A Massive Star Odyssey, from Main Sequence to Supernova
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UCH II regions in extragalactic clusters and associations

Kelsey E. Johnson

National Radio Astronomy Observatory,
PO Box 0, Socorro, NM 87801, USA
and
Department of Astronomy, University of Wisconsin,
475 N. Charter Street, Madison, WI 53706, USA

Abstract. In recent years, a number of extragalactic massive stars clusters have been detected which are still deeply embedded in their birth material. In many cases, these clusters are only visible in the mid-IR to radio regimes, and have typically been detected as 'inverted' spectrum radio sources. These clusters appear to have properties which are analogous to those of ultracompact H II (UCH II) regions in the Galaxy, albeit vastly scaled up in total mass and luminosity. The ultra-young clusters appear to form with a continuum of masses, and the most massive are consistent with being the progenitors of globular clusters. Here I will overview the properties of the currently known sample of ultradense H II (UDH II) regions and examine their relation to Galactic UCH II regions.

1. Introduction

1.1. The role of massive star clusters in the universe

Massive stars are gregarious creatures, and most stars in the Milky Way form in clusters or associations. Therefore, if we wish to understand massive star evolution in general, we need to understand the clustered mode of massive star formation and evolution. The concept also appears to hold true in an extragalactic context — starburst activity in nearby galaxies has typically been resolved into massive star clusters (although IC 10 is a curious and notable exception). In the most massive clusters, the so-called 'super star clusters' (SSCs) roughly 1 000 equivalent O-type stars can be present within a radius of only a few parsecs — these objects are virtually bombs ready to detonate when the massive stars begin to reach the ends of their lifetimes nearly simultaneously. Indeed, these clusters can have a tremendous impact on their environments via the combined effect of the winds and supernovae of their constituent massive stars.

The most ancient star clusters in the universe, globular clusters, no longer contain any massive stars — the massive stars in these objects have long since expired. Rather, globular clusters are fossils of a much earlier time in the universe when the conditions were typically much different than the conditions in local universe today. Nevertheless, globular clusters provide us with an important clue about star formation at an earlier time. Ancient globular clusters appear to be ubiquitous in the local universe, however their formation has been an important unresolved issue for many years. Some of the early theories for globular cluster formation suggested that these objects collapsed directly out of primordial material according to the Jean's mass in the early universe (Peebles & Dicke 1968). Since the launch of the *Hubble Space Telescope*, this scenario began to undergo revision; a great deal of progress has been made in this area since we have been able to resolve populations of compact massive young clusters (super star clusters) in starburst galaxies for the first time. The properties of SSCs strongly suggest that they may be the adolescent versions of the more familiar globular clusters. Therefore, studying the genesis of SSCs may yield information about the environments in which globular clusters were formed so prodigiously in the early universe. Despite the significant role of massive stars throughout the universe, their birth is not well understood, and we are only beginning to piece together a scenario for the youngest stages of massive star evolution. We have made some progress understanding the early stages of massive star formation in the Galaxy, but the current knowledge about the early stages of massive star evolution in other environments is mediocre at best. The conditions required for massive star cluster formation are far from understood, but it seems clear that extreme environments are necessary. The young blue SSCs being detected with *HST* are certainly young on a globular cluster time scale, however they have already emerged from their birth material to be observable in optical light — from a star formation perspective, everything interesting has already happened. In order to study the *youngest* massive star clusters, observations at longer wavelengths are critical.

1.2. The discovery of 'Ultradense H II regions'

High spatial resolution radio observations have now revealed a sample of very young massive star clusters still embedded in their birth material (*e.g.*, NGC 5253, Turner *et al.* 1998; He2-10, Kobulnicky & Johnson 1999). These heavily enshrouded clusters contain hundreds of young massive stars which create surrounding H II regions and manifest themselves as optically thick free-free radio sources. Some of these radio sources have also been confirmed as luminous mid-infrared sources — suggesting they are surrounded by warm natal dust cocoons (Vacca *et al.* 2002; Gorjian *et al.* 2001). Similar dense, inverted spectrum H II regions exist on a smaller scale around individual stars in our Galaxy, *i.e.*, ultracompact H II regions (Wood & Churchwell 1989). Because of their apparent spectral similarity to Galactic ultracompact H II (UCH II) regions, Kobulnicky & Johnson (1999) dubbed these extragalactic objects 'ultradense H II regions' (UDH II regions).

The physical properties of these clusters are truly remarkable; the estimated sizes (a few parsecs), stellar masses (a few $\times 10^6\,M_\odot$), ionizing luminosities ($Q_{\rm Lyc} \simeq 10^{53}\,{\rm s}^{-1}$), and ages (possibly as young as a few times 10^5 yr) of the newly discovered UDH II regions imply that we may be witnessing the birth process of SSCs (and therefore plausibly the birth process of globular clusters). The discovery of these UDH II regions allows us to begin observing the earliest stages of massive star cluster formation for the first time.

2. Current census of UDH II regions

2.1. Where do we find massive star clusters forming?

Perhaps not surprisingly, the most massive and luminous UDH II regions were the first to be 'discovered' (as in NGC 5253 and He2-10). However, unless there is a strongly preferred mass at which star clusters form, we should expect to find a *continuum* of extragalactic star clusters ranging between the individual UCH II regions in the Galaxy to the massive proto-globular clusters. Furthermore, current theory suggests that the properties of massive star clusters will largely be dependent on the pressure of their formation environment (Elmegreen & Efremov 1997). Therefore, we might expect the most vigorous starbursts to host the most massive star clusters, while relatively quiescent galaxies (like our own Milky Way) will tend to contain only low mass clusters and associations. If we wish to understand how massive star cluster formation depends on environmental properties as well as understand it in a statistical sense, we must fill in the continuum between Galactic UCH II regions and extragalactic UDH II regions.

In order to extend the sample of currently known UDH II regions, we have begun to catalog UDH II regions in galaxies with a range of star formation rates. In order to select UDH II candidates, we have applied the condition that the radio spectral index α must be positive (where $S_\nu \propto \nu^\alpha$). This criterion should exclude most other types of radio sources (see Johnson *et al.* 2001 for more detailed discussion). This process resulted in the detection of numerous new UDH II candidates, and has begun to fill in the continuum between objects which appear to be small embedded OB associations up to the massive star clusters which are plausibly proto-globular clusters (Figure 1).

The most massive clusters appear to form in the galaxies with the highest star formation rates. This could be interpreted as either being statistical (the more clusters that are formed, the more likely some of them will be massive), or environmental (the most massive clusters are forming in regions with the highest pressure, which also results in an overall high rate of star formation). In order to differentiate between these two scenarios, direct measurements of the pressures in the clusters will be invaluable. Indirect estimates of the cluster properties will be discussed in the next section.

Curiously, a number of galaxies selected as 'star forming' galaxies, do not appear to have any embedded clusters equivalent to or more massive that W 49A in the Milky Way. In a recent survey of twenty galaxies with the VLA, Johnson *et al.* (in preparation) had 3.6 cm detections in only half of the sample. In many cases, the 5σ luminosity is quite high, and the presence of embedded clusters with moderate masses cannot be ruled out. However, in some cases, the 5σ luminosity is below that of W 49A. There are a number of possible explanations for this: (*i*) since the embedded phase of a cluster's lifetime does not last very long, perhaps catching a glimpse of a cluster in this phase requires some luck; (*ii*) a galaxy which *was* forming stars 5 - 10 Myr ago (based on optical diagnostics) may have shut off star formation subsequently; and (*iii*) the clusters are surrounded by such dense dust cocoons that the ionizing radiation of the massive stars is absorbed by the dust before it can create an H II region. At present, the reason for the absence of ultra-young clusters in these systems is unresolved.

2.2. Properties of the sample

The stellar content of UDH II regions can be inferred from their thermal luminosities. Thermal luminosity can be related to the production rate of Lyman continuum photons $Q_{\rm Lyc}$, which can in turn be used to infer stellar content (under the assumption of a standard IMF). Following the convention of Vacca

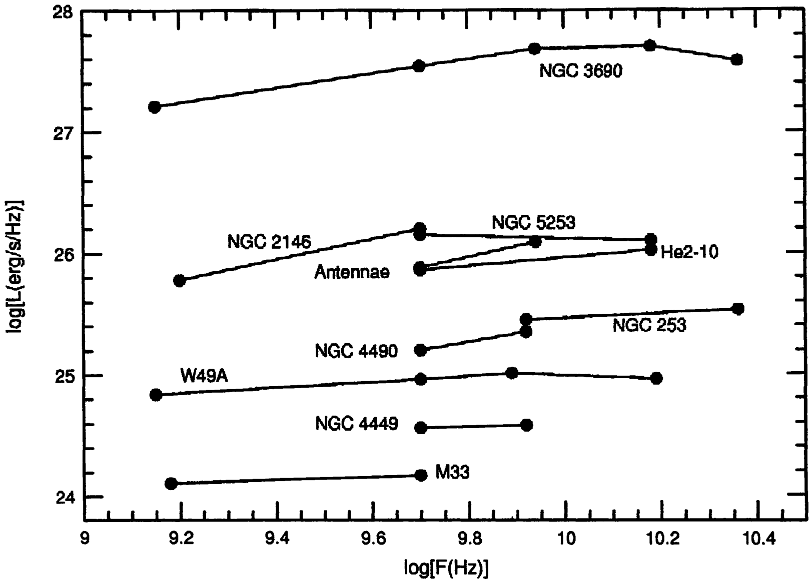

Figure 1. The average spectral energy distributions for the UDH II regions detected in a sample of galaxies (Turner *et al.* 1998; Kobulnicky & Johnson 1999; Tarchi *et al.* 2000; Johnson *et al.* 2001; Neff & Ulvestad 2000; Teng *et al.* in preparation; Johnson *et al.* in preparation.). The Galactic UCH II complex W 49A is also shown for comparison (Mezger *et al.* 1967). There are a continuum of UDH II regions between the objects which are plausibly protoglobular clusters to small associations in M 33. The source in NGC 3690 is likely to contain multiple UDH II regions which are unresolved.

(1994), a 'typical' O-type star (type O7V) produces $Q_{\rm Lyc} \approx 10^{49}\,{\rm s}^{-1}$. Therefore, the $Q_{\rm Lyc}$ value of a UDH II can be directly translated into the number of 'equivalent' O-type stars. Using this method, the sample of known UDH II regions have a range of a few to $\sim$1 000 equivalent O-type stars, with the UDH II regions in the most quiescent galaxies (such as M 33) having the smallest number of equivalent O-type stars. This result is not surprising if the formation of massive star clusters is primarily related to the intensity of star formation in a galaxy as a whole.

To better constrain the properties of UDH II regions, Kobulnicky & Johnson (1999) and Johnson *et al.* (2001) have used model H II regions to reproduce the observed spectral energy distributions. Their models suggest that UDH II regions typically have radii less than a few parsecs and global electron densities as high as $n_{\rm e} \approx 10^5\,{\rm cm}^{-3}$. Interpreted at face value, these electron densities require pressures on the order of $P/k_B \approx 10^9\,{\rm cm}^2\,{\rm K}$. While such high densities and pressures may be common in regions of *individual* massive star formation, it is important to note that these values are global averages over entire regions of massive star cluster formation.

Comparing the mass in ionized gas to that of the embedded stellar clusters, extremely high star formation efficiencies are required — at least greater than 50%, and perhaps much higher. If these clusters are to survive to the old age of globular clusters, it is absolutely critical that they form with high efficiency. 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 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.

3. Comparison between UCH II regions and UDH II regions

Because we are hypothesizing that UDH II regions are (to some degree) scaled-up versions of UCH II regions (see the schematic in Figure 2), it is sensible to make comparisons between the two. Both UDH II regions and UCH II regions are optically obscured. UDH II regions have globally averaged electron densities up to $n_e \approx 10^5\,\mathrm{cm}^{-3}$, which is similar to the values inferred for some UCH II regions (although it is important to stress that densities are likely to reach much higher values for individual cores inside UDH II regions.) Finally, both types of objects appear to spend $\sim$15% of their lifetime enshrouded (see Kobulnicky & Johnson 1999 and Johnson *et al.* 2001 for a discussion of UDH II lifetimes). The most notable difference between the two simply appears to be scale — the most massive UDH II regions contain hundreds or thousands of individual UCH II regions in a relatively small volume. As more detailed observations become available, we may find that the extreme environment of UDH II regions may cause more subtle differences in their behavior compared to UCH II regions.

Clusters or 'complexes' of UCH II regions in the Galaxy might help us further this comparison. In particular, W 49A is one of the most well-studied UCH II complexes in the Galaxy, which makes it well suited for comparison to UDH II regions. W 49A has been resolved into at least 30 UCH II regions (De Pree, Mehringer & Goss 1997). In Figure 1, the radio spectral energy distribution of W 49A (from Mezger *et al.* 1967) is compared to the *average* spectral energy distribution of the UDH II regions for each galaxy in the sample shown. It is striking that the integrated spectral energy distribution of W 49A is nearly identical to those of the UDH II regions in the sample. In some cases, W 49A appears to have a turnover frequency which is lower than that of the UDH II regions, which implies that some UDH II regions have an even higher mean electron density than W 49A. Comparing the luminosity of W 49A with the UDH II values, it is clear that while W 49A would be up to 10 times more luminous than a typical M 33 source, it would be a faint source in the NGC 253 sample, and probably not detected in the He2-10 sample. Indeed, in this set of galaxies, the more intense the star formation a galaxy in undergoing, the more massive the UDH II regions that it hosts.

4. Directions for the future

For the first time, we are now able to study ultra-young extragalactic star clusters, still embedded in their birth material. Given that UDH II regions have only recently been discovered, there are a wide array of issues and questions remaining to be addressed. For most of these issues, increasing the known sample of UDH II regions is critical for gaining a statistical understanding of their properties. Given a large enough sample, hopefully we can begin to understand

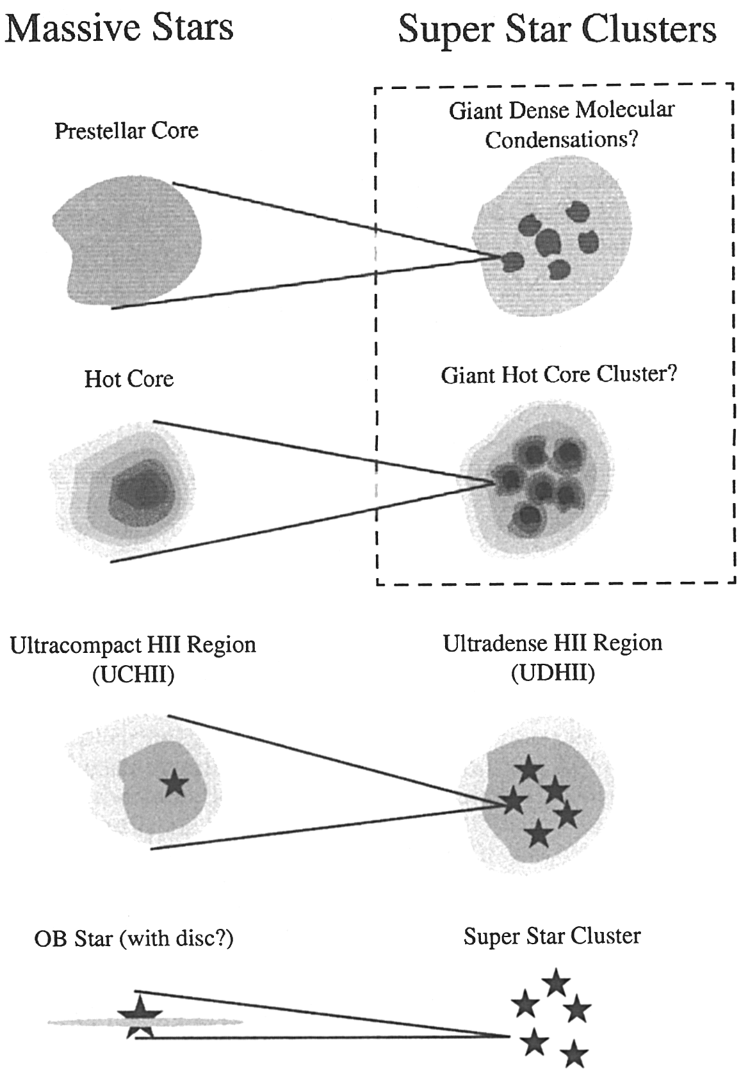

Figure 2. Proposed schematic illustrating the evolution of massive star clusters (*right*) in parallel with the evolution of individual massive stars (*left*). The dashed box indicates the stages of extragalactic star cluster evolution which have not yet been observationally identified.

how the properties of star formation scale between individual UCH II regions and massive UDH II regions. Another important goal is to fill in our knowledge of their spectral energy distributions — our current spectral information for these objects is quite anemic; without more information at many wavelengths, constructing realistic physical models is nearly impossible. Molecular line diagnostics should also aid us in nailing down the physical properties of these objects, such as density and pressure. The coming decade, with both the EVLA and ALMA coming on line, promises to bring many new exciting results to these issues and questions.

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Discussion

VACCA: Just a comment: the ages you have given could actually be upper limits, as some estimates are based on the assumption of pressure equilibrium with the surrounding ISM, which may not be valid for some of these sources.

JOHNSON: Yes, I agree. The pressure equilibrium argument is not fool proof, and these objects could be much younger than 1 Myr.

SCHAERER: Several authors (*e.g.*, Charlot & Fall; Granatio *et al.*) modeling the *global* properties of galaxies have been drawn to propose that a fairly *long* initial phase of massive star formation is hidden from the optical and near-IR. Could you comment on the possible connection with your highly embedded objects?

JOHNSON: I don't know what the resolution to this is. Certainly, the ages we derive are not definitive. It could also be (perhaps) that the H II regions become too diffuse (and therefore invisible) before they emerge from their dust cocoons.

ABEL: Will it be possible to measure the metallicities of your proto-globular clusters?

JOHNSON: With very large telescopes, this might be possible for the young, but optically visible clusters. I have no idea how this might be done for clusters which are still embedded.

LEITHERER: I would like to draw your attention to the poster by Lucimara Martins *et al.* (these Proceedings). We give arguments for a much earlier epoch when H II regions become transparent than proposed by Charlot & Fall.

JOHNSON: Thank, you. I think it is important to get the theory and observations to agree on this.