG. 6. (continued) Examples of giant H II regions which may contain compact core clusters. (e) and (f) NGC 5461 in M101; (g) and (h) the central region of the Sc galaxy NGC 2403.

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