

## YOUNG STAR CLUSTERS IN STARBURST ENVIRONMENTS

Luis C. Ho<sup>1</sup>

### RESUMEN

Observaciones de alta resolución en sistemas con brotes de formación estelar reciente, hechas con el *Telescopio Espacial Hubble (HST)*, frecuentemente muestran cúmulos estelares muy compactos de luminosidad extrema (“supercúmulos”). La formación en cúmulos parece ser el modo dominante en los brotes de formación estelar y aquí resumimos las propiedades principales de estos cúmulos. Un nuevo estudio global de imágenes UV de las regiones centrales de galaxias cercanas, realizado por el *HST*, indica que los cúmulos se forman en una variedad muy amplia de entornos. En concreto, los anillos circumnucleares de formación estelar poseen muchos cúmulos y presentamos varios ejemplos obtenidos con imágenes recientes. Sobre la posibilidad de que los supercúmulos sean los equivalentes actuales de los cúmulos globulares jóvenes, presentamos evidencias que sugieren que al menos algunos de ellos tienen masas y densidades de masa comparables a las de los cúmulos globulares de la Vía Láctea.

### ABSTRACT

Recent high-resolution observations with the *Hubble Space Telescope (HST)* reveal that young star clusters of extraordinary luminosity and compactness (“super star clusters”) are commonly found in starburst systems. Cluster formation appears to be a dominant mode of star formation in starbursts. The principal properties of the young clusters are summarized. A new UV *HST* imaging survey of the central regions of nearby galaxies indicates that young clusters form in a wide range of environments. Circumnuclear star-forming rings, in particular, are richly populated with clusters, and several examples from recent imaging studies are discussed. There has been much speculation that super star clusters represent present-day analogs of young globular clusters. I present evidence suggesting that at least some super star clusters indeed have masses and mass densities comparable to those of evolved globular clusters in the Milky Way.

**Key words:** GALAXIES: COMPACT — GALAXIES: STARBURST — GALAXIES: STELLAR CONTENT — STARS: FORMATION

### 1. INTRODUCTION

In the last few years, *Hubble Space Telescope (HST)* imaging studies of a variety of extragalactic star-forming systems have identified a widespread new class of star clusters. The compactness and high luminosities of these objects, coupled with their inferred youth, have stimulated speculation that they represent present-day analogs of young globular clusters. Although the existence of a few such “super star clusters” (hereafter SSCs) had been known from previous ground-based studies (e.g., Arp & Sandage 1985; Melnick et al. 1985; Lutz 1991), it took the resolving power of *HST* to demonstrate the prevalence of this phenomenon. Such clusters are found in a wide array of environments, ranging from nearby dwarf galaxies (O’Connell et al. 1994; Hunter et al. 1994; O’Connell et al. 1995; Leitherer et al. 1996; Gorjian 1996), to more distant merging and interacting systems (Holtzman et al. 1992; Whitmore et al. 1993; Conti & Vacca 1994; Vacca 1994; Shaya et al. 1994; Whitmore & Schweizer 1995; Meurer et al. 1995), to circumnuclear star-forming rings (Benedict et al. 1993; Barth et al. 1995, 1996; Bower & Wilson 1995; Maoz et al. 1996a). In fact, as I will discuss later, it appears that the formation of compact clusters may be surprisingly commonplace in most regions of galaxies experiencing elevated levels of star formation, and need not be restricted to the most extreme starbursting environments.

This contribution gives an overview of the principal properties of SSCs, describe a new *HST* imaging survey and its applicability to the study of clusters, and summarizes some recent work by my collaborators and myself pertaining to clusters in circumnuclear rings. I also present evidence based on ground-based observations that at least some of the SSCs have dynamical masses resembling those of evolved globular clusters seen in the Galaxy.

<sup>1</sup>Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-42, Cambridge, MA 02138, USA.

## 2. PROPERTIES OF THE CLUSTERS

### 2.1. Environments

The initial results from *HST* imaging studies give the impression that SSCs are only found in rather violent settings such as merging and interacting galaxies. The first announcement, for example, was that of the well-known merging and/or cooling-flow galaxy NGC 1275 (Holtzman et al. 1992). Two similar studies of merger systems quickly followed: numerous SSCs were found in the “Antennae” system (NGC 4038/NGC 4039; Whitmore et al. 1993) and in the “Atoms for Peace” galaxy (NGC 7252; Whitmore & Schweizer 1995). Likewise, Conti and collaborators (Conti & Vacca 1994; Vacca 1994, 1996; Leitherer et al. 1996; Conti et al. 1996) are finding from their ultraviolet (UV) imaging program that SSCs invariably show up in Wolf-Rayet (W-R) galaxies, most of which are known to show signs of interaction. The discovery of luminous, young clusters generated considerable excitement and rekindled interest in the idea that globular clusters might form in galaxy mergers (Burstein 1987; Schweizer 1987; Ashman & Zepf 1992). While these studies certainly point to a plausible relation between galaxy interaction and the formation of SSCs, one must be careful in drawing any direct, causal connection between the two processes. The cases cited above by no means represent an unbiased sample; in fact, they were, to a large extent, selected based on prior knowledge of their extreme characteristics. It is well known that galaxy interactions can give rise to intense starburst activity (see contributions in Shlosman 1994). Similarly, W-R galaxies are among the earliest and most vigorous manifestations of starbursts (Conti 1991; Vacca & Conti 1992). Thus, an equally viable interpretation is that cluster formation is an integral part of star formation in starbursts in general. In as much as galaxy interactions can trigger starbursts, there is a high likelihood of finding SSCs in interacting systems; but such an association is indirect —interactions are sufficient but not necessary for cluster formation. That SSCs are also found in galaxies that are not obviously interacting (O’Connell et al. 1994; Meurer et al. 1995) supports this viewpoint, as does the tendency for some SSCs to be located in circumnuclear rings and other relatively quiescent environments, as will be described below.

### 2.2. Luminosities

SSCs have earned their superlative title largely because of their very high luminosities, which in many cases surpass that of the R136 cluster in the 30 Doradus complex in the Large Magellanic Cloud (LMC). Some of the clusters, for instance, have absolute visual magnitudes exceeding  $-14$  to  $-15$ , whereas  $M_V = -11.3$  mag for R136 (O’Connell et al. 1994). The clusters will fade, of course, as they age, by an amount depending on their current age. According to models of evolving stellar populations (e.g., Bruzual & Charlot 1993), a 10 Myr old cluster will fade by 6 to 7 mag in  $V$  after 10–15 Gyr. Meurer et al. (1995) define SSCs as having an absolute magnitude at  $2200 \text{ \AA} \leq -14$  (roughly corresponding to  $M_V \leq -13$  mag for a cluster with an age of 10 Myr); this criterion, however, is clearly arbitrary, for there exists a *continuum* of luminosities among clusters. The luminosity function at the bright end can be approximated by a power law of the form  $dN \propto L^\alpha dL$ , where  $\alpha \approx -2$  (Whitmore et al. 1993; Meurer et al. 1995; Meurer 1995; Vacca 1996). Although the luminosity function at the faint end is increasingly affected by detection incompleteness, it evidently preserves the same functional form and slope (Maoz et al. 1996a). The luminosity function, however, as pointed out by van den Bergh (1995), does not resemble that of evolved globular clusters, which obey a nearly universal Gaussian function, but rather that of open clusters (e.g., van den Bergh & Lafontaine 1984). Van den Bergh cites this as evidence that the young clusters are more closely related to open clusters instead of globular clusters. Several factors, however, weaken van den Bergh’s argument. As noted by Larson (1993), a direct comparison between the luminosity function of young clusters and globular clusters is inappropriate since the two populations are viewed at very different stages: the former most likely have a heterogeneous mix of ages while the latter represent an evolved, much more uniform group. Dynamical evolution undoubtedly will substantially modify the luminosity function of the young population, especially at the faint, low-mass end. Meurer (1995) has shown that the luminosity function of the clusters in the Antennae system (Whitmore et al. 1993) can be modeled as a combination of a globular cluster mass function and continuous cluster formation.

### 2.3. Ages

The ages of SSCs span a wide range from as young as a few Myr to as much as several hundred Myr. In the case of the UV knots seen in W-R galaxies, the presence of W-R stars constrains the ages to be 3–8 Myr (Meynet 1995). In some cases, the young ages have been independently confirmed by spectral-synthesis modeling

of the UV spectrum (Conti et al. 1996; Leitherer et al. 1996). The ages for the bulk of SSCs, however, have been derived from broad-band optical colors. Ages from this method, unfortunately, are notoriously difficult to interpret, since the broad-band colors also depend on metallicity and reddening. From the narrow range of colors and the apparent absence of a “fading vector” in the distribution of  $V$  magnitude versus  $V-R$  color, Holtzman et al. (1992) argued that the SSCs in NGC 1275 have a relatively small spread in ages, perhaps between 10 to 300 Myr. It has subsequently been shown by Faber (1993); however, that the Holtzman et al. images were not sufficiently deep to allow this test to be performed unambiguously. Faber’s simulations, in fact, cannot rule out cluster ages as large as 1 to 5 Gyr. The age determinations for the clusters in NGC 7252 (30–500 Myr; Whitmore et al. 1993) and the Antennae (4–40 Myr; Whitmore & Schweizer 1995) suffer from similar ambiguity, since they are also based on photometric properties.

In principle, spectroscopic data can furnish more reliable age estimates, but, thus far, attempts to derive ages from optical spectra have not yielded superior results compared to those based on photometric methods. Schweizer & Seitzer (1993) obtained spectra of the two brightest clusters in NGC 7252 and showed that the integrated light comes predominantly from late-A to mid-F stars. But beyond this broad statement, no definitive conclusion could be drawn, since the spectral indices in the blue-red region were of limited use for dating the clusters. The  $Mgb$  and  $Fe\ I\ \lambda 5270$  features, for example, give degenerate values of the age, while the Balmer absorption lines, in addition to being discrepant with model predictions for unknown reasons, can be fitted with a large range of ages spanning almost a factor of 100. Zepf et al. (1995) performed essentially the same analysis for the the brightest cluster in NGC 1275.

#### 2.4. Sizes

Little is known about the detailed structure of the clusters. Even with the superior optics of the refurbished *HST*, the two SSCs in the relatively nearby galaxy NGC 1569 ( $d \approx 2.5$  Mpc) still remain unresolved (Leitherer, this volume). Given these limitations, it is impossible to characterize the size of the clusters by conventional parameters such as the core or tidal radius. Instead, the observationally most straightforward parameter is the half-light radius ( $R_h$ ), sometimes also referred to as the effective radius.  $R_h$  also has the advantage of being relatively insensitive to evolutionary or environmental effects (van den Bergh, Morbey, & Pazder 1991). Unfortunately, even such a simple parameter is difficult to determine with accuracy. As discussed by Meurer et al. (1995), the measurement of cluster radii from *HST* images is complicated by severe crowding and background confusion in many cases, rendering the sizes highly uncertain for galaxies more distant than a few Mpc. Meurer et al. note a tendency to systematically overestimate the sizes of distant clusters located on high-surface brightness backgrounds. In view of these caveats, the half-light radii of well-resolved SSCs seem to fall comfortably within the range of Galactic globular clusters, whose median  $R_h \approx 3$  pc (van den Bergh et al. 1991). The apparent tendency for the  $R_h$  distribution of SSCs to be skewed toward somewhat larger sizes is probably not significant for the reasons mentioned above (Meurer et al. 1995). In particular, Meurer (1995) has shown that the large radii reported by Whitmore et al. (1993) for the clusters in the Antennae have probably been overestimated, thus obviating van den Bergh’s (1995) other major objection to the young globular cluster hypothesis for the SSCs in this system. The compact sizes of SSCs can be used as supporting evidence that the clusters are most likely gravitationally bound. Any conceivable form of perturbation that may lead to the dispersal of the stars will traverse the clusters on a timescale shorter than 1 Myr, whereas the estimated ages are in some cases up to two orders of magnitude larger.

#### 2.5. Masses

SSCs are thought to have masses at least as large as  $10^4 M_\odot$ , and more likely between  $10^5$  to  $10^6 M_\odot$ . Unfortunately, the estimated masses are highly uncertain because invariably they are derived from population synthesis models that depend on a large number of poorly constrained parameters. To obtain the total cluster mass, one must generally adopt a slope for the stellar initial mass function (IMF) and extrapolate it to low, essentially unobserved, masses. A more direct and reliable method to estimate the cluster masses will be described below.

#### 2.6. Metallicities

The presence of compact clusters appears to be uncorrelated with the metallicity of the environment; this is an important factor that should be considered in models attempting to account for the formation of these

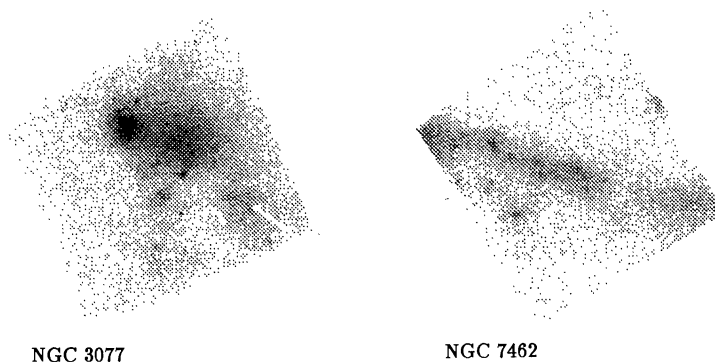


Fig. 1. Sample F220W images from the FOC snapshot survey (Maoz et al. 1996b).

objects. A number of clusters are present in the dwarf galaxy I Zw 18 (Meurer et al. 1995); with a gas-phase oxygen abundance of 1/50 that of the Sun (Dufour, Garnett, & Shields 1988), it is the most metal-deficient galaxy known. The brightest cluster in NGC 1275, on the other hand, evidently has a metallicity roughly close to solar (Zepf et al. 1995), as might be expected considering that the host is a cD galaxy. Finally, circumnuclear rings (§ 4), which occur almost exclusively in early-type spirals (e.g., Ho, Filippenko, & Sargent 1996a), are well known to have high metal abundances, often exceeding solar (e.g., Storch-Bergmann, Wilson, & Baldwin 1996).

### 3. THE *HST* ULTRAVIOLET SNAPSHOT SURVEY

While the *HST* imaging studies discussed up to now have opened a new vista on the importance of young star clusters, we still do not know how common the cluster phenomenon truly is. Are SSCs only found in extreme environments such as mergers and very luminous starbursts, or do they also occur in more quiescent settings? The examples given in § 1 suggest a more widespread occurrence, but it is difficult to be quantitative without access to a proper control sample. Fortunately, there are a number of snapshot imaging surveys of nearby galaxies being conducted with *HST*, and some of these may be useful for addressing the statistical properties of SSCs. Here, I will briefly mention a recently completed UV imaging survey with *HST* (see Maoz et al. 1996b for details). In brief, UV (F220W filter; effective wavelength  $\sim 2270$  Å) images of the central  $22'' \times 22''$  were obtained with the Faint Object Camera (FOC) for 110 nearby galaxies. The images were taken prior to the *HST* refurbishment mission, and hence suffer from the effects of spherical aberration. The final pixel scale is  $0''.0225$ , and the core of the point-spread function has a full width at half maximum (FWHM) of  $\sim 0''.05$ . The targets were selected randomly from a complete sample of 240 large ( $D > 6'$ ) and nearby ( $cz < 2000$  km s $^{-1}$ ) galaxies as listed in the UGC and ESO catalogs, and hence constitute a well-defined, unbiased group suitable for a variety of statistical studies. The UV passband is especially useful for studying regions of recent star formation.

Even a cursory glance at the images in the Maoz et al. (1996b) catalog reveals that the UV emission exhibits a diverse assortment of morphologies. Of relevance in the present context are those images showing compact, point like sources. Figure 1 illustrates two examples. NGC 3077 is a nearby amorphous galaxy interacting with M81 and M82 (Barbieri et al. 1974; Yun, Ho, & Lo 1995). From ground-based images, it is known that its central region contains a single bright knot (Price & Gullixson 1989), which is the dominant feature in the FOC image. The central UV morphology strongly resembles that of NGC 1705 and NGC 5253 (Meurer et al. 1995). Assuming a distance of 3.6 Mpc to M81 (Freedman et al. 1994), the central cluster has  $L_{2200} = 1.0 \times 10^{36}$  ergs s $^{-1}$  Å $^{-1}$ , or  $M_{2200} = -10.9$  mag (Meurer et al. 1995). According to Meurer et al.'s definition, this cluster would not qualify as an SSC; but like other SSCs, its emission is very compact—the half-light radius measures  $\lesssim 0.4$  pc. A number of fainter clusters are also visible in the frame, the faintest of which may be individual O and B stars.

The morphology of NGC 7462, on the other hand is much more complicated. Many compact clusters dot the extent of the large swath of diffuse UV emission running parallel to the major axis of the disk. Assuming a distance of 13 Mpc (Tully 1988), the clusters have typical sizes of  $R_h \approx 1.5$ –6 pc and luminosities of  $L_{2200} \approx 1 \times 10^{36}$  ergs s $^{-1}$  Å $^{-1}$ . Although the full analysis of the data base is yet to be completed (Ho et al. 1996), clusters



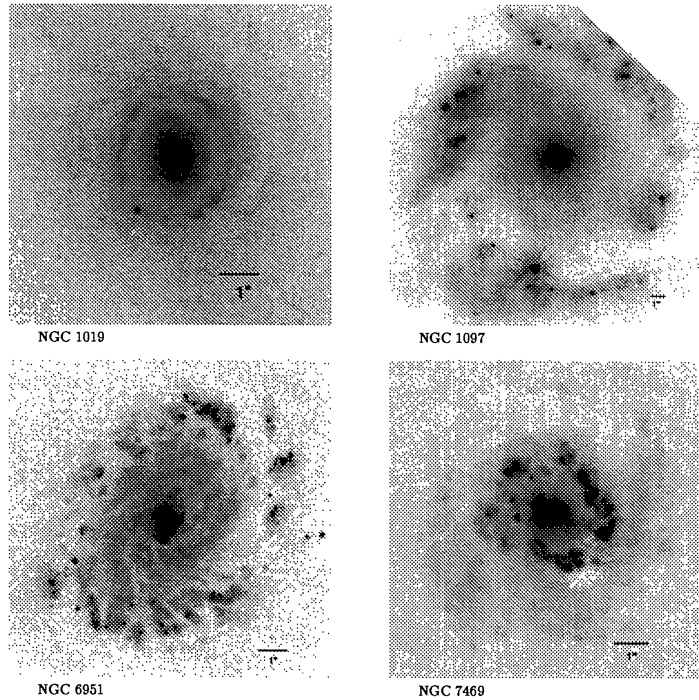


Fig. 2. Four circumnuclear rings containing compact, young clusters from *HST* images taken at visual wavelengths. NGC 1097 and NGC 6951 are from Barth et al. (1995), and NGC 1019 and NGC 7469 are from Barth et al. (1996). The bright point source south of the nucleus is SN 1992bd.

have been identified in approximately 40% of the sample. This fraction is merely a lower limit, since presumably some of the images with no UV emission suffer from high extinction. The vast majority of the galaxies in the survey, strictly speaking, are not considered starbursts. The central regions of a substantial fraction of nearby galaxies undergo some level of current star formation (Ho 1995; Ho, Filippenko, & Sargent 1996b), albeit with quite modest star-formation rates. Moreover, the sample objects generally show no outstanding morphological peculiarities indicative of recent interactions. An immediate conclusion that can be drawn is that cluster formation is very commonplace and does not require very extreme physical conditions.

#### 4. STAR CLUSTERS IN CIRCUMNUCLEAR RINGS

Sérsic & Pastoriza (1965, 1967) noticed thirty years ago that the circumnuclear regions of some barred galaxies have “hot-spots” of very intense star formation. It is now accepted that such hot-spots often delineate a ring-like structure surrounding the nucleus, generally coinciding with the location of the inner Lindblad resonance associated with some barred spirals. Gas torqued by the stellar bar loses angular momentum and flows inward, and if an inner Lindblad resonance is present, it accumulates in a tightly-wound, two-arm spiral or ring-like configuration at the position of the resonance (Elmegreen & Friedli, this volume). Large concentrations of molecular gas have been detected (e.g., Kenney et al. 1992; Kenney, this volume), and signs of intense star formation are often seen (e.g., Hummel, van der Hulst, & Keel 1987; Márquez & Moles 1993). Hence, it is fair to characterize some circumnuclear rings as “starburst-like,” even if the globally-averaged rate of star formation of the entire galaxy may not be that outstanding.

*HST* images show that young clusters are found in great abundance in some circumnuclear rings (Fig. 2). In the case of NGC 1097, nearly 90 clusters were identified by Barth et al. (1995) in a ring-like structure of diameter  $\sim 1$  kpc. Among those for which it was possible to perform reliable aperture photometry, the mean  $R_h \approx 2.5$  pc, in accord with the typical half-light radii seen in other SSCs. The clusters have a range of luminosities, the brightest having  $M_V \approx -14$  mag, with a number between  $M_V = -13$  and  $-14$  mag. Numerous clusters are also seen in the nuclear ring in NGC 6951, whose large-scale morphology appears very similar to the

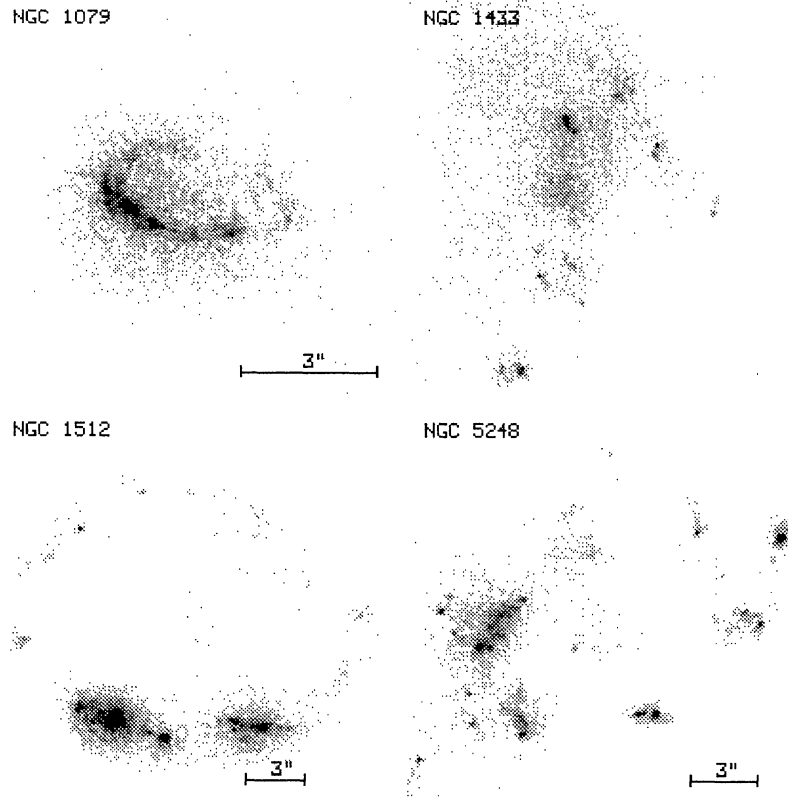


Fig. 3. Four of the 5 circumnuclear rings from the FOC UV snapshot survey (Maoz et al. 1996a) containing compact, young clusters.

ring in NGC 1097. The greater distance of this galaxy, however, renders photometry of its clusters more difficult. Barth et al. (1995) find  $R_h \leq 4$  pc for several clusters and  $M_V$  possibly as luminous as  $-15$  mag, depending on the extinction (which is difficult or impossible to measure for individual clusters). Two other examples of nuclear rings from Barth et al. (1996) are also shown in Figure 2. The ring in NGC 1019 contains just a single bright cluster, whereas that of NGC 7469 has a large number. Note that the apparently strong correlation between circumnuclear rings and active galactic nuclei (all four examples have either Seyfert or LINER nuclei) is a result of a selection effect; the original samples from which these objects were selected largely targeted active nuclei.

The FOC UV imaging survey uncovered 5 additional circumnuclear rings richly populated with young clusters (Fig. 3). Although the rings in all but NGC 1079 were previously known from ground-based studies, what was not known was that the sites of star formation in the rings break up into discrete, compact units (clusters). In fact, Maoz et al. (1996a) find that the clusters constitute a significant fraction (15%–50%) of the total UV light in these objects. This estimate is a lower limit because there could be fainter clusters undetected at the current sensitivities of the snapshot images. The high detection rate of discrete sources implies that cluster formation is a significant, if not dominant, mode of star formation in these systems. Meurer et al. (1995) arrived at a similar conclusion from their study of 9 starburst systems. The luminosities of the clusters in the rings tend to be lower than those in the sample of Meurer et al. Strictly speaking, they do not qualify as SSCs, but it is clear that they are physically similar objects. The power-law luminosity function extrapolated from higher luminosities adequately fits the faint end of the distribution (Maoz et al. 1996a).

### 5. DYNAMICAL MASSES OF SUPER STAR CLUSTERS

One of the central, unanswered questions is whether SSCs are genuine young globular clusters. Thus far, the arguments advanced in favor of this idea have been largely inconclusive because the observational evidence

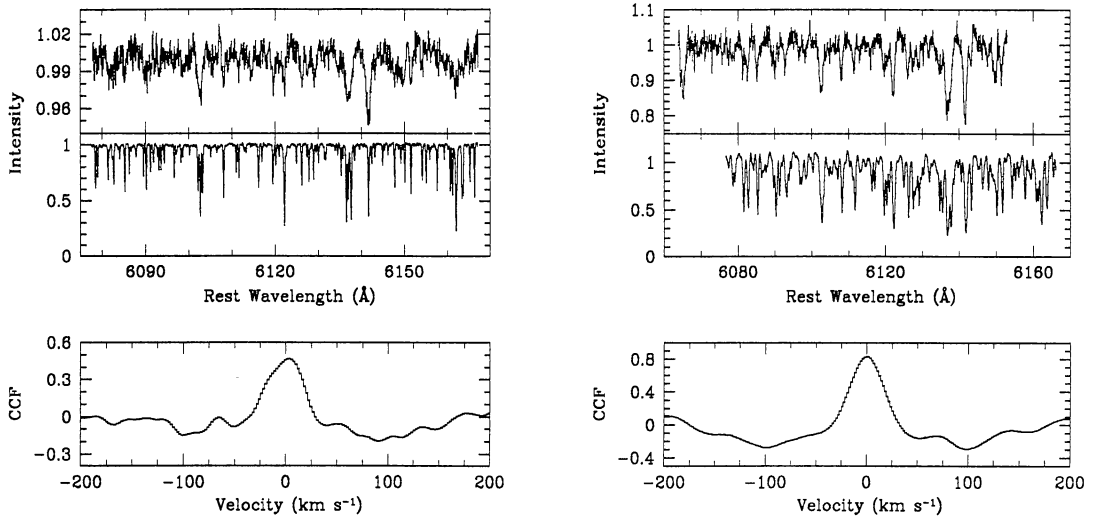


Fig. 4. Measurement of the stellar velocity dispersions in cluster “A” of NGC 1569 (*left*; Ho & Filippenko 1996a) and in the central cluster of NGC 1705 (*right*; Ho & Filippenko 1996b). The top panel in each case shows the cluster spectrum, the middle panel the template star used to derive the velocity dispersion, and the bottom panel the cross-correlation function between the cluster and star. The width of the main velocity peak of the cross-correlation function is related to the velocity dispersion.

is subject to different interpretations. Perhaps the most pertinent piece of missing information is the mass of the clusters. The total stellar mass is very difficult to estimate reliably, since virtually all of the observables trace the young, massive stars, which comprise only a small fraction of the total mass for a normal IMF. It would be highly advantageous to bypass this complication by obtaining a *direct*, model-independent measurement of the dynamical mass.

Using the HIRES spectrograph mounted on the Keck 10-m telescope, Ho & Filippenko (1996a, b) recently acquired high-dispersion ( $\text{FWHM} = 7.9 \text{ km s}^{-1}$ ) optical spectra of the central cluster in NGC 1705 (NGC 1705-1) and of cluster “A” in NGC 1569 (NGC 1569-A), both of which have fairly reliable sizes determined from *HST* images (O’Connell et al. 1994; Meurer et al. 1995). Since these clusters have ages of 10–20 Myr, a substantial population of cool supergiants contributes to the integrated spectrum at visual wavelengths, and Ho & Filippenko demonstrate that it is feasible to derive the line-of-sight velocity dispersion from the weak metal lines detected in both objects. Figure 4 illustrates the cross-correlation technique of Tonry & Davis (1979) applied to the two clusters.

The line-of-sight velocity dispersions are found to be  $\sigma_* = 15.7 \pm 1.5$  and  $11.4 \pm 1.5 \text{ km s}^{-1}$  for NGC 1569-A and NGC 1705-1, respectively. Assuming that the clusters are gravitationally bound (as seems quite likely considering their compactness), spherically symmetric, and isotropic systems, the dynamical mass is given by  $M = 3\sigma_*^2 R/G$  according to the virial theorem, where  $R$  is the effective gravitational radius. As a first-order approximation, let us assume  $R = R_h$ , the half-light radius. Meurer et al. (1995) recently reanalyzed the images of O’Connell et al. (1994) and determined  $R_h = 1.9 \pm 0.2$  and  $0.9 \pm 0.2 \text{ pc}$  for NGC 1569-A and NGC 1705-1, respectively. The corresponding masses  $[(3.3 \pm 0.5) \times 10^5$  and  $(8.2 \pm 2.1) \times 10^4 M_\odot]$  and mass densities  $(1.1 \times 10^4$  and  $2.7 \times 10^4 M_\odot \text{ pc}^{-3})$  agree remarkably well with the typical values of evolved globular clusters in the Galaxy. Galactic globular clusters have an average mass of  $1.9 \times 10^5 M_\odot$  (Mandushev, Spassova, & Staneva 1991), and their sizes (and hence densities) are similar to those of the young clusters. Both clusters have absolute visual magnitudes near  $-14$ , and their estimated ages are 10–20 Myr. In 10–15 Gyr, they will fade by 6 to 7 mag in the  $V$  band (e.g., Bruzual & Charlot 1993), reaching  $M_V = -7$  to  $-8$  mag, in excellent agreement with the peak of the nearly universal luminosity function of globular cluster systems ( $\langle M_V \rangle \approx -7.3$  mag; Harris 1991). Moreover, if mass loss during advanced stages of stellar evolution will not significantly reduce the cluster masses, the mass-to-light ratios of NGC 1569-A and NGC 1705-1 will be  $M/L_V = 2.5$ – $6.3$  and  $0.7$ – $1.6 (M/L_V)_\odot$ , respectively, again in reasonable agreement with the observed range for Galactic globular clusters  $[0.7$ – $2.9 (M/L_V)_\odot$ ; Mandushev et al. 1991]. This finding implies that, to a first approximation, the stellar IMF of the clusters is similar to that of typical globular clusters in the Milky Way.

The apparent similarity between the stellar content of SSCs and globular clusters has important consequences for the IMF of starbursts. In the well-known case of M82, Rieke et al. (1980, 1993) have argued that the star formation is biased toward high-mass stars; specifically, the IMF evidently truncates below  $\sim 3 M_{\odot}$ . This provocative result, however, has been hotly debated (e.g., Scalo 1986, 1987; Zinnecker 1996). Since SSCs appear to be the basic building blocks or “cells” of star formation in starbursts, and, as shown above, at least *some* SSCs seem to be genuine young globular clusters, the implication is that starburst regions may well have an IMF similar to that of globular clusters, which are richly populated with low-mass stars (e.g., Paresce et al. 1995). At this meeting, Moffat, Zinnecker, and others have presented evidence that some nearby starburst regions evidently also have fairly normal IMFs.

## 6. SUMMARY

1. Compact, young star clusters are very common in a wide range of starburst environments. The formation of bound clusters appears to be a major, if not ubiquitous, mode of star formation in starbursts systems.

2. A new *HST* imaging survey in the UV bandpass confirms the widespread occurrence of compact clusters, even in relatively “normal” galaxies. Star-forming circumnuclear rings often contain rich populations of clusters.

3. The clusters are young (ages ranging from a few to a few hundred Myr), compact (half-light radii  $\leq$  few parsecs), and have a wide range of luminosities. The masses of the clusters, as inferred from their photometric properties, generally lie in the range of  $10^4$ – $10^6 M_{\odot}$ . The luminosity function can be represented by a power law with a slope of approximately  $-2$ . The most luminous members—the so-called super star clusters—have luminosities up to 1–2 orders of magnitude higher than that of the R136 cluster in 30 Doradus.

4. Two nearby examples of super star clusters (in NGC 1569 and NGC 1705) have dynamical masses, mass densities, and predicted mass-to-light ratios that are virtually indistinguishable from those of evolved globular clusters in the Galaxy. This provides compelling evidence that at least some super star clusters truly are present-day analogs of young globular clusters.

I thank my principal collaborators Aaron Barth, Alex Filippenko, and Dani Maoz for permission to discuss our results prior to publication. Aaron Barth and Alex Filippenko provided useful comments on a draft of this manuscript. Deidre Hunter kindly made available some digital images used in my talk. I am grateful to the scientific organizing committee for inviting me to the meeting and the local organizing committee for their warm hospitality that made my visit to Mexico so enjoyable. My research is funded by a postdoctoral fellowship from the Harvard-Smithsonian Center for Astrophysics.

## REFERENCES

- Arp, H., & Sandage, A. 1985, *AJ*, 90, 1163  
 Ashman, K. M., & Zepf, S. E. 1992, *ApJ*, 384, 50  
 Barbieri, C., Bertola, F., & di Tullio, G. 1974, *A&A*, 35, 463  
 Barth, A. J., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1995, *AJ*, 110, 1009  
 Barth, A. J., Ho, L. C., Filippenko, A. V., Gorjian, V., Malkan, M., & Sargent, W. L. W. 1996, in *IAU Colloq.* 157, *Barred Galaxies*, ed. R. Buta, B. G. Elmegreen, & D. A. Crocker (San Francisco: ASP), 94  
 Benedict, G. F., et al. 1993, *AJ*, 105, 1369  
 Bower, G. A., & Wilson, A. S. 1995, *ApJS*, 99, 543  
 Bruzual A., G., & Charlot, S. 1993, *ApJ*, 405, 538  
 Burstein, D. 1987, in *Nearly Normal Galaxies*, ed. S. M. Faber (New York: Springer), 47  
 Conti, P. S. 1991, *ApJ*, 377, 115  
 Conti, P. S., Leitherer, C., & Vacca, W. D. 1996, *ApJ*, 461, L87  
 Conti, P. S., & Vacca, W. D. 1994, *ApJ*, 423, L97  
 Dufour, R. J., Garnett, D. R., & Shields, G. A. 1988, *ApJ*, 332, 752  
 Faber, S. M. 1993, in *The Globular Cluster-Galaxy Connection*, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 601  
 Freedman, W. L., et al. 1994, *ApJ*, 427, 628  
 Gorjian, V. 1996, *ApJ*, submitted  
 Harris, W. E. 1991, *ARA&A*, 29, 543  
 Ho, L. C. 1995, Ph.D. thesis, Univ. of California at Berkeley  
 Ho, L. C., et al. 1997, in preparation



- Ho, L. C., & Filippenko, A. V. 1996a, *ApJ*, in press  
 ———. 1996b, *ApJ*, in press  
 Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1996a, in *IAU Colloq. 157, Barred Galaxies*, ed. R. Buta, B. G. Elmegreen, & D. A. Crocker (San Francisco: ASP), 188  
 ———. 1996b, in *The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution*, ed. D. Kunth et al. (Paris: Editions Frontières), in press  
 Holtzman, J. A., et al. 1992, *AJ*, 103, 691  
 Hummel, E., van der Hulst, J. M., & Keel, W. C. 1987, *A&A*, 172, 32  
 Hunter, D. A., O'Connell, R. W., & Gallagher, III, J. S. 1994, *AJ*, 108, 84  
 Kenney, J. D. P., Wilson, C. D., Scoville, N. Z., Devereux, N. A., & Young, J. S. 1992, *ApJ*, 395, L79  
 Larson, R. B. 1993, in *The Globular Cluster-Galaxy Connection*, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 673  
 Leitherer, C., Vacca, W. D., Conti, P. S., Filippenko, A. V., Robert, C., & Sargent, W. L. W. 1996, *ApJ*, in press  
 Lutz, D. 1991, *A&A*, 245, 31  
 Mandushev, G., Spassova, N., & Staneva, A. 1991, *A&A*, 252, 94  
 Maoz, D., Barth, A. J., Sternberg, A., Filippenko, A. V., Ho, L. C., Macchetto, F. D., Rix, H.-W., & Schneider, D. P. 1996a, *AJ*, in press  
 Maoz, D., Filippenko, A. V., Ho, L. C., Macchetto, F. D., Rix, H.-W., & Schneider, D. P. 1996b, *ApJS*, in press  
 Márquez, I., & Moles, M. 1993, *AJ*, 105, 2090  
 Melnick, J., Moles, M., & Terlevich, R. 1985, *A&A*, 149, L24  
 Meurer, G. R. 1995, *Nature*, 375, 742  
 Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, *AJ*, 110, 2665  
 Meynet, G. 1995, *A&A*, 298, 767  
 O'Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, *ApJ*, 433, 65  
 O'Connell, R. W., Gallagher, J. S., Hunter, D. A., & Colley, W. N. 1995, *ApJ*, 446, L1  
 Paresce, F., de Marchi, G., & Romaniello, M. 1995, *ApJ*, 440, 216  
 Price, J. S., & Gullixson, C. A. 1989, *ApJ*, 337, 658  
 Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., & Tokunaga, A. T. 1980, *ApJ*, 238, 24  
 Rieke, G. H., Loken, K., Rieke, M. J., & Tamblyn, P. 1993, *ApJ*, 412, 99  
 Scalo, J. M. 1986, *Fundam. Cosm. Phys.*, 11, 1  
 ———. 1987, in *Starbursts and Galaxy Evolution*, ed. T. X. Thuan, T. Montmerle, & J. T. T. Van (Gulf sur Yvette: Editions Frontières), 445  
 Schweizer, F. 1987, in *Nearly Normal Galaxies*, ed. S. M. Faber (New York: Springer), 18  
 Schweizer, F., & Seitzer, P. 1993, *ApJ*, 417, L29  
 Sérsic, J. L., & Pastoriza, M. 1965, *PASP*, 77, 287  
 ———. 1967, *PASP*, 79, 152  
 Shaya, E. J., Dowling, D. M., Currie, D. G., Faber, S. M., & Groth, E. J. 1994, *AJ*, 107, 1675  
 Shlosman, I. (ed.) 1994, *Mass Transfer Induced Activity in Galaxies*, (Cambridge: Cambridge Univ. Press)  
 Storchi-Bergmann, T., Wilson, A. S., & Baldwin, J. A. 1996, *ApJ*, 460, 252  
 Tonry, J., & Davis, M. 1979, *AJ*, 84, 1511  
 Tully, R. B. 1988, *Nearby Galaxies Catalog* (Cambridge: Cambridge Univ. Press)  
 Vacca, W. D. 1994, in *Violent Star Formation*, ed. Tenorio-Tagle (Cambridge: Cambridge Univ. Press), 297  
 ———. 1996, in *The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution*, ed. D. Kunth et al. (Paris: Editions Frontières), in press  
 Vacca, W. D., & Conti, P. S. 1992, *ApJ*, 401, 543  
 van den Bergh, S. 1995, *Nature*, 374, 215  
 van den Bergh, S., & Lafontaine, A. 1984, *AJ*, 89, 1822  
 van den Bergh, S., Morbey, C., & Pazder, J. 1991, *ApJ*, 375, 594  
 Whitmore, B. C., & Schweizer, F. 1995, *AJ*, 109, 960  
 Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, *AJ*, 106, 1354  
 Yun, M. S., Ho, P. T. P., & Lo, K.-Y. 1995, *Nature*, 372, 530  
 Zepf, S. E., Carter, D., Sharples, R. M., & Ashman, K. M. 1995, *ApJ*, 445, L19  
 Zinnecker, H. 1996, in *The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution*, ed. D. Kunth et al. (Paris: Editions Frontières), in press