Chapter 1

Introduction

"My purpose is to tell of bodies which have been transformed into shapes of a different kind. You heavenly powers, since you were responsible for those changes, as for all else, look favourably on my attempts, and spin an unbroken thread of verse, from the earliest beginnings of the world, down to my own times."

— Ovid (*Metamorphoses*)

The universe is host to a multitude of physical processes, and an equally diverse collection of material elements, which are continually interacting and evolving. Throughout this cosmic dance, generations of stars have been born, died, and created anew from the ashes. This cycle of life continues even today in our own galaxy, the Milky Way. As we look further and further into the depths of the universe, we see that stars have been forming almost since the beginning of time. As their light crosses the vast expanse of time and space, it carries along encrypted information that we have learned how to decode, and in this way have gained much of our understanding of the universe.

Because this thesis is primarily based on observations, I will begin by providing a basic explanation of how astronomers decode this light from the universe in § 1.1, which is included for the benefit of readers outside of the field. In the remainder of this chapter, I will give a broad overview of topics closely related to the subject of this thesis. The nature of starburst galaxies and their impact throughout the universe is discussed in § 1.2. The state of knowledge about super star clusters, which are typically formed in starburst episodes, is discussed in § 1.3.

1.1 Interpreting the Light From Stars

In nature's endless variety, even stars themselves have a rich family of sub-types and species — in fact, there is literally a rainbow of stellar types. One can think of fire as an analogy, a flame is blue at its hottest and red where it is cool. Likewise, stars have a continuum of colors, with the hottest being blue and the coolest red. For most of a star's life (known as the "main sequence") [1] , its color not only tells us about its temperature, but also about its most fundamental property, mass. The lives of stars are deterministic in this way — the mass with which a star is born virtually dictates the rest of its life (with a few more subtle effects intentionally neglected here). The most massive stars live fast and die young: the more massive a star is, the faster it consumes its fuel and the brighter it burns. While our cool and yellow Sun will live some 10 billion years, by contrast a hot blue star will die at the young age (by astronomical standards) of only a few million years. For this reason, if we see a bright blue star on the main sequence, we know it has to be young.

In this way, we can also use color to learn about collections of stars, such as galaxies. Even if we cannot resolve the individual stars themselves, the medley of stellar light coming from a galaxy tells us something about the stars it contains. Even more can be learned from light if we spread it out into a rainbow or "spectrum". Each type of star (and other astrophysical objects as well) has a unique fingerprint which we can identify in its spectrum. These are the main tools astronomers use to understand the universe with observations. For example, a galaxy with an unusually blue color must have an abundance of blue stars [2] . Since these stars must be young, the galaxy's blue color indicates that it must have recently undergone a tremendous spurt of star formation. These are the galaxies which we call "starbursts".

[1] As a star nears the end of its life, it enters the "post main sequence". During post main sequence evolution, a star's color does not directly reflect its mass.

[2] A reader familiar with the field will note that I am neglecting the class of starburst galaxies which are luminous in the infrared due to tremendous amounts of dust which reprocesses the light from the hot blue stars.

1.2 Starburst Galaxies

It has been over 30 years since Sargent & Searle (1970) noted that certain galaxies are undergoing intense episodes of star formation. This extraordinary mode of star formation has come to be know as the starburst phenomenon. The precise definition of a "starburst galaxy" is notoriously ambiguous, and I will not attempt to remedy this situation here. The standard definition one might hear over coffee with an astronomer is something like, "A galaxy which is forming stars at such a rapid rate that the material available to form stars would be used up in a time short compared to the lifetime of the galaxy." Again, ambiguous.

It is perhaps more useful to define what *isn't* a starburst galaxy as, "a galaxy undergoing a normal (or less than normal) rate per unit area of star formation." In this case, "normal" means something like $0.001 - 0.01$ $M_\odot$ yr^{-1} kpc^{-2} (1 pc= 3.09×10^{18} cm), while a typical starburst might have a star formation rate > 1 $M_\odot$ yr^{-1} kpc^{-2} (and there are galaxies with a range of star formation rates between these values). The result of this vigorous star formation in starburst galaxies is an unusually large number of young, bright, massive stars present in the host galaxy at the same time. In practice, this means that starbursts tend to be extremely bright and blue objects, and much of the spectral energy distribution is dominated by the light from massive stars.

While some of the most spectacular starbursts encompass an entire galaxy (a global burst), more commonly regions in a galaxy are bursting (such as a nuclear starburst), while the rest of the galaxy is relatively dormant. This issue only exacerbates the problem of defining a "starburst galaxy", and the situation is quite muddled in the literature. However, if it is the starburst *phenomenon* we wish to study, both large- and small-scale events are of interest. Moreover, even global starbursts have largely been resolved into clusters of bright young stars, a topic to which I will return at length. In this thesis, I will generally refer to starburst "regions", which are typically (but not always) part of a larger starburst event in the galaxies which I discuss.

Starburst galaxies, and the extreme massive star birth events they host, have been an

important aspect of star formation throughout the history of the universe. This mode of star formation is so important that, according to Heckman (1998), in the local universe roughly a quarter of all massive stars have been formed in only a small number of starburst galaxies (M82, NGC 253, M83, and NGC 4945). Thus, if we wish to study the formation and evolution of massive stars, starburst galaxies provide an excellent opportunity.

Massive stars themselves play a major role in the dynamical evolution of galaxies: they are responsible for the ionization of the interstellar medium, their stellar winds and supernovae are major sources of mechanical energy, their ultraviolet radiation powers far-infrared luminosities through the heating of dust, and they are a main driver of chemical evolution in the universe through their end stages (with strong stellar winds and supernovae). The resulting metal-enriched outflows and ionizing radiation from massive stars can have a significant impact on the intergalactic medium.

1.2.1 Relevance of Starburst Galaxies to the Early Universe

In the more distant universe, a large number of star forming galaxies have been discovered at redshifts [3] of $z > 3$ (e.g., Steidel et al. 1996). For these high-z galaxies, the ultraviolet (UV) spectrum is redshifted into the optical regime. Integrated spectra of these galaxies indicate the presence of substantial numbers of massive stars, and the overall spectral morphology of these high-z systems is similar to nearby starburst galaxies (e.g., Conti et al. 1996). Hibbard & Vacca (1997) have simulated photometric observations of starburst galaxies at high redshift using local starburst galaxies as templates. They found a strong similarity in spatial morphology, star formation rates, and spectral energy distributions between nearby starburst galaxies and the high-z objects seen in the Hubble Deep Field (Williams et al. 1996), concluding that nearby starbursts are local analogs to the high-z galaxies.

Galaxy mergers, and their resulting starbursts, may be one of the basic building blocks

[3] Redshift is a measure of how fast an object (in this case a galaxy) is moving away from us. The expansion of the universe leads implies that the farther away a galaxy is, the faster its relative velocity. Because of this, we can use an object's velocity (or redshift) to obtain a distance.

of structure formation in the universe; in hierarchical models of structure formation, mergers of smaller structures create the massive, elliptical galaxies we observe in the local universe today (e.g., Baron & White 1987). There is growing support in the literature for the idea that merging galaxy systems, and the resulting starburst episodes, had a significant role in the high-redshift ($z > 3$) universe. In their survey of high-redshift radio galaxies, van Breugel et al. (1998) found that the visual morphologies of these systems exhibited substructure in the form of multiple components $\sim$ 10 kpc in size. They concluded that these giant elliptical galaxies were likely formed from the merging of smaller stellar systems. There is also evidence that the implied star formation rates Lyman break galaxies at $z \sim 3$ can be accounted for by the frequency of collision-induced starbursts (Kolatt et al. 1999; Hibbard & Vacca 1997; Lowenthal et al. 1997). The semi-analytical models of galaxy collisions and tidal interactions of Balland et al. (1998) illustrate how both spiral and elliptical galaxies can be created by different types of tidal collisions and can determine the morphologies of galaxies we see at the present epoch. Therefore, at earlier times in the universe, the starburst phenomenon in interacting galaxies likely had a far more dominant role than we observe in the local universe.

Starburst episodes may also play a role in the reionization of the universe at $z > 5$ (Madau & Shull 1996; Madau et al. 1999, and references therein). Furthermore, metals produced and expelled by massive stars in these galaxies may provide an explanation for the heavy element abundances observed in Lyα clouds (e.g., Cowie et al. 1995; Johnson et al. 2000). Therefore, in order to understand the general evolution of matter in the universe, understanding the origin and nature of massive star formation in starburst episodes is of great importance.

1.2.2 Wolf-Rayet Galaxies

Before discussing Wolf-Rayet galaxies, we must first discuss Wolf-Rayet (WR) stars. WR stars are the descendents of the most massive stars (Maeder & Conti 1994). These stars are at the end point of their evolution and show the products of nuclear processing in their spectra due to mass loss and mixing processes. WR stars have extremely strong and dense radiatively

driven stellar winds which give rise to broad emission lines of helium and nitrogen (in WN-type Wolf-Rayet stars) or helium, carbon, and oxygen (in WC-type Wolf-Rayet stars). Because WR stars evolve from the most massive stars, this phase of the star's life cycle happens very quickly after the onset of a starbirth event; 3-6 Myr after a burst of star formation, the massive stars will evolve into WR stars.

Wolf-Rayet Galaxies (WR Galaxies) are a subset of starburst galaxies that have such a significant population of Wolf-Rayet stars that the WR star spectral features show up in the integrated spectrum of the galaxy. In particular, WR galaxies are typically classified by the presence of broad He II $\lambda 4686$ emission in their integrated spectra (Conti 1991). Typically WR galaxies are also "emission line galaxies", which also show nebular emission lines in their integrated spectra due to significant numbers of O-type stars. The resulting spectra are often similar to that H II regions (regions of ionized hydrogen), and therefore these galaxies are often referred to as "H II galaxies". Because the WR phase only lasts for a short time, the presence of a large number of WR stars in a galaxy relative to the number of O-type stars allows us to estimate the age of a starburst *a priori*. No other type of galaxy has such a powerful age diagnostic.

According to the most recent catalog of Schaerer et al. (1999b), there are 139 known WR galaxies to date. Of course, we should perhaps use the term "Wolf-Rayet galaxy" with caution — if a spectrum has sufficiently high signal-to-noise, and if this spectrum happens to be taken at precisely the right location, a single WR star could show up in the integrated spectrum of a galaxy! Nevertheless, WR galaxies (with a few exceptions given this caution) provide us with an opportunity to study the early phases of starburst galaxies.

1.2.3 What Causes a Starburst Episode?

It is reasonable to ask why some galaxies flare into starburst episodes, while most galaxies remain relatively quiescent. The main requirement for a starburst episode is a lot of fuel in a small volume. Heckman (1998) argues that even for a modest starburst, energetics imply the

presence of at least 10^8 to 10^{10} $M_\odot$ of cold gas is required to fuel a starburst event (assuming 100% star formation efficiency). Furthermore, this gas must be assembled on very short time scales because of the short times scales for gas depletion in the starburst event and disruption by stellar outflows and supernovae. Thus, one is prompted to ask: what mechanisms could be responsible for collecting large amounts of gas on very short time scales?

Perhaps one of the best ways to concentrate the interstellar medium in a galaxy is to remove its angular momentum, which consequently causes an infall toward the gravitational center. Interactions and mergers of galaxies are particularly adept at accomplishing this inflow; in their numerical simulations, Mihos & Hernquist (1996) find that the rapidly varying gravitational torques in a merging pair of galaxies drives a strong inflow of gas toward the gravitational center. Observations are consistent with this picture; for example, observations of the molecular gas in merging systems often show large amounts of molecular gas in the central regions (e.g., Sargent & Scoville 1991). According to the Mihos & Hernquist (1996) models, the longer the timescale for interaction between two galaxies, the more of an effect dynamical friction can have, the more likely the two galaxies are to merge into a single galaxy, and that this process should be accompanied by a spectacular rate of star formation.

1.3 Super Star Clusters

In relatively nearby starburst galaxies, the most vigorous star formation activity has largely been resolved into massive star clusters. While old globular clusters are ubiquitous in the local universe, only over the past decade have we begun to find their younger and bluer siblings in significant numbers. However, the term "super star cluster" began to appear in the literature well before the 1990s. In 1985, "super star cluster" appeared in reference to a cluster in NGC 1569 (Arp & Sandage 1985). Earlier still, the existence of super star clusters (SSCs) was postulated by Schweizer (1982) in order to explain several knots of star formation in NGC 7252. Perhaps the first reference to super star clusters was as early as the 1970s by van den Bergh (1971) where he called bright infrared knots in M82 super star clusters. These

authors were prompted to use the term “super star cluster” because the star clusters observed were far more luminous and massive than young star clusters found in our own galaxy.

Nevertheless, it was not until the launch of the Hubble Space Telescope in 1990 that SSCs came into their own as a research field. (Advocates of HST will proudly tell you that observations of the star cluster 30 Doradus, the Rosetta Stone for SSC research, were among the first successful images taken with HST.) The first observations of SSCs made with HST were done by Holtzman et al. (1992) who discovered a population of massive blue compact clusters in NGC 1275 which they claimed may evolve into globular clusters. After this discovery, the field of massive extragalactic cluster research blossomed.

The precise definition of “super star cluster” is a bit ambiguous, although there seems to be a consensus that minimum mass and density thresholds are the primary means of distinguishing SSCs from other objects like open clusters which are loosely bound or unbound aggregates of a few hunderd stars (although this distinction is artificial and there is a continuum of cluster types). Typically SSCs are defined as “an object which is likely to evolve into a globular cluster in several billion years”, which usually translates into SSCs having estimated masses of $\gtrsim 10^5$ $M_\odot$ within radii of $\lesssim 5$ pc and ages $\lesssim 100$ Myr. There are certainly examples of objects called “SSCs” in the literature which fall outside of this region in parameter space, and it is not uncommon to see star clusters with masses $\sim 10^3$ $M_\odot$ included in samples of SSCs. One might also argue that only clusters with ages less than ≈ 10 Myr should be considered “super star clusters”, as this is the age by which all of the massive stars have died.

1.3.1 Where are Super Star Clusters Found?

Since their discovery, SSCs have been observed in over 50 galaxies including the work presented here (see the review of Whitmore 2000), and this number is still growing. I am often asked if there are any SSCs in the Milky Way, and I believe the answer is no, although the Arches and Quintuplet clusters near the galactic center might provide the most local analogs with masses of $\sim 10^4$ $M_\odot$ (Figer et al. 1999). However, in such a hostile environment, these

clusters are not likely to survive to the ripe old age of a globular cluster (e.g., Takahashi & Portegies Zwart 2000). The next most nearby "analog" to an SSC is the 30 Doradus (30 Dor) cluster in the Large Magellanic Cloud which has been extensively studied because, unlike more distant clusters, its stellar content can largely be resolved. The 30 Dor cluster has become such a popular comparison for larger clusters that "30 Dor" often appears as a dimensional unit when describing other systems!

However, to find a genuine SSC, one must look farther away. SSCs are predominantly found in starbursting and merging galaxy systems, although some SSCs candidates have also been found in barred galaxies, tidal tails, and a handful of candidates in relatively normal spiral galaxies. The most well known SSC system is that found in the "Antennae" galaxies (NGC 4038/4039) (Whitmore & Schweizer 1995), a prototypical early stage merger at a distance of $\sim$ 30 Mpc. Several hundred SSC candidates were identified in this system, which spawned a host of follow-up observations in virtually every wavelength regime with every possible instrument. To date, SSCs have been identified at least as far away as $\sim$ 80 Mpc (NGC 3921, Schweizer et al. 1996), but Burgarella & Chapelon (1998) estimate that NGST will allow us to observe SSCs out to a redshift of $z \approx 9$, which will provide an unprecedented opportunity for directly observing globular cluster formation.

1.3.2 The Initial Mass Function and Cluster Mass Estimates

In order to really address the question of whether SSCs are "proto globular clusters", it is critical to determine their masses and densities. To this end, it is also important to determine the slope of the stellar initial mass function. The initial mass function (IMF) can be thought of as the probability of a star with a given mass being formed in a star forming region. The standard IMF commonly used in the literature is the Salpeter value of $\Gamma = 1.35$ (where $n(m) \propto m^{\Gamma}$). Knowledge of the IMF in the extreme star forming regions of super star clusters is critical to understanding their evolution — if there are not enough low mass stars, a cluster will evaporate on timescales short compared to the age of the universe because mass loss via stellar evolution

will leave a cluster gravitationally unbound (e.g., Takahashi & Portegies Zwart 2000).

An accurate understanding of the stellar IMF is one of the most important and least understood parameters that affects our understanding of star formation throughout the universe. Some of the questions we wish to answer include: Is the IMF universal? If not, on what parameters does it depend? Is there a limit on the maximum stellar mass which can form? Is there a low-mass cut-off when high mass stars are present? These questions are currently a subject of much discussion in the literature, and a great deal of this discussion has focused on the IMF in clusters of stars — if the IMF does vary, it seems likely that this variation would be the most obvious in extreme star birth events, such as the formation of SSCs.

The primary difficulty in accurately determining the stellar IMF in clusters is that spectroscopy must be obtained for each of the high mass stars in the cluster in order to classify it and thus determine its mass. This necessity immediately limits us to only the clusters in the Milky Way, Magellanic Clouds, and under excellent observing conditions perhaps some of the closest Local Group galaxies. For the highest mass and most luminous stars in a cluster, accurate spectroscopy is relatively trivial. Lower mass stars can in principle be classified with photometry alone. However, because of the crowding and their inherently lower luminosities, obtaining accurate observations for low mass stars in a cluster is exceptionally difficult.

Thus, several authors have turned to the nearest super star cluster analogs in order to address the IMF issue. Figer et al. (1999) attempted to determine the IMF for the Arches and Quintuplet clusters near the Galactic center. They find that these clusters have IMFs flatter (i.e. relatively more massive stars) than the Salpeter IMF above ~ 10 $M_\odot$. Strictly interpreted, Figer et al. (1999) note that this IMF might reflect the affect of strong tidal sheer inhibiting low-mass star formation. However, Kim et al. (1999) point out that mass segregation due to stellar relaxation is likely to take place in these clusters on very short times scales, and consequently we are now seeing the *present day* mass function and not the *initial* mass function. Using the superb spatial resolution of HST, Massey & Hunter (1998) measured the IMF in 30 Dor down to 2.8 $M_\odot$ and found that it is consistent with a standard Salpeter IMF. However, Sirianni et al.

(2000) obtained HST data ~ 1 magnitude deeper than the Massey & Hunter observations, and claim that the IMF is normal above ~ 2 $M_{\odot}$, but flattens at lower masses.

The stellar IMF has a direct relation to the masses of SSCs. In §1.3.1 I quoted a rough lower mass limit of $\approx 10^5$ $M_{\odot}$ for a cluster to be considered an SSC. However, typical mass estimates for super star clusters are dependent on the adopted IMF. By far the most common technique for determining the mass of a super star cluster (which I will employ later in this thesis) is to estimate its mass based on the observed luminosity and estimated age in combination with models, such as those of Leitherer et al. (1999). However, while this method is the simplest and can be applied even to systems the farthest away, it has the obvious pitfalls of being dependent on the model assumptions (perhaps most importantly the IMF) and the (typically unknown) extinction value.

Alternatively, it is possibly to measure the mass relatively directly if a cluster is sufficiently isolated and has a high enough apparent brightness. In this case, one can measure the mass relatively directly with spectroscopy and infer an IMF based on the mass to luminosity ratio. With this method, line widths are used to determine the stellar velocity dispersion (typically using intrinsically narrow absorption lines from the atmospheres of cool supergiants), which in turn are used to estimate the mass (assuming virial equilibrium).

This technique has only been applied to a handful of clusters meeting the above criteria — such measurements have been made for clusters in NGC 1569 (Ho & Filippenko 1996a), NGC 1705 (Ho & Filippenko 1996b), and M82 (Smith & Gallagher 2001). The clusters that have been directly probed with this method have masses in the range of a few $\times 10^5$ to a few $\times 10^6$ $M_{\odot}$. Smith & Gallagher (2001) find that, while the IMF for the cluster in NGC 1705 has a steeper than Salpeter IMF, the clusters in both NGC 1705 and M82 appear to either be flatter or truncated at a mass of $1 - 3$ $M_{\odot}$.

The uncertainties in the IMF determinations are still large, and while there are suggestions of variations in the IMF (as above), there is no conclusive evidence for variations at the present time. Nevertheless, in many areas of astrophysics, an IMF must be assumed as it cannot

Table 1.1: Sample of Cluster Luminosity Functions

Galaxy	Distance[a]	N[b]	α^c	Reference
He 2-10	9 Mpc	76	-1.7	Johnson et al. (2000)
NGC 4038/4039	22 Mpc	800	-2.1	Whitmore & Schweizer (1995)
NGC 3256	37 Mpc	$>$ 1000	-1.8	Zepf et al. (1999)
NGC 1741	51 Mpc	314	-1.9	Johnson et al. (1999)
ESO 565-11	63 Mpc	700	-2.2	Buta et al. (1999)
NGC 7252	63 Mpc	499	-1.8	Miller et al. (1997)
NGC 3921	78 Mpc	102	-2.1	Schweizer et al. (1996)

[a] Distance assuming $H_0 = 75$ km s^{-1} Mpc^{-1}.
[b] Number of super star clusters detected.
[c] Slope of power-law luminosity function for detected clusters.

directly be measured (such is the case in the work presented here), and a standard Salpeter IMF remains arguably the most logical choice.

1.3.3 The Luminosity Function of Super Star Clusters

The luminosity functions for entire systems of SSCs typically have a power law form of $\phi(L) \propto L^{\alpha}$, where the measured values of α are very closely clustered around $\alpha \approx -2$ (see Table 1.1). It is interesting to note that this power-law slope is similar to that observed for Galactic H II regions (McKee & Williams 1997) and molecular clouds (Harris & Pudritz 1994). However, this power-law behavior is not consistent with the luminosity function for galactic globular clusters, which exhibit roughly a lognormal distribution with a peak at $\approx M_V = -7.5$ (Harris 1991) [4] . Opponents of the theory that SSCs are proto-globular clusters have used this as evidence for the two types of objects coming from inherently different processes (e.g., van den Bergh 1995).

However, SSCs are likely to have a significant "infant mortality rate", preferentially affecting the least massive and least dense clusters. Several destruction mechanisms have been proposed, including 2-body relaxation, tidal shocking, and stellar mass loss. Using simple ana-

[4] Some studies have found weak evidence that, over the high luminosity range, a power-law distribution fits the globular cluster luminosity function marginally better than a lognormal distribution (e.g., Secker 1992).

lytical models to account for cluster disruption, Zhang et al. (2000) find that over a wide variety of initial conditions, power law mass functions will evolve into the lognormal distribution similar to that observed for Galactic globular clusters.

Finally, some of the SSC systems show evidence for having a flatter power law at fainter magnitudes (e.g., Whitmore et al. 1999). The break in the power law corresponds to roughly a mass of $\sim 10^5$ $M_\odot$, which Whitmore (2000) has pointed out is similar to the typical globular cluster mass. This loosely suggests that the lower mass SSCs may have already undergone some amount of destruction, and we are beginning to see a hint of the peak in the globular cluster distribution.

If the present-day luminosity function of globular clusters does, in fact, reflect the dissociation of lower mass clusters over approximately a Hubble time, then as we observe globular cluster systems in the earlier universe we should see evidence of this evolution. In particular, the peak of the globular cluster luminosity function should shift to fainter luminosities as we look farther away. To date, we lack the instrumentation with high enough spatial resolution and sensitivity to carry out this experiment.

1.3.4 Formation of Super Star Clusters

It appears that the majority of star formation takes place in clusters or associations of some kind. In surveys of molecular clouds, typically 50% to 90% of the stellar populations appear to be formed in a clustered environment (Clarke et al. 2000, and references therein). Remarkably, massive star clusters, open clusters and associations, and molecular clouds all appear to have initial power-law mass distributions with a slope of ~ -2. Elmegreen & Efremov (1997) have put forth a "universal formation mechanism" for star clusters, arguing that scale-invariant structure in turbulent interstellar gas would naturally result in this observed power law distribution. However, most of these birth clusters will dissociate over relatively short times scales.

While forming stars in clusters (of some kind) appears to be a common mode of star

formation, forming bound massive clusters must require physical conditions which are not typical in normal galaxies given the dearth of massive clusters which appear to be forming in such environments. Two main ingredients appear to be required in order to form bound massive clusters — high star formation efficiency and high pressure. The need for high star formation efficiency is due to the violently disruptive effect massive stars have on the interstellar medium; if a significant fraction of a cluster's initial mass remains in the form of gaseous material when the massive stars are formed, this material will be expelled from the cluster by stellar winds and supernovae, and the cluster will become unbound. Star formation efficiencies greater than ~ 0.2 to 0.5 appear to be required in order to avoid this fate (e.g., Hills 1980).

If mass loss occurs quickly compared to the dynamical time of the cluster, $\tau_D \sim (\mathrm{G}\rho)^{1/2}$ (where ρ is the mass density), then the cluster's stars do not have time to virialize and are left with a higher velocity dispersion than the potential well can compensate for, consequently causing the stars to escape the cluster. An obvious mechanism for reducing this effect is for the cluster to remove the gaseous material only over long timescales in order for the cluster to have time to react adiabatically. Alternatively, angular momentum could act to stabilize the cluster mass loss, but it would also inhibit star formation [5] . Magnetic fields could also protect the cluster from undergoing catastrophic mass loss by essentially storing kinetic energy as the cluster material collapses out of the ISM, compressing the magnetic field. In the final virialized state, the kinetic energy of the cluster would be lower, thus resulting in a lower stellar velocity dispersion at the time of mass loss.

Finally, a high pressure environment can help a cluster to remain bound for several reasons. First, if the virial velocity dispersion of a cluster is large compared to the velocity at which massive stars can drive an outflow (~ 10 km s^{-1}), the gaseous material is more resistant to dispersal (Elmegreen et al. 2000a). Assuming a virialized velocity distribution of roughly,

$$\langle v^2 \rangle \sim \frac{\mathrm{G\ M}}{\mathrm{R_{eff}}}, \tag{1.1}$$

[5] For example, the Toomre criterion (Toomre 1964) predicts that the critical surface density for star formation in a collisionless disk is proportional to the epicyclic frequency.

for a hypothetical cluster with a mass of $M = 10^6$ $M_\odot$ and effective radius of $R_{eff} = 3$ pc, the resulting virial velocity is ~ 30 km s^{-1}. If the pressure is roughly P $\approx \rho v^2$, these parameters imply a necessary pressure of P $\approx 10^{10} k_B$ cm^{-3} K. Along this same line of reason, higher pressures will result in virialized clusters with higher binding energies.

Another benefit of forming a cluster in a high pressure environment is that the star formation process can happen on a shorter timescale. Very heuristically, one can think of this increased rate of star formation as simply being due to the higher density of material which has been compressed, or also due to the increased sound speed allowing for the star formation to take place more quickly over larger scales. The more quickly star formation takes place, the better chance the interstellar medium can be transformed into stars before the young massive stars begin to have a significant impact on the remaining gaseous material, thus potentially increasing the star formation efficiency. A related effect is that, if the surrounding region has a high pressure, it may help to contain the gaseous material after the onset of massive star formation.

In relation to the "universal formation mechanism" proposed by Elmegreen & Efremov (1997), it seems the main difference between the formation of bound massive clusters and other types of clusters is a high pressure environment. To test this prediction, let us return to 30 Dor as a local analog. Chu & Kennicutt (1994) measure a density and velocity of the central cluster in 30 Dor which imply a pressure of $P/k_B \sim 10^7$ cm^{-3} K, which is 3 to 4 orders of magnitude higher than typical pressures in molecular clouds in the Galaxy of $P/k_B \sim 10^3$ to 10^4 cm^{-3} K (Jenkins et al. 1983). Elmegreen & Efremov (1997) note that similarly high pressures would result if interstellar media with a densities of ~ 10 atoms cm^{-3} collided at a typical galactic orbital speed of ~ 200 km s^{-1}. It seems clear that the formation of bound massive clusters requires pressures much higher than those typically found in molecular clouds in the Galaxy, but which may be commonplace in merging and interacting galaxies.

1.4 The Birth Environment of Massive Star Clusters

After the criteria for massive star cluster formation have been achieved and star formation has commenced, the newly born stars will remain swaddled in the material from which they were formed for some time. The timescale over which a massive star will pass through the early stages of development is not well characterized, however the early stages of massive star evolution must take place on faster time scales than low mass stars. As a lower limit, Kurtz et al. (2000) have suggested the free-fall time of $\gtrsim 10^4$ years for an individual massive star.

In the very earliest stages of massive star evolution, the massive proto-star is an extremely dense clump of warm material known as a “hot core”. Hot cores are physically defined by densities $\gtrsim 10^7$ cm^{-3}, and temperatures $\gtrsim 100$ K (Kurtz et al. 2000). These objects are typically detected with high density molecular tracers, such as CS, which have critical densities (below which they are not observable) $\gtrsim 10^5$ cm^{-3}, and many examples of hot cores have been found in the Galaxy.

As the proto-star evolves toward its main sequence lifetime, it will also begin to ionize the surrounding interstellar medium. The resulting H II regions are very dense and compact and have come to be known as “ultra compact H II regions” (UCH IIs). This UCH II phase is also not observable in optical or UV wavelengths, but rather they are generally detected by their mid- to far-infrared or radio spectral energy signatures. UCH IIs are commonly associated with other phenomena such as maser emission or molecular outflows, both of which are additional signs of star formation activity.

It is likely that massive star clusters follow a similar evolutionary sequence to that of the individual massive stars of which they are made. However, this area of research has only recently opened up with radio and mid-infrared instrumentation gaining the sensitivity and spatial resolution necessary to study these objects in an extragalactic context. Indeed, Chapters 4 and 5 of this thesis will focus on these recent developments.

1.5 Thesis Outline

The goal of this thesis is to examine the nature of super star clusters throughout their evolutionary development in starburst galaxies. The globular clusters abundant in the local universe are analogous to fossils on earth and provide a valuable historical record of star formation in the universe. However, unlike archaeologists, we have the ability to make expeditions to pockets of the universe which are earlier in their evolutionary sequence than our own surroundings. In this sense, the chapters of this thesis travel backward in time — beginning with super star clusters which are well into their adolescence and continuing to follow the chronology to a sample of super star clusters which are still embedded in their birth material.

In Chapter 2, I examine several starburst galaxies in the Hickson Compact Group 31 with both Hubble Space Telescope and ground-based data. A large number of super star clusters are identified, and the photometry of these objects indicates that they have a median age of ~ 4 Myr. The luminosity function of these clusters is consistent with that found in numerous other starburst galaxies. The star formation rate and burst environment are also discussed. Perhaps the most striking result of this chapter is the discovery of a dwarf galaxy in the group which shows no sign of previous star formation and may have only recently collapsed out of the intergalactic medium.

A similar case study of the starburst galaxy Henize 2-10 is presented in Chapter 3 using data from the Hubble Space Telescope. The numerous super star clusters identified in this system also appear to have typical ages $\lesssim 10$ Myr. The luminosity function for this system is in accord with the canonical value found elsewhere (and in Chapter 1). A unique result from this Chapter is the detection of a high velocity outflow (~ 360 km s^{-1}) which could potentially have a dramatic impact on the surrounding intergalactic medium.

Chapter 4 provides an overview of the discovery of "ultra dense H II regions" (UDH IIs) with radio and mid-infrared observations. These UDH IIs represent the earliest stage of massive star cluster evolution observed to date. From the radio observations, the electron densities,

radii, and number of ionizing photons (and therefore number of embedded massive stars) are estimated. The mid-infrared observations confirm the presence of hot dust cocoons surrounding these objects. These embedded clusters account for at least $\sim 60\%$ of the mid- to far-infrared flux of the entire galaxy. Finally, the impact of UDH IIs on the well known radio to far-infrared flux ratio is discussed.

Inspired by the discovery of UDH IIs, I searched the literature for possible serendipitous detections which were not classified as such. Chapter 5 presents the result of this search, which resulting in the detection of 35 UDH II candidates in the galaxies M33, NGC 253, and NGC 6946. This sample of objects begins to fill in the continuum between individual UCH IIs and the embedded massive clusters. The properties of this sample are analyzed, such as the electron densities, radii, and number of ionizing photons. Finally, the connection to UCH II complexes in the Galaxy (such as W49) is discussed, and luminosity functions are presented.

Chapter 6 overviews the directions in which I hope my future research will take the field of massive star cluster formation and evolution. Given the very recent discovery of UDH IIs, a large number of questions remain to be addressed. I discuss the possibilities for expanding the sample of UDH IIs, determining the physical properties of their birth environments, developing an evolutionary scenario, and the need for more sophisticated modeling efforts.