THE BIRTH OF SUPER STAR CLUSTERS

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ABSTRACT

Super star clusters (SSCs) are the most extreme star forming environments in the local universe. Packed with massive stars, these clusters have a major impact on the energetics and morphology of galaxies. Massive stars ionize the interstellar medium and power the infrared radiation of dust, and their stellar winds and supernovae release mechanical energy that can trigger further star formation. In addition, the most massive and dense SSCs are the likely progenitors of ancient globular clusters. For all of these reasons, there is widespread interest in the birth and evolution of SSCs. The goal of my research is to improve the current understanding of SSC formation and early evolution by combining observations of starburst galaxies spanning the radio to ultraviolet wavelength regimes. This work capitalizes on the unique capabilities of the Hubble and Spitzer Space Telescopes and the Very Large Array to probe the gaseous and dusty sites of star formation at high resolution.

Introduction

Super star clusters (SSCs) are the most extreme star forming environments in the local universe. Packed with massive stars, these clusters have a major impact on the energetics of galaxies: massive stars ionize the interstellar medium and power the infrared radiation of dust, and their stellar winds and supernovae release mechanical energy that can trigger further star formation. In addition, SSCs containing hundreds to thousands of massive stars can have a dramatic effect on the morphology of their host galaxy when these stars collectively explode at the end of their lives, expelling huge amounts of gas and blowing galactic-scale superbubbles (e.g. Tenorio-Tagle et al. 2007; Marlowe et al. 1995).

SSCs are also a particularly important mode of star formation at high redshift since violent and intense star formation was common in the earlier universe (e.g. Madau et al. 1998). Moreover, the most massive and dense SSCs have properties consistent with those expected for young globular clusters (e.g. Whitmore 2003). The prevalence of ancient globular clusters around massive galaxies today suggests that these extreme star clusters were forming ubiquitously in the early universe as galaxies began to merge and coalesce hierarchically.

Despite the importance and widespread interest in SSCs, their birth and early evolution are not well understood. The goal of my research is to improve the current understanding of SSC formation and early evolution by combining multi-wavelength observations of starburst galaxies, capitalizing on the unique capabilities of the Hubble and Spitzer Space Telescopes to probe the gaseous and dusty sites of star formation at high resolution. This project will also help lay the groundwork for future research in this field using Hubble’s new Wide Field Camera 3 and the James Webb Space Telescope (JWST).

Background: SSCs at Optical, Infrared and Radio Wavelengths

Interest in SSCs was sparked by the discovery of these young, massive, and compact star clusters in the 1990’s using the Hubble Space Telescope (HST). HST has continued to be the work-horse in this field, providing high resolution imaging at ultraviolet (UV), optical, and near-infrared (IR) wavelengths (e.g. Whitmore 2003). Broad-band observations at UV and optical wavelengths probe the stellar populations in the SSCs and narrow-band imaging captures emission lines from the nebular gas. Near-IR observations are particularly important for probing the dusty birth environments of embedded SSCs and the wavelength range of \( \sim 1 - 2 \mu m \) is well-suited to assessing a cluster’s evolutionary state because it samples the spectral energy distribution (SED) at the nexus of emission from dust
and stellar light.

In the past decade, ultra-young SSCs still deeply embedded in their birth material have been discovered using IR and radio imaging (e.g. Kobulnicky & Johnson 1999; Turner et al. 2000; Neff & Ulvestad 2003; Johnson et al. 2001; Beck et al. 2002; Johnson et al. 2003; Johnson & Kobulnicky 2003; Johnson et al. 2004; Tsai et al. 2006; Reines et al. 2008a). These long wavelength observations, essentially unhindered by extinction, are useful for identifying extremely young embedded SSCs. IR observations, with Spitzer for example, capture emission from the heated dust associated with young SSCs and radio observations probe the ultra-dense H\textsubscript{II} regions that are produced when hot massive stars within the clusters ionize the surrounding gas. The ultra-dense H\textsubscript{II} regions are short-lived, so thermal radio emission is a good indicator of youth.

My work aims to improve the current understanding of SSC formation and early evolution by combining observations of starburst galaxies spanning the radio to ultraviolet wavelength regimes. Multi-wavelength observations are essential for probing the various components of SSCs (i.e. stars, gas & dust) and gaining a complete picture of this fundamental mode of star formation occurring throughout the universe.

Scientific Goals and Methodology

This multi-wavelength study of SSCs will address the following questions:

- What are the physical properties of emerging massive star clusters?
- What evolutionary stages do natal SSCs go through and what are the timescales involved in their evolution?
- What type of environments give rise to SSCs?
- How did the ancient globular clusters that we see today form in the early universe?
- How should observations of unresolved starburst galaxies at high redshift be interpreted?

Deep, high resolution observations at multiple wavelengths must be compared and analyzed in order to address these questions. I primarily utilize (new and archival) data from HST, Spitzer and the Very Large Array (VLA) in this work. HST and Spitzer make this study of individual extragalactic SSCs possible, providing sensitive, high-resolution images and access to important regions of the electromagnetic spectrum unobtainable from the ground. An outline of the methodology I use for investigating young embedded SSCs is given below.

i. Identify young SSCs in starburst galaxies using infrared and radio imaging.

ii. Utilize multi-wavelength observations from HST, Spitzer and the VLA. Broad- and narrow-band imaging with HST probes the stellar populations and nebular gas within SSCs, while Spitzer detects thermal emission from the heated dust cocoons. Radio observations with the VLA provide an unobscured view of the ultra-dense H\textsubscript{II} regions associated with natal SSCs.

iii. Measure flux densities of the SSCs across multiple wavebands using a new photometry code (SURPHOT) I developed which allows for consistent irregular apertures (such as radio contours) and background annuli.

iv. Derive physical properties of SSCs using stellar population synthesis models. Estimates of ages, masses and extinctions can be derived from both the nebular emission from the H\textsubscript{II} regions and fitting model spectral energy distributions (SEDs) to the stellar continuum. Modeling the IR SEDs can provide information about dust properties, such as temperature, and emission from polycyclic aromatic hydrocarbons (PAHs).

v. Develop a self-consistent picture relating the observable properties of young emerging SSCs to model predictions. Emission from the stellar populations, nebular gas and heated dust cocoons provide independent estimates of the properties of SSCs. Comparing these results gives a comprehensive view of the conditions in the young clusters.

vi. Explore trends in the data and draw conclusions. Synthesizing results from a large sample of SSCs in a variety of environments can provide new insight into the physical processes involved in the formation and early evolution of these massive star clusters.

I have already begun to make progress towards answering the questions posed at the beginning of this section by exploiting multi-wavelength data sets from the radio to the ultraviolet and developing innovative analysis techniques (e.g. Reines et al. 2008a). Some results from my work are given in the next section.

What We Have Learned So Far
From This Study

Many interesting results have emerged from this multi-wavelength study of SSCs and been published in refereed journals (Reines et al. 2008a; Reines et al.
The majority of radio-detected SSCs have detectable optical counterparts. These infant SSCs have ages $\lesssim$ a few Myr, suggesting the transition from being completely obscured to visible at optical wavelengths happens on very short timescales (Reines et al. 2008a; Reines et al. 2008b).

Warm dust associated with infant SSCs dominates the mid-IR emission from starburst galaxies. The mid-infrared morphology of nearby starbursts is almost identical to that of the radio, indicating that nearly all of the warm dust is associated with infant SSCs (e.g. Figure 1; Reines et al. 2008a). This illustrates the importance of SSCs in the interpretation of observations of unresolved starburst galaxies at high redshift.

Hot dust or Red Supergiants can dominate the near-IR continuum of young SSCs depending on their evolutionary state. Young SSCs have red near-IR colors and large near-IR excesses with respect to model SEDs fit to optical photometry. The red near-IR colors, however, are quantitatively different (redder) in extremely young SSCs ($\lesssim$ 3 Myr) compared to slightly older SSCs ($\sim 5 - 15$ Myr). The near-IR light is dominated by evolved red supergiants in these older SSCs, whereas the near-IR light from the ultra-young SSCs is dominated by host dust emission (Reines et al. 2008b).

The geometry of an infant SSC is consistent with that of a dust-free star cluster surrounded by a clumpy shell of gas and dust. This scenario was previously proposed by Gordon et al. (1997) and a number of results from my work support this conclusion.

First, the ionized gas emission from infant SSCs underpredicts the expected ionizing luminosities from the optical stellar continuum, suggesting ionizing photons are leaking out of the immediate vicinity of the clusters before ionizing hydrogen and contributing to the gas emission. In addition, extinction estimates at various wavelengths suggest that short wavelengths are completely absorbed when they intercept dense dust clumps and only escape the cluster through diffuse interclump regions (Reines et al. 2008b).

The formation of SSCs may be sparked by either local processes such as stellar winds and supernovae or by large galactic-scale disturbances. In NGC 4449, for example, many infant clusters are located along the peripheries of giant Hα shells and a possible superbubble (Reines et al. 2008a). The SSCs in the blue compact dwarf galaxy SBS 0335-052, however, are associated with a large-scale disturbance traveling through the galaxy with a velocity of $\sim 35$ km s$^{-1}$ (Figure 2; Reines et al. 2008b).

Synthesizing high quality data sets across the electromagnetic spectrum has provided us with a unique and detailed view of young SSCs in nearby starbursts. These findings would not have been possible without the combination of optical, infrared, and radio observations. The results presented here are the first of a larger program (my thesis) to study SSCs as they emerge from their birth material and transition from being visible in the radio to optical wavelength regimes.

The Next Steps

Although a good deal of progress has been made...
in this study of the birth and early evolution of SSCs, there is still much to learn. In order to continue addressing the questions posed above, I will expand my sample of young SSCs using observations from HST, Spitzer and the VLA. I already have new near-IR HST/NICMOS data in hand and will incorporate complementary archival observations at other wavelengths. This multi-wavelength study of young SSCs in a variety of environments will shed light on an important mode of star formation throughout the universe and provide insight into the origin of globular clusters. Looking towards the future, the results obtained with the help of the VSGC will provide the groundwork to fully exploit the capabilities of NASA’s upcoming facilities (HST’s new Wide Field Camera 3 and JWST) in the field of extragalactic massive star clusters and starburst galaxies, both locally and at high redshift.

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REFERENCES


