Star Formation in the W49A Molecular Cloud: Birth of a Massive Star Cluster

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Abstract. The W49A star-forming region is embedded in a $10^6 M_\odot$ molecular cloud, one of the most massive in our Galaxy. It has been long known as one of the most luminous radio H II regions, containing 30 – 40 compact and ultracompact H II regions and several hot cores. We have detected a previously unknown massive star cluster (Cluster 1) embedded in the W49 molecular cloud using JHK$'$s observations with SOFI+NTT. We find that the inferred mass of Cluster 1 is $1 - 2 \times 10^4 M_\odot$, and is 2 pc in projected distance from the largest grouping of ultracompact H II regions (including the Welch ring). We use the extensive line-of-sight extinction to isolate a population of objects associated with W49A, and use this sample to obtain a mass function. The slope of the derived mass function for objects associated with W49A, $-1.3 \pm 0.3$, is consistent with a Salpeter slope. About 3 pc away from the main star-forming complexes seen in near-infrared and radio observations is an $\sim 80 M_\odot$ star ionizing a compact H II region (object CC). We obtained adaptive optics imaging with NACO on the VLT of the 1.5 pc surrounding this object to search investigate the stellar initial mass function in the vicinity of a massive star. On the global molecular cloud scale in W49, massive star formation apparently did not proceed in a single concentrated burst, but in small groups, or subclusters.

1. Introduction

The W49 Giant Molecular Cloud extends more than 50 pc in diameter and weighs in at $\sim 10^6 M_\odot$ [Simon et al. 2001], the most massive in our Galaxy outside of the Galactic Center. Embedded within this cloud, W49A is one of the most luminous Galactic giant radio H II regions ($\sim 10^7 L_\odot$). The W49A star-forming region lies in the Galactic plane at a distance of $11.4 \pm 1.2$ kpc [Gwinn et al. 1992], has $\sim 40$ well studied UC III regions (e.g. DePree et al. 1997), associated with a minimum of that number of central stars earlier than B3 [1]. About 12 of these radio sources are arranged in the well known Welch “ring” [Welch et al. 1987]. A few other young Galactic clusters have a large number of massive stars, e.g., the Carina nebula (e.g. Rathborne et al. 2002), NGC 3603 (e.g. Drissen et al. 1995), and the Arches cluster (e.g. Figer et al. 2002), or are very young, e.g. NGC 3567 [Barbosa et al. 2003, Figueredo et al. 2002], W42 and W31 (e.g. Blum et al. 2001) but no other known region has a large number of massive stars in such a highly embedded and early evolutionary state. For this reason W49A is unique in our known Galaxy.

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2. Star Formation in the W49A Molecular Cloud

Our images contain many stars along the line of sight, but we can use the reddening within the Galactic disk to our advantage. We identify a stellar population associated with the W49A region by first selecting objects with $H - K_s$ colors red enough to be consistent with a distance of 11.4 kpc along the Galactic plane, estimated by assuming an exponential distribution of Galactic dust. We arrive at $A_K = 2.1$ and $H - K = 1.2$ (Rieke & Lebofsky (1985) reddening law).

To get an unbiased luminosity function for the stars associated with W49, so we select an extinction-limited sample of stars, with limits set by the extinction and completeness limits (see Homeier & Alves 2004) As the sample suffers from severe non-uniform extinction, we corrected for this effect assuming an intrinsic color of $H - K_s = 0.15$. This was chosen based on the knowledge that all stars without hot dust are intrinsically nearly colorless in the near-infrared, with $H - K_s$ ranging from 0.0 to 0.3. We expect objects associated with the W49A star-forming region to be early-type stars with intrinsic $H - K_s$ near 0.0, whereas giant stars should have intrinsic $H - K_s$ up to 0.3.

We convert the extinction-limited extinction-corrected $K_s$ luminosity function for our entire field into a mass function by transforming each magnitude bin to a mass. The relationship between mass and absolute magnitude is taken from the $4 \times 10^5$ yr isochrones of Lejeune & Schaerer (2001). We extrapolated the magnitude-mass relation to infer masses for the most luminous stars, which are more luminous than the 120 $M_\odot$ models. The error in the slope is large and there are many sources of uncertainty in our measurement, but we can say that we do not see evidence for a top-heavy IMF. We find a mass function slope of $-1.3 \pm 0.3$, which is consistent with Salpeter.

2.1. Total Stellar Mass

We estimate the total stellar mass of the W49A star cluster by counting stars with masses greater than 20 $M_\odot$ and using a Salpeter slope, with upper and lower mass limits as 120 $M_\odot$ and 1 $M_\odot$. For Cluster 1, we find 54 stars within $45''$, implying a total mass of $\sim 1 \times 10^4$ $M_\odot$. In our entire field, we count 269 stars with masses $\geq 20$ $M_\odot$, implying a total mass of $5 - 7 \times 10^4$ $M_\odot$. The stars
we have identified as massive stars are certainly contaminated by background objects, but we are also certainly incomplete in our census of massive stars due to extinction and angular resolution. Even if the stellar mass estimate for W49A is a factor of 2 too high, W49A is as or more massive than any known young Galactic star cluster. It is important to note that this is a lower limit to the final stellar mass, as there is circumstantial and direct evidence for ongoing star formation in this region. There is abundant molecular gas, and hot cores near the ring of UC HII regions (Wilner et al. 2001).

2.2. NACO observations: Low-mass star formation near a $60-80 \, \text{M}_\odot$ star and a popped bubble

We obtained $JHKsL$ adaptive optics imaging observations with NACO on the VLT of the $1' \times 1'$ (3pc×3pc) region surrounding the 'CC' object (2), which is appears to be a single (to 600 AU) massive star, $60 - 80 \, \text{M}_\odot$, ionizing a compact HII region. Our objective is to search for the occurrence of low-mass star formation in the vicinity of this high mass star. To accomplish this, we look for evidence for clustering of sources with extinction consistent with association with the W49A star-forming region. We find tentative evidence for an excess of sources within $0.5 - 1.0$ pc of the CC star, however, this is a work in progress and needs to be more carefully examined for the statistical significance.

The radius of the compact HII region surrounding the CC star is $0.1 - 0.2$ pc. Our NACO NIR images show that the HII region has broken out of the confining material on the eastern side. We detect diffuse emission extending away from the star and HII region, which is most likely due to strong nebular lines of H in the $H$ and $Ks$ passbands. This is supported by the 3.6cm radio observations by de Pree et al. (1997), in which the ionized gas shows the same morphology. This ionized emission extends over 10 times the radius of the HII region, to $\sim 1$ pc.

3. Conclusions

Some of the NIR sources associated with W49A were detected by Conti & Blum (2002), but they did not have a large enough FOV to identify a NIR cluster with the radio HII region. Our observations clearly show a massive star cluster adjacent to the UC HII regions (2 pc distant) (Alves & Homeier 2003). This means that the W49A region began forming stars earlier than previously thought, and that the ultra-compact HII regions which have been long-known to radio astronomers are not the first generation of massive stars. We use these data to estimate a total stellar mass of $5 - 7 \times 10^4 \, \text{M}_\odot$. Since molecular gas is abundant, this is a lower limit to the final stellar mass of the cluster. With these observations, W49A joins the list of Galactic giant radio HII regions with the coexistence of two or more phases of massive star formation. This means that the formation of massive stars in clusters is not completely synchronized, but there is some spread in age.

What does the core of Cluster 1 hold? Given the high internal extinction, we are certainly incomplete in our near-infrared census of star formation and therefore any mass or density estimates. The core is very crowded; high spatial resolution observations are needed. Taken at face value and without correcting for the large extinction, the cluster core appears to be significantly less dense.
than the Arches, NGC 3603, or 30 Doradus. If it is truly less dense, then the different formation environment of W49A may be an important clue for understanding the processes which drive clustered star formation.

The subclustering phenomenon is useful in describing the star formation pattern in the W49A molecular cloud. When the cloud has ceased forming stars, the resulting stellar group will likely be called a 'cluster', but at the time of current observation, the massive star formation does not appear to be distributed uniformly throughout the region, or with a radial dependence relative to a cluster 'center'. Rather it is better described as occurring in 'subclusters'. In this sense we could count 4 to 5 subclusters within ∼ 13 pc using the combined NIR and radio observations: Cluster 1, the (Welch) “ring” of UC HII regions, W49A South, the RQ complex, and perhaps the CC source. We speculate that star formation within a subcluster is essentially synchronized, and a massive star cluster is a collective of several (or many) subclusters. There is also evidence for subclustering in lower-mass star-forming regions [Lada et al. 1996, Testi et al. 2000], which can be reproduced in star formation simulations [Bonnell et al. 2003]. Possible examples of subclustering in extragalactic star clusters are: SSC-A in NGC 1569 and NGC 604 in M33. SSC-A in NGC 1569 has a stellar concentration with red super giants and another with Wolf-Rayet stars. The massive stars in NGC 604 are certainly subclustered, but the region itself is of sufficiently low density to be termed a Scaled OB Association (SOBA) rather than a star cluster [Maíz-Apellániz 2001]. The applicability of the subclustering description to other young massive Galactic star clusters remains to be seen, but we conclude that it is a useful concept to describe and understand massive star formation in W49A.

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