GUM 48d: AN EVOLVED H II REGION WITH ONGOING STAR FORMATION

J. L. Karr1, P. Manoj2, and N. Ohashi1

1 Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan
2 Department of Physics and Astronomy, University of Rochester, NY, USA

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ABSTRACT

High-mass star formation and the evolution of H II regions have a substantial impact on the morphology and star formation history of molecular clouds. The H II region Gum 48d, located in the Centaurus Arm at a distance of 3.5 kpc, is an old, well evolved H II region whose ionizing stars have moved off the main sequence. As such, it represents a phase in the evolution of H II regions that is less well studied than the earlier, more energetic, main-sequence phase. In this paper, we use multiwavelength archive data from a variety of sources to perform a detailed study of this interesting region. Morphologically, Gum 48d displays a ring-like faint H II region associated with diffuse emission from the associated photodissociation region, and is formed from part of a large, massive molecular cloud complex. There is extensive ongoing formation in the region, at scales ranging from low to high mass, which is consistent with triggered star formation scenarios. We investigate the dynamical history and evolution of this region, and conclude that the original H II region was once larger and more energetic than the faint region currently seen. The proposed history of this molecular cloud complex is one of multiple, linked generations of star formation, over a period of 10 Myr. Gum 48d differs significantly in morphology and star formation from the other H II regions in the molecular cloud; these differences are likely the result of the advanced age of the region, and its different evolutionary status.

Key words: H II regions – ISM: bubbles – stars: formation – stars: pre-main sequence

1. INTRODUCTION

High-mass star formation has a profound impact on the interstellar medium (ISM), through a combination of effects including ionizing radiation and expanding H II regions, stellar winds and supernovae. The effects and appearance of high-mass star formation vary dramatically throughout the evolution of an OB star. When a high-mass star begins burning hydrogen, it produces significant amounts of ultraviolet (UV) radiation, which immediately start to ionize the surrounding neutral and molecular gas. At very early stages, the star is still heavily embedded in its natal cloud, surrounded by a small (0.1 pc) ultracompact H II region (UCHII), and visible only at radio and infrared (IR) wavelengths. The region then expands into a classic H II region. At this phase of evolution, the OB star(s) are surrounded by a hot bubble of ionized gas, the Stromgren Sphere, initially a few parsecs in size, which due to the pressure imbalance expands into the ambient medium and compresses the surrounding molecular material.

The H II region, now several parsecs or more in size, is bright in both radio (free-free and recombination line emission) and optical (particularly Hα emission). The heating of dust grains in the vicinity of the region leads to bright emission from dust in the mid to far-IR, particularly in the photodissociation region (PDR) between the ionized and molecular gas. If the star-forming region contains multiple OB stars, the H II region can evolve into a giant H II region as individual H II regions combine to form an extended, often irregularly shaped ionized region up to 100 pc in diameter. Ongoing star formation is generally seen surrounding the H II region.

During the main-sequence phase and later the post-main-sequence phase, the ionizing stars can experience significant mass loss in the form of supersonic stellar winds. These winds expand into the already ionized H II region, creating a stellar wind bubble, and eventually deposit their mechanical energy into the surrounding ISM (Arthur 2007). In the final stages, supernova explosions from the OB stars can expand into the combined H II region/stellar wind bubble, further disrupting the remnants of the original molecular cloud (Garcia-Segura & Franco 1996).

At the very end of the H II region evolutionary sequence only the remnants of the violent disruptions of the molecular cloud remain; shells and super shells of neutral material that have been swept up through the combined effects of the H II region, stellar winds and supernova remnants (SNRs), eventually slowing down and fragmenting (Tenorio-Tagle & Bodenheimer 1988). By this point, the presence of the initial high-mass ionizing stars is inferred from the shape of the ISM, as the ionizing stars have long since progressed through the main sequence to the later stages of evolution, to supernovae, to the point where even the SNR are no longer readily observable.

The detailed effects of high-mass star formation on the ISM and on subsequent star formation activity are complex and contradictory. The expanding H II region, stellar winds and supernovae will eventually combine to disrupt the natal molecular cloud. At shorter timescales there is a significant influx of energy into the cloud, increasing turbulence as well as potentially truncating circumstellar disks. On the other hand, H II regions have long been thought to enhance star formation in molecular clouds through triggered or sequential star formation (Elmegreen 1998). The expanding H II region can compress existing overdensities in the molecular material, leading to instability and collapse; the RDI or radiatively driven implosion model (Lefloch & Lazareff 1994). Alternatively, a shell of material can be swept up around the expanding ionized region, eventually becoming unstable, fragmenting and collapsing into new stars; the collect and collapse model (Elmegreen & Lada 1977). Quantifying the effects of an H II region of the star formation rate of a region (or even attempting to “prove” a proposed example of triggered star formation), is
nontrivial, and in the case of an individual H II region often inconclusive.

The classic H II region, ionized by one or more stars, is to date the best studied of the various stages of evolution of the H II region, due to its high brightness, relatively large size and the fraction of the lifetime of an H II region spent in this phase. The UC/CHII phase is relatively short (a few $10^5$ years) compared to the classic/giant H II region phase, which is on the order of the main-sequence lifetime of the ionizing stars: approximately $1–7 \times 10^6$ years depending on the initial masses of the stars.

The shorter-lived post-main-sequence phase involves a change in the effective spectral type of the star and a corresponding drop in the total flux of ionizing photons compared to the main sequence, resulting in an extended but fainter H II region in the radio and optical. The later phases, including the SN phase, are transitory. The final remnant shell phase is longer lived but observationally elusive, due to the absence of strong ionizing radiation and the complexity of the ISM in neutral hydrogen, making the positive identification of remnant shells difficult.

The H II region Gum 48d, located in the Centaurus Arm, presents an interesting example of the post-main-sequence phase of a classic H II region. The region is ionized by a B0Ip supergiant, HR 5171B, with a companion G8 Ia supergiant, HR 5171A, a high luminosity, extremely variable star (aka V766 Cen, HD 119796), of interest in its own right (Humphreys et al. 1971; van Genderen 1992). The region was initially identified in the Gum and RCW catalogs of optical H II regions as Gum 48d and RCW 80, respectively (Gum 1955; Rodgers et al. 1960). Some subsequent studies identify it as RCW 80 (Georgelin et al. 1988; Humphreys et al. 1971; Saito et al. 2001), while others confuse it with a radio bright SNR to the south (Whiteoak & Green 1996; Rakowski et al. 2001; Green 2004). The distance to the SNR region has been variously estimated as 4 kpc, 5.4 kpc, and 7.8 kpc (Guseinov et al. 2004), and is most likely at a further distance than the H II region. For clarity we will keep the identification Gum 48d for the H II region and RCW 80 for the SNR.

In this paper, we use multiwavelength archived survey data from various sources to investigate Gum 48d. Multiwavelength archive data provide a powerful tool for the study of extended H II regions. The use of multiple wavelengths allows us to probe the different components of the ISM; from hot ionized gas to cold molecular gas to dust, as well as tracing the population of embedded stars. Archived data, on the other hand, permits the exploration of large regions of sky, and the discovery and selection of interesting H II regions which would not necessarily be readily selected for more specific, pointed observations.

In Section 2, we outline the sources and utility of the archive data used. In Section 3, we discuss the multiwavelength morphology, ionization and structure of the region. In Section 4, the star formation content at various mass scales is investigated. We then discuss the dynamic evolution and history of the region, including its local history (Section 5.1) and speculate as to the possibility of triggered star formation caused by Gum 48d (Section 5.2). Finally, the position of Gum 48d in the larger scale structure and evolution of the region is discussed in Section 5.3.

2. DATA

There are a number of archived data sets available for this region. The region was observed as part of the Spitzer GLIMPSE Legacy Survey of the inner galaxy, at 3.6, 4.8, 5.6, and 8 μm, all with a resolution of about 1/2 (Benjamin et al. 2003). All the bands except 4.8 μm contain emission features from polycyclic aromatic hydrocarbons (PAHs), large, complex interstellar molecules. PAHs absorb UV radiation and re-emit in various mid-infrared (mid-IR) spectral features. The 8 μm band, in particular, contains two of the strongest PAH features, at 7.7 and 8.6 μm. Emission from PAHs is an excellent tracer of photodissociation regions (PDRs), the interface between neutral and molecular hydrogen, as PAHs are destroyed by shock fronts in the interior of ionized regions, and are effectively shielded from UV radiation in dense molecular material. The 4.8 μm band contains a rotational line of shocked molecular hydrogen, while all four bands also contain thermal emission from small grains.

In addition to the GLIMPSE data we have used archive data from the MIPSGAL survey at 24 μm, a longer wavelength companion survey to GLIMPSE. At this wavelength, the relevant emitter is small dust grains, which may or may not correspond to the PAH morphology, depending on the physical conditions in the region; PAH emission and warm dust continuum generally coincide, but warm dust frequently exists in the absence of PAH emission.

Point-source catalogs are available for both the GLIMPSE data and the 2 Micron All Sky Survey (2MASS), the latter at J, H, and Ks (Skrutskie et al. 2006). We have performed point-source extraction on the 24 μm data archive data (which are of good quality) and combined the results with the preceding two catalogs to create 1–24 μm spectral energy distributions (SEDs) for all point sources in the region. The point-source SEDs provide an excellent tracer for young stellar objects (YSOs), due to the strong near- and mid-IR emission from protostellar disks and envelopes, and the low extinction at these wavelengths.

Optical images were obtained from the Southern H Alpha Sky Survey Atlas (SHASSA) (Gaustad et al. 2001), with a resolution of 1'. Radio continuum (1420 MHz) and line (HI 21 cm) data sets at 1' were obtained from the Southern Galactic Plane Survey (SGPS) (McClure-Griffiths et al. 2005). Both data sets trace the morphology and brightness of the ionized gas, through Hα and free–free emission, respectively. The optical data are strongly affected by extinction, unlike the radio data, and so the combination can provide a probe of three-dimensional H II region morphology.

3. GUM 48D

Figure 1 shows the large-scale structure of the region surrounding Gum 48d on a 2 deg scale; 1420 MHz emission, tracing ionized gas in H II regions and SNRs, is shown in blue, GLIMPSE 8 μm data, tracing PAH emission PDRs, is shown in green, and 24 μm MIPSGAL data, tracing warm dust, is shown in red. The contours show the location of molecular gas ($^{13}$CO($J = 1 - 0$)) in the velocity range of the Centaurus Arm, from the survey of Saito et al. (2001). Individual H II regions in the area are labeled, while the region containing Gum 48d is outlined with a box.

The emission from ionized gas is shown in Figure 2, in optical (left panel) and radio (right panel). The optical emission in Hα shows a faint, semi-circular nebulosity surrounding the central star. The central star seen in the image is HR 5171A, the high luminosity G8 Ia supergiant which dominates the optical- and mid-IR images. It is a binary star, whose companion, HR 5171B, is a much fainter B0 Ip supergiant and source of ionization for the region. The two stars have a kinematic distance of 3.9 kpc and a photometric distance of 3.5 kpc (Humphreys et al. 1971). If we place the two stars on an H-R diagram evolutionary track, using the models of Schaller et al. (1992), HR 5171A has an age of 3.5 Myr and a main-sequence mass of 60 $M_\odot$, while
HR 5171B has an age of 4 Myr and a main-sequence mass of 40 \( M_\odot \), corresponding to main-sequence spectral types of O7 and O5.5, respectively (Schaerer & de Koter 1997). This is consistent with the conclusions of van Genderen (1992). This implies that Gum 48d was once a very energetic H\( \text{\textsc{ii}} \) region, ionized by multiple massive O stars. The above studies of this region identify only two stars in this system. An inspection of the Tycho catalog shows two stars at the location of HR 5171B with similar optical magnitudes, which might indicate the possibility of an additional star. No spectral information is available to confirm this, but the ionization balance calculations shown in Section 5.1 rule out the need for an additional ionizing source. We will discuss the evolutionary history of Gum 48d in more detail in Section 5.1.

The optical morphology is mirrored in the radio data. The radio image is dominated by the SNR RCW 80 to the south-west of Gum 48d. The ionized gas of the H\( \text{\textsc{ii}} \) region has measured velocities of \(-48\) km s\(^{-1}\) (Georgelin et al. 1988), corresponding to a near kinematic distance of 4 kpc, using the galactic rotation model of Brand & Blitz (1993). This value is in good agreement with the distances to the central stars. There are five other 1420 MHz features in the region of Figure 2. Gal 309.54–0.737 is an H\( \text{\textsc{ii}} \) region with a velocity of \(-43\) km s\(^{-1}\) (Caswell et al. 1981). The other four are compact 1420 MHz sources without known velocities. G309.14–0.18 is a small but extended H\( \text{\textsc{ii}} \) region with a spectral index consistent with an H\( \text{\textsc{ii}} \) region (Caswell et al. 1992), while G309.17–0.02, G309.27–0.03, and G309.24–0.18 have no spectral index measurements. All four sources are positionally coincident with extended emission at 24 and/or 8 \( \mu \)m, as described in the following section.

3.1. Dust and Gas

In the mid-IR Gum 48d has a striking morphology, as seen in Figure 3. The main feature is an extended, bow-shaped region of reasonable thickness compared to its full extent, and centered on a bright IR point source (HR 5171A). The morphology within the region is complex and detailed on smaller scales, with significant substructure. There is a small, bright region to the very south-east of the image, corresponding to the H\( \text{\textsc{ii}} \) region Gal 309.54–0.737, as well as a number of bright, compact mid-IR features scattered along the bow-shaped region. There are also small, arc-shaped structures, most noticeably one to the east of the center of the image. Finally, there are several infrared dark clouds, seen in extinction (areas of no emission) in the 8 \( \mu \)m map, silhouetted against brighter emission, and a large number of infrared point sources.

This morphology is mirrored at 24 \( \mu \)m, as seen in Figure 4. In this image, tracing the location of warm dust, the substructure and compact features are even more prominent than at 8 \( \mu \)m.
The locations of the compact features (discussed more fully in Sections 4.1 and 4.2) are marked in Figure 4. Several of the IR dark clouds persist at 24 μm, while others are now seen in emission. There are two saturated regions in the 24 μm image, one corresponding to HR 5171B (the central region) and one to the asymptotic giant branch star GLMP 363, to the southwest. Post-main-sequence stars are often extremely bright in the mid-IR, due to the presence of surrounding dust.

Saito et al. (2001) conducted 13CO(J = 1 − 0) observations of this region, identifying an extensive molecular cloud at velocities corresponding to the Centaurus Arm of the galaxy and a kinematic distance of 3.2−5.5 kpc, with a total mass of 2.3 × 10^6 M⊙, an extremely massive molecular complex. The whole molecular cloud observed by Saito et al. (2001) is shown in Figure 1. The molecular cloud forms an extensive “ridge” perpendicular to the Galactic plane and with a physical extent of 80 pc. This molecular ridge curves slightly, and Gum 48d is located at its inner edge.

Saito et al. (2001) also carried out C18O(J = 1 − 0) observations in the same region to investigate more detailed structures of the molecular cloud, identifying several dense molecular cores. The locations of the C18O molecular cores are marked in Figure 3: diamonds mark the location of cores with velocities corresponding to Gum 48d, crosses mark cores at more negative velocities. The C18O is arrayed around the edge of the 8 μm PAH emission, outside of the emission from the ionized gas, with velocities ranging from −40.6 to −50.2 km s^{-1}. This demonstrates that the bulk of the 8 μm emission occurs at the interface between the ionized region and the molecular cloud. In addition, it can readily be seen that the locations of the IR dark clouds are coincident with the positions of the C18O dense cores. These infrared dark clouds are very dense, often filamentary clouds of molecular material that are optically thick in the mid-IR (Carey et al., 1998), and are sometimes associated with highly embedded, very young protostars. We note that the smaller arclike 8 μm feature located at 309.4−0.37 is associated with molecular gas at −60 km s^{-1}. This region is either not physically associated with Gum 48d, or it is located at the front of the H II region cavity, and is moving toward us with respect to the central velocity of the ionized gas.

The H II region Gal 309.54−0.737 is associated with a molecular cloud at −52.6 km s^{-1}. Its morphology at 24 and 8 μm, when compared with the 1420 MHz emission and location of the molecular cloud, is indicative of a compact blister H II region, sharply bounded to the south east and venting to the northwest. The region shows a strong alignment between the location of the emission of ionized gas and mid-IR emission from dust. The nebula is only very faintly seen in the optical, at the unbounded northwest edge, corresponding to the fainter radio emission of the venting gas.

The other four compact H II features are all associated with features at 24 and 8 μm. G309.14−0.18 is associated with an IR dark cloud at 8 μm, but with clumpy emission at 24 μm, brighter to the western edge (denoted S10 in Figure 4). G309.17−0.02 is associated with compact emission at both 24 and 8 μm (denoted S11 in Figure 4), while G309.27−0.03 is associated with compact emission at only 24 μm (denoted S12 in Figure 4). G309.24−0.18 is located near an arclike structure at 8 μm and faint interior emission at 24 μm (denoted S4 in Figure 4). The molecular emission components are not well aligned, however, and most likely are the result of a coincidental projection onto G309.24−0.18.

The velocities of the molecular material are consistent with the published values for the ionized material, and have kinematic distances consistent with the photometric distance of the ionizing star. That, combined with the morphological correspondence between the dust, molecular and ionized emission, indicates that all observed components of the region are located at a distance of 3.5 kpc and are physically associated with each other.

### 4. STAR FORMATION

Gum 48d shows extensive, ongoing star formation over a range of masses. Low- and intermediate-mass star formation
is well traced in the near to mid-IR, with several methods of identifying young stars based on IR photometry available. The first is by color; at IRAC wavelengths young stars show redder colors, with more embedded sources being progressively redder (Allen et al. 2004). At these wavelengths, extinction is minimal and shows little variations with wavelength (Indebetouw et al. 2005). A complementary technique is the measurement of the mid-IR spectral slope, $\alpha$, using the definitions of Adams et al. (1988). Sources with rising mid-IR slopes are identified as Class I sources, young stars still heavily embedded in their molecular envelope. Those with negative slopes that are shallower than photospheric emission are Class II sources (Classical T-Tauri and Herbig Ae/Be stars), which are less embedded but still have a significant circumstellar disk, and possibly remnant envelope. An additional category, flat-spectrum sources, straddles the boundary between the two. The even younger Class 0 sources, are not well identified by this method, due to the extreme extinction at shorter wavelengths.

There are a total of 48,411 2MASS sources, 39,176 GLIMPSE catalog sources and 517 extracted MIPS 24 $\mu$m sources in the region shown in Figure 3. The three catalogs were combined to produce a single band merged catalog; this final catalog contains 76,696 sources. Of these, 12,670 have sufficient fluxes for an IRAC color–color diagram (i.e. fluxes are measured in all four IRAC bands). The IRAC color–color diagram is shown in Figure 5. The sources at 0, 0 are photospheric SEDs, with more embedded (redder) sources occurring to the upper right.

We also calculate the mid-IR spectral slopes for all sources with photometry in at least four bands between 2MASS $K_s$ and IRAC 8 $\mu$m (21,284 sources), and identify Class I, flat-spectrum and Class II sources, for a total of 1827 sources. The classification based on the mid-IR SED slope is, in general, very well correlated with the classification via IRAC colors, however the method is more robust in the presence of a missing IRAC flux. Figure 6 shows the distribution of young stars identified above over the region. In the upper panel Class I sources are marked with crosses and flat-spectrum sources with diamonds, shown over the IRAC 8 $\mu$m image and tracing the most embedded phase of star formation. In the lower panel the location of Class II sources are shown with triangles.

There are several sources of contamination in this method for identifying potential YSOs; foreground and background galactic

Figure 3. Gum 48d at 8 $\mu$m (left) tracing PAH emission. The positions of molecular clouds at velocities ranging from $-36$ to $-64$ km s$^{-1}$ (the velocity of the Centaurus Arm) are marked, as listed in Saito et al. (2001). The diamonds indicate material in the velocity range of Gum 48d, and crosses those clouds at slightly higher velocities. The IR dark clouds can be seen as regions of no emission at 8 $\mu$m, here seen as light patches against the diffuse emission.
and extragalactic sources. The high levels of extended emission in the mid-IR minimizes the contamination by faint background sources, either galactic or extragalactic, as the detection limits at 24 and 8 μm are generally limited by background levels rather than sensitivity to the point-source flux. Unresolved star-forming galaxies have IRAC colors indistinguishable from young stars; however, the location of this region in the Galactic plane, combined with the low flux of many of these sources, minimizes this contamination. For comparison, we took a nearby region in the sky, of similar galactic latitude, without an H II region in either the optical or radio, and without bright features in the mid-IR, and determined the number of sources with YSO colors. This gives us an estimate of the line of sight contamination of sources. The region from $l = 309.56$ to 310 and $l = -0.273$ to $-0.705$ was the largest potential region; if we scale the YSO counts to match the angular size of the Figure 6 the expected contributions from line of sight contaminants are 2%, 14%, and 29% for Class I, flat-spectrum and Class II sources, respectively.

At the distance of Gum 48d the 2MASS fluxes are of limited usefulness, due to the typical limiting magnitude of the survey. Only the brightest and/or reddest of the young stars at 3.5 kpc will be detected, due to both the intrinsic luminosity and the high extinction in the Galactic plane. The IRAC and MIPS data are considerably more sensitive to objects with the SEDs of YSOs and are much less affected by extinction. $K_s$ band fluxes are the most commonly detected, and are useful for the calculation of the spectral slope in cases where one of the IRAC fluxes is missing.

In this region the Class II sources are primarily correlated with the large molecular ridge, indicating ongoing star formation throughout the cloud, even though Class II sources have a higher level of contamination through background or foreground sources. The more heavily embedded Class I and flat-spectrum sources, however, are more strongly clustered. There are several clusters or small aggregates of very embedded young stars, many of which are associated with dense cores identified in $^{13}$CO($J = 1 - 0$). The locations of the clusters, determined by eye, are marked in the first panel of Figure 6. A cluster at 309.42–0.64 is associated with a molecular clump with a velocity of $-42.4$ km s$^{-1}$, one at 309.53–0.75 with central velocity of $-52.6$ km s$^{-1}$, one at 309.22–0.47 with a clump with a central velocity of $-40.6$ km s$^{-1}$, and at 309.14–0.19 with material at $-46.4$ km s$^{-1}$. A cluster at 309.38–0.14 is associated both with a molecular clump with a velocity of $-50.5$ km s$^{-1}$ and with a maser (a star formation tracer) at $-50$ km s$^{-1}$ (Caswell et al.)
All of these velocities are consistent with the velocities of the H II region and its constituent components. A final cluster at 309.54−0.12 is not associated with a high-density region, although it is superposed on extended 13CO emission. From this distribution it is apparent that star formation is continuing throughout the molecular ridge, and that the most embedded phases of star formation are preferentially occurring in the densest molecular gas; many of these clusters are also associated with IR dark clouds.

Age estimates of young stars are difficult to derive, as stars of different masses evolve at different rates, and even stars of similar masses can show a range of different spectral slopes for a given age, due in part to the effects of orientation (Robitaille et al. 2007). The general consensus, however, is that rising and flat-spectrum sources are, on average, a younger and more embedded phase of star formation (Allen et al. 2004). Thus, the younger population of young stars is more highly clustered than the older population.

**4.1. Intermediate-Mass Star Formation**

In addition to the IRAC point sources tracing primarily low- and intermediate-mass star formation, there is evidence for ongoing star formation at higher masses. There are a number of IR features throughout this region, which share the common properties of being bright, compact (less than a few arcseconds) and clearly non-point sources while at the same time not being diffuse. Some of the sources are associated with emission from ionized gas, while others are not. We will divide the sample into two groups; intermediate- and high-mass star formation, based on the absence or presence of emission from ionized gas. Intermediate mass star formation is discussed below, while high-mass star formation is discussed in Section 4.2.

The first sample of IR sources shows compact but distinctly non-pointlike morphology at 24 μm, and compact but structured morphology at 8 μm. Figure 7 shows a gallery of these sources, while Table 1 lists the positions, angular sizes, physical sizes (assuming a distance of 3.5 kpc) and 8 and 24 μm fluxes. The 24 μm flux is in general smoothly distributed, even considering the larger 24 μm point-spread function (PSF), but occupies the same physical extent as the more structured 8 μm emission. To confirm this, we convolved the 8 μm data with the 24 μm PSF for comparison. These sources do not show an obvious 24 or 8 μm embedded point source, and show no evidence of compact or pointlike 1420 MHz emission at the sensitivity of the SGPS survey. The diameters of the sources range from 0.5–2 pc.

A possible explanation for these sources is that they are enshrouded intermediate-mass stars (Fuente et al. 1998, 2002; Roger & Dewdney 1992; Díaz-Miller et al. 1998). The lack of
Figure 6. Gum 48d shown at 8 μm with star formation overlayed. Upper panel: class I sources: crosses, Flat-spectrum: diamonds, with the location of clusters marked. Lower panel: class II sources marked with triangles.

radio continuum emission associated with these sources argues against the presence of an UCHII region and therefore rules out the presence of stars earlier than type B1, as a UCHII region around more massive stars at this distance would be visible at the sensitivity of the radio data. On the other hand, bright, extended 8 μm emission is often indicative of a photodissociation region, which can be created by sub-Lyman UV radiation. The 24 μm emission traces warm, small grained dust, which can also be heated by sub-Lyman photons. Intermediate mass stars of type later that B1 could satisfy these irradiation conditions, while stars lower in mass than B8 would not provide enough UV radiation to illuminated a strong PDR. The lack of a clearly defined point source within the region could be due to sensitivity, extinction, or the high level of mid-IR emission making point sources difficult to detangle from the structured, extended emission, a particular problem at 24 μm.

Although there are no distinguishable point sources within the compact features, there is a spatial correlation between the compact features and the embedded young stars, which strengthens the claim that they are associated with ongoing star formation. Sources S7 and S8 are associated with a small aggregate of deeply embedded sources, as well as a maser source, while S3 is at the edge of another small aggregate. Sources S5 and S6 are associated with the star formation at the inner edge of the HII region, and S1 and S2 are associated with another concentration of embedded star formation. Source S9 is located near the heavily embedded star formation of Gal 309.54−0.737, as well as a small cluster of highly embedded sources. These positional coincidences indicate that these sources are physically related to star formation in this region; they are unlikely to be fore or background projections.

Kerton (2002) identified 165 potential candidates similar to those described above based on CO data in the Canadian Galactic Plane Survey and Midcourse Space Experiment (MSX) 8 μm survey data, with a limiting distance of 2 kpc, indicating that these might not be particularly rare objects. The objects shown here are of comparable size (1−2 pc in diameter) to the objects in the MSX sample, albeit of smaller angular size. We computed IRAS luminosities and colors for those sources with IRAS counterparts (S1, S2, S3, S7, S8, S10, and S11), as tabulated in Table 1. The luminosities, sizes, and colors are all within the range found by Kerton (2002). We attempted to duplicate the HI velocity analysis performed therein, but did not have sufficient spatial resolution in the 21 cm data to reach a conclusion. The SGPS data are of similar resolution to the previous study, but the sources are more distant by a factor of at least two than those sources.

It should be noted that at a distance of 3.5 kpc a B0 star would be expected to have a visual magnitude of at least 14.7, and a B5 star 18.0, using the standard value of 1.6 magnitude of extinction per kpc in the Galactic plane. The actual magnitude of an enshrouded B star could be much greater due to the high-density cocoon of material. Therefore, we are unlikely to detect an enshrouded B star at this distance in the available survey data. High-sensitivity near-IR observations could provide a probe of the embedded B star and potential lower mass cluster.

Sources S7 and S8 show a particularly interesting morphology; a vaguely bipolar structure (two lobed) with several deeply embedded sources (24 μm bright) in between. The morphology is reminiscent of a bipolar outflow with a wide opening angle. The SEDs and 8 and 24 μm morphologies are similar of those of the other compact sources which have been identified as possible enshrouded B stars. This might be an outflow near an enshrouded star, or could possible be a pair of enshrouded B stars in a cluster of young stars. The lack of bright IRAC Band 2 data (tracing molecular shocks) argues against the first option, as do the SEDs. Therefore, these are most likely to be enshrouded B stars.

It is worth considering the likelihood of observing an intermediate-mass B star in this phase, as these are not widely observed objects. Estimates of the ages of this class of objects vary; however, consensus is that they are less than 10^6 years old (Fuente et al. 1998, 2002; Roger & Dewdney 1992; Díaz-Miller et al. 1998). The general lack of associated masers indicates a rel-
Figure 7. Gallery of compact features, shown at 8 μm (grayscale) tracing PAH emission and 24 μm (contour) tracing warm dust. The source numbers are labeled.
atively evolved status (Kerton 2002). This is a longer timescale than the typical estimated ages of UCHII regions (up to a few 10^7 years), a much better studied class of object. A young, enshrouded B star would not be identified through radio surveys, the typical method of discovery for UCHII regions, and mid-IR data suitable for a general search have only recently become generally available. Furthermore, an enshrouded B star would only be detected with this morphology under the right conditions. In a lower-density environment the B star could more easily break out of its cocoon, while in the close presence of ionizing stars the observational signature of the B star would be overwhelmed. Therefore, the relative lack of previous studies of these objects is likely the result of both the difficulty of detecting them in previously available data and the combination of factors required to make them detectable in the IR.

4.2. High-Mass Star Formation

There is further evidence for ongoing high-mass star formation in this region, as traced by emission from ionized gas. The IR morphologies of the high-mass star formation candidates are shown in Figure 8 (S9, S10, S11, and S12; see also Table 1), while the H\(\text{II}\) regions themselves are labeled in Figure 2, with additional information in Table 1. In general, the high-mass star formation candidates show more extended emission in the IR than the intermediate-mass candidates. The first source, S10, is associated with the H\(\text{II}\) region, G309.14—0.18 which coincides with an IR-dark cloud at 8 \(\mu\)m, a bright arc along the west side and bright, clumpy emission (including several bright point sources) at 24 \(\mu\)m. The IR-dark cloud is associated with one of the C\(^{18}\)O clumps observed by Saito et al. (2001), with a velocity of \(-46.4 \text{ km s}^{-1}\) and with a cluster of embedded young stars, as discussed above. The 1420 MHz radio emission has a spectral index consistent with an H\(\text{II}\) region and is resolved in the 1\(^{\prime}\) resolution SGPS data. The ionizing star is not known and is undetectable at optical- or mid-IR wavelengths due to the high foreground extinction.

To the south of Gum 48d there is another high-mass star formation region, Gal 309.54—0.737, a blister H\(\text{II}\) region. This H\(\text{II}\) region is clearly identified as an H\(\text{II}\) region by its spectral index, although the ionizing star is not seen due to high extinction. The velocity of the C\(^{18}\)O emission associated with this region (\(-52.6 \text{ km s}^{-1}\)) corresponds to the Centaurus Arm, although Saito et al. (2001) place it at the far kinematic distance, based on the lack of associated optical emission. However, the region is actually visible in the H\(\alpha\) data in the northwest (corresponding with the direction of the champagne flow), although it is extremely faint. Therefore, it is likely that the faintness of the region in the optical is due to strong local extinction, rather than the region being at a significantly larger distance than the other H\(\text{II}\) regions in the area.

Though the ionizing stars associated with these two compact H\(\text{II}\) regions are unknown, we can use the 1420 MHz flux to estimate the spectral type of the star required to produce the ionizing flux necessary to maintain the observed free–free emission, using the radio free–free spectral luminosity

\[
\frac{N_{\text{flu}}}{s^{-1}} \approx 6.3 \times 10^{52} \left(\frac{T_e}{10^4 \text{ K}}\right)^{-0.45} \left(\frac{v}{10^8 \text{ Hz}}\right)^{0.1} \left(\frac{L_v}{10^{20} \text{ W Hz}^{-1}}\right)^{-1},
\]

where \(N_{\text{flu}}\) is the flux of ionizing photons, \(T_e\) is the electron temperature, and \(L_v\) is the observed luminosity at frequency \(v\). This calculation has several uncertainties. It assumes ionization equilibrium. The calculated value will be a lower limit, as a matter bounded H\(\text{II}\) region will leak ionizing flux into the surrounding lower-density medium. In addition, the ionizing flux could be the result of multiple, lower mass stars rather than a single, higher-mass star. Gal 309.54—0.737 has a background subtracted flux of 1.6 Jy at 1420 MHz, a distance of 3.5 kpc and an electron temperature of 5900 K (Caswell & Haynes 1987). These values give a Lyman flux of \(1.5 \times 10^{44}\), corresponding to a main-sequence spectral type of B0.5 (Vacca et al. 1996). The calculated Lyman flux of G309.14—0.08 is below the model values for OB stars, indicative of its young age. This implies that these H\(\text{II}\) regions are ionized by single stars, unless significant ionizing flux is escaping from these regions. This is unlikely due to the extremely dense surrounding material.

There are two further H\(\text{II}\) regions with mid-IR counterparts. The compact H\(\text{II}\) regions G309.17—0.02 is associated with a compact feature at 8 and 24 \(\mu\)m (S11) and is morphologically similar to the B star candidates, but its spectral index and velocity are not known. The region at G309.27—0.03 is associated with compact emission at 24 \(\mu\)m only (S12), although there is a faint arclike 8 \(\mu\)m feature at its edge.

To summarize the star-forming properties of this region:

1. There is extensive, ongoing, low-mass star formation associated with the molecular material surrounding Gum 48d.
2. The more embedded and younger phases of star formation are more strongly clustered than the more evolved Class II sources, and are strongly correlated with the densest molecular material.
3. There is evidence for intermediate-mass star formation, in the form of potential enshrouded B1-B8 stars. These
Figure 8. Compact features associated with emission from ionized gas. Grayscale: 8 μm PAH emission; contour: 1420 MHz emission. The source numbers are labeled.
Figure 9. Schematic diagram of the history of Gum 48d. (a) $\approx 10$ Myr ago: a giant H\textsc{ii} region ionized by multiple OB stars creates a shell as it expands into giant molecular cloud, (b) $\approx 4$ Myr ago: the giant H\textsc{ii} region has consumed much of the cloud and has accelerated the surrounding molecular material. HR 5171A and B have formed at the periphery, in the surrounding shell, and have produced their own H\textsc{ii} and B0 Ip post-main-sequence star. This is the remnant of the more energetic H\textsc{ii} region.

1. There are several possible explanations for the discrepancy between the calculated value for the density and physically plausible values. One scenario is a blow-out: if the H\textsc{ii} region breaks out of the ambient material into a lower-density region, a champagne flow will occur. This will slow the expansion of the H\textsc{ii} region into the denser medium (Tenorio-Tagle 1979).

2. How much did Gum 48d extend into the surrounding ambient material when the two ionizing stars were in the main-sequence phase? The expansion of an H\textsc{ii} region into a uniform density ambient medium can be simply described by the model of Dyson & Williams (1997), in which

$$R = 4.5 \left( \frac{N_{\text{Ly}}}{10^{49} \text{s}^{-1}} \right)^{1/7} \left( \frac{n}{10^3 \text{cm}^{-3}} \right)^{-2/7} \left( \frac{t}{\text{Myr}} \right)^{4/7}$$

where $R$ is the radius of the H\textsc{ii} region, $N$ is the flux of ionizing photons, $n$ is the ambient density of the surrounding material, and $t$ is the timescale of the expansion, which should be equivalent to the age of the ionizing star. Based on the main-sequence masses and spectral types of HR 5171A and B, estimated using an H-R diagram in Section 3, the timescale of the expansion and the ionizing flux during the main-sequence phase are 3.8 Myr and $1.1 \times 10^{50}$ photons s$^{-1}$, respectively. If we assume that the radius of Gum 48d during its main-sequence phase is the same as its current size, 8.4 pc measured from the radio free–free emission at 1420 MHz, the estimated ambient density of the original molecular cloud is $5.7 \times 10^3$ cm$^{-3}$, an unreasonably high value for a molecular cloud. For comparison, the average density of the current molecular ridge is 500 cm$^{-3}$, estimated from its averaged column density, $1.9 \times 10^{22}$ cm$^{-2}$ (Saito et al. 2001), assuming that the molecular ridge is of a similar physical scale along the line of sight as it is in width.

3. Sources are also correlated with the location of molecular material and low-mass star formation.

4. There are five UC-small H\textsc{ii} regions in the area, indicating high-mass star formation. Four of them are positively identified with either a cluster of embedded young stars, or molecular material at Centaurus arm velocities, indicating a physical association with Gum 48d.

5. DISCUSSION

In the following discussion, we attempt to describe the dynamical and star formation history of Gum 48d, and its place in the large-scale structure and history of the Centaurus arm region. In Section 5.1, we describe the dynamical history of Gum 48d, using known physical parameters, and compare it with values predicted by models for the expansion of an H\textsc{ii} region. In Section 5.2, the proposed history and the current observed star formation activity are compared to evaluate the region in the context of triggered star formation. Finally, in Section 5.3, Gum 48d is compared with other H\textsc{ii} regions in the area, and its place in the large-scale structure and star formation history of the Centaurus arm is analyzed.

5.1. History of Gum 48d

In this subsection, we attempt to describe the history of Gum 48d, illustrated in panels (a)–(d) in Figure 9. We then discuss Gum 48d’s atypical appearance when compared to other nearby H\textsc{ii} regions in the context of this history.

As briefly discussed in Section 3, Gum 48d is currently ionized by HR 5171B, a B0 Ip post-main-sequence star. This is fully consistent with a spectral type estimation of the ionizing star using Equation (1) and the 1420 MHz radio flux of Gum 48d. We should note, however, that the duration of the post-main-sequence phase is short compared to the main-sequence lifetime of the ionizing stars, suggesting that the dynamical evolution of Gum 48d and its expansion into the surrounding ambient material will have been mostly determined when HR 5171 B and its companion, HR 5171A, were in the main-sequence phase, with spectral type of O5.5 and O7, respectively (see Section 3).

How much did Gum 48d extend into the surrounding ambient material when the two ionizing stars were in the main-sequence phase? The expansion of an H\textsc{ii} region into a uniform density ambient medium can be simply described by the model of Dyson & Williams (1997), in which

$$R = 4.5 \left( \frac{N_{\text{Ly}}}{10^{49} \text{s}^{-1}} \right)^{1/7} \left( \frac{n}{10^3 \text{cm}^{-3}} \right)^{-2/7} \left( \frac{t}{\text{Myr}} \right)^{4/7}$$

where $R$ is the radius of the H\textsc{ii} region, $N$ is the flux of ionizing photons, $n$ is the ambient density of the surrounding material, and $t$ is the timescale of the expansion, which should be equivalent to the age of the ionizing star. Based on the main-sequence masses and spectral types of HR 5171A and B, estimated using an H-R diagram in Section 3, the timescale of the expansion and the ionizing flux during the main-sequence phase are 3.8 Myr and $1.1 \times 10^{50}$ photons s$^{-1}$, respectively. If we assume that the radius of Gum 48d during its main-sequence phase is the same as its current size, 8.4 pc measured from the radio free–free emission at 1420 MHz, the estimated ambient density of the original molecular cloud is $5.7 \times 10^3$ cm$^{-3}$, an unreasonably high value for a molecular cloud. For comparison, the average density of the current molecular ridge is 500 cm$^{-3}$, estimated from its averaged column density, $1.9 \times 10^{22}$ cm$^{-2}$ (Saito et al. 2001), assuming that the molecular ridge is of a similar physical scale along the line of sight as it is in width.

There are several possible explanations for the discrepancy between the calculated value for the density and physically plausible values. One scenario is a blow-out: if the H\textsc{ii} region breaks out of the ambient material into a lower-density region, a champagne flow will occur. This will slow the expansion of the H\textsc{ii} region into the denser medium (Tenorio-Tagle 1979). Another possibility is that the H\textsc{ii} region created during its main-sequence phase was larger than the currently ionized region. This makes more sense physically because the difference between the ionizing fluxes during the main-sequence and post-main-sequence phases is substantial, and we would expect a more energetic H\textsc{ii} region in the past. For example, the W5–West H\textsc{ii} region, with an ionizing flux half that of Gum 48d during its main-sequence phase, has a current radius of 35 pc (Karr & Martin 2003). Similarly, the wind-blown bubble models of Arthur (2007) for a 40 solar mass star predict a final radius at the end of the stellar wind phase of on order of 30 pc.

How do we recognize the maximum size of Gum 48d during the main-sequence phase? One potential way is to use the PAH emission at 8 $\mu$m arising from the PDR region, which occurs at the interface between the molecular and neutral gas, and can be excited by sub-Lyman UV photons. Consequently, it is a better tracer of the edge of the molecular shell than the emission from ionized gas. The material surrounding the H\textsc{ii} region forms a roughly semi-circular shell, illuminated by the PAH emission. The molecular ridge is significantly larger in scale than the PAH shell around Gum 48d, as is indicated in panel (d) of Figure 9.

The recombination timescale for ionized hydrogen is approximately $10^4/n$ years, where $n$ is the number density of the gas.
The timescale for the formation of molecular hydrogen from atomic hydrogen is approximately $10^9$ yr (Tielens & Hollenbach 1985). For a typical H II region density of $10^{-3}$ cm$^{-3}$ this corresponds to $10^4$ and $10^8$ years, respectively. Therefore, in the time since HR 5171B has left the main sequence and the ionizing flux has dropped, there has been sufficient time for the ionized region to recombine into atomic hydrogen, but not to re-form molecular hydrogen, leaving an extended neutral envelope around the current H II region.

If we take this PAH shell as the boundary of the original H II region, the radius of the H II region is roughly estimated to be $15$ pc when measured across the carved out semi-shell. The ambient density calculated via the model above is now $840$ cm$^{-3}$, approaching physically plausible values. It should be noted that the H II region is not spherically symmetric, and the radius estimated changes somewhat with the assumed geometry of the H II region. The assumed shape and center of the PAH shell were chosen as an intermediate estimate of the size of the partial shell.

The current structure and appearance of Gum 48d, therefore, seem to be the result of its evolutionary status. The shape of the surrounding molecular/neutral material is dominated by the large-scale structure of the molecular ridge and the actions of the energetic main-sequence phase, while the current ionization state is the product of the post-main-sequence star, HR 5171B. Gum 48d differs significantly in appearance when compared with nearby, more typical H II regions, where the ionized region borders directly on a bright PDR (as discussed further in Section 5.3). Unlike these regions, the PDR and the edge of the ionized regions are not congruent in Gum 48d, and the PDR is fainter and more diffuse.

### 5.2. Triggered Star Formation

When studying H II regions and ongoing star formation, the question of triggered star formation inevitably arises. Is the ongoing star formation a consequence of the effects of the expanding H II region on the surrounding ISM? Proving this conclusively is problematic at best. Typical methods involve “not disproving” the hypothesis, often by assembling a consistent time line for the different phases of star formation.

The best case for triggered star formation in this region, given its age and morphology, is the collect and collapse model, where the expanding H II region compresses the surrounding material and sweeps up a shell of dense gas. At some point, the dense shell becomes unstable, fragments, and collapses to form stars (Elmegreen & Lada 1977). In order for a region to be consistent with a triggered star formation scenario, the time from the formation of the ionizing star and turning on of the associated H II region to the gravitational instability and fragmentation of the swept up shell, plus the age of the putatively triggered star formation population must be comparable to the total age of the region.

As discussed earlier, the age of Gum 48d is $\approx 4$ Myr, based on the ages of the ionizing stars. The age of the YSO population is not easily calculated, and it is not possible to perform such a calculation from the mid-IR SEDs alone. However, a typical age for embedded low-mass YSOs is on the order of or less than 1 Myr. It is difficult to assign a precise age for the embedded B star phase of intermediate-mass star formation, but their lifespan is estimated at less than 1 Myr (Dewdney et al. 1991; Roger & Dewdney 1992). The age of UCHII regions are also not well understood, largely due to uncertainties in modeling the early stage of expansion, but they are a similarly young phase of star formation (a few times $10^5$ years; Garcia-Segura & Franco 1996). To summarize, the ages of the various populations of young stars at different masses are on order of 1 Myr or less.

This leaves the epoch of the fragmentation of the shell to be determined. This can be estimated via a simple analytical model. Following the equations of Whitworth et al. (1994), which progress from the expansion model of Dyson & Williams (1997) used earlier, a shell created around an expanding H II region becomes unstable to fragmentation and collapse at a time

$$ t_{\text{frag}} \approx 1.56 \left( \frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{7/11} \left( \frac{N_{Ly}}{10^{49} \text{ s}^{-1}} \right)^{-1/11} \left( \frac{n}{10^3 \text{ cm}^{-3}} \right)^{-5/11} \text{ Myr} $$

where $a_s$ is the speed of sound (0.2 km s$^{-1}$ an extreme lower limit), $n$ is the number density of the ambient medium ($10^3$ cm$^{-3}$ an extreme upper limit), and $N_{LY}$ is the flux of ionizing photons.

At this point the H II region and its corresponding shell have reached a radius

$$ R_{\text{frag}} \approx 5.8 \left( \frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{4/11} \left( \frac{N_{Ly}}{10^{49} \text{ s}^{-1}} \right)^{1/11} \left( \frac{n}{10^3 \text{ cm}^{-3}} \right)^{6/11} \text{ pc} $$

with the variables as described above. Using the estimated size of the original H II region calculated from the molecular/PAH shell (15 pc) we can then work backward; solving for the initial density from the current size via Equation (4), and then calculating the fragmentation timescale from Equation (3). For a sound speed $a_s = 0.5$ km s$^{-1}$ this gives an estimate of the fragmentation timescale of 3.1 Myr and an initial ambient density of 490 cm$^{-3}$, comparable to the current density of the extended molecular ridge. The fragmentation timescale could be decreased if the ionizing stars were to depart from the main sequence, which corresponds to a decrease in ionizing radiation and subsequent cooling of the swept-up shell.

This timescale for fragmentation, plus the ages of the various populations of young stars of different masses (about 1 Myr), is comparable to the original H II region. Therefore, the star formation can be explained as the result of triggering by the original H II region. The locations of the enshrouded B stars are significant in this scenario, as they are located around the larger PAH shell (corresponding to the original H II region) rather than the smaller, currently ionized region. This is also consistent with formation via triggering and the collect and collapse model.

More detailed modeling of Gum 48d would be problematic due to the nonstatic large-scale structure. The H II region has formed and evolved in an expanding, increasingly more massive giant ridge of molecular material. This type of dynamically changing environment in the surrounding ISM and its interaction with an evolving H II region is beyond the scope of current models.

### 5.3. Large Scale Structure

Gum 48d is part of a large molecular complex containing a significant amount of star formation activity; this region is shown in the three-color image of Figure 1. This molecular complex is one of the most massive in the galaxy ($2.3 \times 10^6 M_{\odot}$ as traced by $^{12}$CO($J = 1 \rightarrow 0$)) and forms a massive ridge in CO with velocities corresponding to the Centaurus Arm (Saito et al. 2001). The CO ridge is associated with an even larger ridge in neutral hydrogen.
There are a number of H\textsc{ii} regions associated with this ridge. All of the H\textsc{ii} regions are associated with high-mass condensations in the molecular ridge and have velocities consistent with the Centaurus Arm; their locations are marked in Figure 1. Gum 48d, Gal 309.1+0.2, Gal 309.8+0.5, and Gal 309.54−0.737 are associated with the molecular supershell, while RCW 79 is located slightly to the north−west. Gal 309.54−0.737 shows the classic morphology of a young blister H\textsc{ii} region, while Gal 309.1+0.2, Gal 309.8+0.5, and RCW 79 show prototypical main-sequence H\textsc{ii} region morphologies.

This entire region is studied in more depth in J. L. Karr et al. (2009, in preparation). In that paper, the masses of the ionizing stars needed to maintain the current 1420 MHz luminosity were calculated using the free−free continuum luminosity. The Dyson & Williams (1997) model for H\textsc{ii} region expansion was used to estimate the ages of the regions. The radio luminosities are consistent with each H\textsc{ii} region being ionized by a single OB star (ranging from O9.5 to O6.5 for all the regions) and the expansion timescales are consistent with the H\textsc{ii} regions being in the 1−3 Myr age range, with ionizing sources still firmly on the main sequence.

As discussed in Section 5.1, Gum 48d is significantly different from these regions in both morphology and star formation content. The emission from ionized gas is faint and diffuse in the radio, where extinction is not a factor. The morphology of the region is structured on small scales and the star formation in the region includes compact H\textsc{ii} regions and enshrouded B-stars in addition to low-mass star formation. The other H\textsc{ii} regions are bright in the radio, with clearly defined H\textsc{ii} region morphologies and shell like PDR regions directly bordering on the bright H\textsc{ii} regions. They show neither the compact features of Gum 48d nor secondary intermediate- and high-mass star formation indicative of triggering, although there is still significant low-mass star formation. On the other hand, they, contain bright rims, cometary globules and other characteristic morphological features of the classic H\textsc{ii} region which are absent in Gum 48d. These differences point to a significantly different evolutionary phase of Gum 48d from that of the classic H\textsc{ii} regions.

The proposed history of the star formation over this whole region is one of multiple, linked generations of star formation, as illustrated schematically in Figure 9. The first generation of stars, forming 10 Myr ago and consisting of multiple OB stars, culminated in a series of supernova explosions 4−6 Myr in the past. The combined energy of the young OB stars, culminated in a series of supernovae explosions 4–6 Myr of stars, forming 10 Myr ago and consisting of multiple OB as illustrated schematically in Figure 9. The first generation region is one of multiple, linked generations of star formation, regions.

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The proposed history of the star formation over this whole region is one of multiple, linked generations of star formation, as illustrated schematically in Figure 9. The first generation of stars, forming 10 Myr ago and consisting of multiple OB stars, culminated in a series of supernova explosions 4−6 Myr in the past. The combined energy of the young OB stars, stellar wind and supernovae created an extensive, massive expanding supershell and are similarly clustered. The timescales of expansion, fragmentation, and star formation are consistent with triggered star formation by the collect and collapse model.

1. Gum48d is an old, highly evolved H\textsc{ii} region in a post-main-sequence phase that is the remnant of a larger, more energetic main-sequence H\textsc{ii} region. The current morphology of the molecular gas and PDR region reflects this history, as does the faint remnant H\textsc{ii} region seen in the radio and optical. The region has progressed though the classic main-sequence H\textsc{ii} region phase and is now in a late H\textsc{ii} region phase (before the existence of supernovae and a remnant molecular shell). This represents an interesting and not particularly well studied phase of H\textsc{ii} region evolution.

2. There is significant ongoing star formation associated with Gum 48d at a variety of masses. Low-mass young stars are seen throughout the molecular cloud, with the more embedded, younger phases being more highly clustered and associated with the densest molecular gas. Intermediate-mass star formation, in the form of enshrouded B stars, and high-mass star formation, in the form of compact H\textsc{ii} regions, are seen around the periphery of the molecular/neutral PAH shell and are similarly clustered. The timescales of expansion, fragmentation, and star formation are consistent with triggered star formation by the collect and collapse model.

3. Gum 48d is part of a much larger molecular cloud complex consisting of a very massive expanding partial supershell/ridge of molecular and neutral material, the result of a previous generation of massive star formation 10 Myr ago. The ridge contains a number of H\textsc{ii} regions with ages in the 1−3 Myr range, but Gum 48d is unique in its older age, diffuse radio morphology, extended PDR and variety
of secondary star formation. While the other regions are clear candidates for secondary star formation within the expanding molecular supershell/ridge, Gum 48d is most likely the first and the highest mass of these triggered massive stars, and consequently in a later state of spectral evolution.

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REFERENCES

Adams, F. C., Shu, F. H., & Lada, C. J. 1988, ApJ, 326, 865
Allen, L. E., et al. 2004, ApJS, 154, 363
Arthur, S. J. 2007, RevMexAA, 30, 64
Benjamin, R. A., et al. 2003, PASP, 115, 953
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Carey, S. J., Clark, F. O., Egan, M. P., Price, S. D., Shipman, R. F., & Kuchar, T. A. 1998, ApJ, 508, 721
Caswell, J. L., & Haynes, R. F. 1987, A&A, 171, 261
Caswell, J. L., Kesteven, M. J., Stewart, R. T., Milne, D. K., & Haynes, R. F. 1992, ApJ, 399, L151
Caswell, J. L., Milne, D. K., & Wellington, K. J. 1981, MNRAS, 195, 89
Caswell, J. L., Vaile, R. A., Eillingsen, S. P., Whiteoak, J. B., & Norris, R. P. 1995, MNRAS, 272, 96
Dewdney, P. E., Roger, R. S., Purton, C. R., & McCutcheon, W. H. 1991, ApJ, 370, 243
Diaz-Miller, R. I., Franco, J., & Shore, S. N. 1998, ApJ, 501, 192
Dyson, J. E., & Williams, D. A. 1997, in The Graduate Series in Astronomy, The Physics of the Interstellar Medium, ed. J. E. Dyson & D. A. Williams (2nd ed.; Bristol: Institute of Physics Publishing)

Elmegreen, B. G. 1998, in ASP Conf. Ser. 148, Origins, ed. C. E. Woodward, J. M. Shull, & H. A. Thronson, Jr. (San Francisco, CA: ASP), 150
Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725
Fuente, A., Martin-Pintado, J., Bachiller, R., Neri, R., & Palla, F. 1998, A&A, 334, 233
Fuente, A., Martin-Pintado, J., Bachiller, R., Rodriguez-Franco, A., & Palla, F. 2002, A&A, 387, 977
Garcia-Segura, G., & Franco, J. 1996, ApJ, 469, 171
Gaustad, J. E., McCullough, P. R., Rosing, W., & Van Buren, D. 2001, PASP, 113, 1326
Georgelin, Y. M., Boulesteix, J., Georgelin, Y. P., Le Coarer, E., & Marcelin, M. 1988, A&A, 205, 95
Green, D. A. 2004, Bull. Astron. Soc. India, 32, 335
Gum, C. S. 1955, Mem. R. Astron. Soc., 67, 155
Guseinov, O. H., Ankay, A., & Tagieva, S. O. 2004, Serb. Astron. J., 169, 65
Humphreys, R. M., Strecker, D. W., & Ney, E. P. 1971, ApJ, 167, L35
Indebetouw, R., et al. 2005, ApJ, 619, 931
Karr, J. L., & Martin, P. G. 2003, ApJ, 595, 900
Kerton, C. R. 2002, AJ, 124, 3449
LeFloch, B., & Luzareff, B. 1994, A&A, 289, 559
McClure-Griffiths, N. M., Dickey, J. M., Gaensler, B. M., Green, A. J., Havercorn, M., & Strasser, S. 2005, ApJS, 158, 178
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Rakowski, C. E., Hughes, J. P., & Slane, P. 2001, ApJ, 548, 258
Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, ApJS, 169, 328
Rodgers, A. W., Campbell, C. T., & Whiteoak, J. B. 1960, MNRAS, 121, 103
Rogers, R. S., & Dewdney, P. E. 1992, ApJ, 385, 536
Saito, H., Mizuno, N., Moriguuchi, Y., Matsunaga, K., Onishi, T., Mizuno, A., & Fukui, Y. 2001, PASJ, 53, 1037
Schaerer, D., & de Koter, A. 1997, A&A, 322, 598
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Tenorio-Tagle, G. 1979, A&AS, 71, 59
Tenorio-Tagle, G., & Bodenheimer, P. 1988, ARA&A, 26, 145
Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 747
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
van Genderen, A. M. 1992, A&A, 257, 177
Whiteoak, J. B. Z., & Green, A. J. 1996, A&AS, 118, 329
Whitworth, A. P., Bhattachar, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994, MNRAS, 268, 291