

Low and High Mass Star Formation in the W3, W4, and W5 Regions

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Abstract. Since their discovery, the W3, W4, and W5 regions have been extensively studied from multi-parsec down to 100 AU size scales. W3 contains one of the richest and best studied populations of young, deeply embedded massive stars within 2 kpc of the Sun. W4 is one of the nearest examples of a galactic superbubble powered by the winds and supernovae of OB stars. W3 and W5 contain new generations of star formation that appear to have been triggered by previous generations of OB stars. Although these regions have been primarily studied as sites of massive star formation, more recent work has also established the presence of thousands of young, low-mass stars. In total, these regions form an excellent laboratory to study the formation and early evolution of massive stars, the relationship between low- and high-mass star formation, and the role of feedback in regulating star formation.

1. Introduction and Overview

W3, W4, and W5 (hereafter W3/4/5) comprise an extensive complex of molecular clouds, HII regions, and star-forming regions in the Perseus spiral arm of our Galaxy. They were first identified in a 1390 Hz survey of the Galaxy made with the 25-m telescope at Dwingeloo (Westerhout 1958). W3/4/5 were identified as the third, fourth and fifth discrete sources in the survey, which in fact traced the radio continuum emission from the numerous compact and extended HII regions in each of these regions. Westerhout (1958) cross identified these with the optically visible nebulae IC 1795 (W3), IC 1805 (W4), and IC 1848 (W5) (Fig. 1).

Surrounding these regions is an extensive complex of molecular and atomic gas detected in wide field HI and CO mapping. W3 appears to be the most active region of ongoing star formation in the complex; this region is associated with a 70,000 $M_{\odot}$ giant

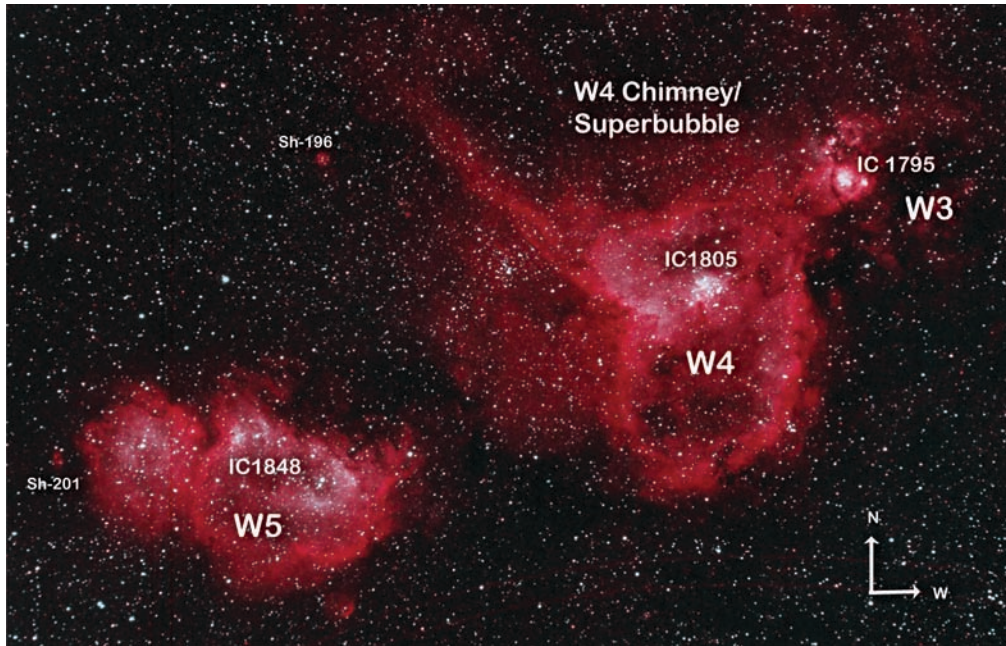


Figure 1. Optical image of the W3/4/5 region. The nebulae and clusters discussed in this chapter that are visible in this image are labeled. Image courtesy of Richard Crisp.

molecular cloud (hereafter: GMC, Lada et al. 1978). W4 contains a 40 pc diameter bubble; this region has been largely cleared of atomic and molecular gas by the OB stars within W4. Numerous small molecular clouds and globules remain in the region, including a $3500 M_{\odot}$ cometary cloud with a 31 pc tail generated by the interaction of the cloud with OB stars (Heyer et al. 1996a,b, Fig. 2). The W3 GMC forms the eastern edge of the W4 bubble (Fig. 3); the region of the GMC adjacent to the bubble (containing W3 Main, W3(OH), and AFGL 333 and showing the brightest emission in CO) is referred to as the W3 *high density layer* (HDL). W5 also shows a spectacular bubble, with three individual molecular clouds containing a total of $4 \times 10^4 M_{\odot}$ bordering the northern edge of the bubble (Figs. 2 & 3, Karr & Martin 2003). In total, the W3/4/5 region appear to form a coherent 200×70 pc complex which is relatively isolated in the sky.

2. The Distance to W3/4/5

The distance to the W3 region is known to great accuracy from VLBI parallax observations. VLBI measurements of the parallax of CH_3OH masers associated with the W3(OH) region give a distance of 1.95 ± 0.04 kpc (Xu et al. 2006). Complementary parallax measurements of H_2O masers associated with W3(OH) give a distance of 2.04 ± 0.07 kpc (Hachisuka et al. 2006). *Thus the maser parallax measurements agree within 1 sigma and point to a distance of 2 kpc for the W3 region.* In the literature, distances of 2.2 to 2.35 kpc are commonly used; these were derived from the spectroscopic parallax to the Cas OB6 association, including IC 1805 and IC 1795

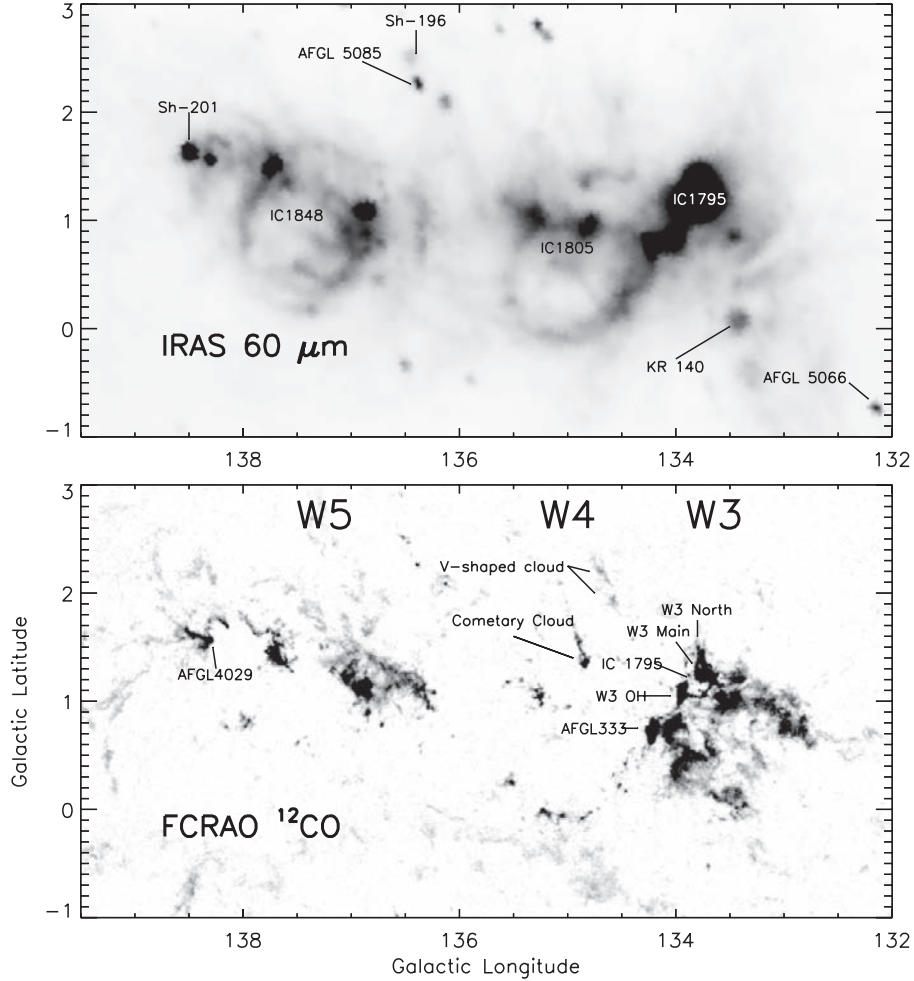


Figure 2. The morphology of the W3/4/5 complex. The upper panel is the IRAS 60 μm map. The bottom panel is the Five Colleges Radio Astronomy Observatory (FCRAO) ^{12}CO ($1 \rightarrow 0$) map integrated over -35 to -50 km s^{-1} (Heyer & Terebey 1998). The major star-forming regions and optical nebulae are labeled. Molecular gas is associated with each of the three components of the complex. The most massive molecular cloud is in W3. The most active region of ongoing star formation in the entire complex is found in the section of the W3 cloud adjacent to W4 containing W3 North, W3 Main, W3(OH), and AFGL 333; this region is referred to as the high density layer (HDL). W4 contains what appear to be remnants of a larger cloud, including a cometary cloud, the molecular component of the V-shaped cloud seen in HI, a small cloud at $l = 135.2^\circ, b = 1.1^\circ$, and a small arc of clouds at the southern edge of the W4 superbubble. The northern edge of W5 is defined by a complex containing three main clouds.

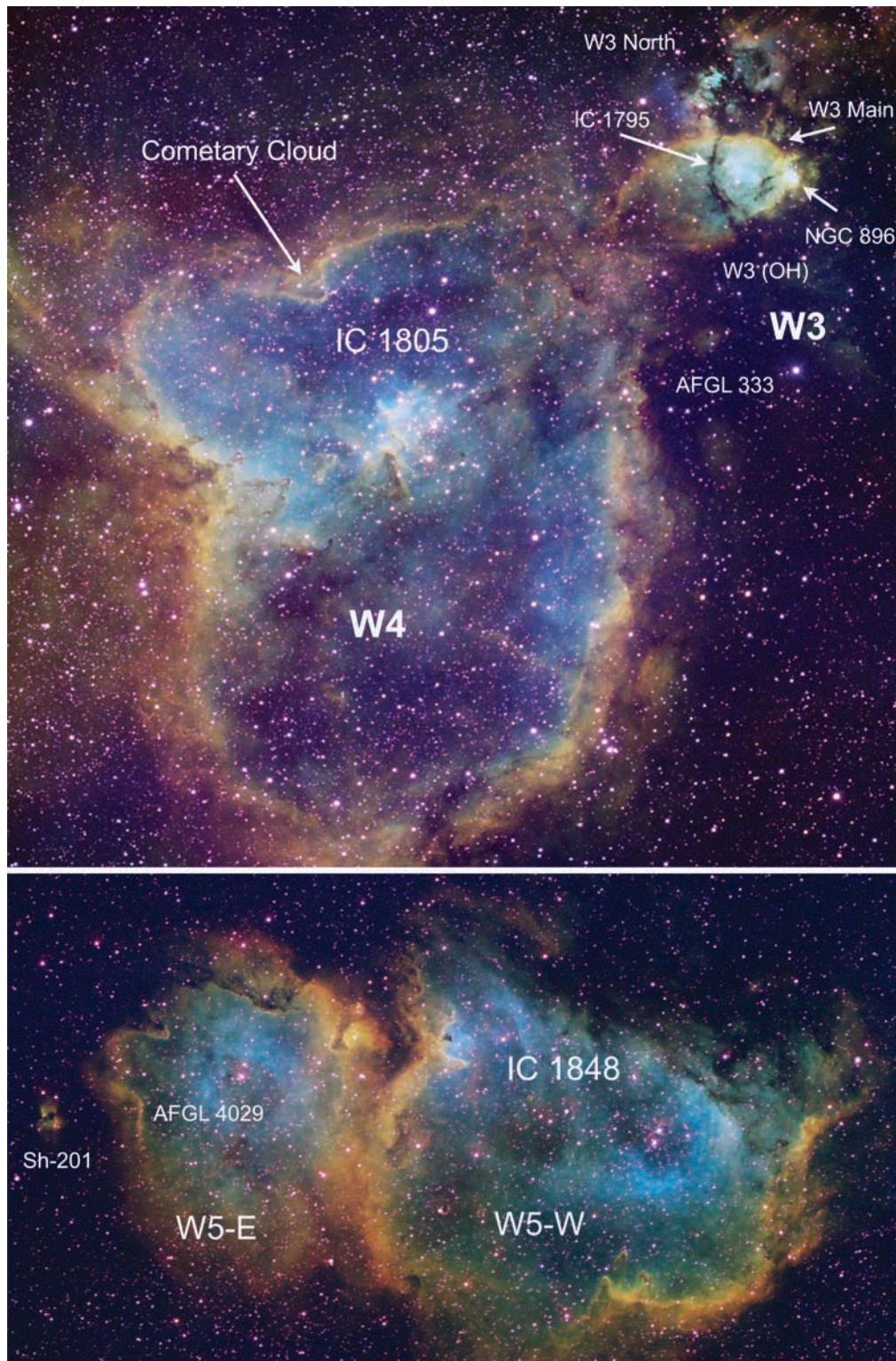


Figure 3. Combined [SII], $H\alpha$ and [OIII] images of the W3, W4 and W5 regions, including IC 1795, IC 1805 and IC 1848. Image courtesy of Richard Crisp.

(Georgelin & Georgelin 1976; Humphreys 1978; Massey et al. 1995). A distance of 1.83 ± 0.14 kpc, which was derived from kinematic models of the proper motions of H_2O masers in outflows, has also been used (Imai et al. 2000). These distances are discrepant with the kinematic distances of 3.5 to 4 kpc derived from the radial velocities of the molecular clouds (Heyer & Terebey 1998); this discrepancy is probably due to deviations from the Galactic rotation law in the Perseus spiral arm.

Since W4 is clearly adjacent to W3, this distance applies to W4 as well. The ^{12}CO maps presented by Heyer & Terebey (1998) show that W3/4/5 form a contiguous structure in both spatial projection and velocity, suggesting that W5 is also at the same distance. Determinations of the spectroscopic parallax of IC 1848 give a distance of 2.2 kpc, similar to the distance found for Cas OB6 and IC 1805 using the same technique (Becker & Fenkart 1971; Moffat 1972; Georgelin et al. 1973). The detection of H_2O and CH_3OH masers in W5 promises that future VLBI observations may measure the parallax of this region (Churchwell 1990; Lyder et al. 1997).

In this chapter, we have scaled all masses, luminosities, sizes, and values of N_{lyc} to a distance of 1.95 kpc for the entire W3/4/5 complex.

3. The OB Associations and their Interaction with the ISM

3.1. W3

The W3 star-forming region encompasses a number of sub-regions within a $70,000 M_{\odot}$ molecular cloud, including W3 North, W3 Main, and W3(OH). The molecular cloud has a shell morphology, with the optical regions IC 1795 and NGC 896 located in the hollowed cavity within the shell (Fig. 3). The first broadband photometry of the IC 1795 and NGC 896 field was carried out by Sato (1970), and followed by Ogura & Ishida (1976). Both of these *UBV* studies were based on a combination of photographic and photoelectric measurements. More recently, Oey et al. (2005) obtained deeper CCD photometry in the same bands for a total of 399 stars, as well as 19 spectroscopic classifications.

The central dominant star in IC 1795 is BD +61° 411, classified as O6.5 V((f)) by Mathys (1989). Three other OB stars within the molecular cavity were confirmed by Oey et al. (2005), classified as O9.7 Ia, B1–2 V, and B2 V. Note that Sato (1970) gives inferred OB spectral types for many stars in the region that are not otherwise spectroscopically confirmed, as is necessary for secure identification of these early types (Massey 1985). As an example, Sato star #67 was inferred to be of type O5, but spectroscopically turns out to be B1 V. For the stars within the cavity by projection, Oey et al. (2005) construct an H-R diagram, which yields an age of 3–5 Myr based on evolutionary tracks by Schaller et al. (1992). Another B1 V star, #3018 from Oey et al. (2005), is located outside the west boundary of the cavity, which is seen as a wall of extinction in optical images. NGC 896 is a brighter nebular region adjoining IC 1795 to the west; this region does not show a well defined concentration of stars. Oey et al. (2005) confirm an O8–O8.5 V star, #10032, on its northern side. To the north and south of IC 1795 are the embedded OB stars in the W3 Main and W3(OH) regions (see Fig. 4); these will be discussed in Section 4.

The only other spectroscopically confirmed OB stars in W3 are associated with W3 North: Oey et al. (2005) #7044, a substantially obscured O6 V star, and 9th-magnitude BD +61° 412, considered a foreground B6 V by Guetter & Vrba (1989).

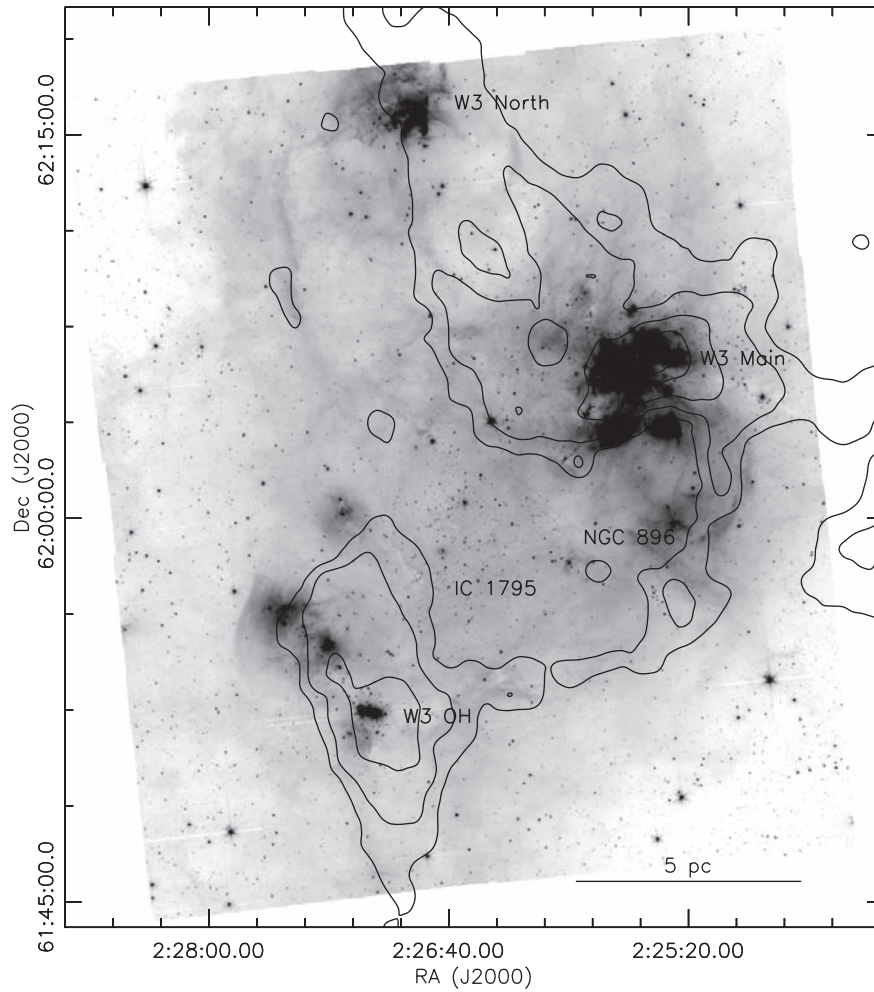


Figure 4. The *Spitzer* image of IC 1795. Above is the $4.5\ \mu\text{m}$ image of the W3 molecular cloud centered on the IC 1795 region (Ruch et al. 2007). The contours are velocity integrated ^{12}CO temperature from the FCRAO map (Heyer & Terebey 1998). The W3 Main and W3 North regions are visible to the top, and the W3(OH) region is found near the bottom.

3.2. W4

The W4 region has the configuration of a large shell, roughly $1^\circ \times 1.5^\circ$ in angular size, with a bright nebulosity associated with the central OB association/Galactic cluster, IC 1805 (also known as OCL 352, Collinder 26 and Melotte 15; see Figs. 1, 2 & 3). A wider distribution of OB stars, Cas OB6, associated with the entire W3/4/5 region, is often considered to be largely coincident with IC 1805. There have been numerous studies of IC 1805 and Cas OB6, beginning with the work of Ishida (1969, 1970). Individual luminous stars were also identified and classified in work by Hoag et al. (1961), Hoag & Applequist (1965), Walborn (1972, 1973), and Shi & Hu (1999). Analyses of the basic properties of IC 1805 (age, size, and IMF) are provided by Ninkov et al.

(1995) and Guetter & Vrba (1989). The most definitive work on this region to date is by Massey et al. (1995), although our total knowledge of the stellar population must be considered cumulative. Massey et al. (1995) identify 24 stars with masses $> 10 M_{\odot}$ including nine stars with O spectral types; the ages of these stars range from 1-3 Myr. Although IC 1805 has a radius ≥ 18 pc, the O stars and half of the early B-stars are within a 10 pc radius (Fig. 5, Guetter & Vrba 1989). Hillwig et al. (2006) and De-Becker et al. (2006) obtained time-resolved spectroscopy for six of the O-stars in W4 and found that two are binaries (BD+60° 497 and HD 15558).



Figure 5. The IC 1805 cluster at the center of W4 as seen in a color composite of broadband images obtained at the Canada-France-Hawaii Telescope. Courtesy Jean-Charles Cuillandre.

W4 is of unique interest because it is directly associated with perhaps the best-known candidate for a superbubble blowing out of the Galactic plane, the so-called “Perseus Chimney” (Fig. 6). In this picture, the shell seen in $H\alpha$ images is the inner wall of a bubble which is exposed to ionizing radiation from the OB stars in W4. This structure was first discovered in HI (Normandeau et al. 1996, 1997) and subsequently also identified in $H\alpha$ (Dennison et al. 1997). While the lower part of the bubble ($b = 0^\circ$) is constrained by dense gas (Terebey et al. 2003), the upper part of the bubble appears to be open above $b = 1^\circ$, forming a “U” shaped structure with the diameter at the top of the “U” being 115 pc (Normandeau et al. 1996). The estimated combined mechanical luminosity of the winds from the nine O-stars in IC 1805 is $3 \times 10^{37} \text{ erg s}^{-1}$ (Normandeau et al. 1996); models of the expansion of the bubble adopting this energy input produce a bubble of the observed size in 2.5 Myr (Basu et al. 1999). This age for

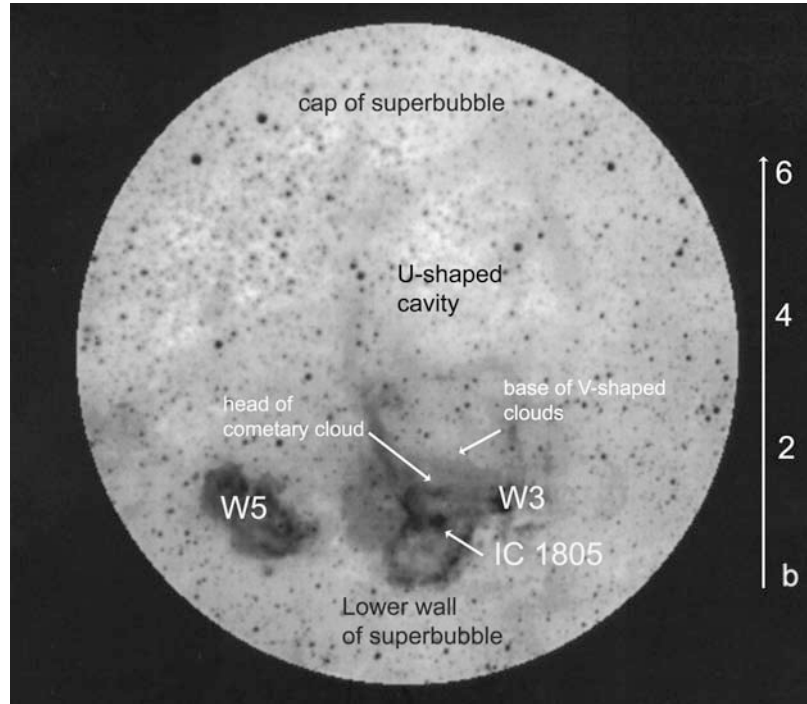


Figure 6. $H\alpha$ image of the W4 supershell; this figure is adapted from Fig. 1 of Dennison et al. (1997). The arrow to the right of the image gives the Galactic longitude in degrees. The shell of $H\alpha$ emission is interpreted as the inner wall of the superbubble. This image and radio continuum maps from West et al. (2007) suggest that the superbubble does not open into a galactic chimney, but is instead capped.

the bubble is consistent with the 1–3 Myr age estimated for the IC 1805 cluster (Massey et al. 1995; Llorente de Andres et al. 1982; Ninkov et al. 1995).

Within this bubble are several small molecular clouds (Fig. 2, Carpenter 2000). One of the two most prominent clouds in the bubble is associated with a V-shaped structure observed in HI, the vertex of which points toward the IC 1805 cluster (Normandeau et al. 1996). The molecular and atomic gas in this structure exhibit a continuous gradient with a total velocity shift of 11.5 km s^{-1} , suggesting that the cloud is being ablated by the winds and UV radiation from the cluster. Assuming that the velocity perpendicular to the plane is higher than the measured line-of-sight velocity, Normandeau et al. (1996) estimate a dynamical age of $< 4 \text{ Myr}$. The other of the two is a $3500 M_{\odot}$ cometary cloud extending 31 pc (Heyer et al. 1996a,b). The morphology of this cloud indicates that it is being shaped by an interaction with the UV radiation from IC 1805; Heyer et al. (1996a) suggest that the long tail is in the shadow cast by the dense cometary head of the cloud. They further argue that the tail may be compressed by the pressure from ambient hot, ionized plasma in the bubble. In addition to the clouds within the bubble, a chain of small clouds is found at the southern edge of the bubble and a cloud is found at the edge of the bubble directly east of IC 1805 (Fig. 2, Heyer & Terebey 1998); these clouds have not been studied in detail. Interestingly, the cloud directly east of IC 1805 is coincident with a kink in the wall of the bubble, suggesting that it may have retarded the bubble's expansion.

Although the size of the bubble suggests that it was created by the winds of the young O stars in IC 1805, there is also evidence for at least one supernova in IC 1805 during the last 2.5 Myr. The high mass X-ray binary LSI +61° 303 is a system consisting of a Be star and a neutron star or black hole (Gregory & Tayler 1978; Bignami 1981; Massi 2004). Based on measurements of the proper motion which show that the binary is moving directly away from IC 1805 (Lestrade et al. 1999), and based on a common distance for the binary and the cluster (Frail & Hjellming 1991; Steele et al. 1998), Mirabel et al. (2004) argued that the binary is a runaway system that was ejected from IC 1805 by the supernova explosion that formed the compact object. They estimate that the runaway is moving at $23 \pm 5 \text{ km s}^{-1}$ (adopting a distance of 1.95 kpc), implying that the supernova occurred $1.7 \pm 0.7 \text{ Myr}$ ago. This supernova would have contributed additional energy to the superbubble. If the progenitor of the supernova was part of the current generation of O stars in IC 1805, the implied short lifetime would require an initial stellar mass much higher than that calculated for the combined mass of the compact object and its remnant. This would imply either that the progenitor lost 90% of its mass before the explosion or that the progenitor may have been formed in an older generation of stars (Mirabel et al. 2004).

As reviewed by Oey et al. (2005), the literature does point to multiple episodes of star formation in the vicinity of W4. From $\text{H}\alpha$ imaging, Reynolds et al. (2001) found a 1200-pc loop of ionized hydrogen emerging off the Galactic plane from about the same location. This structure is thought to be 10–20 Myr old (Reynolds et al. 2001), indicating that it was generated by previous generations of stars. The simulations of Basu et al. (1999) imply an unusually small scale height (25 pc) for the Galactic ISM at this location; West et al. (2007) measure the HI scale height to be $120 \pm 30 \text{ pc}$. Oey et al. (2005) argue that the small scale height apparently required for the current bubble/chimney may result from previous clearing of the ISM by an earlier generation of massive stars. That earlier generation could then be responsible for the larger, 1200-pc loop above the Galactic plane. Carpenter (2000) report many small molecular clouds and globules scattered about the region which they suggest are the remnants of a GMC that was shredded by an earlier episode of star formation.

More recent observations of the 408 and 1420 MHz radio continuum (tracing ionized gas) indicate that W4 may not be a chimney, but a fragmenting superbubble (West et al. 2007). These data detect a faint, filamentary cap over W4 and show the superbubble to have an egg-shaped structure with a width of 135 pc, confirming an initial detection of the cap made in $\text{H}\alpha$ (Fig. 6, Dennison et al. 1997). The bubble extends to a height of 203 pc above the Galactic plane, twice the HI scale height. West et al. (2007) argue that the superbubble has not expanded to a height where it can blow out of the Galactic disk and form a chimney. Based on the models of Basu et al. (1999), they argue that the thin (and apparently fragmenting) upper wall of the superbubble detected in the radio continuum is fully ionized and allows UV radiation to leak through and ionize the HI above the bubble, thus giving the appearance of a chimney in HI maps (also see Terebey et al. 2003). They further argue that the narrow egg shape of the bubble is not due to a small (25 pc) scale height (as proposed by Oey et al. 2005), and they propose that the bubble may be contained by a magnetic field component perpendicular to the Galactic plane. Such a perpendicular component could have been generated by bubbles swept up by previous generations of OB stars.

In summary, although the chimney model for W4 is in question, there is strong evidence that the W4 region contains an elongated superbubble driven by the OB stars

in IC 1805. Furthermore, current explanations for both the elongation of the bubble and the 1200 pc $H\alpha$ loop require previous generations of OB stars which shaped the ISM in W4 over the last 10-20 Myr. Indeed, closer examination of the H-R diagram of IC 1805/Cas OB6 presented by Massey et al. (1995, their Fig. 4) shows the turn-off of an older population. The presence of an older population in W4 can be established by future observations confirming the membership of the stars comprising the turn-off.

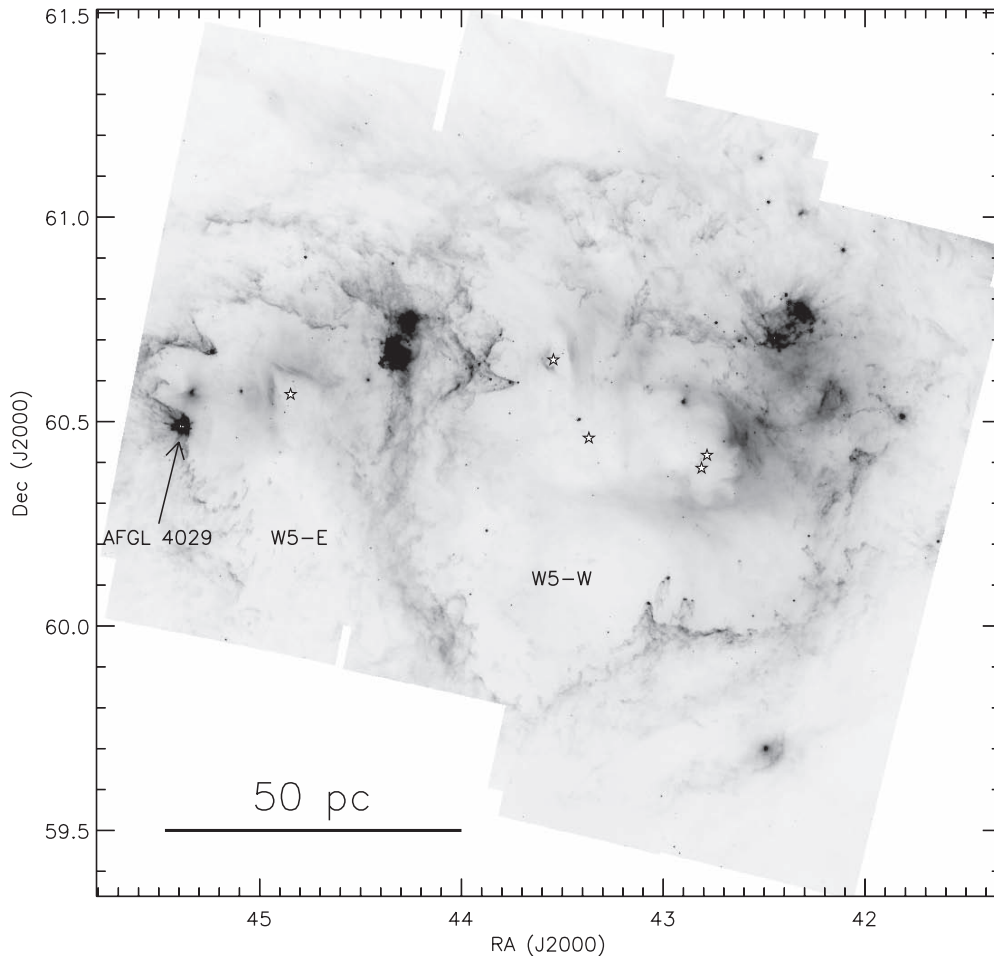


Figure 7. *Spitzer* 24 μ m image of the W5 region (Koenig et al. 2008). The image shows the rim of the bubble in emission, with a bright arc of emission dividing the W5-W and W5-E region. The stars indicate the locations of the five optically visible O stars in the region. Along the edges of the bubbles are numerous bright rimmed clouds and pillars, many of which are in the process of forming stars.

3.3. W5

The W5 region is two degrees east of W4 in Galactic longitude. In contrast to W3 and W4, W5 appears to be physically distinct (Fig. 2). W5 hosts the OB association IC 1848 (also known as OCL 364); the stellar population of this association has not been extensively studied (Fig. 3). The work of Hoag et al. (1961) is again a principal early

resource. Moffat (1972) made a further *UBV* investigation, suggesting that IC 1848 and IC 1805 are indeed physically close and probably indirectly associated. W5 also shows a shell morphology, but no apparent relation to any external blow-outs or superbubbles (Fig. 7, Normandeau et al. 1997). The ionized gas that fills the shell has been divided into two components by Karr & Martin (2003): W5-E and W5-W; these are 35 and 52 pc in diameter, respectively. W5-E contains a single O7V star, BD+59° 0578, which appears to be sufficient to ionize the region (Karr & Martin 2003). In contrast, W5-W contains four O stars: BD+59° 0552 (O6e), BD+59° 553 (O9V), BD+59° 0562 (O8V) and BD+60° 0586 (O7) (Karr & Martin 2003). Karr & Martin (2003) calculated that these four O-stars produce more ionizing photons than required to ionize the HII regions, indicating that the region is not entirely ionization bound. They also suggested that there may be additional, hidden, ionizing stars in the northwestern portion of W5-W. As will be discussed in Section 4, there are embedded objects with luminosities comparable to B stars on the eastern edge of W5, including AFGL 4029 and Sh-201 (see Fig. 3). At least two of the O-stars in W5 are multiple systems: BD+59° 553 is a likely triple system while BD+59° 0552 (O6e) is a quadruple system containing an O6.5 III, an O8.5 V, and two O7.5 V stars (Hillwig et al. 2006).

3.4. The Supernova Remnant HB3

The HB 3 supernova remnant is found 1 degree west of W3. It appears as a diffuse shell in optical images (van den Bergh 1973; Fesen & Gull 1983). Radio continuum measurements are difficult due to the bright radio emission in neighboring W3; however, the continuum maps of Landecker et al. (1987) and Normandeau et al. (1997) at 408 and 1420 MHz, respectively, clearly show the shell. Adopting a distance of 1.95 kpc, the dimensions are 53×70 pc. X-ray data from Einstein and ASCA show diffuse emission filling the shell and a bright ring, 20 pc in diameter, near the center of the shell (Leahy et al. 1985; Seward 1990; Urošević et al. 2007). In an analysis of the 408 MHz continuum, HI, and CO emission toward HB3, Routledge et al. (1991) found that the 408 MHz continuum from the radio shell is enhanced adjacent to a ridge of molecular gas extending from W3. At the velocity of the molecular gas (-43 km s^{-1}) they discovered a thick HI shell which approximately traces the shell as seen in the optical observations. On the basis of this evidence, they argued that HB3 is interacting with the W3 molecular cloud. Further evidence for the interaction was found by Urošević et al. (2007), who analyzed ASCA X-ray spectra and determined that the column density of ionized gas in HB3 is highest near the molecular ridge. They argued that the radio continuum emission contains a component of thermal bremsstrahlung produced in a thin shell; this shell may have been created by the interaction of the remnant with the neighboring molecular cloud.

4. Current High-Mass Star Formation in W3/4/5

Next to Orion, the W3 GMC contains two of the most intensively studied high-mass star-forming regions in the sky. The relative proximity of this cloud and its visibility in the northern hemisphere winter have made it historically a favorite target. There are two primary regions of high-mass star formation in the W3 GMC: W3 Main and W3(OH). In this section, we review the extensive literature on these two regions, with the goal of building a coherent picture of each region. We also briefly discuss the remaining, less studied sites of high-mass star formation in W3/4/5.

4.1. The W3 Main Region

W3 Main is a well known site of high-mass star formation showing one of the richest known clusters of HII regions within 2 kpc of the Sun (Fig. 8). These HII regions appear to be ionized by a recently formed association of OB stars still embedded in their natal cloud (Harris 1976; Colley 1980; Tieftrunk et al. 1997). Tieftrunk et al. (1997) presented a multi-frequency VLA study of these radio continuum sources, identifying a total of ten distinct HII regions ranging from the diffuse HII regions W3H, J, and K, to the compact HII regions W3A, B, and D, to the ultra-compact HII regions W3C, E, F, and G. The VLA observations also detected eight rare hyper-compact HII regions with diameters less than $1''$, or 0.01 pc (regions W3Ma–g and Ca in Tieftrunk et al. 1997). Optical $H\alpha$, [OIII], and [SII] images of W3 Main show a jet of emission from the W3 A region; this HII region appears to be breaking out of the molecular cloud surrounding it (Dickel et al. 1983). Interestingly, interferometer maps of the W3 A region show clumps where the He abundance is enhanced by up to 40% (Roelfsema et al. 1991; Adler et al. 1996). Roelfsema et al. (1991) proposed that these clumps have been enriched by the ejecta from a Wolf-Rayet star, although no Wolf-Rayet stars are currently known in the W3 Main region and its surroundings.

The stars responsible for ionizing the HII regions W3 A, B, E, F, H, J, and K have been identified in imaging at 1–2.2 μm (Hayward et al. 1989; Megeath et al. 1996; Ojha et al. 2004b). In addition to a star with a near-IR luminosity equivalent to an O5 star (W3 IRS 2), W3 A contains three other bright stars with luminosities equivalent to O6–B0 stars, W3 IRS 2a, 2b, and 2c (Hayward et al. 1989; Ojha et al. 2004b). The exciting stars of W3 A, B, E, F, H, K, and possibly the exciting stars of W3 C and G, have been detected in X-rays (with energies > 0.5 keV) by *Chandra* ACIS observations (Hofner et al. 2002; Feigelson & Townsley 2008).

The W3 Main region is also notable for the presence of luminous infrared sources. Near and mid-IR observations show both extended emission from the dust in the HII regions as well as the presence of two luminous, compact infrared sources: IRS 4 and IRS 5 (Werner et al. 1980; Wynn-Williams et al. 1972). These sources have luminosities of $2 \times 10^5 L_{\odot}$ and $6 \times 10^4 L_{\odot}$, respectively (Campbell et al. 1995). W3 IRS 5 is associated with only weak radio emission from the hypercompact HII regions W3 Ma–g. W3 IRS 4 is near the ultracompact HII region W3 C and the hypercompact HII region W3 Ca; it is not clear which of these sources is associated with the infrared source (Tieftrunk et al. 1997). These infrared sources also show many of the classic signposts of star formation: OH masers are found toward IRS 4 and 5 (Gaume & Mutel 1987), H_2O masers are found toward IRS 5 (Claussen et al. 1984), and molecular line observations show a bipolar outflow toward IRS 5 and evidence for an outflow from IRS 4 (Claussen et al. 1984; Mitchell et al. 1992; Choi et al. 1993; Hasegawa et al. 1994).

The molecular gas toward W3 Main is separated into two massive clumps moving at mean velocities differing by 4 km s^{-1} (Jaffe et al. 1983; Hayashi et al. 1989). The two clumps are commonly referred to as the IRS 5 and IRS 4 clumps after the bright infrared sources embedded within them. The masses obtained from molecular line and submillimeter dust continuum observations range from 600 to 1300 $M_{\odot}$ for the IRS 5 clump and 1000 to 2000 $M_{\odot}$ for the IRS 4 clump (Richardson et al. 1989; Hayashi et al. 1989; Oldham et al. 1994; Tieftrunk et al. 1995; Roberts et al. 1997). Higher resolution ($\sim 10''$) mapping in CO and CS isotopomers further resolved the clumps into as many as eight distinct condensations with masses between 50 and 200 $M_{\odot}$ (Tieftrunk et al.

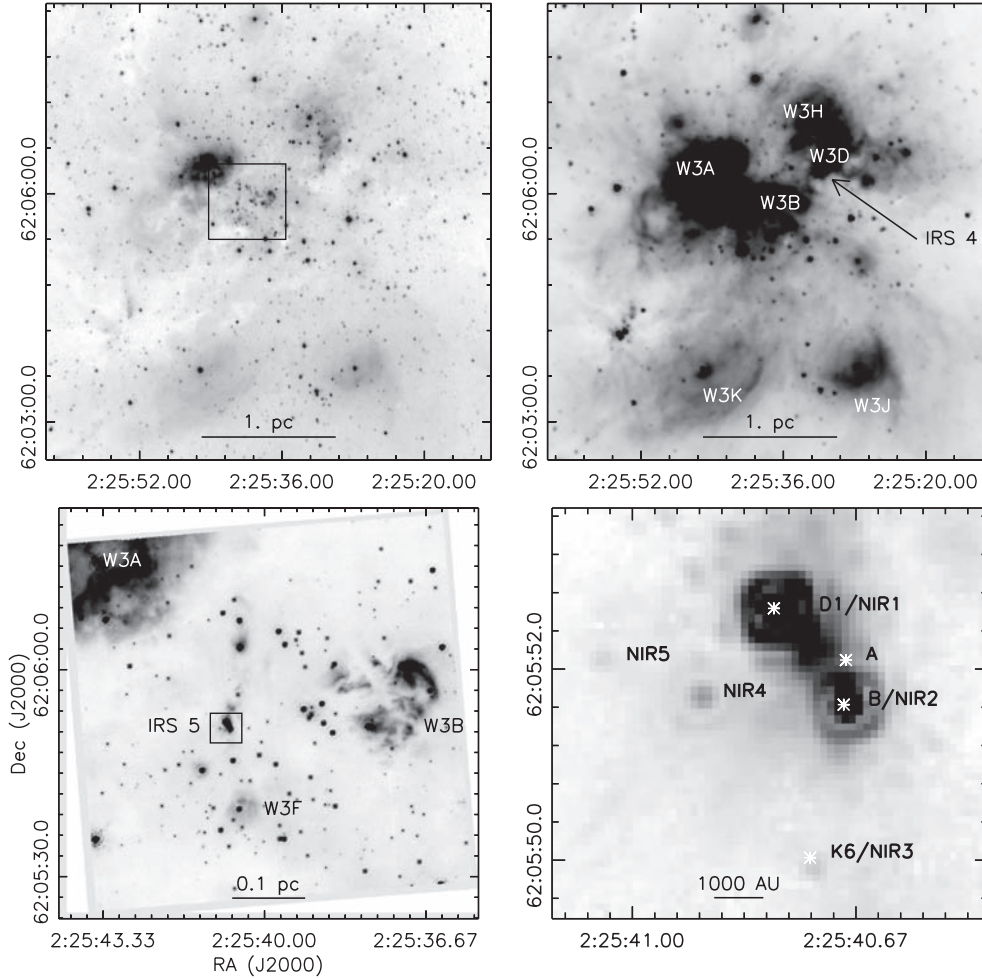


Figure 8. The W3 Main Region. The **upper left panel** is the K' image of the W3 Main Region (Tieftrunk et al. 1998b). The box outlines the field of the HST/NICMOS observations shown in the lower left panel. The **upper right panel** is the *Spitzer* 4.5 μm image of the W3 Main region (Ruch et al. 2007). The main compact HII regions and the luminous infrared source IRS 4 are labeled. The **lower left panel** shows the HST/NICMOS 2.22 μm image of the central part of the W3 Main cluster surrounding the luminous source IRS 5 (Megeath et al. 2005). The (ultra)compact HII regions are labeled and the IRS 5 source is outlined by the box. The **lower right panel** shows the region of the NICMOS 2.22 μm image within the box. The bright double source is IRS 5. The hypercompact HII regions from Wilson et al. (2003) and Van der Tak, Danchi, & Tuthill (2005) are shown by the white asterisks, and are labeled with the notation from Claussen et al. (1994) and Van der Tak, Danchi, & Tuthill (2005). Highly reddened near-IR sources without radio counterparts are also labeled using the notation of Megeath et al. (2005).

1995; Roberts et al. 1997); the volume densities of these condensations range from $0.6 - 1.3 \times 10^6 \text{ cm}^{-3}$. Wide field NH_3 mapping detected a third clump $3'$ southeast of W3 Main; this clump, W3 SE, has a mass of $300 M_\odot$ (Tieftrunk et al. 1998b).

The UV radiation from the massive stars in W3 Main penetrates into the surrounding cloud, heating and photodissociating the surrounding molecular gas. The resulting photon dominated region (PDR) has been observed in lines of CI, CII, and CO. Observations of the CII $158 \mu\text{m}$ line by Howe et al. (1991) showed that the emission extended far beyond the HII regions. Since the production of CII requires UV photons, they argued that the molecular gas must be highly clumped for the UV radiation to penetrate into the cloud. This has been confirmed by Kramer et al. (2004), who combined ISO measurements of high-J infrared transitions of CO, sub-millimeter maps of lower level transitions of CO and ^{13}CO , and maps of the two CI fine structure transitions at 492 GHz and 809 GHz. The data were best fit by models where the CI and high-J CO emission originates in a dense ($n \sim 10^5 \text{ cm}^{-3}$) and warm (100-200 K) component that fills less than 10% of the molecular cloud. Given that the PDR extends throughout much of the W3 Main complex, Kramer et al. (2004) argued that the gas is highly clumped and that the warm gas is found on the surfaces of clumps. The interclump medium would be tenuous, allowing the UV radiation to travel deeply into the cloud. The clumps would have to be small and dense, with typical diameters of 0.025 pc and masses of $0.044 M_\odot$. Direct evidence for the existence of small and very dense molecular clumps is found in $3''$ resolution VLA maps of NH_3 in W3 Main (Tieftrunk et al. 1998a); these show several filaments and clumps with radii of $\sim 0.02 \text{ pc}$ and densities of a few 10^6 cm^{-3} (Fig. 9).

The HII regions in this area are segregated as a function of molecular gas density, with the compact HII regions embedded in moderate density molecular gas surrounding the dense clumps, the ultracompact HII regions found in the higher density gas in the peripheries of these clumps, and the luminous IR sources IRS 5 and IRS 4 and their associated hyper-compact HII regions located towards peaks in the molecular column density within the clumps (Fig. 9, Thronson et al. 1985; Tieftrunk et al. 1995; Roberts et al. 1997). This may be indicative of an evolutionary sequence, with IRS 4 and IRS 5 being the regions of current high-mass star formation. The one known quiescent region in the W3 Main complex is the SMS 3 source which was identified by 450-800 μm mapping (Ladd et al. 1993). This source, which is located south of IRS 4, contains no bright infrared or radio sources. VLA observations of the NH_3 (1,1) and (2,2) transitions toward SMS 3 showed extended emission with comparatively narrow linewidths, consistent with a quiescent core (Fig. 9); however, these observations also show that the 250-340 $M_\odot$ SMS 3 clump is surrounded by four compact clumps with masses $\sim 25 M_\odot$ (Tieftrunk et al. 1998a). These observations suggest that the region has fragmented into multiple clumps that may be the next sites of star formation in the W3 Main complex.

The luminous IRS 5 source appears to be the most active and potentially youngest area of ongoing high-mass star formation in W3 (Helmich & van Dishoeck et al. 1997). A particularly interesting aspect of IRS 5 is its multiplicity. The source was first resolved into a binary source in infrared observations (Howell, McCarthy & Low 1981; Neugebauer, Becklin & Matthews 1982). VLA 1.3 and 2 cm continuum observations by Claussen et al. (1994) detected seven distinct radio continuum sources and a cluster of H_2O masers toward W3 IRS 5; the proper motions of these masers suggest the presence of two separate outflows (Imai et al. 2000). It was not initially clear whether

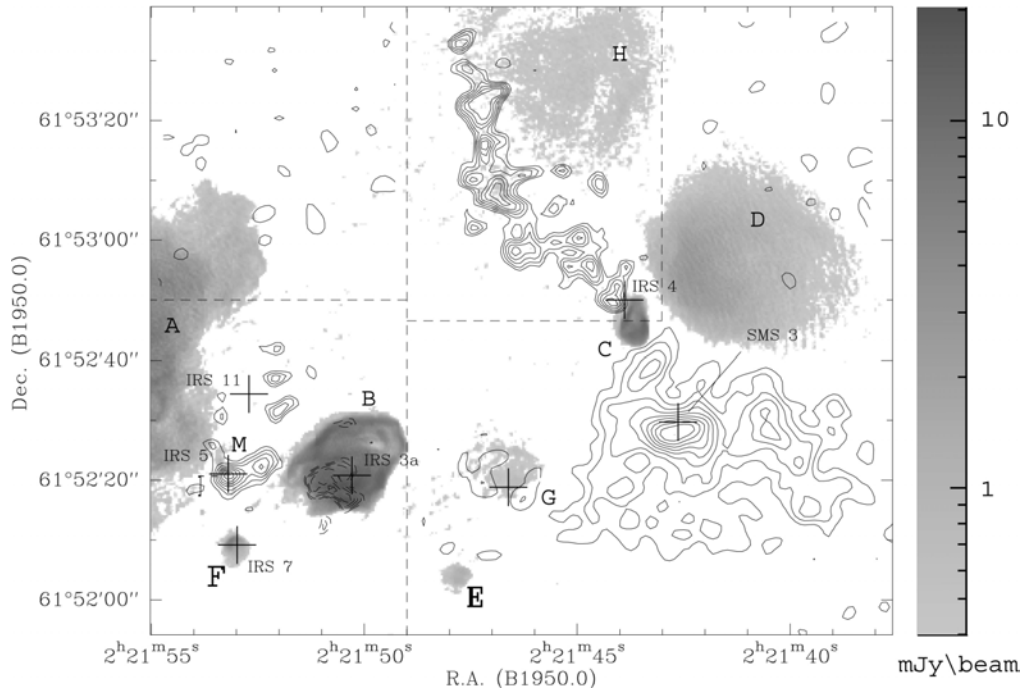


Figure 9. Centimeter continuum and NH_3 maps of W3 Main region made with the VLA. The grayscale image shows the 4.9 GHz continuum while the contours show the velocity integrated NH_3 (1,1) line temperature. The compact and ultracompact regions are labeled A-H and the IRS-3a, 4, 5 and 7 sources are also marked. NH_3 is detected in absorption against the ultracompact HII region W3 B. The submillimeter source SMS 3 source is the most prominent source in the NH_3 maps; this region is also notable for its apparent quiescence. The figure was taken from Tiefrunk et al. (1998a).

the radio continuum sources were HII regions surrounding embedded stars or ionized gas formed by shocks in the observed outflows. Subsequent VLA observations at 0.7 and 1.3 cm by Wilson et al. (2003) and Van der Tak, Danchi, & Tuthill (2005) detected four and seven radio sources, respectively. In total, there are three epochs of high resolution VLA observations of these regions spanning more than 10 years. The separation of two of the radio sources (the D2 and B sources of Claussen et al. 1994) remained unchanged during this time interval. Furthermore, the separation of these two sources is the same as that measured between the infrared double in Hubble Space Telescope $2.22 \mu\text{m}$ observations and Keck $4.7\text{--}11.7 \mu\text{m}$ mid-IR observations, indicating that they contain embedded stars. These two sources appear to be hypercompact HII regions with radii $< 240 \text{ AU}$ (Wilson et al. 2003; Van der Tak, Danchi, & Tuthill 2005). A third radio source discovered by Van der Tak, Danchi, & Tuthill (2005) is coincident with a $2.22 \mu\text{m}$ and mid-IR source; this source also appears to be an embedded star with a hypercompact HII region (Megeath et al. 2005). The remaining sources exhibit 100 km s^{-1} proper motions and/or extreme variability, leading Wilson et al. (2003) and Van der Tak, Danchi, & Tuthill (2005) to suggest that these are formed in shocks within the known outflows. In addition to the three hypercompact HII regions, Megeath et al. (2005) found four additional highly reddened $2.22 \mu\text{m}$ sources within a region 6000

AU in diameter, including two possible companions within 900 AU of one of the hypercompact HII regions. They proposed that these sources constitute a proto-Trapezium, and consequently, these sources will form a non-hierarchical system of closely spaced massive stars similar to the Trapezium found in the Orion Nebula.

4.2. The W3(OH) Region

In comparison to W3 Main, W3(OH) is a less active region of massive star formation (Fig. 10). It is embedded in a 0.5 pc radius core with a total luminosity of $6 \times 10^4 L_{\odot}$ (Mueller et al. 2002), and a mass estimated to range from $600 M_{\odot}$ (Mueller et al. 2002) to $1300 M_{\odot}$ (the combined virial mass of Tieftrunk et al. 1998b). Although first identified by the presence of bright OH masers, W3(OH) has been subsequently resolved into two centers of massive star formation separated by $7''$ (0.07 pc): one dominated by OH masers (Reid et al. 1980; Norris et al. 1981) and one dominated by H_2O masers (Forster et al. 1977). The nomenclature used in the literature for these sources is not entirely consistent: the name W3(OH) is often used for the entire parsec-scale region including both the OH and H_2O maser sub-regions, but it is also used to refer to the small sub-region dominated by the clusters of OH masers.

The OH maser region is the location of a shell-like ultracompact HII region that is only 0.012 pc in diameter (Dreher & Welch 1981). Both the OH masers and a cluster of CH_3OH masers are seen in projection against the HII region (Menten et al. 1988). The properties of the ionizing star, which Dreher & Welch (1981) found to correspond to a main sequence O7 star, need to be re-evaluated. Considering the revised luminosity for the entire W3(OH) region given above and taking into account the $2 \times 10^4 L_{\odot}$ luminosity of the neighboring H_2O maser region, the total luminosity of W3(OH) must be around $4 \times 10^4 L_{\odot}$. This is one quarter of the $1.8 \times 10^5 L_{\odot}$ quoted by Dreher & Welch (1981). The total luminosity and the N_{lyc} estimated from the radio continuum data ($0.8 \times 10^{48} s^{-1}$) both correspond to the values expected for an O9.5 ZAMS star (Hanson et al. 1997). Feigelson & Townsley (2008) detect a deeply embedded ($A_V \sim 75$), hard X-ray source in the HII region; this may be the first direct detection of the exciting star.

The kinematics of this HII region have been studied in exceptional detail, making W3(OH) one of the most extensively studied ultracompact HII regions to date. Kawamura & Masson (1998) detected the expansion of W3(OH) by comparing three epochs of VLA images spanning almost 10 years. They measured an expansion speed of $3\text{--}5 \text{ km s}^{-1}$; this is similar to the expansion velocity of the OH and CH_3OH masers (Bloemhof et al. 1992; Muscadelli et al. 2002). The resulting kinematic age for the HII region is 2300 years. However, the expansion of the shell does not appear to be uniform. Radio wavelength, hydrogen recombination line measurements show an unusual shift in velocity as a function of the principal quantum number (Keto et al. 1995). This shift can be understood as the result of a champagne flow toward the observer, in which the higher principal quantum number transitions (such as $H110\alpha$) trace lower density gas accelerated toward the observer, while the low quantum number transitions (such as $H42\alpha$) trace the higher density gas which has not yet been fully accelerated by the champagne flow (Keto et al. 1995; Sams et al. 1996). Further evidence for a champagne flow is an east-west gradient in the $H92\alpha$ velocity across the HII region; Keto et al. (1995) interpret the gradient as consistent with the gas being accelerated to the east and towards the observer. The champagne flow may explain the “jet” of lower surface brightness emission that extends to the northeast of the source in the centimeter-wave maps (Keto et al. 1995; Wilner et al. 1999). Kawamura & Masson (1998) find that their

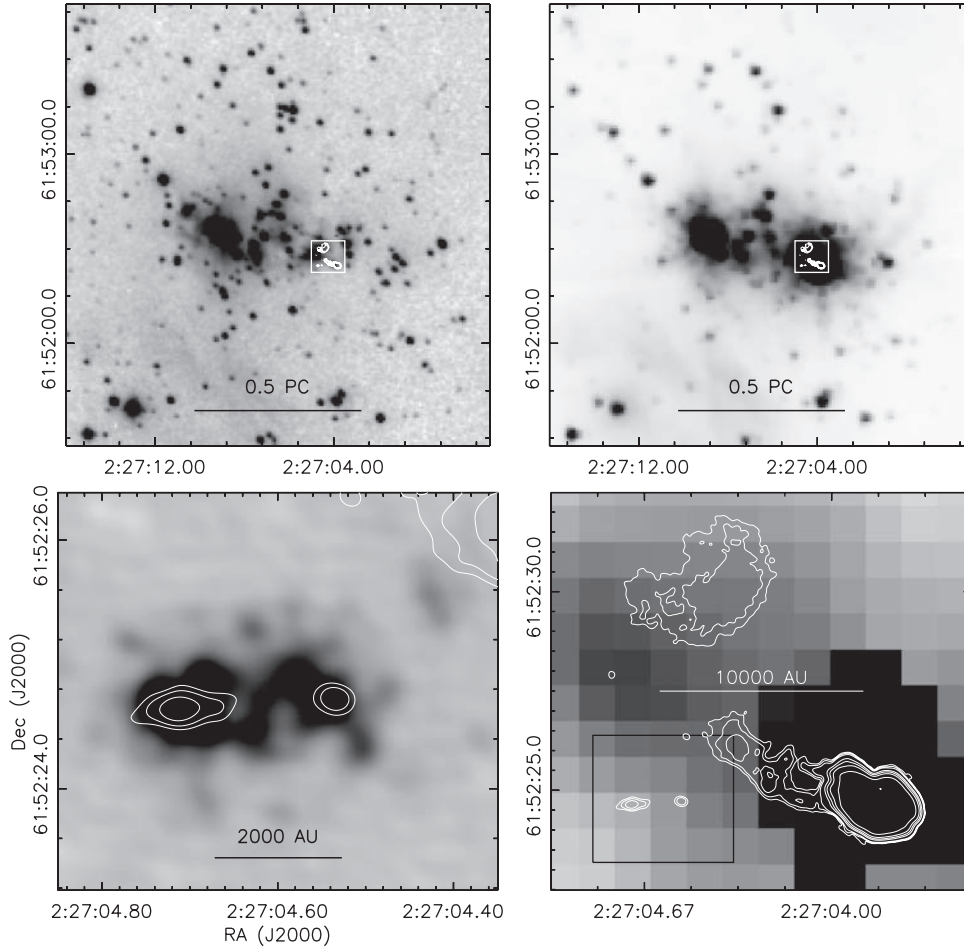


Figure 10. The W3(OH) Region. The **upper left panel** is the K' image of the W3(OH) region and the surrounding cluster. The **upper right panel** is the *Spitzer* 4.5 μm image. The box contains the W3(OH) HII region and H₂O maser region; the contours show the 8.4 GHz map of Wilner et al. (1999). The **lower right panel** shows the region within the box, with the contours showing the VLA 8.4 GHz map and the image the *Spitzer* 4.5 μm map. Note that there is strong infrared emission from the HII region, but not from the H₂O maser region. The box in this panel outlines the H₂O maser region. The region within the box is shown in the **lower left panel**, which displays a BIMA 1 mm map of the H₂O masers with the contours of the 8.4 GHz map overlaid. This shows the proto-binary system proposed by Chen et al. (2006).

data are consistent with a champagne flow in which the observed expansion of the shell is sufficient to continually supply ionized gas for the flow. The champagne flow model is also consistent with observations of the high density molecular gas observed both in emission and absorption against the HII region (Dickel & Goss 1987; Wilson et al. 1991, 1993). The total molecular mass in the high density region surrounding the HII region is less than 3 $M_{\odot}$ (Wink et al. 1994).

To the north of the ultracompact HII region, at the end of the jet, is a diffuse HII region which has not been studied in any detail (Wilson et al. 1993; Wilner et al. 1999). It is not clear if this HII region is ionized by UV radiation escaping from W3(OH) or by a star embedded in that region. Mid-infrared images show bright, compact emission towards the shell-like ultracompact HII region, and weaker, extended emission towards the jet and diffuse HII region (Keto et al. 1992; Stecklum et al. 2002).

In comparison to the OH maser region, the H₂O maser region (hereafter: W3(H₂O)) appears to be in an earlier stage of massive star formation/evolution. Although an HII region is not present, W3(H₂O) does contain a compact mm-wave source showing both compact molecular gas and thermal dust continuum emission (Turner & Welch 1984; Wink et al. 1994; Wilner et al. 1995; Wyrowski et al. 1999; Chen et al. 2006). The continuum source is 4000×2000 AU in diameter in 220 GHz observations and is dominated by two peaks (Wyrowski et al. 1999; Chen et al. 2006). Coincident with the continuum source is a compact CH₃CN emission and NH₃ source (Wilson et al. 1993; Wink et al. 1994). The derived gas temperature above 105 K indicates that the source is a hot core heated by internal sources (Wink et al. 1994; Chen et al. 2006). The total mass of the hot core is about $10 M_{\odot}$ (Wyrowski et al. 1997); however, the molecular gas appears to extend beyond the hot core and as much as $50 M_{\odot}$ may be contained in a 0.05 pc diameter region centered on the core (Wink et al. 1994). The lack of detectable 8.8-17.9 μm emission toward the core indicates that it must be deeply embedded with over 12 mag of extinction at 11.7 μm (Stecklum et al. 2002). The luminosity, temperature, and high extinction observed toward this source, which is referred to as the Turner-Welch object or W3(OH) Hot Core in the literature, suggests that it contains one or more high mass protostars (Wilner et al. 1995). Further evidence for ongoing star formation in the hot core is found in the proper motions of the H₂O masers, which show a roughly bipolar flow away from the hot core (Alcolea et al. 1992). Aligned with this outflow is an elongated, non-thermal centimeter-wave source; this emission may originate in shocks within the outflow (Reid et al. 1995; Wilner et al. 1999).

Similar to the case of W3 IRS 5, high resolution measurements are now providing evidence for multiplicity in W3(H₂O) (Fig. 10). Sub-arcsecond 100 and 200 GHz observations of this region have resolved the hot core into two distinct peaks separated by 2.3×10^4 AU at 1.95 kpc (Wyrowski et al. 1999; Chen et al. 2006). Each of the peaks has a luminosity of $\sim 10^4 L_{\odot}$, equivalent to that of a ZAMS B0–B0.5 star. Sub-arcsecond CH₃CN maps show a velocity gradient in the hot core; Chen et al. (2006) argue that the gradient results from the orbital motions of the two peaks, and they propose that the hot core is a high mass proto-binary system. The minimum required binding mass for the system is $22 M_{\odot}$, more than the combined masses of the two peaks estimated from the thermal dust continuum (4 and $5 M_{\odot}$). However, if the masses of the stars embedded in the peaks are included (likely to be 10–15 $M_{\odot}$ if each peak contains a proto B0–B0.5 star), the total mass would be in excess of the minimum required binding mass.

Although the OH and H₂O regions are separated by only 12,000 AU in projected distance, they appear to have quite different kinematics. Comparison of maser radial velocities and proper motions for the CH₃OH masers associated with the W3(OH) HII region and the H₂O masers for the Turner-Welch object indicate that the two sources are moving at 7 km s^{-1} relative to each other (Hachisuka et al. 2006).

4.3. Other High-mass Star-Forming Regions in W3/4/5

Much less is known about ongoing high-mass star formation in W4 and W5 and in the areas of W3 outside the W3 Main and W3(OH) regions. Carpenter (2000) selected IRAS point sources in the W3/4/5 region with colors and fluxes consistent with star-forming regions. In total 34 sources were identified within a 9×6.5 degree region with luminosities ranging from 6 to 32,000 $L_{\odot}$. In addition to the W3(OH) and W3 Main region, there is one star-forming region with a far-IR luminosity greater than $10^4 L_{\odot}$: the W3 North region. Six additional sources are found with luminosities in excess of $10^3 L_{\odot}$: one in W3 (AFGL 333), three in W5 (these include AFGL 4029 and Sh 201), one in a small cloud to the southeast of W3 (AFGL 5066, see Fig. 2), and one in a small cloud to the north of W5 (AFGL 5085, see Fig. 2). The Sh 201 region may contain a single O6-O8 stars and two B2 stars (based on near-IR magnitudes Ojha et al. 2004a). The source to the north of W5 appears to be in a chain of three small clouds, the most northern of which is associated with the HII region Sh-196 (Figs. 1 and 2). This HII region was not identified in the analysis of Carpenter (2000).

In the southeastern quadrant of the W3 GMC is the small blister HII region KR 140, which is ionized by the O8.5 V(e) star VES735 (Kerton et al. 1999). Immediately surrounding the HII region is a clumpy, 3000 $M_{\odot}$ molecular ring (Ballantyne et al. 2000). In addition to the O star, there is evidence for a small cluster of young stars including two IRAS sources coincident with submillimeter clumps, each with luminosities consistent with B5 V stars, and five highly reddened stars (Kerton et al. 2001).

One of the four massive star-forming regions in W5 has been studied in some detail. This source, often referred to as AFGL 4029, contains two sites of massive star formation detected in mid-IR imaging: IRS 1 and IRS 2 (Beichman 1979; Zavagno et al. 1999). Both sites contain ultracompact HII regions with $N_{Ly\alpha}$ consistent with B1 stars (Panagia 1973; Beichman 1979; Kurtz et al. 1994). The exciting star for IRS 2 was detected in near-IR imaging (Deharveng et al. 1997; Zavagno et al. 1999). The exciting star of IRS1 is deeply embedded, has a $10^4 L_{\odot}$ luminosity, and is associated with a small HII region and reflection nebulosity. The detection of broad optical emission lines towards the reflection nebula suggests that the source is an embedded Herbig Be star (Deharveng et al. 1997). An optical jet is seen extending from this source in [SII] emission (Ray et al. 1990). Other signposts for ongoing massive star formation in AFGL 4029 are a massive molecular outflow and an H_2O maser (Snell et al. 1988; Churchwell 1990).

5. Low Mass Star Formation in W3/4/5

Near-IR surveys of the high-mass star-forming regions in W3/4/5 have revealed numerous clusters of low mass stars. Megeath et al. (1996) detected a cluster of low-mass stars toward the W3 Main region in *J*, *H*, and *K*-band imaging. The densest part of the cluster was surrounding IRS 5, where 80 stars were found in a region $20''$ in diameter. Megeath et al. (1996) also found evidence of an extended halo of young low-mass stars surrounding this central cluster. This halo is apparent in the subsequent near-IR imaging encompassing a 24 arcmin^2 field (Ojha et al. 2004b). Although Megeath et al. (1996) claimed a very young age for this region (~ 0.3 Myr) on the basis of the *K*-band luminosity function, an accurate determination of the age of this cluster awaits spectroscopy of the constituent stars. Many of these low-mass stars were subsequently

detected in *Chandra* X-ray imaging (Hofner et al. 2002; Townsley 2006; Feigelson & Townsley 2008).

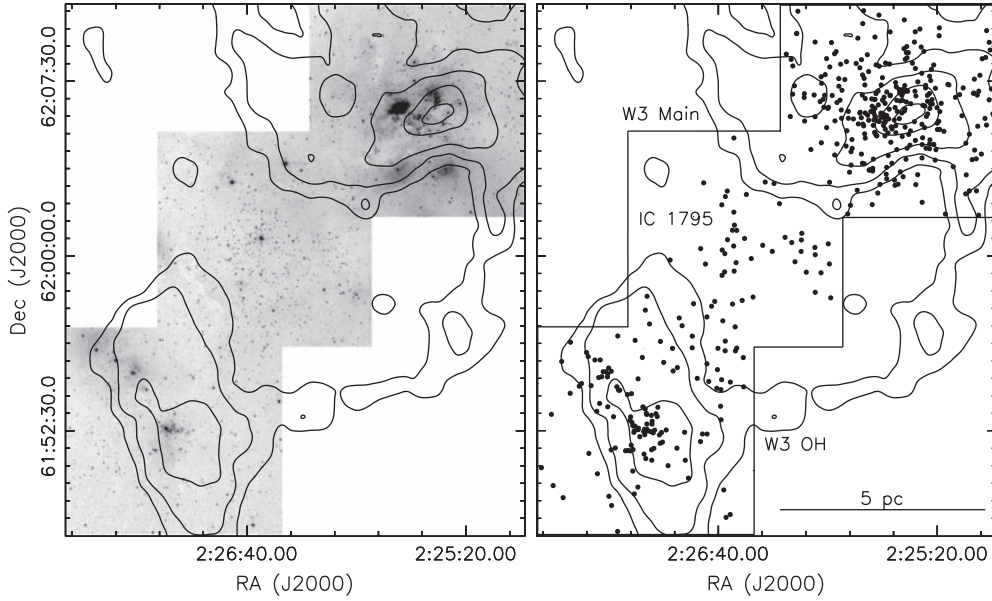


Figure 11. The left panel displays the K' mosaic of the W3 high density layer from Tiefrunk et al. (1998b). The right panel shows the distribution of X-ray sources with K' -band counterparts; the X-ray point sources were identified from *Chandra* observations (Townsley 2006, also see Fig 12). These sources are likely pre-main sequence stars. The outline of the K' -band mosaic is displayed. Note that the *Chandra* data do not completely cover IC 1795 (compare with Fig. 12). In both panels, the contours are the velocity integrated ^{12}CO temperatures (Heyer et al. 1996a,b).

Subsequent K' imaging of the section of the HDL extending from W3 Main to W3(OH) showed two dense clusters, one associated with W3 Main and one with W3(OH) (Fig. 11, Tiefrunk et al. 1998b). *Chandra* imaging of this same region detected clusters of ~ 900 X-ray sources toward W3 Main and ~ 50 X-ray sources toward W3(OH) (Townsley 2006; Feigelson & Townsley 2008). To identify the most likely members in the field covered by both the *Chandra* and K' mosaics, we merged the K' data from Tiefrunk et al. (1998b) with a list of *Chandra* identified X-ray point sources from Townsley (2006) (Figs 11 and 12). Note that the *Chandra* data only covered the western half of IC 1795. These data show that the W3 IRS 5 cluster is much more extended, confirming that the central region surrounding IRS 5 is part of a larger cluster. In total, outside the central $20''$ around IRS 5, 297 sources having both X-ray and K' emission are identified, out to a radius of 3 pc. The K' -band observations detect sources down to 16 mag; however, the histogram of K' magnitudes for the X-ray detected sources peaks at 13.6 mag, and then drops slowly to 15 mag. These magnitudes (13.6 and 15) corresponds to $1 M_{\odot}$ and $0.3 M_{\odot}$, respectively, for a 1 Myr old population at an extinction of $A_K = 0.5$. The actual membership is potentially much larger; both the X-ray observations and the near-IR observations do not detect the lower mass stars, suffer from source confusion in the crowded regions, and can miss deeply embedded objects due to sensitivity limits. Indeed, Megeath et al. (1996) argue that there

are as many as ~ 200 additional low-mass stars in the central core surrounding IRS 5 that are too deeply embedded to be detected in their near-IR observations. Note that the much larger membership for W3 Main (900 stars) quoted by Feigelson & Townsley (2008) is over a region 10 pc in diameter; consequently, this value for the membership may be boosted by contamination from the IC 1795 region and by the inclusion of more isolated young stars surrounding W3 Main.

There is also evidence for young low-mass stars and protostars outside the W3 Main and W3(OH) clusters. The K' image in Fig. 11 shows a less concentrated clustering of stars in the IC 1795 region; this is confirmed by *Chandra* imaging and the combined *Chandra/K*-band analysis above (Townsley 2006, Fig. 11 & 12). In addition to the IC 1795 cluster, two small groups of young stars are apparent to the north-east of W3(OH) in the K' -band and *Chandra* maps (Tieftrunk et al. 1998b; Townsley 2006). Ruch et al. (2007) presented *Spitzer* IRAC 3–8 μm imaging of the region from W3 Main to W3(OH) (Fig. 4). Although the bright infrared emission significantly reduced *Spitzer*'s sensitivity to low-mass stars and protostars in the W3 Main cluster and (to a lesser extent) in the W3(OH) cluster, Ruch et al. (2007) identified an extended cluster of stars with infrared excesses centered on IC 1795. These sources appear to belong to the IC 1795 cluster apparent in the K' -band and *Chandra* maps (this is called the “central cluster” by Ruch et al.). In addition, they find 16 Class I (protostellar) objects and 33 Class II (star+disk) objects which are outside the clusters and are found in either isolation or in small groups. Many of these sources comprise a previously unknown arc of objects to the west of W3 Main and IC 1795; these follow the ridge of CO emission which defines the western boundary of IC 1795 (Fig. 4). Part of this arc is evident at the extreme western edge of the K' image in Fig. 11. Since Ruch et al. (2007) relied on the detection of the objects in all four bands of the IRAC camera on-board *Spitzer*, they were limited by the point source sensitivity in the 8 μm band to the detection of 1 Myr old pre-main sequence stars with masses $\geq 0.5 M_{\odot}$ (using pre-main sequence tracks of Baraffe et al. 1998).

Outside of the portion of the W3 GMC extending from W3 Main to W3(OH), the only comprehensive search for low-mass stars has been targeted near-IR observations of previously identified regions of star formation. Carpenter (2000) obtained K' images of the 34 selected IRAS sources described in Section 4. W3(OH) was one of these 34 sources; W3 Main was not included since it is confused at 60 μm in the IRAS survey and did not satisfy their IRAS selection criteria. Carpenter (2000) examined the surface density of K' -band sources toward 32 of the IRAS sources. Their data were 95% complete at a K' magnitude of 17.5, equivalent to the hydrogen burning limit for a 1 Myr old population with an extinction of $A_V = 10$ (using pre-main sequence tracks of Baraffe et al. 1998). In addition to W3(OH) and W3 Main, they found nineteen clusters with 20 to 240 stars. The largest cluster identified by Carpenter (2000) is that associated with AFGL 4029 in W5, with 240 stars; this is only surpassed in the number of stars by W3 Main. All of the regions with luminosities greater than $2000 L_{\odot}$ showed clusters with one significant exception: the $11000 L_{\odot}$ source W3 North. This has been confirmed by the lack of associated X-ray sources in the *Chandra* data (Fig. 12, Townsley 2006). Thus, W3 North has become a rare example of a presumably young O6 star in a GMC without an associated cluster (spectral type from Oey et al. 2005). Feigelson & Townsley (2008) proposed that it could be a runaway O-star ejected from W3 Main or IC 1795. The lack of associated clusters seems to be more common for the high-mass star forming regions with lower luminosities: the two IRAS sources with luminosities between 1000 – $2000 L_{\odot}$ do not show clusters.

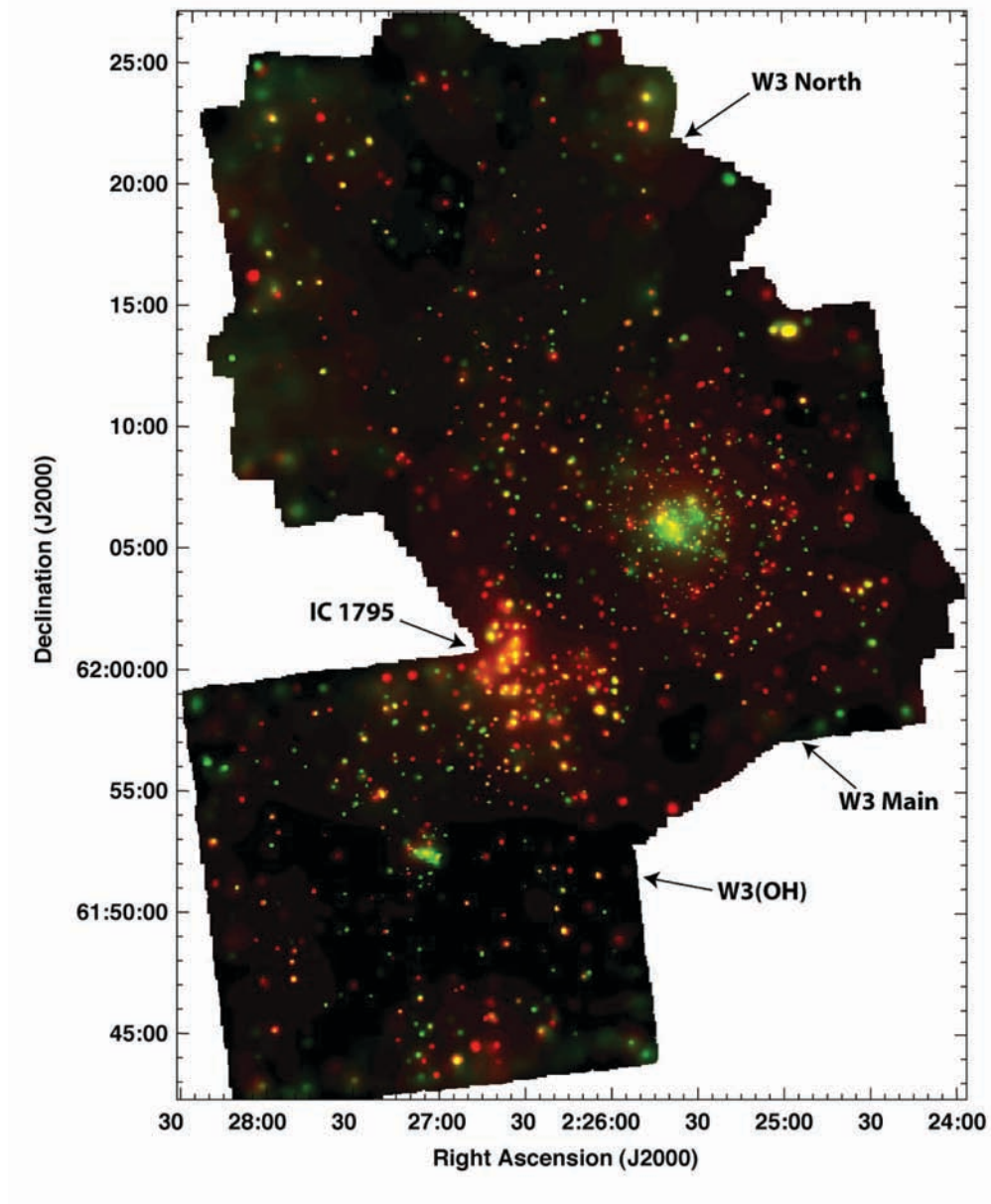


Figure 12. Chandra X-ray images of the section of the W3 HDL extending from W3 North to W3 OH made with three pointings of the ACIS-I instrument (each $17' \times 17'$) centered on W3 North (top), W3 Main (middle), and W3(OH) (bottom). The red color shows soft X-rays (0.5–2 keV) while the green color shows hard X-rays (2–7 keV). Image taken from Feigelson & Townsley (2008)

Using the Carpenter (2000) values for the number of young stars in every region except W3 Main (giving 1595 stars in total) and using the 297 members for W3 Main from our combined K' -band/*Chandra* analysis, we find a total of 2092 young stars identified in clusters in the W3/4/5 complex. Although an analysis of the mass function has not been performed, these clusters are likely dominated by low-mass stars (Megeath et al. 1996). Approximately 60% of these stars are found in the seven large clusters with over 100 members. The current census is likely to be far from complete. The surface density criteria used by Carpenter (2000) may exclude stars in low surface density halos around young clusters, while the combined *Chandra* and K' survey of W3 Main is not sensitive to the most deeply embedded sources or to very low-mass stars. Furthermore, as indicated by the *Spitzer Space Telescope* observations of Ruch et al. (2007), a significant number of relatively isolated, young, low-mass stars may be present which have not been observed and/or identified by the existing surveys of this complex. These would include stars that formed in isolation, as well as stars that formed in clusters which have begun to disperse, such as the low-mass stars found in IC 1795. For the IRAS sources with luminosities of 6–830 $L_{\odot}$ (corresponding approximately to 1–5 $M_{\odot}$ sources using the tracks of Palla & Stahler 1993), 12 out of 24 have clusters. The remaining 12 IRAS sources show no evidence for dense clusters of stars; however, they still may have small groups of stars. These remaining 12 include sources spread throughout the complex, indicating the presence of a more distributed mode of star formation which has not been well characterized in existing studies.

6. Evidence for Triggered Star Formation

The W3/4/5 regions have long been claimed to be the sites of triggered star formation. Large scale CO maps of the W3 GMC show the HDL, a prominent ridge of emission facing the W4 region (Fig. 2). Lada et al. (1978) proposed that the HDL was a layer of gas swept up by the expanding W4 HII region, thus triggering the current epoch of star formation in W3. Subsequent ^{13}CO maps showed a radial velocity shift between the HDL and the more diffuse molecular gas to the west of the layer (Thronson et al. 1985). However, there are a number of observations which complicate this simple interpretation. First, the sign of the velocity shift changes: the southern part of the HDL is blueshifted relative to the more diffuse gas while the northern part is redshifted (Thronson et al. 1985). Furthermore, the maps also show that the layer is not continuous, but is broken in the center where the OB stars in IC 1795 appear to have cleared out the gas (Thronson et al. 1985; Tiefrunk et al. 1998b, also see Figs. 2 & 4). Finally, the three regions of ongoing or recent star formation in the HDL appear to be in different evolutionary stages, with W3(OH) as the youngest region and IC 1795 as the oldest.

More recently, Oey et al. (2005) argued that the W3/W4 complex shows an apparent series of three generations of hierarchical, triggered star-forming events. The original star formation event in W4, 6–10 Myr ago, must have been energetic, as evidenced by the 1200 pc extraplanar loop. A second event generating the current superbubble may have happened as recently as 2.5 Myr ago (see discussion in Section 3.2). These events could have swept up the gas into the shell of molecular, atomic and ionized gas seen around W4 (Fig. 2). Molecular clouds formed in this shell may have been subsequently compressed by UV radiation, stellar winds, and supernovae, all of which would have varied with time as multiple epochs of massive stars formed in the bubble and then evolved off the main sequence. In total, the long and active period of star formation in

W4 could have triggered the formation of IC 1795 in the W3 molecular cloud about 3–5 Myr ago.



Figure 13. The W5-NE region. The bright star at the center of the image is BD +60°596, a B1V star ($V \sim 9.7$). The displayed field is about $12' \times 12'$, with north up and east left. W5-NE is located on the northern end of the dark ridge of material separating W5-E and W5-W (Fig. 3). It is the site of recent and ongoing star formation and includes a cometary cloud and a cavity around BD +60°596. The young variable LW Cas (sometimes erroneously considered a cataclysmic variable) is located here. Wilking et al. (1984) mapped W5-NE at far-infrared wavelengths and detected an IR source, IR-2. The combined [OIII], $H\alpha$, [SII] image is courtesy of Ken Crawford.

Mechanical and radiation feedback from IC 1795, in turn, could have generated the smaller W3 molecular shell. The embedded regions of the third and current generation of star formation, W3 Main and W3(OH), appear to have formed in this shell. Examples of two-generation sequential star-forming events associated with superbubbles are commonplace, and often cited as evidence of triggered star formation. However,

sequential events are not necessarily causally related. The three-generation example seen in the W3/W4 system is much stronger evidence of a causal relationship, since the spatial configuration of the third-generation triggered events appear to be linked only to the shell morphology resulting from IC 1795, and otherwise unrelated to W4. There remain, however, lingering uncertainties about the triggered star formation scenario. While Feigelson & Townsley (2008) agree with Oey et al. (2005) regarding the triggering of W3(OH) and the small clusters near W3(OH) by IC 1795, their Chandra data show that W3 Main is a large, spherical, centrally-condensed cluster that does not appear to be the result of a simple collect-and-collapse process due to a passing shock from IC 1795.

Residual triggered star formation may also occur in the small molecular clouds and globules which remain in the W4 bubble and in the wall of the bubble. The cometary head of the 31 pc long cloud in W4 contains a $800 L_{\odot}$ IRAS source (02310+6133, Heyer et al. 1996a) and several young stars with $H\alpha$ emission (associated with cloud 7 in Ogura et al. 2002); the star formation here may have been triggered by the ionization front driven compression of the cloud (Heyer et al. 1996a). Another possible candidate is in an isolated molecular cloud on the southeastern wall of the W4 bubble; in this cloud, Carpenter (2000) find a $190 L_{\odot}$ IRAS source (02327+6019) and a small cluster of 20 sources. The position of this cloud on the wall of the bubble suggest that it may have been compressed by the ionizing radiation and winds from IC 1805. A small group of $H\alpha$ emission stars and an IRAS source (02252+6120) are found in a bright rim cloud on the eastern edge of W4 (Ogura et al. 2002). The interaction of the W4 clouds with IC 1805 may also lead to the formation of very low mass objects. The cloud on the edge of the bubble directly east of IC 1805 is associated with seven small “globulettes”: 2000 AU diameter globules with estimated masses of only 3-250 M_J (Gahm et al. 2007). They are probably formed by the erosion of the cloud by the UV radiation from IC 1805. Gahm et al. (2007) suggest that the globulettes could form low mass brown dwarfs or planetary mass objects.

In the molecular cloud complex along the edge of the W5 bubble that surrounds IC 1848, only one of the five known star-forming sites is recessed inside the cloud complex (Wilking et al. 1984; Carpenter 2000; Karr & Martin 2003). Based on this observation, as well as kinematical evidence for shock acceleration from the ^{13}CO line profiles, Wilking et al. (1984) and Karr & Martin (2003) argued that star formation in W5 is being triggered by the expanding IC 1848 HII region. Many of the bright rimmed clouds in W5-W and W5-E harbor small groups of $H\alpha$ emission stars, further evidence of triggered star formation (Ogura et al. 2002, see also Fig. 13). The most dramatic example of this is AFGL 4029 (Fig. 3). Recent *Spitzer* imaging of this region shows two massive bright rimmed clouds protruding into the bubble (Allen et al. 2005; Morgan et al. 2004). The *Spitzer* 3–8 μm images show Class I/0 objects clumped near the edges of the bright rimmed clouds, and Class II objects outside the clouds extending into the HII region (Fig. 14). These are suggestive of a wave of star formation progressing into the cloud driven by the photoevaporation of the molecular gas. Support for such a sequence is found in recent optical photometry of $H\alpha$ emission stars in the W5-E region (Nakano et al. 2008). These data show that the low mass stars in the center of the W5-E shell are systemically older than the stars near the bright rimmed clouds.

Interestingly, the distribution of star-forming regions in W3 and W5 seems distinctly different. In W3, the young stellar clusters and massive protostars appear recessed within the molecular clouds. Although the HDL that contains these star-forming

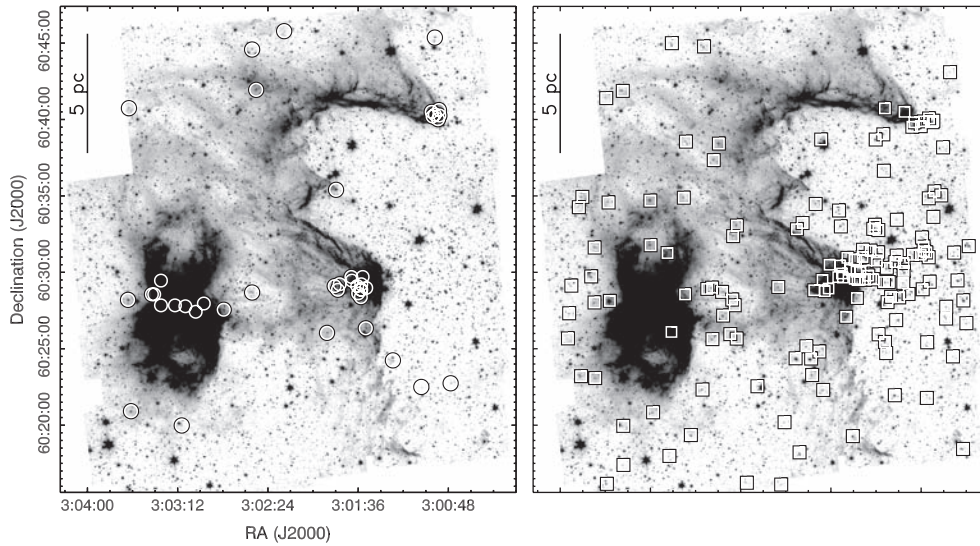


Figure 14. *Spitzer*/IRAC image of the AFGL 4029 Region in W5 (Allen et al. 2005). These are $8\ \mu\text{m}$ images encompassing three star-forming regions; the circles in the left panel are *Spitzer* identified protostars (Class I/0 objects), the squares in the right panel are identified as young stars with disks (Class II objects). The largest cluster is seen toward AFGL 4029, which is the most southern of the two large bright rimmed clouds. The bipolar source to the east is Sh-201.

regions may have been swept up and compressed by expanding superbubbles and HII regions, the current star formation events do not appear to be interacting with previous generations of OB stars (see Fig. 11). A SCUBA $850\ \mu\text{m}$ survey of this region showed that 37–25% of the gas in the HDL is in dense clumps, but only 13–5% of the gas is in dense clumps toward the more diffuse regions of the GMC (Moore et al. 2007). Thus, the compression of the gas in the HDL by W4 and IC 1795 appears to have increased the fraction of dense gas capable of forming stars. The result may be an enhancement in the rate and density of massive star formation relative to the more diffuse regions of the cloud. This is consistent with the fact that the diffuse regions have produced at most only a few massive stars, such as the O star in KR 140. Perhaps, once the cores are formed, the gravity of the most massive cores dominates the ensuing fragmentation and collapse of the gas into clusters; potentially resulting in the centrally condensed morphology observed for W3 Main (Feigelson & Townsley 2008).

In contrast, star formation in W5 is occurring preferentially at the surfaces of the molecular clouds currently exposed to strong UV radiation, i.e. the pillars and bright rimmed clouds protruding into IC 1848 (see Fig. 14). In the case of W5, star formation may be occurring in pre-existing molecular clumps which, as the W5 bubble expanded, have become exposed to the UV radiation from the central O stars. The resulting photoevaporation can compress the clumps, thereby triggering or enhancing star formation.

It is not clear whether the differences between W3 and W5 result from different environmental conditions, such as the density of the ambient gas into which the bubbles expanded or the number OB stars driving the expansion of the bubbles, whether W3 is different due to hierarchical triggering in that region, or whether the two regions represent two different evolutionary phases. Understanding the differences between these

two regions could provide unique insights into the processes that trigger and enhance star formation and mediate the evolution of bubbles around OB associations.

7. Summary

The W3/4/5 complex is a valuable laboratory for studying both the relationship between high and low mass star formation and the interaction of massive stars with the ISM. Observations of this complex are providing an unparalleled view of the feedback of massive stars on the ISM through outflows, ionization, winds, and supernovae. There are several features that make this region attractive. It contains one of the richest assemblages of young high mass stars and massive protostars within 2 kpc of the Sun. It is at a well known distance and appears relatively isolated. Furthermore, its location in the outer Galaxy reduces the amount of line-of-sight contamination; although distant, the lack of contamination facilitates the identification of clusters and groups of low mass stars. Perhaps most importantly, it is a region where we can study star formation over the full range of relevant size scales, from 240 AU diameter hypercompact HII regions, to 40 pc diameter bubbles, and finally to the width of the Perseus spiral arm.

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References

- Alcolea, J., Menten, K. M., Moran, J. M. & Reid, M. J. 1993, in *Astrophysical Masers*, ed A. W. Clegg and G. E. Nedoluha, publ. Springer (Heidelberg), 225
- Adler, D. S., Wood, D. O. S. & Goss, W. M. 1996, *ApJ*, 471, 871
- Allen, L. E., Hora, J. L., Megeath, S. T., Deutsch, L. K., Fazio, G. G., Chavarria, L. & Dell, R. W. 2005, in *Massive Star Birth: A Crossroads of Astrophysics* ed R. Cesaroni, M. Felli, E. Churchwell, & M. Walmsley, publ. Cambridge University Press, 352
- Ballantyne, D. R., Kerton, C. R. & Martin, P. G. 2000, *ApJ*, 539, 283
- Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P. H. 1998, *A&A*, 337, 403
- Basu, S., Johnstone, D., & Martin, P. G. 1999, *ApJ*, 516, 843
- Becker, W, Fenkart, R. 1971, *A&AS*, 4, 241
- Beichman C. 1979, Ph.D. thesis, University of Hawaii
- Bignami, G. F., Caraveo, P. A., Lamb, R. D. et al. 1981, *ApJ*, 247, L85
- Bloemhof, E. E., Reid, M. J. & Moran, J. M. 1992, *ApJ*, 397, 500
- Campbell, M. F., Butner, H. M., Harvey, P. M., Evans, N. J., II, Campbell, M. B. & Sabbey, C. N. 1995, *ApJ*, 454, 831
- Carpenter, J. M., Heyer, M. H., & Snell, R. L. 2000, *ApJS*, 130, 381
- Chen, Huei-Ru, Welch, William J., Wilner, David J., Sutton, Edmund C. 2006, *ApJ*, 639, 975
- Choi, M., Evans N. J., Jaffe D. T., 1993, *ApJ*, 417, 624
- Churchwell, E., Walmsley, C. M., Cesaroni R. 1990, *A&AS*, 83, 119

- Claussen, M. J., Berge G. L., Heiligman G. M., et al. 1984, *ApJ*, 285, L79
- Claussen, M. J., Gaume, R. A., Johnston, K. J., & Wilson, T. L. 1994, *ApJ*, 424, L41
- Colley, D. 1980, *MNRAS*, 193, 495
- DeBecker, M., Rauw, G., Manfroid, J. & Eenens, P. 2006, *A&A*, 456, 1121
- Dennison, B., Topasna, G. A., & Simonetti, J. H. 1997, *ApJ*, 474, L31
- Deharveng, L., Zavagno, A., Cruz-González, I., Salas, L., Caplan, J. & Carrasco, L. 1997, *A&A*, 317, 459
- Dreher, J. W., & Welch, W. J. 1981, *ApJ*, 245, 857
- Dickel, H. R., Harten, R. H., & Gull, T. R. 1983, *A&A*, 125, 320
- Dickel, H. R. & Goss, W. M. 1987, *A&A*, 185, 271
- Feigelson, E. D. & Townsley, L. K. 2008, *ApJ*, 673, 354
- Fesen, R. A. & Gull, T. R. 1983, *PASP*, 95, 196
- Forster, J. R., Welch, W. J., & Wright, M. C. H. 1997, *ApJ*, 215, L121
- Frail, D. A. & Hjellming, R. M. 1991, *AJ*, 101, 2126
- Gahm, G. F., Grenman, T., Fredriksson, S., & Kristen, H. 2007, *AJ*, 133, 1795
- Gaume, R. A., Mutel, R. L. 1987, *ApJS*, 65, 193
- Georgelin, Y. M., Georgelin, Y. P., & Roux, S. 1973, *A&A*, 25, 337
- Georgelin, Y. M. & Georgelin, Y. P. 1976, *A&A*, 49, 57
- Gregory, P. C., Taylor, A. R. 1978, *Nature*, 272, 104
- Guetter, H. H. & Vrba, F. J. 1989, *AJ*, 98, 611
- Hachisuka, K., Brunthaler, A., Menten, K. M., Reid, M. J., Imai, H., Hagiwara, Y., Miyoshi, M., Horiuchi, S. & Sasao, T. 2006, *ApJ*, 645, 337
- Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, *ApJ*, 489, 698
- Hayward T. L., Grasdalen G. L., Woodward C. E., et al., 1989, *ApJ*, 345, 894
- Harris S., Wynn-Williams C. G. 1976, *MNRAS*, 174, 649
- Hasegawa, T. I., Mitchell, G. F., Matthews, H. E., & Tacconi, L. 1994, *ApJ*, 426, 215
- Hayashi M., Kobayashi H., Hasegawa T., 1989, *ApJ*, 340, 298
- Helmich, F.P. & van Dishoeck, E.F. 1997, *A&A*, 124, 205
- Heyer, M. H., Brunt, C., Snell, R. L., Howe, J., Schloer, F. P., Carpenter, J. M., Normandeau, M., Taylor, A. R., Dewdney, P. E., Cao, Y., Tereby, S. & Beichman 1996, *ApJ*, 464, L175
- Heyer, M. H., Brunt, C., Snell, R. L., Howe, J., Schloer, F. P., Carpenter, J. M., Normandeau, M., Taylor, A. R., Dewdney, P. E., Cao, Y., Tereby, S. & Beichman 1996, *ApJ*, 469, L139
- Heyer, M. H., & Terebey, S. 1998, *ApJ*, 502, 265
- Hillwig, T. C., Gies, D. R., Bagnuolo, W. G. Jr., Huang, W., McSwain, M., Virginia, M., Wingert, D. W. 2006, *ApJ*, 639, 1069
- Hoag, A. A., & Applequist, N. L. 1965, *ApJS*, 12, 215
- Hoag, A. A., Johnson, H. L., Iriarte, B., Mitchell, R. I., & Hallam, K. L., 1961, *Publ. U.S. Naval Obs.*, 17, Part 7
- Hofner, P., Delgado, H., Whitney, B., Churchwell, E., & Linz, H. 2002, *ApJ*, 579, L95
- Howe, J. E., Jaffe, D. T., Genzel, R., & Stacey, G. J. 1991, *ApJ*, 373, 158
- Howell, R. R., McCarthy, D. W. & Low, F. J. 1981, *ApJ*, 251, L21
- Humphreys, R. M. 1978, *ApJS*, 38, 309
- Imai, H., Kameya, O., Sasao, T., Miyoshi, M., Deguchi, S., Horiuchi, S. & Asaki, Y. 2000, *ApJ*, 538, 751
- Ishida, K. 1969, *MNRAS*, 144, 55
- Ishida, K. 1970, *PASJ*, 22, 277
- Jaffe D. T., Hildebrand R. H., Keene J. & Whitcomb S. E., 1983, *ApJ*, 273, L89
- Karr, J. L. & Martin, P. G. 2003, *ApJ*, 595, 900
- Kawamura, J. H. & Masson, C. R. 1998, *ApJ*, 509, 270
- Kerton, C. R., Ballantyne, D. R. & Martin, P. G. 1999, *AJ*, 117, 2485
- Kerton, C. R., Martin, P. G., Johnstone, D. & Ballantyne, D. R. 2001, *ApJ*, 552, 601
- Keto, E., Procter, D., Ball, R., Arens, J. & Garret, J. 1992, *ApJ*, 401, L113
- Keto, E. R., Welch, W. J., Reid, M. J. & Ho, P. T. P. 1995, *ApJ*, 444, 765

- Koenig, X. K., Allen, L. E., Hora, J. L., Brunt, C. M. & Muzerolle, J. 2008, in prep.
- Kramer, C., Jakob, H., Mookerjee, B., Schneider, N., Brüll, M. & Stutzki, J. 2004, *A&A*, 424, 887
- Kurtz, S., Churchwell, E. & Wood, D. O. S., 1994, *ApJS*, 91, 659
- Lada, C. J., Elmegreen, B. G., Cong, H.-I., & Thaddeus, P., 1978, *ApJ*, 226, L39
- Ladd, E. F., Deane, J. R., Sanders, D. B., & Wynn-Williams, C. G. 1993, *ApJ*, 419, 186
- Landecker, T. L., Vaneldik, J. F., Dewdney, P. E. & Routledge, D. 1987, *AJ*, 94, 111
- Leahy, D. A., Ventaksesan, D., Long, K. S. & Naranan, S. 1985, *ApJ*, 294, 183
- Lestrade, J.-F., Preston, R. A., Jones, D. L., Phillips, R. B., Rogers, A. E. E., Titus, M. A., Rioja, M. J., & Gabuzda, D. C. 1999, *A&A*, 344, 1014
- Llorente de Andrés, F., Burki, G., & Ruiz de Arbol, J. A. 1982, *A&A*, 107, 43
- Lyder, D. A. & Galt, J. 1997, *AJ*, 113, 131
- Massey, P. 1985, *PASP*, 97, 5
- Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995, *ApJ*, 454, 151
- Massi 2004, *A&A*, 422, 267
- Mathys, G. 1987, *A&AS*, 71, 201
- Mathys, G. 1989, *A&AS*, 81, 237
- Megeath, S. T., Herter, T., Beichmann, C., et al. 1996, *A&A*, 307, 775
- Megeath, S. T., Wilson, T. L. & Corbin, M. R. 2005, *ApJ*, 622, L141
- Menten, K. M., Johnston, K. J., Wadiak, E. J., Walmsley, C. M. & Wilson, T. L. 1988, *ApJ*, 331, L41
- Mirabel, I. F., Rodriguez, I. & Liu, Q. Z. 2004, *A&A*, 422, L29
- Mitchell, G. F., Hasegawa, T. I. & Schella, J. 1992, *ApJ*, 386, 604
- Moffatt, A. F. J. 1972, *A&AS*, 7, 355
- Morgan, L. K., Thompson, M. A., Urquhart, J. S., White, G. J. & Miao, J. 2004, *A&A*, 426, 535
- Moore, T. J. T., Bretherton, D. E., Fujiyoshi, T., Ridge, N. A., Allsopp, J., Hoare, M. G., Lumsden, S. L. & Richer, J. S. 2007, *MNRAS*, 379, 663.
- Mueller, K. E., Shirley, Y. L., Evans, N. J. II, Jacobson, H. R. 2002, *ApJS*, 143, 469
- Muscadelli, L., Menten, K. M., Walmsley, C. M. & Reid, M. J. 2002, *ApJ*, 564, 813
- Nakano, M., Sugitani, K., Niwa, T., Itoh, Y. & Watanabe, M. 2008, accepted to *PASJ* (arXiv:0802.2624)
- Neugebauer, G., Becklin, E. E. & Matthews, K. 1982, *AJ*, 87, 395
- Ninkov, Z., Bretz, D. R., Easton, R. L., & Shure, M. 1995, *AJ* 110, 2242
- Normandeau, M., Taylor, A. R., & Dewdney, P. E. 1996, *Nature* 380, 687
- Normandeau, M., Taylor, A. R., & Dewdney, P. E. 1997, *ApJS*, 108, 279
- Norris, R. P., Booth, R. S. & Davis, R. J. 1980, *MNRAS*, 190, 163
- Oey, M. S., Watson, A. M., Kern, K., & Walth, G. L. 2005, *AJ*, 129, 393
- Ogura, K. & Ishida, K. 1976, *PASJ*, 28, 651
- Ogura, K. & Sugitani, K. & Pickles, A. 2002, *AJ*, 123, 2597.
- Ojha, D. K., Ghosh, S. K., Kulkarni, V. K., Testi, L., Verma, R. P. & Vig, S. 2004, *A&A*, 415, 1039.
- Ojha, D. K., Tamura, M., Nakajima, Y., Fukagawa, M., Sugitani, K., Nagashima, C., Nagayama, T., Nagata, T., Sato, S., Pickles, A. J. & Ogura, K. 2004, *ApJ*, 608, 797.
- Oldham P. G., Griffin M. J., Richardson K. J. & Sandell G., 1994, *A&A*, 284, 559
- Palla, F. & Stahler, S. W. 1993, *ApJ*, 418, 414
- Panagia, N. 1973, *AJ*, 78, 929
- Ray, T. P., Poetzel, R., Solf, J., Mundt, R. 1990, *ApJ*, 357, L45
- Reid, M. J., Hascick, A. D., Burke, B. F., Moran, J. M., Johnston, K. J. & Swenson, G. W. Jr. 1980, *ApJ*, 239, 89
- Reid, M. J., Argon A. L., Masson, C. R., Menten, K. M., & Moran, J. M. 1995, *ApJ*, 443, 238
- Reynolds, R. J., Sterling, N. C., & Haffner, L. M. 2001, *ApJ*, 558, L101
- Richardson, K., Sandell, G., White, G., Duncan, W., & Krisciunas, K. 1989, *A&A*, 221, 95
- Roberts, D. A., Crutcher, R. M., & Troland, T. H. 1997, *ApJ*, 479, 318
- Roelfsema P. R., Goss W. M., 1991, *A&AS*, 87, 177

- Routledge, D., Dewdney, P. E., Landecker, T. L. & Vaneldik, J. F. 1991, A&A, 247, 529
- Ruch, G. T., Jones, T. J., Woodward, C. E., Polomski, E. F., Gehrz, E. F., Gehrz, R. D., Megeath, S. T. 2007, ApJ, 654, 338
- Sams, B. J. III, Moran, J. M., & Reid, M. J. 1996, ApJ, 459, 632
- Sato, F. 1970, Ann. Tokyo Astron. Obs., 2nd Ser., 12, 34
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
- Seward, F. D. 1990, ApJS, 73, 781
- Shi, H. M. & Hu, J. Y. 1999, A&AS, 136, 313
- Snell, R. L., Huang, Y.-L., Dickman, R. L., Claussen, M. J. 1988, ApJ, 325, 853
- Stecklum, B., Brandl, B., Henning, Th., Pascucci, I., Hayward, T. L., Wilson, J. C. 2002, A&A, 392, 1025
- Steele, I. A., Negueruela, I., Coe, M. J., & Roche, P. 1998, MNRAS, 297, L5
- Terebey, S., Fich, M., Taylor, R., Cao, Y. & Hancock, T. 2003, ApJ, 590, 906
- Thronson, H. A., Lada, C. J., Hewagama, T. 1985, ApJ, 297, 662
- Tieftrunk, A. R., Wilson, T. L., Steppe, H., et al. 1995, A&A, 303, 901
- Tieftrunk, A. R., Gaume, R. A., Claussen, M. J., Wilson, T. L., & Johnston, K. J. 1997, A&A, 318, 931
- Tieftrunk, A. R., Gaume, R., & Wilson, T. 1998a, A&A, 340, 232
- Tieftrunk, A. R., Megeath, S. T., Wilson, T. L., & Rayner, J. T. 1998b, A&A, 336, 991
- Townsley, L. K., 2006, in *Massive Stars: From Pop III and GRBs to the Milky Way* ed. M. Livio, in press (arXiv:astro-ph/0608173)
- Turner, J. L. & Welch 1984, ApJ, 287, L81
- Urosevic, D., Pannuti, T. G., Leahy, D. 2007, ApJ, 655, L41
- van den Bergh, S., Marscher, A. P. & Terzian, Y. 1973, ApJS 26, 19
- van der Tak, F. F. S., Tuthill, P. G., & Danchi, W. C. 2005, A&A, 431, 993
- Walborn, N. R. 1972, AJ, 77, 312
- Walborn, N. R. 1973, AJ, 78, 1067
- Walborn, N. R. & Fitzpatrick, E. L. 1990, PASP, 102, 379
- Werner M. W., Becklin E. E., Gatley L., et al. 1980, ApJ, 242, 601
- West, J. L., English, J., Normandeau, M. & Landecker, T. L. 2007, ApJ, 656, 914
- Westerhout, G. 1958, BAN, 14, 215
- Wilking, B. A., Harvey, P. M., Lada, C. J., Joy, M., Doering, C. R. 1984, ApJ, 291, 303
- Wilner, D. J., Welch, W. J. & Forster, J. R. 1995, ApJ, 449, L73
- Wilner, D. J., Reid, M. J. & Menten, K. M. 1999 ApJ, 513, 775
- Wilson, T. L., Johnston, K. J. & Mauersberger, R. 1991, A&A, 251, 220
- Wilson, T. L., Gaume, R. A., & Johnston, K. J. 1993, ApJ, 402, 230
- Wilson, T. L., Boboltz, D. A., Gaume, R. A., & Megeath, S. T. 2003, ApJ, 597, 434
- Wink, J. E., Duvert, G., Guilloteau, S., Güsten, R., Walmsley, C. M. & Wilson, T. L. 1994, A&A, 281, 505
- Wynn-Williams C. G., 1971, MNRAS, 151, 397
- Wynn-Williams, C., Becklin, E. E., & Neugebauer, G. 1972, MNRAS, 160, 1
- Wyrowski, F., Hofner, P., Schilke, P., Walmsley, C. M., Wilner, D. J. & Wink, J. E. 1997, A&A, 320, 117
- Wyrowski, F., Schilke, P., Walmsley, C. M., & Menten, K. M. 1999, ApJ, 514, L43
- Xu, Y., Reid, M. J., Zheng, X. W., & Menten, K. M., 2006, Science, 311, 54
- Zavagno, A., Lagage, P. O., & Cabrit, S. 1999, A&A, 344, 499