

Uncovering the Beast: Discovery of Embedded Massive Stellar Clusters in W49A¹

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ABSTRACT

We present subarcsecond J , H , and K_s images (FWHM $\sim 0.5''$) of an unbiased $5' \times 5'$ (16 pc \times 16 pc) survey of the densest region of the W49 giant molecular cloud. The observations reveal 4 massive stellar clusters (with stars as massive as $\sim 120 M_\odot$), the larger (Cluster 1) about 3 pc East of the well known Welch ring of ultra-compact H_{II} regions. Cluster 1 is a) extinguished by at least $A_V > 20$ mag of foreground (unrelated and local) extinction, b) has more than 30 magnitudes of internal inhomogeneous extinction implying that it is still deeply buried in its parental molecular cloud, and c) is powering a 6 pc diameter giant H_{II} region seen both at the NIR and radio continuum. We also identify the exciting sources of several UC H_{II} regions. The census of massive stars in W49A agrees or is slightly overabundant when compared with the number of Lyman continuum photons derived from radio observations. We argue that although the formation of the Welch ring could have been triggered by Cluster 1, the entire W49A starburst region seems to have been multi-seeded instead of resulting from a coherent trigger.

Subject headings: H_{II} regions — ISM: individual (W49A) — open clusters and associations: individual (W49A) — stars: formation

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Fig. 1.— Subset $5' \times 5'$ JHK_s color composite of our survey. North is up and East is to the left. The red, green, and blue channels are mapped logarithmically to the K_s , H , and J -band respectively. The labels identify known radio continuum sources (De Pree et al. 1997). Sources F and J2 are UCH_{II} regions in the Welch ring. The main cluster (Cluster 1) is seen NE of O3. Several candidate exciting sources of compact H_{II} regions are visible (e.g., the sources at the center of the CC, O3, W49A South H_{II} regions). Dark pillars of molecular material are seen associated with radio sources Q, and W49A South. None of W49A sources are optically visible. The coordinates of the image center are: 19:10:16.724 +09:06:11.16 (J2000).

1. Introduction

Massive stars are the main suppliers of heavy elements and energy into a galaxy’s interstellar medium (ISM), play a role in regulating star formation, and in a sense, drive galaxy evolution. Yet our knowledge of the early phases of massive stellar evolution is rather primitive, in part because objects for study are rare due to the combination of small number statistics and the rapidity with which they pass through their early stages (for a review see Churchwell (1999); Garay & Lizano (1999); Churchwell (2002)). With this in mind, the abundance of embedded massive stars in the Galactic star-forming region W49A marks it as a scientific gem.

W49A (Mezger et al. 1967) is one of the brightest Galactic giant radio H II regions ($\sim 10^7 L_\odot$), powered by the the equivalent of about 100 O7 stars (e.g., Conti & Blum (2002)). It is embedded in the densest region of a $\sim 10^6 M_\odot$ Giant Molecular Cloud (GMC) extending more than ~ 100 pc in size (Simon et al. 2001) and is the best Galactic analogue to the starburst phenomenon seen in other galaxies. The W49A star forming region lies essentially on the Galactic plane ($l = 43.17^\circ, b = +0.00^\circ$) at a distance of 11.4 ± 1.2 kpc (Gwinn et al. 1992), has ~ 40 well studied UC H_{II} regions (e.g., De Pree et al. (1997, 2000)), each associated with at least one stars earlier than approximately B3. About 12 of these radio sources are arranged in the well known Welch “ring” (Welch et al. 1987).

In an attempt to uncover the embedded stellar population in W49A we performed an unbiased $5' \times 5'$ ($16 \text{ pc} \times 16 \text{ pc}$), deep J , H , and K_s -band imaging survey centered on the densest region of the W49 GMC (Simon et al. 2001). In this Letter we present the first results of this survey, namely a previously unknown massive stellar cluster about 3 pc East of the Welch ring of ultra-compact H_{II} regions and still deeply embedded in the GMC, as well as 3 relatively smaller stellar clusters.

Fig. 2.— J (blue), K_s (green), and 3.6 cm radio continuum (red) color composite of W49A star forming region. Red only features represent radio H_{II} regions too embedded to be detected in our deep K_s image (e.g., most of the Welch ring of UC H_{II} regions). Yellow represents features seen in both the radio continuum and K_s -band, green-only sources are K_s sources too reddened to be detected at the J -band (essentially all of W49A young stellar population), while blue sources are foreground stars unrelated to the star forming region.

2. Observations and Data Reduction

The observations were taken in June 2001, with the SofI near-infrared camera on the ESO’s 3.5m New Technology Telescope (NTT) on La Silla, Chile, during a spell of good weather and exceptional seeing (FWHM $\sim 0.5''$). A set of 30 dithered images of 60 seconds each were taken in the J , H , and K_s filters. The images were combined with the DIMSUM³ package and calibrated through observations of standard stars taken right after the program observations and at similar airmasses. Photometry was performed with the DAOPHOT package in IRAF⁴. The full details of the data reduction will be given in a companion paper (Homeier & Alves 2003).

3. Results

In Figure 1 we present the composite JHK_s color image for our NTT-SofI survey. The image covers an area of $5' \times 5'$ on the sky and the red, green, and blue channels are mapped logarithmically to the K_s , H , and J -band respectively. Because most field stars are essentially colorless in the near-infrared (e.g. Alves et al. 1998) one expects the color of a star in this image to be, to first order, a qualitatively measure of the amount of extinction towards this star. Hence, all blue stars in this Figure are foreground sources to the star forming region.

In Figure 2 we present a 3.6 cm radio continuum (red), K_s (green), and J (blue) color composite of the central regions of the survey. The radio continuum data is taken from De Pree et al. (1997) and has a spatial resolution of $0.8''$, close to the spatial resolution of the NTT images. The red-only features in this image represent regions of ionized hydrogen so deeply embedded in the W49A molecular cloud that they cannot be detected in our

³DIMSUM is the Deep Infrared Mosaicing Software package developed by Peter Eisenhardt, Mark Dickinson, Adam Stanford, and John Ward.

⁴IRAF is distributed by the National Optical Astronomy Observatories

K_s –band image, e.g., the Welch ring of UC H_{II} regions with the exception of sources F and J2 (that appear in yellow in the image). Several H_{II} regions and UC H_{II} regions detected at radio continuum wavelengths are clearly detected on the K_s –band, suggesting that the K_s extended emission is dominated by hydrogen lines. The most prominent are identified in Figure 1 following De Pree et al. (1997) nomenclature. Several point sources lie prominently in the center of some of these regions (e.g., CC, O3, W49A south), are extinguished by $A_V > 24$ mags of visual extinction (see below), and are excellent candidates to the exciting sources powering these H_{II} regions (Homeier & Alves 2003).

The main feature in Figures 1 and 2 is the central 6 pc diameter H_{II} region E of the ring of radio sources, with a stellar cluster at its projected center. From here on we will refer to this cluster as Cluster 1. Note that only the North part of this 6 pc H_{II} region is visible in the JHK_s color composite, suggesting that there is a larger optical depth towards the South of Cluster 1, perhaps due to chance alignment of the embedded compact H_{II} regions (e.g., JJ, O3) in front of it.

Recently, Conti & Blum (2002) conducted a H and K –band imaging survey covering about 1.5 arcmin² roughly centered on the Welch ring, and were able to identify 2 of the exciting massive stars associated with UC H_{II} regions (sources F and J2). They also identified several candidate O stars at the edges of their image, and speculated that star formation may have begun on the periphery of the UC H_{II} concentration. Here we can clearly see that these sources are associated with Cluster 1, at the center of a giant H_{II} region in Figure 2, and with Clusters 3 and 4 to the SW.

We present in Figure 3 the spatial distribution of the detected sources as a function of $(H - K_s)$ color. In Figure 4 we present the $H - K_s$ vs. K_s Color–Magnitude diagram for our survey. The solid line represents a 1 Myr old population taken from the Geneva tracks (Lejeune & Schaerer 2001) and the slanted dotted lines represent a reddening in this diagram of $A_V = 48$ mag. The black circles represent sources likely associated with the new clusters (see Figure 3).

4. Discussion

4.1. Spatial distribution of reddened sources

Since the W49A star forming region is at a distance of 11.4 kpc, virtually on the Galactic plane, one expects a large amount of unrelated line-of-sight dust extinction to W49A, as well as dust associated with the star forming region. We will take advantage of the large amounts of dust extinction to isolate a reliable stellar population associated with W49A giant

molecular cloud. We present in Figure 3 the spatial distribution of the detected sources as a function of $(H - K_s)$ color. Starting with the bluer sources, $(H - K_s < 1 \text{ mag})$ we find a non-uniform distribution where about $\frac{2}{3}$ of the sources are found on the southern half of the field. Sources in this first bin are mainly foreground sources to the W49A star forming region, extinguished by less than about 14 magnitudes of visual extinction, and the non-uniform distribution is likely caused by an intervening cloud at a distance of about 3 kpc (cloud GRSMC 43.30-0.33, (Simon et al. 2001)). The second panel ($1 < H - K_s < 1.5 \text{ mag}$; $14 < A_V < 24 \text{ mag}$) further suggests this interpretation. We see the opposite spatial distribution with an increase in extinction and the region that in the first bin seemed under-populated is now over-populated. The majority of these stars are likely to be highly reddened stars in the background of GRSMC 43.30-0.33 but further work would have to be done to confirm this. In the third panel we clearly detect 4 clusterings of reddened sources. These make up the stellar population of W49A and some are still visible in the fourth panel where we find sources extinguished by over 32 magnitudes of visual extinction, more than half associated with the newly found clusters. The positions of these 4 clusters are given in Table 1.

4.2. Star formation in the W49A Starburst Region

Based on $H - K_s$ color and K_s magnitude, we preliminarily identify around 100 O-stars candidates associated with the W49A region, among which ~ 30 within the 6 pc diameter region defined by the ionized bubble central to our images (Cluster 1), and ~ 10 in each of the smaller clusters to the South (clusters 2, 3, and 4). We should bear in mind that due to the very high values of foreground and local (inhomogeneous) extinction we are not complete even for the most luminous stars in W49A. Nevertheless, this number compares surprisingly well with the luminosity of the entire region (about 10^{51} Lyman continuum photons emitted per second; Smith et al. 1978, Gwinn et al. 1992) or the equivalent of about 100 O7 V stars (Vacca 1994). We can now say that the census of massive stars in W49A agrees with the number of Lyman continuum photons derived from radio observations. In fact, photon leakage or absorption by dust could be operating in the W49A region, as our count of candidate O-stars (incomplete due to severe inhomogeneous extinction), added to the number of known UC H_{II} regions, gives ~ 140 stars with masses greater than $15 - 20 M_{\odot}$, suggestive perhaps of a slight overabundance of ionizing stars.

It is remarkable that the Welch ring of UCH_{II} regions is seen in projection against the edge of the giant H_{II} region powered by Cluster 1 (Figure 2). It necessarily invokes the classical triggering scenario of Elmegreen & Lada (1977) as one can easily imagine that, chronologically, the densest part of the W49A GMC collapsed to form Cluster 1, and the

combined action of stellar winds and UV radiation compressed the abundant nearby gas to the West, triggering its collapse into the Welch ring. Recent theoretical calculations (McKee & Tan 2002) suggest timescales for massive star formation of the order of $\sim 10^5$ yr which for a typical sound speed of ~ 10 kms $^{-1}$ agrees well with the crossing time in the Welch ring. However, we argue that the formation of the three smaller clusters to the South, undoubtedly associated with the burst of star formation in W49A, is unlikely to have been triggered by Cluster 1. The minimum distance (because of projection) between these less massive clusters and Cluster 1 is ~ 6 pc, which is larger than the bubble of ionized gas surrounding it, the giant central H $_{\text{II}}$ region in Figure 2. Also, given the short lifetimes of compact H $_{\text{II}}$ regions (Churchwell 1999) and the fact that they can be found almost over the entire surveyed region (e.g., the projected distance between source CC and W49A South is ~ 11 pc) suggests a multi-seeded, largely coeval, star formation episode in the W49A.

Finally, this work suggests that star formation in W49A, the most massive and youngest known star forming region in the Galaxy, began earlier and extends over a larger area than previously thought. Moreover, star formation in W49A is still ongoing (the GMC is not exhausted yet) as 6 hot cores (the precursors of UC H $_{\text{II}}$ regions) were recently found in the vicinity of the Welch ring (Wilner et al. 2001). Our results show that a considerable part of the stellar population of this Galactic starburst is accessible in the $2\mu\text{m}$ window. Further characterization of the embedded population (via H and K -band spectra and adaptive optics techniques) is called for and will surely provide much needed information on the starburst phenomenon seen across the Universe.

5. Summary

The main results can be summarized as follows:

- 1) A deep $5' \times 5'$ NIR survey of the W49 star forming region reveals the presence of a massive stellar cluster about $1'$ (3 pc in projection) to the East of the well known Welch ring

Table 1. W49A stellar clusters.

Cluster	RA (J2000)	Dec (J2000)	Assoc. radio source
1	19:10:17.5	+9:06:21	extended
2	19:10:21.9	+9:05:04	W49A South
3	19:10:11.9	+9:05:28	S
4	19:10:10.8	+9:05:14	Q

of ultra-compact H_{II} regions. About 2' (6 pc) to the Southeast of the main cluster we find a smaller cluster associated with W49S and about 2' (6 pc) to the Southwest we find two smaller clusters associated with radio continuum sources S and Q.

2) We find more than 100 O-stars candidates in the entire survey, mostly associated with the stellar clusters. We are able to identify the likely exciting sources of well known compact and ultra-compact H_{II} regions, and a companion paper will follow with these results. The census of massive stars in W49A agrees or is slightly overabundant when compared to the number of Lyman continuum photons derived from radio observations.

3) We argue that although the formation of the Welch ring of UC H_{II} regions could have been triggered by the interaction of the main cluster with the densest regions of the giant molecular cloud, the entire W49A starburst region seems to have been multi-seeded instead of resulting from a coherent trigger.

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Fig. 3.— Spatial distribution of detected sources as a function of $(H - K_s)$ color. The clusters (labeled 1, 2, 3, and 4) become apparent in the third panel (where $A_V \sim 20$ mag). The non-uniform distribution of sources in panel 1 and 2 could be due to intervening cloud GRSMC 43.30-0.33 located at a distance of ~ 3 kpc. The field showed is the same as in Figure 1.

Fig. 4.— $(H - K_s)$ vs. K_s Color-Magnitude diagram for our survey. The solid line represents a 1 Myr old population taken from the Geneva tracks (Lejeune & Schaerer 2001) and the slanted lines represent a reddening of $A_V = 4.8$ mag. The black circles identify stars likely associated with the W49A clusters. The 90% completeness limit for a star with errors less than 15% is marked as a bold grey line.

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