MASSIVE STAR FORMATION AT THE PERIPHERY OF THE EVOLVED GIANT H II REGION W 39

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ABSTRACT

We present the first detailed study of the large, ~30 pc diameter, inner-Galaxy H II region W 39. Radio recombination line observations combined with H I absorption spectra and Galactic rotation models show that the region lies at \( V_{\text{LSR}} = +65.4 \pm 0.5 \text{ km s}^{-1} \), corresponding to a near kinematic distance of 4.5 \pm 0.2 kpc. Analysis of radio continuum emission shows that the H II region is being powered by a cluster of OB stars with a combined hydrogen-ionizing luminosity of \( \log(Q) \geq 50 \), and that there are three compact H II regions located on the periphery of W 39, each with \( \log(Q) \sim 48.5 \) (single O7–O9 V star equivalent). In the infrared, W 39 has a hierarchical bubble morphology, and is a likely site of sequential star formation involving massive stars. Kinematic models of the expansion of W 39 yield timescales of the order of Myr, consistent with a scenario where the formation of the smaller H II regions has been triggered by the expansion of W 39. Using Spitzer GLIMPSE and MIPS GAL data, we show that star formation activity is not distributed uniformly around the periphery of W 39 but is concentrated in two areas that include the compact H II regions as well as a number of intermediate-mass Class I and Class II young stellar objects.

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

Online-only material: color figures

1. INTRODUCTION

W 39 is a large H II region in the inner Galaxy (\( l = 19^\circ, b = -0^\circ.4 \)) first identified in the Westerhout (1958) 1.4 GHz radio continuum survey and more recently cataloged as a large infrared “bubble” by both professional astronomers (N24; Churchwell et al. 2006) and citizen scientists (MWP1G18908-003146; Simpson et al. 2012). It is a significant high-mass star-forming region and a possible example of sequential or triggered star formation based on the hierarchical bubble structure seen in the infrared, but, owing to its highly obscured location in the inner Galaxy, it has been poorly studied. Recent high-resolution (sub-arcminute) surveys at radio and infrared wavelengths have provided an opportunity to examine this region in detail for the first time. This paper presents an analysis of the H II region itself along with an investigation of the influence of the H II region on star formation in its vicinity.

In the next section, the key parameters of the various data sets used in the study are summarized. The determination of the radial velocity and distance to the H II region is described in Section 3. An analysis of W 39 and three associated compact H II regions follows in Section 4. In Section 5, the young stellar object (YSO) distribution surrounding W 39 is explored, and our conclusions are presented in Section 6.

2. OBSERVATIONS

2.1. Radio Line and Continuum

At cm radio wavelengths, we use VLA Galactic Plane Survey (VGPS; Stil et al. 2006) 21 cm line and continuum data. The VGPS maps have an angular resolution of ~1 arcmin, and the H I line spectra have a velocity resolution of 1.56 km s\(^{-1}\). The maps include single-dish short-spacing data, making them ideal for obtaining flux density measurements of large angular scale (\( \gtrsim 30 \text{ arcmin} \)) objects like W 39.

To trace molecular gas, we use \(^{13}\text{CO} (J = 1–0)\) observations from the Boston University/Five College Radio Astronomy Observatory Galactic Ring Survey (BU/FCRAO GRS; Jackson et al. 2006). These data have an angular resolution of 46 arcsec and 0.21 km s\(^{-1}\) velocity resolution. We also make use of 1.1 mm continuum data from the BoloCam Galactic Plane Survey (BGPS; Rosolowsky et al. 2010).

2.2. Infrared

At infrared wavelengths, we primarily use data from the GLIMPSE (Benjamin et al. 2003) Spitzer legacy survey. GLIMPSE provides 1.7–2.0 arcsec resolution images in four bands centered at 3.6, 4.5, 5.8, and 8.0 \( \mu \text{m} \) along with a point-source catalog that contains near- and mid-infrared photometric data. In addition, we use the 6 arcsec resolution images at 24 \( \mu \text{m} \) from the MIPS GAL Spitzer legacy survey (Carey et al. 2009). For near-infrared photometry of point sources, we use data from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Surveys-Galactic Plane Survey (UKIDSS-GPS; Lucas et al. 2008).

3. RADIAL VELOCITY AND DISTANCE

3.1. Radial Velocity

In Figure 1, we show the VGPS 1420 MHz continuum map of the area around W 39 along with the position and velocity of cm-wavelength observations of the radio recombination lines (RRLs) H\(85\alpha\), H\(87\alpha\), and H\(88\alpha\) (Lockman 1989). W 39 has a bubble morphology best seen in the infrared. At radio wavelengths, the brightest emission (\( \gtrsim 50 \text{ K} \)) from W 39 is concentrated along a U-shaped ridge opening to lower Galactic longitudes. Fainter emission (\( \sim 30–40 \text{ K} \)) is found within the bubble and also tracing the bubble edges at lower Galactic longitude. There is a local minimum in the radio emission around...
Figure 1. VGPS 1420 MHz continuum image of the W 39 region. Crosses indicate the positions of RRL observations from Lockman (1989). The peak velocity ($V_{\text{LSR}}$, km s$^{-1}$) of each RRL profile is also shown with the fit uncertainty given in parentheses. The position of the H$\alpha$ region G18.94-0.43 is also shown. The white ellipse approximately traces the position of the bubble structure best seen in the infrared (see Figure 3).

$l = 19^\circ.025, b = -0^\circ.38$ that is a likely location for the exciting OB star(s). Three of the RRL observations that lie on the strong ridge of emission have very similar velocities, and we adopt the average of these values, $V_{\text{LSR}} = 65.4 \pm 0.5$ km s$^{-1}$, as the radial velocity of W 39. The RRL velocity of G18.95-0.02 is significantly different from the main ridge and, as we discuss in Section 3.1.2, this region is likely not directly associated with W 39.

The nature of the RRL emission associated with the arc-shaped structure G18.64-0.29 is more speculative. Both Helfand et al. (2006) and Brogan et al. (2006) classify this object as a supernova remnant (SNR) based on multi-frequency radio observations, and H$\alpha$ absorption studies by Johanson & Kerton (2009) place the object at a distance of $\sim 5$ kpc. RRL emission is not expected from SNRs, so it is likely that the observed RRL emission, with a difference in velocity of $\sim 5$ km s$^{-1}$ from the main W 39 ridge, is originating from the edge of the W 39 bubble.

3.1.1. H$\alpha$

H$\alpha$ absorption spectra, obtained from the VGPS, were used to determine if all three of the RRL sources are located at the same near or far kinematic distance. A radio continuum source in the inner Galaxy at the near distance can only show absorption up to $V_{\text{LSR}}$, while a source at the far distance can show absorption at velocities beyond $V_{\text{LSR}}$ up to the tangent velocity, which at $l \sim 19^\circ$ is 110–140 km s$^{-1}$ depending on the kinematic model used (see Section 3.2).

For each of the RRL sources, H$\alpha$ “ON” spectra were obtained by averaging H$\alpha$ spectra where the 1420 MHz continuum brightness temperature was above a threshold of 100 K for G19.07-0.28, 100 K for G18.88-0.49, and 55 K for G19.04-0.43. “OFF” spectra were then calculated by taking the average H$\alpha$ spectrum of a nearby (1–2 arcmin offset) similarly sized region. The resulting ON–OFF absorption spectra are shown in Figure 2.

The uncertainty in an absorption spectrum $\sigma_{\text{abs}}$ can be quantified by taking the maximum of either the standard deviation in channels where no absorption is expected to occur (e.g., at negative $V_{\text{LSR}}$ in this case) or by constructing “OFF–OFF” spectra that measure the intrinsic variability of H$\alpha$ emission structure. We found $\sigma_{\text{abs}} \sim 5$ K in each case. Looking at Figure 2, we see that the two brightest RRL sources are clearly at the near kinematic distance because of the lack of absorption at velocities $\gtrsim 65$ km s$^{-1}$. The ridge RRL source has a much poorer quality spectrum, but there is no evidence for absorption beyond $\sim 65$ km s$^{-1}$. We conclude that all of the emission associated with the three RRL observations is at the near kinematic distance.

3.1.2. IR Morphology

In Figure 3, we show an 8 and 24 $\mu$m image of the W 39 region using data from Spitzer GLIMPSE and MIPSGAL. The infrared bubble structure, best seen at 8 $\mu$m and identified by Churchwell et al. (2006) and Simpson et al. (2012), is indicated by an ellipse. As expected for a thermal radio source, W 39 is very bright in the infrared. Of particular interest though is the layered structure of the infrared emission; moving from the interior of the U-shaped structure to the exterior, we first see 24 $\mu$m emission followed by a layer of 8 $\mu$m emission. This is exactly what would be expected for a region being heated from one side by ionizing radiation. Within the H$\alpha$ region, polycyclic aromatic hydrocarbons (PAH) are strongly depleted, allowing 24.0 $\mu$m emission from small dust grains to dominate while in the photodissociation region surrounding the H$\alpha$ region PAHs can survive, resulting in strong 8 $\mu$m emission (e.g., Tielens et al. 1993; Giard et al. 1994; Kerton et al. 2008; Arvidsson & Kerton 2011). The continuity of this layered infrared morphology is consistent with W 39 being a single large H$\alpha$ region.
We note that this layered infrared morphology does not extend to the region around $l = 18.95, b = -0.01$. In Figure 4, we show GRS maps of $^{13}$CO emission between $0 \leq V_{\text{LSR}} \leq +130 \text{ km s}^{-1}$ integrated in $20 \text{ km s}^{-1}$ increments between 0 and $+40 \text{ km s}^{-1}$, $10 \text{ km s}^{-1}$ increments between 40 and $+70 \text{ km s}^{-1}$, and a single $60 \text{ km s}^{-1}$ interval between +70 and $+130 \text{ km s}^{-1}$. The G18.95-0.01 region is morphologically very similar to CO emission seen in the GRS at $V_{\text{LSR}} \sim +45 \text{ km s}^{-1}$ consistent with the lower RRL velocity observed by Lockman (1989). Based on this, we do not consider this region to be part of W 39. The CO maps also show that most of the molecular gas along the line of sight to W 39 is found between +60 and $+70 \text{ km s}^{-1}$.

### 3.2. Kinematic Distance

The (near) kinematic distance to W 39 was calculated using $V_{\text{LSR}} = 65.4 \pm 0.5 \text{ km s}^{-1}$ and three different Galactic rotation models: (1) the $R_0 = 8 \text{ kpc}$ hydrodynamical model of Pohl et al. (2008), (2) the $R_0 = 8.5 \text{ kpc}, V_0 = 220 \text{ km s}^{-1}$ model of Clemens (1985), and (3) a version of the Clemens (1985) model scaled to $R_0 = 8.0 \text{ kpc}$. The resulting distances are 4.5 kpc, 4.7 kpc, and 4.4 kpc, respectively. In each case, the error in the calculated distance caused by the uncertainty in $V_{\text{LSR}}$ is only $\sim 0.04 \text{ kpc}$, much less than the systematic uncertainty associated with the choice of rotation model. We adopt the average (standard deviation) of these values as the distance (uncertainty) to W 39: $d = 4.5 \pm 0.2 \text{ kpc}$. At this distance, W 39 is probably part of the Scutum-Centaurus Arm of our Galaxy (Churchwell et al. 2009; Russell 2003).

### 4. A GIANT H II REGION

#### 4.1. Exciting Stars and Ionized Mass

The flux density at 1420 MHz of W 39, $F_{1420} = 40 \pm 0.6 \text{ Jy}$, was measured from VGPS data using imview (Higgs et al. 1997) to integrate the emission within a user-defined area roughly following the $T_B = 30 \text{ K}$ contour, but omitting emission at $b > -0^\circ 1$ and subtracting the contribution from compact and point sources found within the contour. The main contribution to the uncertainty comes from the definition of the background level, which varies depending on the number and location of the points used to define it and the order of the two-dimensional polynomial fit used.

The observed radio continuum flux density ($F_{\nu}$) of an H II region at a distance ($d$) can be related to the ionizing radiation luminosity ($Q$) of the star(s) located within the H II region by

$$\log (fQ) = 40.95 + \log \left( \frac{F_{\nu}}{\text{Jy}} \right) + 2 \log \left( \frac{d}{\text{pc}} \right). \tag{1}$$

where $f$ is the fraction of the ionizing radiation from the star(s) that is intercepted by the H II region (e.g., $f = 1$ for an ionization-bounded region, $f \sim 0.5$ for a “blister” H II region), and we used $\nu = 1.4 \text{ GHz}$ and $T_e = 7500 \text{ K}$ to calculate the constant (Kerton et al. 1999; Matsakis et al. 1976). As pointed out by Rubin (1968), Equation (1) does not depend on the details of the density structure of the H II region.

For $d = 4500 \text{ pc}$ and $F_{\nu} = 40 \text{ Jy}$, we find $\log (fQ) = 49.86$, equivalent to the output of two O3 V stars (or 10 O7 V stars) using the calibration of Crowther (2005). Varying distance and $F_{\nu}$ within the uncertainties, and allowing $T_e$ to range between 7500 K and 10,000 K, we find the full range of $\log (fQ) = 49.75–49.90$. Given the morphology of the H II region, it is very likely that $f < 1$ and W 39 is a giant H II region (GHIIR; Conti & Crowther 2004) being powered by numerous OB stars.

The formulae given in Matsakis et al. (1976), and derived in detail in Mezger & Henderson (1967), can be used to estimate the average electron density of the H II region and the total mass of ionized gas given $F_{\nu}, d, T_e$, and the angular size of the region.
Figure 3. GLIMPSE and MIPSGAL image of W 39. This image combines 8 and 24 μm images from the GLIMPSE and MIPSGAL surveys (green and red, respectively). The hierarchical bubble structure of W 39, consisting of the main bubble (white ellipse) and the two compact H II regions G18.88-0.49 and G19.07-0.28, is best seen at 8.0 μm. As discussed in the text, the relative position of the 24 and 8 μm emission is consistent with W 39 being a single large H II region. The white ellipse is the same as that shown in Figure 1.

(A color version of this figure is available in the online journal.)

An appropriate size scale for W 39 is given by the separation between the two sides of the H II region, ~0:4, or 30 pc at 4.5 kpc. This is slightly smaller than the value of 0:6 reported in Westerhout (1958), but that value included emission at higher Galactic latitude that we do not associate with the H II region. We find values of \( n_e \sim 20 \text{ cm}^{-3} \) and \( M \sim 10^4 M_\odot \). Unlike the log(\( f_Q \)) calculation, these values depend strongly on the details of the H II region’s density structure and should only be considered order-of-magnitude estimates.

4.2. G19.07-0.28 = IRAS 18239-1228

The radio source G19.07-0.28 is the brightest of the compact radio sources found on the periphery of W 39 with \( F_v = 1.77 \pm 0.08 \) Jy. Using the same formulae and calibrations from the previous subsection, we find \( \log(f_Q) = 48.50 \) equivalent to a single O8 V star. The ionized gas mass is \( M \sim 50 M_\odot \) and the average electron density is \( n_e \sim 160 \text{ cm}^{-3} \). This radio source is also the infrared source IRAS 18239-1228 and has four well-defined IRAS flux density measurements. Using the technique of Emerson (1988), we calculate the far-infrared luminosity \( \log(L_{IR}/L_\odot) = 5.2 \pm 0.1 \), which is the luminosity of an O7–O8 V star.

The higher resolution GLIMPSE 8.0 μm image of the region is shown in Figure 5. At this wavelength, the source is clearly a bubble structure with a radius of ~0:01 (~0.8 pc). Ionized gas, traced by the 1420 MHz radio emission, and warm dust, traced by 24 μm emission, fill the central region. The compact bubble morphology of the region and the agreement in the stellar spectral type determined by the radio and infrared flux support the idea that the region is ionization bounded (\( f \sim 1 \)).

4.3. G18.88-0.49

The radio source G18.88-0.49 is the second brightest of the compact radio sources found on the periphery of W 39 with \( F_v = 1.53 \pm 0.02 \) Jy. From this, we find \( \log(f_Q) = 48.45 \) equivalent to a single O8 V star. The ionized gas mass is \( M \sim 44 M_\odot \) and the average electron density is \( n_e \sim 160 \text{ cm}^{-3} \).
Figure 4. Integrated $^{13}$CO GRS images between $0 \text{ km s}^{-1} \leq V_{LSR} \leq +130 \text{ km s}^{-1}$. The velocity increments are shown in the lower-left corner of each panel, and the gray scale is the same in all panels. Note the similarity of the emission seen at high latitude in the 40–50 km s$^{-1}$ panel and the IRDCs seen in Figure 3, and the concentration of material associated with the two main regions of star formation around W 39 shown in the 60–70 km s$^{-1}$ panel. The ellipse is the same as that shown in Figure 1.

Unlike G19.07-0.28, there is no IRAS point source associated with this region. The higher resolution GLIMPSE 8.0 μm image of the region is shown in Figure 6. Although the morphology is more complex than G19.07-0.28, the presence of bright-rimmed structures at the edge of the radio continuum emission along with the coincident 24 μm emission suggest that we are also looking at a dusty, ionization-bounded, bubble structure similar in size to G19.07-0.28.

4.4. G18.94-0.43

The remaining radio source on the periphery of W 39 is G18.94-0.43. We measured $F_{\nu} = 0.8 \pm 0.09$ Jy, which corresponds to $\log (f \nu) = 48.16$, equivalent to a single O9 V star. The ionized gas mass is $M \sim 32 M_\odot$, and the average electron density is $n_e \sim 110 \text{ cm}^{-3}$.

As with G18.88-0.49, there is no IRAS point source associated with the region. The high-resolution image of the region shown in Figure 6 reveals a complex morphology that is difficult to interpret in detail. As we would expect for an H II region, there appears to be bright-rimmed structures along the low-latitude portion of the region and a minimum in the 8 μm emission coincident with the radio continuum maximum.

4.5. Timescales and Triggered Star Formation

The radio continuum view of the W 39 region is of an evolved massive H II region (powered by multiple mid-
Figure 5. G19.07-0.28 H\textsc{ii} region. The bubble structure of this H\textsc{ii} region is clearly shown in the GLIMPSE 8.0 \(\mu\)m image. The red (or lighter) contour (at 950 MJy sr\(^{-1}\)) traces 24 \(\mu\)m emission from hot dust filling the interior of the bubble. The 24 \(\mu\)m emission is saturated in the MIPSGAL image within the innermost contour shown. Radio continuum emission at 1420 MHz from the VGPS (blue/darker contours; 100–175 K at 25 K intervals) also peaks within the infrared bubble.

(A color version of this figure is available in the online journal.)

While proving this idea is difficult, we can at least investigate the relevant timescales for the most clearly defined secondary region, G19.07-0.28, to see if this scenario is at all plausible.

We can obtain a rough estimate of the age of G19.07-0.28 using the classic description of the evolution of an H\textsc{ii} region (Spitzer 1978; Osterbrock 1989). The O star first creates a ionized gas region about the size of the Strömgren sphere on an essentially instantaneous timescale of \(\sim 10^5/\rho_s\) yr. The overpressurized H\textsc{ii} region then expands from its initial radius, \(r_s\) to the observed radius \(R\) at time \(t\) as

\[
\frac{R}{r_s} = \left(1 + \frac{7C_{\text{II}} t}{4r_s}\right)^{4/7},
\]

where \(C_{\text{II}}\) is the isothermal sound speed in the ionized gas (\(\sim 10\) km s\(^{-1}\)).

To estimate the initial density of the cloud in which the H\textsc{ii} region formed, we examined the nearby 1.1 mm source from the BGPS, G019.077-00.287. The peak brightness of this source is 2.3 Jy beam\(^{-1}\), corresponding to a column density of \(N_{\text{H}_2} = 7.9 \times 10^{22}\) cm\(^{-2}\) using Equation (A.27) in Kauffmann et al. (2008). The deconvolved radius of the source is 93.82 (\(\sim 2\) pc). Adopting a path length of 4 pc, we obtain a density \(n \sim 10^{3.8}\) cm\(^{-3}\). In such an environment, an O8 V star would rapidly create an H\textsc{ii} region of size \(r_s\sim 0.2\) pc. Using this value and the observed size of the region \(\sim 0.8\) pc in Equation (2), we find \(t\sim 10^5\) years.

While this is clearly a rough estimate, it is important to note that this timescale is approximately one order of magnitude smaller than the timescales appropriate for the evolution of the much larger W 39 region. As pointed out by Churchwell (1975), an approximate lower limit to the age of an evolved H\textsc{ii} region can be obtained by the sound crossing time, \(\sim 1.5 \times 10^6\) years in the case of W 39. The lack of non-thermal radio emission from SNRs gives a consistent upper limit to the age of 2–4 \(\times 10^6\) years.

Figure 6. H\textsc{ii} regions G18.88-0.49 and G18.94-0.43. This GLIMPSE 8.0 \(\mu\)m image shows two of the compact H\textsc{ii} regions surrounding W 39. Red (or lighter) contours (at 550, 1000, and 1550 MJy sr\(^{-1}\)) trace MIPS\textsc{gal} 24 \(\mu\)m emission, and blue (or darker) contours trace 1420 MHz radio continuum emission (80–110 at 10 K intervals). Note that the MIPS\textsc{gal} image is saturated at the center of the G18.88-0.49 H\textsc{ii} region.

(A color version of this figure is available in the online journal.)
based on the main-sequence lifetime of early O stars (Schaerer & de Koter 1997). We conclude that the probable timescales associated with the expansion of W 39 ($\sim 10^5$ years) and the likely ages of the secondary regions of massive star formation ($\sim 10^5$ years) are consistent with a scenario of triggered star formation.

5. STAR FORMATION TRACED BY MIPS GAL AND GLIMPSE

5.1. GLIMPSE Detected YSO Candidates

In order to determine if the only recent, and thus likely triggered, star formation activity surrounding W 39 is restricted to the three compact H ii regions discussed previously, we used the Spitzer GLIMPSE catalog to identify YSO candidates (YSOs hereafter) in the W 39 field within $18.5 < l < 19.3$, $-0.55 < b < -0.1$. The high-latitude cutoff was chosen to avoid including the prominent infrared dark clouds (IRDCs) found at $b > -0.1$, which are not associated with W 39. A total of 10,657 sources with valid magnitudes in all four IRAC bands were identified. Figure 7 is a color–color (CC) diagram showing all of these sources along with the YSO classification criteria from Allen et al. (2004). We identify 57 Class I YSOs, 129 Class II YSOs, and 57 Class I/II YSOs ($[3.6]–[4.5] < 0.4$ and $[5.8]–[8.0] > 1.1$). Class I YSOs are objects with a substantial circumstellar envelope, Class II YSOs have most of the circumstellar material residing in a disk, and Class I/II objects are most likely Class II or stellar objects with poor [8.0] photometry causing them to scatter into this region of the CC diagram. In the canonical picture, a Class I YSO will evolve to a Class II YSO with each stage of evolution lasting for $\tau_I \sim 10^5$ years and $\tau_{II} \sim 10^6$ years, respectively (Ward-Thompson 2002).

In Figure 8, the sample is plotted in a [3.6]–[4.5] versus [3.6] color–magnitude (CM) diagram. We see that there is a bright cutoff at [3.6] $\sim 7$ due to saturation and a faint, color-dependent, sensitivity cutoff at [3.6] $\sim 13–15$. Included in the CM diagram...
Figure 9. W 39 YSO candidates. The location of the various YSO candidates identified using the GLIMPSE CC diagram (Figure 7) are shown: Class I = square, Class II = +, Class I/II = diamond. The rectangles indicate regions around G18.88-0.49 and G19.07-0.28 where the YSO population was investigated in more detail.

are two lines showing the position of main-sequence stars (B0 V to M5 V) and giant stars (G5 III to M0 III) at a distance of 4.5 kpc. The crosses are T Tauri stars from Hartmann et al. (2005) shifted from the distance of Taurus-Auriga to W 39. The diamonds are intermediate-mass Herbig AeBe stars from The et al. (1994) and Finkenzeller & Mundt (1984), again shifted to the distance of W 39. For the Herbig AeBe sample, we have used $L$- and $M$-band magnitudes as rough proxies for $[3.6]$ and $[4.5]$. Finally, the asterisks represent AGB stars from the Spitzer/IRAC study of Galactic AGB stars by M. Reiter et al. (in preparation). The CM diagram illustrates that our sample is primarily sensitive to intermediate-mass YSOs at a distance of 4.5 kpc. The CM diagram also provides some insights into likely contaminants in our sample. We see that the majority of background main-sequence stars are too faint to be detected, while foreground main-sequence stars with moderate amounts of reddening will be a source of contamination for the least-red Class II YSOs. The major contaminant, for both Class I and Class II YSOs, is reddened background AGB stars. Unfortunately, since we are looking toward the inner Galaxy, background stellar distances approaching 20–30 kpc are possible, meaning even the faintest, reddest sources in our sample could be matched by a distant, heavily reddened AGB.

In Figure 9, we show the spatial distribution of the various YSO classes. It is clear that star formation activity is not uniformly distributed along the periphery of the W 39 bubble, with the most striking feature being the lack of YSOs at the high and low longitude ends of the bubble around $b = -0:15$ and $b = -0:45$, respectively. This is consistent with the lack of molecular gas seen at these locations in the $^{13}$CO images shown in Figure 4. There is also a swath of YSOs located within the infrared bubble that roughly follows the $^{13}$CO distribution seen in the lower-left panel of Figure 4. Almost all of the ~10 Class I sources found within the bubble are associated with an IRDC that runs roughly from $l = 19:0$ to $l = 18:8$ at $b \sim -0:3$. If associated with W 39, then these sources could represent recent star formation occurring in the near or far wall of the bubble, but it is also possible that the IRDC is not directly related to W 39. We tried to measure the $V_{LSR}$ of the IRDC, but were unable to clearly identify any $^{13}$CO features that were unambiguously associated with the IRDC. Higher resolution radio/mm line observations of this IRDC in tracers of cold, dense gas would help to clarify its relation to W 39.

Qualitatively, it appears from Figure 9 that most of the star formation activity located on the periphery of W 39 is concentrated around the compact H\textsc{ii} regions. In order to examine this quantitatively, we divided our search area into 32 roughly $0:1 \times 0:1$ areas and calculated the percentage of sources in each area that have a YSO classification (see Figure 10). The “background” YSO percentage, using the median of the eight high and low longitude columns, is 1.8%, with an interquartile range of 0.85%. The YSOs within the bubble show up as
Figure 10. YSO Candidate Frequency. The percentage of GLIMPSE sources in each $\sim 0.1 \times 0.1$ area classified as YSO candidates is shown. For reference, the gray scale shows VGPS 1420 MHz emission and the white ellipse indicates the extent of the IR bubble. Note that the regions around G18.88-0.49 and G19.07-0.28 have the highest YSO percentage in the field and stand well above the median background value of 1.8%, which was defined using the eight high and low longitude areas.

Figure 11. GLIMPSE and MIPSGAL color–color diagram. YSOs in the G18.88-0.49 and G19.07-0.28 regions (the rectangles in Figure 9) with 24 $\mu$m photometry are plotted along with the YSO classification criteria of Rho et al. (2006). A reddening vector for $A_V = 20$ from Rho et al. (2006) is shown.

5.2. MIPSGAL Detected YSOs around G18.88-0.49 and G19.07-0.28

We investigated the YSO population around G18.88-0.49 (19 YSOs; G18 hereafter) and G19.07-0.28 (17 YSOs; G19 hereafter) in more detail (the areas are shown in Figure 9). For each YSO, $JHK$ photometry was obtained either from 2MASS or UKIDSS, and 24 $\mu$m photometry was obtained from MIPSGAL images if possible. UKIDSS photometry was used if an unambiguous match to the IRAC source could be made using a 0.6 search radius, otherwise the associated 2MASS photometry given in the GLIMPSE catalog was used. Aperture photometry on the MIPSGAL images was obtained for 15 of the YSOs using a 6 arcsec radius aperture, a user-defined aperture correction of 1.67, and a zero-magnitude flux density of 7.17 Jy (Engelbracht et al. 2007). We have adopted a slight excess over the background ($\sim 4\%$) but the main outliers are the areas around G18.88-0.49 and G19.07-0.28 with YSO percentages of 6.6% and 6.0%, respectively.
a conservative uncertainty of 10% of the [24] photometry due to image background variations and uncertainty in the aperture correction estimate. The YSO sample photometry is summarized in Table 1.

When available, the 24 μm photometry provides a very clear discriminant between Class I and Class II YSOs. At or around 24 μm, a Class II YSO’s spectral energy distribution (SED) is typically flat or falling while a Class I YSO’s SED will typically be rising. In Figure 11, we plot the sample of YSOs with 24 μm photometry on a [3.6]–[8.0] versus [8.0]–[24] CC diagram along with the YSO classification criteria from Rho et al. (2006). As can be seen from comparing Columns 2 and 3 of Table 2, the IRAC-only and IRAC and MIPS YSO classifications are typically in agreement. Two of the YSOs are classified in the Rho et al. (2006) scheme as possible “hot excess” sources, which are either very heavily embedded Class II YSOs or Class I YSOs undergoing very rapid accretion.

To confirm that our YSOs are most likely intermediate-mass objects (i.e., ~2–10 M⊙) we obtained YSO model fits using the SED fitting program of Robitaille et al. (2007) for those sources with 24 μm photometry. Following Alexander et al. (2013), we use apertures of 2″ for UKIDSS, 3″ for 2MASS and GLIMPSE, and 7″ for MIPSGAL and set a minimum flux uncertainty of 10% to prevent any one data point from dominating the fit. We allowed the distance to vary between 4.3 and 4.7 kpc and Av to vary between 5 and 50 mag. In Table 3, we show the details of the best-fitting YSO model as well as the YSO stage, where Stage I has M∗/M⊙ > 10−6 yr−1, Stage II has M∗/M⊙ < 10−6 yr−1 and M/Me > 10−6, and Stage III has M/Me < 10−6 and M/Me < 10−6 (M is the envelope accretion rate in M⊙yr−1, and M and M are the stellar and disk masses, respectively, in M⊙), and the stages typically correspond one-to-one with the observationally defined Classes I, II, and III.

The SED fitter typically returned multiple models that were equally good fits statistically. As outlined in Alexander et al. (2013), there are techniques that can be used to obtain a weighted average model for the YSO based on this redundancy. In this paper, since we are using the SED fitter primarily to compare with CC diagram classifications and as a rough check on the YSO mass, we simply report the details of the single best-fitting model. We find that our best-fit models are all in the intermediate-mass range ~2–10 M⊙.

A comparison between the SED fitting results and the results from the Rho et al. (2006) CC diagram is interesting. Sources G18-1, G18-2, G19-3, and G19-7 all lie well within the Class I region of the CC diagram and are also identified as Stage
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6. CONCLUSIONS

This study represents the first study of W 39 at high resolution at infrared and radio wavelengths. The main conclusions of our study are as follows.

1. W 39 is a GHIIR powered by numerous OB stars with a likely total ionizing luminosity \( \log(Q) > 50 \), roughly equivalent to a cluster of over 30 O8 V stars. Future work will focus on identifying the OB stars powering W 39, using techniques described in Alexander et al. (2013), as the first step toward obtaining a non-kinematic distance estimate to the region.

2. Three compact H\( ^{\text{ii}} \) regions are located on the periphery of W 39. These regions are each likely powered by a single late O-type star (O7–O9 V). Two of the regions have a distinct dust-filled bubble morphology seen in infrared 8.0 and 24 \( \mu \)m images.

3. Simple kinematic models suggest that the Myr timescales associated with the expansion of W 39 are about an order of magnitude larger than the evolutionary timescales associated with the smaller H\( ^{\text{ii}} \) regions. This is consistent with the scenario where the formation of the smaller H\( ^{\text{ii}} \) regions is triggered by the expansion of W 39.

4. Recent star formation surrounding W 39 is not restricted just to the massive stars powering the small H\( ^{\text{ii}} \) regions. We used infrared data to identify a number of young/heavily embedded intermediate-mass YSOs not directly associated with the H\( ^{\text{ii}} \) regions.

5. Star formation activity is not distributed uniformly around the periphery of W 39, rather it is concentrated in the two regions surrounding the small H\( ^{\text{ii}} \) regions and potentially in an IRDC that may be associated with the front or rear wall of a bubble structure. Future studies of the W 39 region will explore the stellar content of the compact H\( ^{\text{ii}} \) regions.

I objects by the SED fitter. All but one of the YSOs with [3.6]–[5.8] between 1.5 and 2.5, including the two “hot excess” sources, are classified as reddened Stage II objects by the SED fitter. The exception is the reddest source, G19-17, which is classified as Stage I. For the sources with [3.6]–[5.8] \(< 1\), agreement between the CC diagram and the SED fitter is mixed; the SED fitter classifies G19-6 as Stage II, but classifies G18-9 as Stage III and the very red G19-8 YSO as Stage I.

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**Table 2**

| YSO Classification | ID | [3.6]–[4.5] vs. [5.8]–[8.0] | [3.6]–[5.8] vs. [8.0]–[24] | HE II |
|--------------------|----|--------------------------|--------------------------|-------|
| 1                  |    |                          |                          | I     |
| 2                  |    |                          |                          | I     |
| 3                  |    |                          |                          | I     |
| 4                  |    |                          |                          | II    |
| 5                  |    |                          |                          | II    |
| 6                  |    |                          |                          | II    |
| 7                  |    |                          |                          | II    |
| 8                  |    |                          |                          | II    |
| 9                  |    |                          |                          | II    |
| 10                 |    |                          |                          | II    |
| 11                 |    |                          |                          | II    |
| 12                 |    |                          |                          | II    |
| 13                 |    |                          |                          | I     |
| 14                 |    |                          |                          | I     |
| 15                 |    |                          |                          | I     |
| 16                 |    |                          |                          | I     |
| 17                 |    |                          |                          | I     |

Note. HE = Hot Excess (Rho et al., 2006); I/II = red sources outside of Class I or II areas for IRAC colors or objects in I/II overlap region for IRAC and MIPS colors; SED fitting done only for sources with [24] data.

**Table 3**

| SED Best-fit YSO Models for IRAC–MIPS Sources | ID | Model No. | Inclination Angle (°) | \( A_V \) (mag) | Stellar Mass \( M_\star \) (\( M_\odot \)) | Envelope Accretion Rate \( \dot{M}_e \) (\( M_\odot \) yr\(^{-1}\)) | Disk Mass \( M_d \) (\( M_\odot \)) | YSO Stage |
|----------------------------------------------|----|-----------|-----------------------|-----------------|---------------------------------|---------------------------------|-----------------|-----------|
| G18-1                                        | 3008766 | 18.19     | 14.52                 | 3.16            | \( 8.25 \times 10^{-3} \)        | \( 7.50 \times 10^{-2} \)        | I               |
| G18-2                                        | 3009923 | 49.46     | 12.28                 | 7.72            | \( 4.59 \times 10^{-4} \)        | \( 1.89 \times 10^{-1} \)        | I               |
| G18-3                                        | 3002489 | 81.37     | 9.75                  | 4.15            | 0                                | \( 6.65 \times 10^{-4} \)        | II              |
| G18-4                                        | 3012453 | 81.37     | 45.36                 | 5.77            | 0                                | \( 1.03 \times 10^{-2} \)        | II              |
| G18-5                                        | 3014840 | 81.37     | 8.89                  | 4.39            | 0                                | \( 5.68 \times 10^{-3} \)        | II              |
| G18-9                                        | 3003037 | 49.46     | 22.31                 | 6.90            | 0                                | \( 2.98 \times 10^{-8} \)        | III             |
| G19-3                                        | 3012136 | 18.19     | 13.20                 | 3.41            | \( 1.27 \times 10^{-3} \)        | \( 1.41 \times 10^{-2} \)        | I               |
| G19-4                                        | 3002683 | 81.37     | 12.81                 | 4.37            | 0                                | \( 3.66 \times 10^{-3} \)        | II              |
| G19-5                                        | 3014289 | 75.52     | 28.43                 | 7.65            | 0                                | \( 1.04 \times 10^{-1} \)        | II              |
| G19-6                                        | 3018962 | 18.19     | 5.11                  | 4.55            | 0                                | \( 1.39 \times 10^{-3} \)        | II              |
| G19-7                                        | 3010932 | 18.19     | 14.35                 | 7.51            | \( 4.38 \times 10^{-4} \)        | \( 7.37 \times 10^{-3} \)        | I               |
| G19-8                                        | 3008529 | 41.41     | 6.19                  | 2.66            | \( 3.26 \times 10^{-5} \)        | \( 9.28 \times 10^{-2} \)        | I               |
| G19-9                                        | 3015777 | 41.41     | 16.34                 | 4.93            | \( 9.86 \times 10^{-7} \)        | \( 4.52 \times 10^{-2} \)        | II              |
| G19-14                                       | 3017501 | 75.52     | 16.34                 | 8.84            | 0                                | \( 5.09 \times 10^{-2} \)        | II              |
| G19-17                                       | 3013269 | 18.19     | 5.34                  | 2.14            | \( 3.13 \times 10^{-3} \)        | \( 5.09 \times 10^{-3} \)        | I               |
in more detail, and will examine the potential relationship of the IRDC with W 39.

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