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The Youngest Star-Forming Regions in Galaxies: Giant Compact HII Regions and Protoglobular Clusters?

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Abstract. Subarcsecond radio and infrared observations reveal a class of luminous, obscured, optically thick HII regions associated with extremely large young clusters in nearby starburst galaxies. VLA images show bright radio nebulae with $n_e \sim 10^4$ cm^{-3}, densities characteristic of young Galactic compact HII regions. Excitation of the nebulae requires the presence of several thousand O stars within regions of 1-10 pc extent, corresponding to clusters containing 10^5-10^6 stars. The compact nebulae are also bright in the mid-infrared, and can for significant fractions of not only the total IR luminosity, but also the total bolometric luminosity, of the parent galaxies. The prototype for these "supernebulae" is the large, obscured cluster in the dwarf galaxy NGC 5253.

1. The Formation of Super Star Clusters: The High Resolution Infrared and Radio View

One of the distinguishing characteristics of a starburst is the spatial concentration of its star formation. Star formation rates of 1-10 $M_\odot$ yr^{-1} are not unusual for a large spiral galaxy; the concentration of this star formation into a region of a few hundred parsecs extent, corresponding to a size of an OB association, is the conventional signature of the starburst.

The new generation of high resolution imaging instruments is changing the current picture of starbursts, which is based on low ($>1''$) resolution optical and infrared observations. Instruments capable of subarcsecond resolution such as Hubble and the VLA have shown that starbursts are even more spatially concentrated than previously believed. A revelation of the Hubble Space Telescope was that starbursts may be as efficient, luminous, and concentrated as they are because they are forming extremely large clusters, super star clusters, or SSCs.

How do SSCs form? These clusters, containing hundreds of thousands to millions of stars, are so very different from the types of star clusters that we see forming in the Galaxy that at present we have no idea how they might form. Finding a very young SSC might allow us to "catch" the formation of a super cluster in progress, with its natal evidence still in place.

The search for the youngest SSCs must be pursued in the infrared and radio, as is done for star-forming regions in the Galaxy. Extinctions of 1 magnitude at K band are common in starbursts, as indicated by Brackett recombination line observations (Ho, Beck, & Turner 1990). These near-IR extinctions correspond to A_V of 10 or more in the visual. It is clear that to see into the dustiest regions, infrared or radio observations are required.

In addition to the high extinctions, spatial confusion is also a problem in the study of starbursts. Super star clusters, for example, are about the size of globular clusters. The star formation sizescales in these systems are on the order of 10 pc or less. Even for the nearest galaxies (D < 10 Mpc), subarcsecond resolution is required. Infrared and radio instruments capable of this resolution are the VLA at high frequencies, the VLBA, and the new generation of 10-meter class optical telescopes such as the Keck Telescope, which can provide subarcsecond, diffraction-limited imaging in the infrared.

2. NGC 5253. A Protoglobular Cluster in Formation?

The prototype for a new class of young, presently forming super star clusters may be within the starburst in NGC 5253. A dwarf galaxy of ambiguous Hubble type (S0/I0: dwarf spheriodalish), NGC 5253 is known for its proximity to M83, and for the anomalous dust lane intruding into the nucleus along its minor axis. There is a large central starburst of $L_{IR} \sim 1.8 \times 10^8\ L_\odot$ (Beck et al. 1996) with a large and luminous Hα source (Calzetti et al. 1997).

VLA multifrequency images of the starburst at 1″ resolution revealed a complex region, largely dominated by free-free emission, but with some nonthermal synchrotron emission (Beck et al. 1996; Turner, Ho, & Beck 1998). The radio emission is dominated by a bright source of spectral index $\alpha_{2\,cm}^{6\,cm} \sim -0.1$, which is typical of free-free emission from a classical HII region such as Orion. However, there were indications of optically thick emission, such as observed in the very youngest Galactic HII regions, "compact" HII regions. Compact HII regions are extremely young, no more than a few hundred thousand years old. No compact HII region observed in the Galaxy would be detectable in NGC 5253, nor in any other Galaxy beyond the Local Group (Turner & Ho 1994.) The nature of this emission was unclear.

Subarcsecond VLA images revealed that the nebula in NGC5253 is extremely compact, 2 pc x 1 pc in extent (Figure 1). The high resolution allowed the separation of the free-free emission from surrounding diffuse nonthermal emission. The free-free emission is optically thick in NGC 5253 at 2 cm and possibly even at 1.3 cm, requiring densities of greater than $4 \times 10^4\ cm^{-3}$. The radio flux and the volume and density of the nebula require Lyman continuum fluxes of $4 \times 10^{52}\ s^{-1}$, or the equivalent of 4000 O7 stars (Turner et al. 1998, 2000). The stars must be localized to the 2 pc × 1 pc region, or else the excitation requirements become even more severe (i.e., more stars). If this cluster has a Salpeter IMF, which seems to be the case for R136 (Massey & Hunter 1998, Zinnecker 2000, pvt. comm.), then it has $\sim 10^6$ stars.

High resolution mid-infrared observations with the Long Wavelength Spectrometer (LWS) on the Keck Telescope have confirmed that this cluster does appear to be an HII region, and definitely is not a supernova remnant, and is most unlikely to be an AGN (Gorjian, Turner, & Beck 2000). The 12μm flux of 2 Jy and 18μm flux of 10 Jy are exactly what would be expected for a nebula of this radio flux, based on the IR and radio characteristics of Galactic HII

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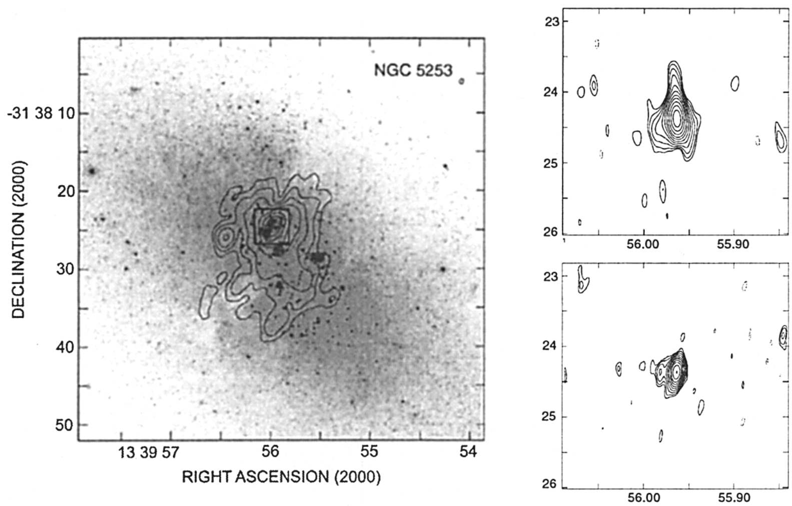

Figure 1. (Left) VLA 6 cm continuum contours (Turner et al. 1998) atop an HST photo of NGC 5253 (Calzetti et al. 1997). (Right) VLA continuum images at 2 cm (top; $0.3''$ resolution) and 1.3 cm (bottom; $0.2''$ resolution) of the central nebula (Turner et al. 2000). The maps on the right correspond approximately to the box on the larger figure.

regions. Diffraction-limited imaging shows that the mid-IR source is $<0.5''$ in size, in agreement with the radio size.

The really remarkable result of the mid-IR study of NGC 5253 is that it demonstrates how energetically dominant this source is. The compact source accounts for 80% of the 12 and 25μm IRAS fluxes of the entire galaxy. *This 2 pc $\times$ 1 pc nebula is responsible for fully one-third of the total infrared luminosity of NGC 5253, and at least a quarter of its total bolometric luminosity.*

3. Is NGC 5253 Alone? Other Possible Super Star Clusters on the Make

Another relatively nearby dwarf galaxy has revealed a nebula similar to that of NGC 5253 – perhaps even larger – but since it is twice as distant as NGC 5253, this source is more difficult to study, even at subarcsecond resolution. II Zw 40 was identified as an "extragalactic HII region" by Searle & Sargent (1972), who estimated that the source contained as many as 10^3 to 10^5 O stars, with a Lyman continuum rate of 4×10^{52} s^{-1}. Our VLA observations indicate that the actual rate is an order of magnitude higher. Although Searle and Sargent knew that this was an exceedingly luminous star-forming region, what was not known thirty years ago was just how compact this source is. Subarcsecond VLA observations reveal a double source of total extent $\sim 0.5'' \times 0.2''$, or about 25 pc $\times$ 15 pc. In spite of its great distance, the nebula still has a brightness temperature of $\sim 10^4$ K, indicating that it is optically thick over a region of roughly this extent. The number of O stars required within the 25 pc by 15 pc region is more than 16,000 – for a Salpeter IMF this could be 4 million new stars. Compact HII regions have also been detected in the dwarf galaxy He 2-10 (Kobulnicky & Johnson 1999, and Johnson, this volume.)

Are super star clusters and super nebulae restricted to dwarf galaxies? Early models of globular cluster formation suggested that they form in low metallicity systems, such as dwarf galaxies. However, SSCs have been observed in HST images of the nearby large Sbc galaxy NGC 253 (Watson et al. 1999). One might infer that it is also possible to find them in the process of actively forming, as indeed they may be in NGC 253, which has bright, compact mid-infrared knots (Pina et al. 1992, Keto et al. 1993), or in other spirals with bright, flat spectrum radio sources (Carral et al. 1990; Tarchi et al. 2000).

We have found radio and infrared evidence for compact HII regions in M83, which has a well-known nuclear starburst (Turner & Ho 1994; Telesco, Dressel, & Wolstencroft 1994). Brackett line observations suggested the presence of optically thick free-free emission, hence compact HII regions (Turner, Ho, & Beck 1987). Until recently it has been difficult to confirm this finding. With the LWS on Keck we have identified regions of high mid-infrared brightness on sizescales < 10 pc within the starburst in M83. Although the full starburst region has yet to be mapped, it would appear that "supernebulae" may be present in the starburst of this large spiral as well, in a decidedly high metallicity environment.

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