Finding Signatures of the Youngest Starbursts

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Abstract. Embedded massive starclusters have recently been identified in several nearby galaxies by means of the radio-wave thermal bremsstrahlung emission from their surrounding HII regions. Energy requirements imply that these optically-obscured starclusters contain 500-1000 O-type stars, making them similar to the "super starclusters" observed in many dwarf starbursts and mergers. Based on their high free-free optical depth and visual extinctions of $A_V \gg 10$ mag., these massive "ultra-dense" HII regions (UDHIIs) are distinct signatures of the youngest, most compact super starclusters. UDHII regions may represent the earliest stages of globular cluster formation. We review the properties of presently-known UDHIIs, and we outline a pictoral evolutionary taxonomy for massive cluster formation which is analogous to the more familiar evolutionary sequence for individual stars.

The Youngest Stages of Massive Star Formation

Massive ($M > 10M_{\odot}$) stars are observed predominantly in dense clusters or OB associations. They are associated with high visual extinctions and large masses of molecular gas (Brown et al. 1999). Current theories of massive star formation are incomplete. Some propose that massive stars form by molecular cloud collapse and subsequent accretion like low-mass stars, while others require that massive stars form via mergers and accretions of stellar-mass objects in high-density ($\rho > 10^4$ star/pc^3) molecular clumps at the bottom of the cluster gravitational potential (Bonnell, Bate, & Zinnecker 1998 and refs therein). Within massive molecular star-forming complexes (e.g., W49 in the Milky Way), the youngest massive stars are seen only indirectly via thermal bremsstrahlung emission from their surrounding HII regions. These ultra-compact HII regions (UCHII) have sizes of several hundred A.U., densities of $> 10^4$ cm^{-3}, emission measures of $> 10^7$ pc cm^{-6}, visual extinctions of $A_V > 50$ mag., and typically contain 1-2 massive stars (review by Habing & Israel 1979; Wood & Churchwell 1989a; Dreher et al.1984; Wynn-Williams 1971; Becklin, Neugebauer, & Wynn-Williams, 1973). The lifetime of UCHII regions is ∼10%-15% of the lifetime of an O star (∼500,000 yr) based on the observations that 10%-15% of Galactic O stars lie obscured within dense molecular clouds (Wood & Churchwell 1989b).

Given this picture of the earliest phases of single massive stars, we might expect that the earliest phases of massive cluster formation could be modeled as a collection of several hundred UCHII regions. Identifying such objects is problematic. Many nearby galaxies contain young, massive, blue star clusters with typical ages of several Myr (see contributions by Whitmore and others in this volume), but these have been discovered predominantly at optical wavelengths, an approach which biases the current census of massive starclusters toward the least-obscured, and, therefore, older, more evolved examples (ages $\geq$2-3 Myr). Understanding of the formation and evolution of massive starclusters requires identifying objects in their formative proto-cluster stages ($\leq$ 1 Myr). These stages will be characterized by enormous visual extinctions ($A_V > 50$ mag) which mandate the use of radio–IR techniques to uncover the physics of cluster formation. Recent radio-wave studies have pinpointed the likely precursors of super starclusters still embedded in their molecular birthplaces.

A Case Study of the Blue Compact Galaxy Henize 2-10

The blue compact galaxy Henize 2-10 contains five radio sources with no optical counterparts and constant flux density over 10 year time baselines (Kobulnicky & Johnson 1999. Figure 1 (upper left) shows a Hubble Space Telescope F555W broadband image of the central 300 pc region along with a VLA 2 cm map (lower left) and an HST Hα image. The radio sources have no optical counterparts in the F555W image, but there is a good correlation between the radio map and the Hα morphologies, suggesting that the source of the radio emission is related to the ionized gas. The radio sources have inverted spectral indices between 2 cm and 6 cm ($S_\nu \propto \nu^{+0.5\pm0.3}$), consistent with an optically-thick thermal bremsstrahlung origin (upper right).

We model the spectral shape and luminosity of the observed sources as spheres of uniform-density plasma with an electron temperature of 6000 K. H II regions with radii between 3 pc and 8 pc, densities of 5000 cm^{-3}, and 500-1000 ionizing O7V stars are most consistent with the data. These high densities imply an overpressure compared to typical warm ionized medium pressures. Such HII regions should expand and become undetectable in the thermal radio continuum on timescales of 500,000 yr. Thus, is seems likely that the ages of these HII regions are very small, consistent with their heavily-obscured nature. For a typical Salpeter IMF extending from 0.5 to 100 $M_\odot$, the clusters contain 6×10^5 total stars, implying peak stellar densities of 5000 pc^{-3}.

Several other galaxies harbor UDHIIs discovered by their peculiar radio spectral index and high brightness temperature: one in NGC 5253 (Turner, Ho, & Beck 1998; Turner, Beck, & Ho 2000); six in NGC 2146 (Tarchi et al. 2000); 1-2 in NGC 4214 & Tololo 35 (Beck et al. 2000). Radio recombination line studies of suggest the presence of UDHIIs in NGC 3628 and IC 694 (Zhao et al. 1997).

Towards An Evolutionary Taxonomy for Massive Starclusters

Low Mass Stars: The evolutionary sequence of low-mass star formation has been outlined by Lada (1987) and André, Ward-Thompson & Barsony (1993). Low-mass stars begin as prestellar molecular cores, and evolve through stages (Class 0 through Class III as depicted in Figure 3) characterized by an increasing faction of infrared emission from the central star and a decreasing fraction of submillimeter emission from dust in the accretion disk.

Massive Stars: For massive stars, no clearly defined evolutionary sequence has yet been agreed upon. In Figure 3 (center column) we attempted to sketch an evolutionary sequence based on current literature. At the earliest times, massive stars begin a a collection of dense molecular cores **(1)**. Because there are theoretical problems with forming stars more massive than $\sim 10\ M_\odot$ in the collapse of a single molecular core (Bonnell et al. 1998 and refs therein), mergers among nearly-formed proto-stars are invoked to produce the most massive objects **(2)**. Once accretion or merging terminates and the massive star is formed, high-energy photons begin to ionize the surrounding molecular gas, producing an UCHII region **(3)**. UCHII regions have sizes $\leq$0.1 pc, and often exhibit cometary morphologies. The massive star hidden within an UCHII region emerges from its natal molecular cloud through the combined actions of its stellar wind, ionizing radiation, and space velocity **(4)**. Massive stars spend the latter 80% of their lifetimes visible as luminous O stars **(5)** (see review by Churchwell 1990).

Massive Star Clusters: In the case of massive starclusters (Figure 3, right column), our theoretical and observational understanding of their evolutionary phases is even less secure. Because bound massive stellar clusters contain $> few \times 10^5\ M_\odot$ of stars in a region just a few pc in size (Ho & Filippenko 1996; O'Connell, Gallagher, & Hunter 1994) they must begin with the collapse and fragmentation of exceptionally compact and massive molecular structures exceeding $10^7\ M_\odot$. We term these "Massive Molecular Aggregates" in Figure 3 **(1)**. The star formation efficiencies in massive clusters must exceed the typical values of $\sim$0.5% in Galactic SF regions (Lada 1987) and 2%–5% in M33 OB associations (Wilson & Matthews 1995) in order to form the required mass of stars from typical 10^4–$10^6\ M_\odot$ Giant Molecular Clouds. Star formation efficiencies exceeding 50% appear reasonable in some young clusters (Arp 220—Anantharamaiah et al. 2000; young Galactic clusters—Lada, Evans, & Falgarone 1997), and may also help increase the binding energy of the resultant cluster since there is less residual gas to be swept out of the gravitational potential (Adams 2000; Goodwin 1997). At the center of the gravitational potential, an aggregate of thousands of warm, massive molecular cores in a space just a few pc across provides the environment for the formation of massive stars through mergers and accretion (Bonnell et al. 1998). Such objects should be detectable as a collection of extremely compact subillimeter sources, so we term these "Massive Submillimeter Aggregates" **(2)**. These first two stages are somewhat speculative schematics predicated on extrapolation of massive molecular complexes in the Milky Way where giant molecular clouds range only from 10^4-$10^6\ M_\odot$ and have sizes from 50-100 pc (Sanders, Scoville, & Solomon 1985). To our knowledge, *there have not yet been observed any molecular structures which are sufficiently massive and compact to be identified as the likely predecessors of super starclusters.* The newly-identified class of ultra dense HII regions (UDHIIs) are the massive analogs of the more familiar single-star UCHIIs, and they represent a transition phase **(3)** between the warm molecular and massive submillimeter aggregates and the familiar UV-bright starclusters **(4, 5)**.

Unusually compact, massive ($10^7\ M_\odot$) gravitationally-bound concentrations of molecular gas and dust on size scales of 2-6 pc could signify the genesis sites of super starclusters. However, these early phases have not yet been specifically identified. Wilson et al. (2000) report the discovery of massive molecular resevoirs, termed “super giant molecular complexes”, in the Antennae merger system (NGC 4038/39) which could be the source material for the “Massive Molecular Aggregates”. Given the abundance of massive extragalactic starclusters, their predecessors, the “Massive Molecular Aggregates” and the “Massive Submillimeter Aggregates”, should be detectable in extragalactic sources with current millimeter and upcoming sub-millimeter arrays. Identification of these precursors to massive starclusters is the first step toward understanding the dynamical conditions that produce OB associations, super starclusters, and the venerable globular cluster systems.

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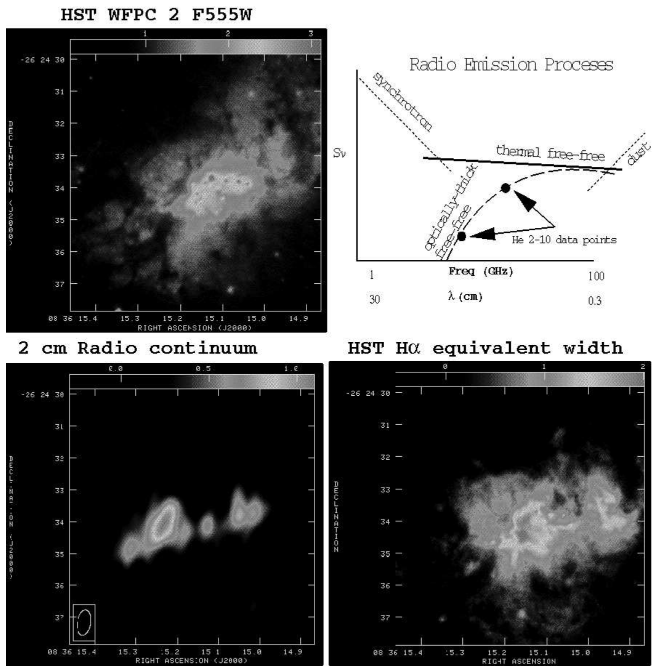

Fig. 1. Images of Henize 2-10 in optical HST F555W (top left), 2 cm radio continuum (lower left) and Hα equivalent width (lower right). The schematic at the upper right illustrates the frequency dependence of non-thermal (synchrotron emission), thermal bremsstrahlung, and optically-thick thermal bremsstrahlung emission mechanisms.

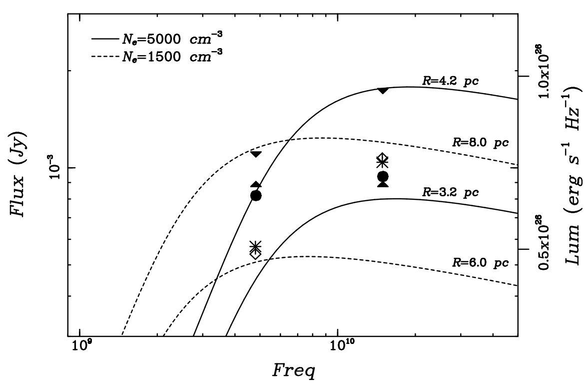

Fig. 2. VLA 6 cm (4.8 GHz) and 2 cm (14.9 GHz) fluxes and luminosities for the five radio knots in Henize 2-10. A different symbol represents data for each knot. Solid and dotted lines represent thermal bremsstrahlung plasmas modeled as spheres of radius, R, electron temperature T_e=6000 K, and mean electron densities of 1500 cm^{-3} and 5000 cm^{-3} respectively.

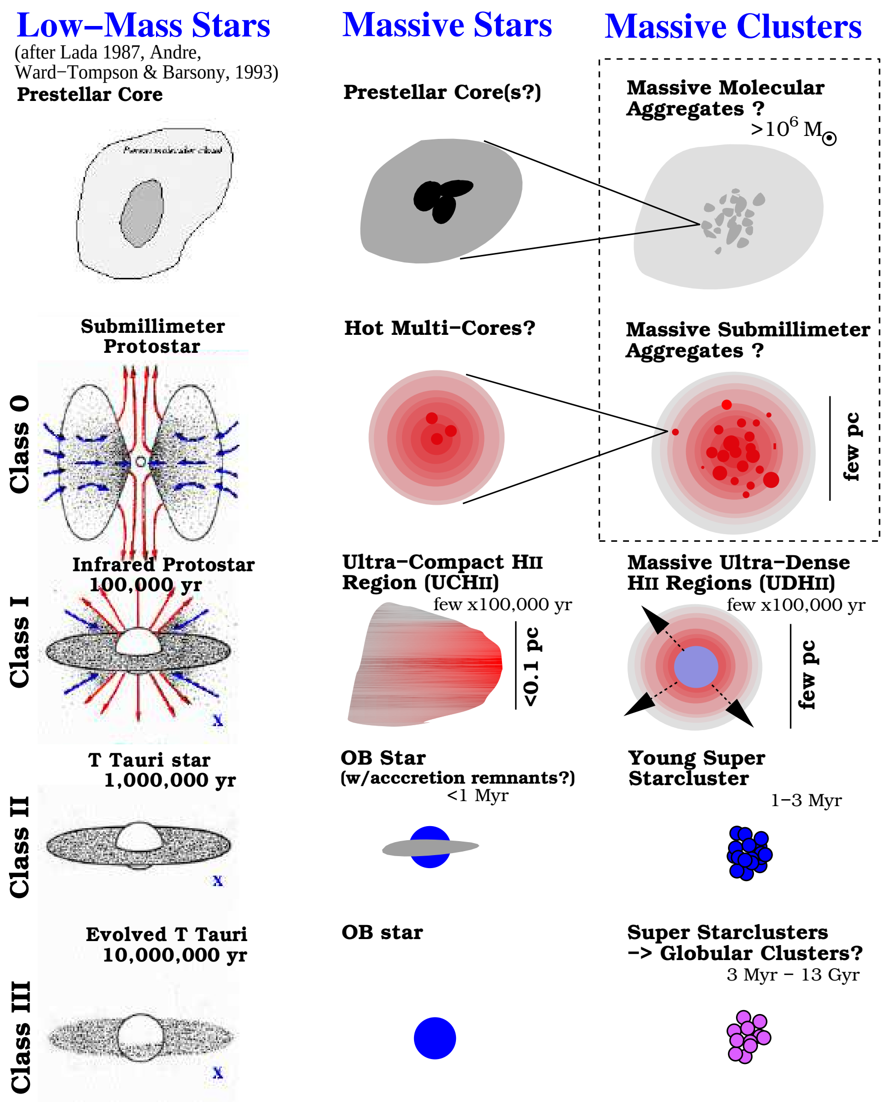

Fig. 3. A tentative, and somewhat speculative, schematic illustrating the stages of low-mass star formation (left, from Lada 1987; Andre, Ward-Thompson, & Barsony 1989), massive star formation (center) and massive cluster formation (right). Ultra-dense HII regions represent the youngest phase of massive cluster formation yet identified. Dashed lines surround phases of massive cluster formation which are speculative and have no identified examples.