Massive Star Birth: A Crossroads of Astrophysics
Proceedings IAU Symposium No. 227, 2005
R. Cesaroni, M. Felli, E. Churchwell & C. M. Walmsley, eds.

doi:10.1017/S174392130500431X

Nearby regions of massive star formation

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Abstract. Observations of the nearest regions of massive star formation such as Orion are reviewed. Early-type stars in the local OB associations, as well as their superbubbles and supershells provide a fossil record of massive star birth in the Solar vicinity over about the last 40 Myr. This record shows that most massive stars are born from dense, high-pressure, hot cores which spawn transient clusters that dissipate into the field soon after formation. A large fraction (15 to 30%) of massive stars are high-velocity runaways moving at more than 20 km s^{-1}. High-mass stars have a larger companion fraction than their lower-mass siblings. The Orion star forming complex contains the nearest site of on-going massive star formation. Studies of the Orion Nebula and the dense molecular cloud core located immediately behind the HII region provide our sharpest view of massive star birth. This region has formed a hierarchy of clusters within clusters. The Trapezium, OMC-1S, and OMC-1 regions represent three closely spaced sub-clusters within the more extended Orion Nebula Cluster. The oldest of these sub-clusters, which consists of the Trapezium stars, has completely emerged from its natal core. The OMC-1S and OMC-1 regions, are still highly embedded and forming clusters of additional moderate and high mass stars. Over a dozen YSOs embedded in OMC-1S are driving jets and outflows, many of which are injecting energy and momentum into the Orion Nebula. Recent proper motion measurements indicate that the Becklin-Neugebauer object is a high-velocity star moving away from the OMC1 core with a velocity of 30 km s^{-1}, making it the youngest high-velocity star known. Source I may be moving in the opposite direction with a velocity of about 12 km s^{-1}. The projected separation between source I and BN was less than few hundred AU about 500 years ago. The spectacular bipolar molecular outflow and system of shock-excited H_2 fingers emerging from OMC-1 has a dynamical age of about 1100 years. It is possible that a dynamical interaction between three or more stars in OMC-1 led to the formation of this eruptive outflow.

1. Introduction

The formation of massive stars and star clusters remains one of the outstanding problems in star formation research. Massive stars and star clusters are the most detectable signs of on-going star formation in distant molecular clouds and galaxies. Massive stars and clusters are visible across cosmological distances; they regulate the state of surrounding ISM, and dominate feedback and the self-regulation of star formation. Massive star and cluster formation in its most extreme forms may be related to the birth of globular clusters, the central bulges of galaxies, black holes, and AGN. However, the birth of the most massive stars and star clusters remains poorly understood.

OB associations, HII regions, and massive star forming molecular cloud cores within a few kpc of the Sun provide the best opportunity to obtain observational constraints on the formation of massive stars and clusters. Unfortunately for students of massive star birth, massive stars are relatively rare. Furthermore, massive protostars evolve much faster than their lower-mass siblings. By the time massive stars emerge from their parent molecular

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cloud cores, they are fully mature main-sequence objects. Massive protostars also tend to be embedded within very opaque cloud cores with visual wavelength extinctions greater than 100 magnitudes. Thus, the formation and early evolution of massive stars is difficult to observe.

The birth of isolated low-mass stars with masses below a few Solar masses is becoming relatively well understood. The evolution of young stellar objects (YSOs) starts with the gravitational collapse and fragmentation of dense molecular cloud cores (Shu 1977; Shu *et al.* 1991). The youngest self-luminous protostars (Class 0 objects) emit most of their luminosity in the sub-mm portion of the spectrum. In less than 10^4 to 10^5 years, Class 0 YSOs evolve into Class I YSOs which emit the bulk of their radiation in the far infrared around 100 μm. Powerful, highly collimated, bipolar jets are launched from the immediate vicinity ($r <$ few AU) of Class 0 and I YSOs. As outflows, radiation, and accretion clear the protostellar environments, protostars become visible at progressively shorter wavelengths. As low-mass YSOs evolve through the Class II and Class III stages on a time-scale of a few to tens of million years, their peak emission shifts from the near infrared to the visible. These pre-main sequence objects are the classical and weak-line T Tauri stars. This progression from cloud core through the Class 0, I, II, and III phases may not be as smooth and steady as once thought. Dynamical interactions in clusters and multiple star systems may enable cataclysmic transitions from one stage to another on a dynamical time scale (Reipurth 2000). Nevertheless, there are well defined evolutionary sequences and established time scales for the evolution of isolated low mass stars.

Most low-mass stars in the sky appear to form in the same dense environments which spawn massive stars and clusters. Massive star forming regions are very different from the quiescent dark clouds such as Taurus which only produce low-mass stars. In contrast to low-mass YSOs, our understanding of massive star birth is in its infancy. We do not have a clear prescription for the pre-main sequence evolutionary stages of massive stars. Do massive stars form by direct accretion from the parent cloud in a scaled-up version of low-mass star formation in high-pressure cores with enhanced accretion rates (Yorke, & Sonnhalter 2002; Tan & McKee 2004)? Are new processes, such as interactions with sibling stars, dynamical processes in dense clusters, or even mergers involved (Bonnell, Bate, & Zinnecker 1998)? Under what conditions do open and globular clusters form? There are many open questions regarding massive star formation. In this review, we first discuss the fossil record of massive star birth near the Sun, and then we present a discussion of the closest massive star forming regions.

2. The OB Associations of the Gould's Belt: A Fossil Record of Massive Star Birth

T-Tauri stars, embedded IR sources, and dense HII regions trace sites of on-going or recent star formation with ages up to a few million years. Stars with spectral type O through B3 mark somewhat older sites of star formation active over about the last 40 million years, the main-sequence lifetime of 8 $M_\odot$ stars (the least massive star that ionizes hydrogen and explodes as a type II supernova). Studies of stellar ages show that OB associations form on a time-scale of about 5 to 15 million years (Blaauw 1991). This is one measure of the duration of star formation in a typical GMC. It is difficult to identify gravitationally unbound stellar groups older than about 40 million years. Nevertheless, some "fossil" OB associations older than 40 Myr have been identified in the Solar vicinity by the common motion of their member stars (Blaauw 1991; de Zeeuw *et al.* 1999).

The combined impact of ionizing radiation, stellar winds, and supernova explosions of massive stars in OB associations create superbubbles in the interstellar medium (ISM).

The expanding bubbles sweep-up dense shells (supershells) from the surrounding medium (Mac Low & McCray 1988; Mac Low, McCray, & Norman 1989). The Sun appears to be moving through the low-density interior of an ancient superbubble. Most of the cool ISM in the Solar vicinity (which consists of GMCs and atomic hydrogen clouds) is expanding with a mean velocity of 2 to 5 km s^{-1} from a point located near Galactic longitude and latitude l=150°, b=0°, d=200 pc, the approximate centroid of the 50 Myr old Cas–Tau group, a "fossil" OB association (Blaauw 1991). This systematic expansion of the local gas was first identified by Lindblad (1967, 1973) and is sometimes called 'Lindblad's ring' of HI , but it is even more apparent in the kinematics of the nearby molecular gas (Dame *et al.* 1987, 2001; Taylor, Dickman, & Scoville 1987; Poppel *et al.* 1994). The nearest OB associations, such as Sco-Cen (d $\approx$ 150 pc), Per OB2 (d $\approx$ 300 pc), Orion OB1 (d $\approx$ 400 pc), and Lac OB1b (d $\approx$ 500 pc), and the somewhat older B and A stars that trace the so-called 'Gould's Belt' of nearby young and intermediate-age stars may also be expanding from this location (Lesh 1968; De Zeeuw *et al.* 1999). Thus, the Lindblad ring appears to be a 30 to 60 Myr old fossil supershell driven into the local ISM, possibly by the Cas–Tau group and the associated α Persi cluster (Blaauw 1991). The nearby OB associations and star forming dark clouds may represent secondary star formation in clouds condensed from the ancient Lindblad ring supershell.

Molecular clouds may form from gravitational instabilities behind spiral density waves (e.g. Elmegreen 1979), from stochastic cooling in the gas disk of the galaxy (Wada & Norman 2001; Wada *et al.* 2000), or by a variety of other mechanisms. McCray & Kafatos (1987) demonstrated that as supershells sweep up surrounding ISM and decelerate, they can fragment into clouds due to gravitational instabilities. On small-scales, supershells are stabilized by thermal and turbulent motions. On large-scales, supershell expansion dominates. But, on intermediate scales where the gravitational escape speed from a piece of the shell becomes larger than the local velocity dispersion, gravity can condense the shell into clouds having properties similar to GMCs. In the Solar vicinity, gravitational instabilities can lead to the formation of 10^5 Solar mass clouds from the decelerating shells of aging superbubbles. Support for cloud formation from supershells in the Solar vicinity comes from the agreement between the observed radial velocity fields of the local HI emission and nearby CO clouds with models of an expanding and tidally sheared 30 to 60 Myr old superbubble (Poppel *et al.* 1994).

The Gould's Belt/Lindblad Ring contains several young (τ <20 Myr old) OB associations; Sco-Cen, Perseus OB2, Orion OB1, and perhaps Lac OB1 (de Zeeuw *et al.* 1999). The Sco-Cen OB association, the nearest group of massive stars and on-going sites of low-mass star formation, located about 150 pc from the Sun. Several well-known low-mass star forming clouds such as ρ-Oph and Lupus are associated with the this OB association. A giant HI shell over 100° in diameter is centered on the centroid of the association and many high latitude clouds are associated with these features (Hartmann & Burton 1997). The non-thermal radio emission features known as Loops 1 and 2 coincide with the outer periphery of this HI supershell. The outermost portions of the expanding network of clouds and hot plasma emerging from the Sco-Cen OB association have already overrun the Solar system. Evidence for this hypothesis is provided by Solar Lyman-α back-scatter and the streaming of the ISM through the Solar system which, when corrected for the Solar motion with respect to the Local Standard of Rest coordinates, has a vector velocity of about 20 km s^{-1} from the general direction of the Sco-Cen OB association (Crutcher 1982; Frisch 1996a, b; Frisch *et al.* 1999). In this model, the nearby 'hot cavity' may be an outlying portion of the Sco-Cen superbubble which is presently over-running the Solar system.

The next nearest OB association is the Perseus OB2 group located at a distance of about 300 pc. This group contains a small HI shell about 20° in diameter and has a much smaller stellar content than either Orion or Sco-Cen. Like Sco-Cen, Per OB2 is only forming low to intermediate mass stars at present. In addition to Sco-Cen, Per OB2, and Orion, the Gould's Belt/ Lindblad Ring system may also include a fourth member, the Lac OB1 association. The Ring also contains a number of giant molecular clouds and dark cloud complexes that are not at present forming high mass stars. These clouds include the Great Rift (or the Aquila Rift) extending from Ophiucus to Cygnus, the Cepheus Flare clouds, and some of the clouds in Taurus and Perseus.

The Orion star forming region (distance $D \approx 380$ to 460 pc contains the nearest GMCs, bright HII regions, and some of the closest young clusters in the sky. The Orion OB1 association contains four major subgroups ranging in age from about 12 to 14 Myr (OB1a) to less than a 2 Myr (OB1d). Over a dozen supernovae along with the winds and radiation fields of their progenitor main-sequence stars have blown a superbubble in the surrounding medium which is visible in HI, infrared dust emission, Hα emission, and soft X-rays (Reynolds & Ogden 1979; Brown, Hartmann, & Burton, 1995; Cowie *et al.* 1979; Burrows *et al.* 1993). The bubble subtends 20^o by 40^o, which corresponds to about 140 by 300 pc. The closest portion (the Eridanus Loop; Boumis *et al.* 2001) may lie only 160 pc from the Sun (Guo & Burrows 1996).

The massive star populations in these younger OB associations provide a fossil record of the birth of massive stars, expanding star clusters, and their impact on the surrounding ISM. Several lessons have been learned from these nearby and relatively recent episodes of massive stars formation:

- OB associations are formed from Giant Molecular Clouds (GMCs) with masses ranging from 10^5 to over 10^6 $M_\odot$ (e.g. Dame *et al.* 1987; 2001).
- OB associations produce stars of all masses according to a universal Initial Mass Function (IMF; Kroupa 2002). Thus, low mass stars are the most common stellar product in OB associations. While typical OB associations produce anywhere from a few to many dozens of massive stars with masses larger than 8 $M_\odot$, they produce thousands to tens of thousands of lower mass stars. The star formation efficiency, given by total final mass of stars, divided by the initial mass of gas, is typically only 3 to 15%.
- Stars in GMCs form from dense cores which give rise to a hierarchy of OB association sub-groups and short-lived clusters of stars. In Orion, for example, 4 major subgroups have been recognized with the oldest (the 1a sub-group) having an age of about 10 - 15 Myr. This was followed by the formation of the 1b and 1c subgroups. The youngest (1d) subgroup is giving birth to the stars in the Orion A and B cloud today. These very young ($<$ 2 Myr) stars are forming in at least a dozen small and probably transient clusters spread throughout the remaining Orion molecular clouds. The largest currently forming cluster is associated with the Orion Nebula. It contains several thousand low mass stars and about a dozen massive ones.
- There is mounting evidence that most if not all stars more massive than about 8 $M_\odot$ form in groups (Beuther & Schilke 2003).
- 10% of massive stars are high-velocity (> 30 km s^{-1}) runaways. Up to 30% of massive stars are moderate-velocity ($10 < V < 30$ km s^{-1}) runaways (Hoogerwerf, de Bruijne, & de Zeeuw 2000, 2001).
- The multiplicity fraction among massive stars is higher than low-mass stars (Schertl *et al* 2003). Massive binaries with equal mass companions are much more common than low mass binaries. Unequal-mass companions are also more common among massive stars than low-mass stars. The companion star fraction (Reipurth & Zinnecker 1993) is about 1.5 for massive and only 0.5 for low-mass stars (Zinnecker & Bate 2002).

3. The Orion Nebula, OMC-1, and OMC-1S

The Orion star forming region contains the nearest GMCs, bright HII regions, and some of the closest young clusters in the sky. Orion contains two 10^5 $M_{\odot}$ giant molecular clouds: The Orion A cloud located behind Orion's Sword in the southern portion of the constellation, and the Orion B cloud that lies east of Orion's Belt. Both GMCs are located in the projected interior of the Orion/Eridanus superbubble and appear to have been shaped by energy release from the Orion OB association (Maddalena *et al.* 1986; Bally *et al.* 1987; 1991). Orion A is cometary in appearance with a compact ridge of dense gas at the northern end (the "integral shaped filament" or ISF; Johnstone & Bally 1999) and a lower density and wider tail that extends directly away from the centroid of the OB association.

The Orion Nebula, located in the middle of the ISF, marks the site of its most spectacular and recent stellar nursery. In a region only a few parsecs in diameter, about 3,000 mostly low-mass stars formed here within the last few million years. This young cluster (known as the Orion Nebula Cluster or ONC - Hillenbrand 1997; Hillenbrand & Hartmann 1998) also contains about a half-dozen massive (spectral type earlier than B3) stars. Although most star formation in Orion is occurring in the Orion A and B clouds located between 380 to 460 pc from the Sun, there is evidence that several smaller clouds embedded in the near-side of the Orion-Eriduanus bubble at adistance of 200 to 250 pc have also given birth to low and high-mass stars. Two of Orion's massive stars, Betelgeuse and Rigel, must have formed from clouds located no more that about 250 pc from the Sun. Betelgeuse ($d \sim 130$ pc) is a low-velocity runaway star moving through Orion towards the northeast. Rigel illuminates a small molecular cloud ($d \sim 220$ pc) that contains IC 2118 and a groups of T Tauri stars (Kun *et al.* 2001).

3.1. *The Trapezium*

The Trapezium cluster of four massive stars which marks the center of the Orion Nebula and the ONC has cleared away its placental cloud. Therefore, it is the most evolved of the three sub-clusters in or near the Orion Nebula which have spawned moderate to high-mass stars within the last million years.

The most massive star in the Orion Nebula, θ^1Ori C (spectral type O7), is most responsible for ionizing the HII region (see O'Dell 2001 for a recent review). HST images show that the nearest-neighbor distance between low-mass stars in the cluster core is only a few thousand AU (e.g. Bally *et al.* 1998) and that the density of stars there currently exceeds 10^5 stars pc^{-3} (McCaughrean and Stauffer 1994; Henney & Arthur 1998).

Adaptive-optics and speckle interferometry have revealed that the companion fraction of the Trapezium stars is very large. Three of the four Trapezium stars are multiple. One massive member (θ^1B) has at least four companions (Schertl *et al.* 2003; Close *et al.* 2003).

The velocity dispersion of the ONC is about 1.5 km s^{-1} (van Altena *et al.* 1988). However the Trapezium stars have proper motions ranging from 1.8 to 5 km s^{-1}. θ^1Ori C is moving with a velocity of 5 km s^{-1} towards the southeast. Tan (2004) pointed out that the motion of θ^1 Ori C is directly opposite to the high velocity ($V \approx 30$ km s^{-1}; Plambeck *et al.* 1995; Rodríguez *et al.* 2005) Becklin-Neugebauer object (BN; located about 10" northwest of OMC-1 and 70" northwest θ^1 Ori C) and proposed that these two interacted dynamically about 5,000 years ago. Tan (2004) also noted that the trajectory of BN paced it within 0.5" of the embedded radio source I in OMC-1 about 500 years ago. One problem with the interpretation that BN is a runaway star expelled from the

Trapezium is that it exhibits traits of a star much younger than any of the Trapezium members (Scoville *et al.* 1983).

3.2. *OMC-1S*

Two dense cloud cores located less than one arcminute in projection from the Trapezium contain highly embedded sub-clusters of moderate to high mass stars, OMC-1 and OMC-1S. OMC-1S, located about 1' southwest of the Trapezium and 90" south of the BN-KL complex first attracted attention after Keene *et al.* (1982) found a luminous far-infrared source. OMC-1S contains powerful molecular outflows (Ziurys, Wilson, & Mauersberger 1990; Schmid-Burgk *et al.* 1990; Rodríguez-Franco *et al.* 1999) and contains numerous water masers (Gaume *et al.* 1998). Several CO outflows originate from near the 1.3 mm continuum source FIR-4 (Mezger *et al.* 1990). HST observations of jets and outflows in the Orion Nebula drew attention to OMC-1S. Most of the large Herbig-Haro outflows in the Orion Nebula, including HH 202, 203/204, 269, 528, and 528 radiate from the OMC-1S cloud core (Bally *et al.* 2000). These HH flows trace the blueshifted portions of over a dozen outflows bursting out of this core in all directions. These flows drew attention to intense star formation within the OMC-1S cloud core. Subsequently, Zapata *et al.* (2004) and Smith *et al.* (2004) identified clusters of embedded radio and thermal-IR sources in this core. Thus, OMC-1S is currently forming a small sub-cluster of several dozen low to moderate mass stars.

3.3. *OMC-1*

OMC-1, located 1' northwest of the Trapezium, contains the Becklin-Neugebauer object and the Kleinmann-Low infrared nebula (BNKL for short). Its total luminosity is about 10^5 $L_\odot$ (Gezari *et al* 1998). OMC-1 is the closest dense cloud core currently forming massive stars.

Thermal infrared imaging with 8 to 10 meter class-telescopes provides 0.3" ($<$ 200 AU) resolution (Shuping *et al.* 2004; Smith, *et al.* 2005). Although many stars such as BN and IRc9, which are located more than 10 arcseconds from the dense OMC-1 hot-core, are easily detected near 10 μm, most stellar sources within the core are obscured. The most intense 11.7 μm emission (Figure 1) is apparently produced by clumps of warm dust. Even in the thermal-IR, OMC-1 is too opaque to reveal its litter of young stars. Therefore, radio emission provides the best tracer of young stars still buried in the core.

The VLA studies of Menten & Reid (1995) indicate that, in addition to BN, the region contains at least two other ultra-compact radio sources, I and n, separated by about 3" (1,500 AU in projection) from each other. Sources I and n in OMC1 are associated with strong maser emission (Johnston *et al.* 1989; Genzel *et al.* 1981; Greenhill *et al.* 2003; 2004). An expanding arcminute-scale complex of high velocity (v = 30 to 100 $km\ s^{-1}$) OH and H_2O masers surround the entire OMC1 region and are centered on radio source n. However, the brightest H_2O masers and the intense SiO maser ($V < \pm 18 km\ s^{-1}$) are concentrated within a 0.5" strip centered on source I.

A fast (30 to 100 km s^{-1}), poorly collimated bipolar outflow emerges from this region orthogonal to the 'shell' maser disk with a blueshifted lobe towards the northwest. The OMC1 outflow has a mass of about 10 $M_\odot$ and a kinetic energy of about 4×10^{47} ergs (Kwan & Scoville 1976). The OMC1 outflow and the H_2 fingers (Kaifu *et al.* 2000) indicate that a powerful explosion occurred in OMC1 within the last 10^3 years. Some of the H_2 fingers are visible in Hubble Space Telescope images and thus have known proper motions. Greenhill *et al.* (1998) interpreted the 'shell' water masers and the 18 km s^{-1} outflow as tracers of an expanding disk surrounding source I with a northeast– southwest major axis that lies orthogonal to the fast wide-angle bipolar outflow that emerges along a northwest–southeast axis. However, Greenhill *et al.* (2003) presented an argument, based on new VLBA and 7 mm VLA data, that the disk is oriented southeast–northwest and that the "shell" masers trace a jet. In this latter picture, the four SiO maser chains trace the surface of the disk, which produces a ridge of 7 mm radio continuum emission along the disk plane. However, this new re-interpretation leaves the H_2 fingers and associated CO flow without a known driving source. It is possible that the 7 mm radio emission actually traces a thermal radio jet rather than dust emission from a disk. Thus, the interpretation in which the "shell" and SiO masers surrounding source I trace a thick, expanding disk, and the 7 mm emission traces a jet oriented northwest-southeast which drives the H_2 fingers and associated CO outflow provides a simpler explanation for the various phenomena in OMC1.

Rodriguez *et al.* (2005) used the VLA to measure the proper motions of radio sources in the OMC-1 region. They found that radio sources I and BN are moving in opposite directions with velocities $V_{BN} = 27 \pm 1$ km s^{-1} towards $PA = -43 \pm 3^o$ and $V_I = 12 \pm 2$ km s^{-1} towards $PA = 141 \pm 3^o$). Scoville *et al.* (1983) found a redshifted radial velocity of +12 km s^{-1} for BN respect to the OMC-1 core. The SiO and shell masers associated with source I exhibit a blueshift of -4 km s^{-1}. Thus, proper motions and radial velocities indicate that these two stars are moving apart at 40 km s^{-1}. They were separated by less than a fraction of an arcsecond (< 225 AU) about 500 years ago. Thus, BN is a high-velocity runaway star that was probably launched by a recent interaction with source I.

Rodríguez *et al.* (2005) propose that a three-body interaction in the OMC-1 cloud core occurred 500 years ago in which BN was launched at high velocity and the two remaining stars formed radio source I, which in this model is predicted to be a close-binary. From the ratio of velocities with respect to OMC-1, the total mass of I must be about 2.3 times that of BN. BN's mass is estimated to be 8 to 13 $M_\odot$, implying that I has a mass of 18 to 29 $M_\odot$. If the kinetic energy of motion of I and BN are derived from the binding energy of the newly-formed binary, the binary is predicted to have separation of order 14 to 22 AU and a period of 4 to 7 years. The total kinetic energy of motion of I and BN is about 5×10^{47} ergs, comparable to the energy of the OMC-1 outflow.

Bally & Zinnecker (2005) proposed that a dynamical interaction 500 years ago, possibly leading to a merger, may have produced the OMC-1 outflow and H_2 finger system. In their scenario, interactions with surrounding gas have decelerated the impulsive outflow powered by the interaction by about a factor of two, thereby reconciling the 10^3 year dynamical age of the outflow with the 500 year time scale for the interaction. The detection of oppositely directed motions in radio sources I and BN provide support for models in which the OMC-1 outflow was powered by a dynamical interaction between massive stars in an ultra-dense environment.

4. Lessons from Nearby Regions

Orion's OMC-1 is the only dense cloud core with a luminosity of 10^5 $L_\odot$ currently forming stars within 1 kpc of the Sun. However several other regions with luminosities of order 10^4 $L_\odot$ can be found within 1 kpc including NGC 2024 in Orion, S106, and the W40 complex located on the far-side of the Great Rift clouds (D $\sim$ 300 pc).

Cepheus A is perhaps the best studied of these regions. A hot core containing a cluster of UCHII regions, masers, and compact radio sources powers a spectacular complex of Herbig-Haro objects, H_2 jets, and molecular outflows (Narayanan & Walker 1996; Garay *et al.* 1996; Torrelles *et al.* 1998; Curiel *et al.* 2002). Although the multi-shell structure of HH 168 (Hartigan *et al* 2000) superficially resembles portions of the H_2 fingers in Orion, the multiple outflows from Cep-A appear more collimated than the eruptive outflow emerging from OMC-1. Superficially, the outflow morphologies in Cep-A are intermediate between the flows emerging from OMC-1S and OMC-1. Indeed, the Cep-A core region exhibits many of the characteristics of OMC-1 and OMC-1S such as molecular hot-core tracers, intense maser emission, ultra-compact HII regions. These nearby regions provide important clues about the unique environmental factors which lead to massive stars and clusters. These include:

- High density, pressure, and initial mass of the parent cloud cores. Relatively large-molecular line-widths and warmer temperatures imply higher effective sound-speeds than in low-mass star forming cores.
- Massive star forming regions are associated with intense maser emission with very complex velocity structure.
- Massive star forming cores contain dense clusters of embedded IR and radio sources. Densities exceed 10^5 stars pc^{-3}.
- In Orion's OMC-1, a dynamical interaction 500 years ago launched BN and radio source I in opposite directions with a relative speed of 40 km s^{-1}. Radio source I may be a binary. This event may have produced the spectacular OMC-1 outflow and associated fingers of shock-excited H_2 emission.

5. Summary and Conclusions

During the last few years, there had been much progress in our understanding of massive star and cluster formation. Speckle interferometry and adaptive optics on 8 to 10 meter telescopes have shed new light on the high companion fraction and multiplicity statistics of massive stars. Sub-arcsecond thermal IR images have revealed many new features of known objects and many new sources in massive star forming regions. Hubble Space Telescope, Fabry-Perot imaging, and spectroscopy have revealed a plethora of overlapping outflows and jets emerging from regions of moderate and massive star formation such as Trapezium, OMC-1, OMC-1, and Cep-A. Sub-arcsecond imaging has revealed intricate but important details in both the outflows and the cores from which they emerge. Radio telescopes have measured proper motions and shown that high-velocity runaway stars exist even in the youngest regions. Numerical modeling has also advanced greatly in the last decade.

Much remains to be learned from OB associations and active, embedded massive star-forming cloud cores. It is becoming evident that stochastic interactions in ultra-dense environments play a crucial role in massive star birth and cluster formation. High-velocity runaway stars, especially in young regions such as Orion, provide evidence for the importance of dynamical processes. However, we will probably need to wait for the next generation of instruments to determine if massive stars form only by direct accretion, establish the roles of interactions, and to study the roles of mergers, if any.

Better resolution and sensitivity is coming soon, especially at radio and thermal IR wavelengths. The EVLA and ALMA will enable us to finally determine the stellar densities of embedded clusters, image the launch and collimation of jets and outflows, and measure the mass, composition, and motions in circummstellar environments. The VLBA will enable precise parallax distances, proper motions, and temporal variations to be measured for many regions. IR interferometry with VLT-I and Keck-I in the near term, and space-based interferometers such as TPF-I in the long-term should produce stunning images of AU-scale structure and processes in the nearest regions. These future studies will enable us to probe deeper, sharper, and better. Perhaps we will start to understand the connection between the most virulent forms of star formation, the birth of open and globular clusters, central clusters and bulges in galaxies, and the formation of their black holes and active nuclei.

Acknowledgements

We thank useful conversations with Hans Zinnecker. This work was supported in part by NASA grant NCC2-1052 from the NASA Astrobiology Institute, and the National Science Foundation under Grant No. 9819820.

References

Bally, J., Langer, W. D., Stark, A. A., & Wilson, R. W. 1987, ApJ, 312, L45
Bally, J., Langer, W. D., & Liu, W. 1991, ApJ, 383, 645
Bally, J., Sutherland, R. S., Devine, D., & Johnstone, D. 1998, AJ, 116, 293
Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281
Beuther, H., & Schilke, P. 2004, Science, 303, 1167
Blaauw, A. 1991, in *The Physics of Star Formation and Early Stellar Evolution* eds. C.J. Lada & N. D. Kylafis, Kluwer, p. 125
Bonnell, I. A., Bate, M., & Zinnecker, H. 1998, MNRAS, 298, 93
Boumis, P., Dickinson, C., Meaburn, J., Goudis, C. D., Christopoulou, P. E., Lopez, J. A., Bryce, M., & Redman, M. P. 2001, MNRAS 320, 61
Brown, A. G. A., Hartmann, D., & Burton, W. B. 1995, A&A, 300, 903
Burrows, D. N., Singh, K. P., Nousek, J. A., Garmire, G. P., & Good, J. 1993, ApJ, 406, 97
Close, L. M. *et al* 2003, ApJ, 599, 537
Cowie, L. L., Songaila, A., & York, D. G. 1979, ApJ, 230, 469
Crutcher, R. M. 1982, ApJ, 254, 82
Curiel, S., *et al.* 2002, ApJ, 564, L35
Dame, T. M., Ungerechts, H., Cohen, R., DeGeuss, E., Grenier, I., May, J., Murphy, D., Nyman, L. A., & Thaddeus, P. 1987, ApJ, 322, 706
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001 ApJ, 547, 792
Elmegreen, B. G. 1979, ApJ, 231, 372
Frisch, P. C. 1996a, Sp. Sci. Rev., 78, 213
Frisch, P. C. 1996b, BAAS, 188, 4408
Frisch, P. C. *et al.* 1999, ApJ, 525, 492
Garay, G., Ramirez, S., Rodriguez, L. F., Curiel, S., & Torrelles, J. M. 1996, ApJ, 459, 193
Gaume, R. A., Wilson, T. L., Vrba, F. J., Johnston, K. J., & Schmid-Burgk, J. 1998, ApJ, 493, 940
Genzel, R., Reid, M. J., Moran, J. M., & Downes, D. 1981, ApJ, 244, 884
Gezari, D. Y., Backman, D. E., & Werner, M. W. 1998, ApJ, 509, 283
Greenhill, L.J. *et al.* 2003, IAUS 221, 203 (Sydney)
Greenhill, L.J. *et al.* 2004, ApJ 605, L57
Guo, Z., & Burrows, D. N. 1996, Bulletin of the American Astronomical Society, 28, 834
Hartmann, D., & Burton, W. B. 1997, *Atlas of Galactic Neutral Hydrogen* Cambridge University Press, ISBN 0521471117
Henney, W. J., & Arthur, S. J. 1998, AJ, 116, 322
Hillenbrand, L. A. 1997, AJ, 113, 1733
Hillenbrand, L. A. & Hartmann, L. W. 1998, ApJ, 492, 540
Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2000, ApJ, 544, L133
Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2001, A&A, 365, 49
Johnston, K. J., Migenes, V., & Norris, R. P. 1989, ApJ, 341, 847
Johnstone, D. & Bally, J. 1999, ApJ, 510, L49
Kaifu, N. *et al.* 2000, PASJ, 52, 1
Keene, J., Hildebrand, R. H., & Whitcomb, S. E. 1982, ApJ, 252, L11

Kroupa, P. 2002, Science, 295, 82
Kun, M., Aoyama, H., Yoshikawa, N., Kawamura, A., Yonekura, Y., Onishi, T., & Fukui, Y. 2001, PASJ, 53, 1063
Kwan, J., & Scoville, N. Z. 1976, ApJ, 210, L39
Lesh, J. R. 1968, ApJS, 17 371
Lindblad, P. O. 1967, Bull.Astron.Soc.Net. 19, 34
Lindblad, P. O. 1973, A&A, 24, 309
Mac Low, M., & Mc Cray, R. 1988, ApJ, 324, 776
Mac Low, M., McCray, R., Norman, M. L. 1989, ApJ, 337, 141
Maddalena, R. J., Morris, M., Moscowitz, J., & Thaddeus, P. 1986 ApJ, 303, 375.
McCaughrean, M. J. & Stauffer, J. R. 1994, AJ, 108, 1382
McCray, R., & Kafatos, M. 1987, ApJ, 317, 190
McKee, C. F., & Tan, J. C. 2003, ApJ, 585, 850
Menten, K. M. & Reid, M. J. 1995, ApJ, 445, L157
Mezger, P. G., Wink, J. E., & Zylka, R. 1990, A&A, 228, 95
Narayanan, G., & Walker, C. K. 1996, ApJ, 466, 844
O'Dell, C. R. 2001, ARAA, 39, 99
Plambeck, R. L., Wright, M. C. H., Mundy, L. G., & Looney, L. W. 1995, ApJ, 455, L189
Poppel, W. G. L., Marronetti, P., & Benaglia, P. 1994, A&A, 287, 601
Reipurth. B., & Zinnecker, H. 1993, A&A, 278, 81
Reipurth, B. 2000, AJ, 120, 3177
Rodríguez, L. F., Poveda, A., Lizano, S., & Allen, C. 2005, ApJ (in press; astro-ph/0504134)
Reynolds, R. J., & Ogden, P. M. 1979, ApJ, 229, 942
Rodríguez-Franco, A., Martín-Pintado, J., & Wilson, T. L. 1999, A&A, 344, 57
Scoville, N., Kleinmann, S. G., Hall, D. N. B., & Ridgway, S. T. 1983, ApJ, 275, 201
Schertl, D., Balega, Y. Y., Preibisch, T., & Weigelt, G. 2003, A&A, 402, 267
Schmid-Burgk, J., Güsten, R., Mauersberger, R., Schulz, A. & Wilson, T. L. 1990, ApJ, 362, L25
Shu, F. 1977, ApJ, 214, 488
Shu, F., Ruden, S. P., Lada, C. J., & Lizano, S. 1991, ApJ, 370, L31
Shuping, R. Y., Morris, M., & Bally, J. 2004, AJ, 128, 363
Smith, N., Bally, J., Shuping, R. Y., Morris, M., & Kassis, M. 2005, AJ (in press).
Smith, N., Bally, J., Shuping, R. Y., Morris, M., & Hayward, T. L. 2004, ApJ, 610, L117
Tan, J. 2004, ApJ, 607, L47
Taylor, D. K., Dickman, R. L., & Scoville, N. Z. 1987, ApJ, 315, 104
Torrelles, J. M., Gómez, J. F., Garay, G., Rodríguez, L. F., Curiel, S., Cohen, R. J., & Ho, P. T. P. 1998, ApJ, 509, 262
van Altena, W. F., Lee, J. T., Lee, J. F., Lu, P. K., & Upgren, A. R. 1988, AJ, 95, 1744
Wada, K., Spaans, M., & Kim, S. 2000, ApJ, 540, 797
Wada, K., & Norman, C. A. 2001, ApJ, 547, 172
Yorke, H. W., & Sonnhalter, C. 2002, ApJ, 569, 846
Zapata, L. A., Rodríguez, L. F., Kurtz, S. E., O'Dell, C. R., & Ho, P. T. P. 2004, ApJ, 610, L121
Zinnecker, H., & Bate, M. 2002, in *Hot Star Workshop III: The Earliest Stages of Massive Star Birth* eds. P. A. Crowther, ASP Conf.Ser., 267, 209
Ziurys, L. M., Wilson, T. L., & Mauersberger, R. 1990, ApJ, 356, L25

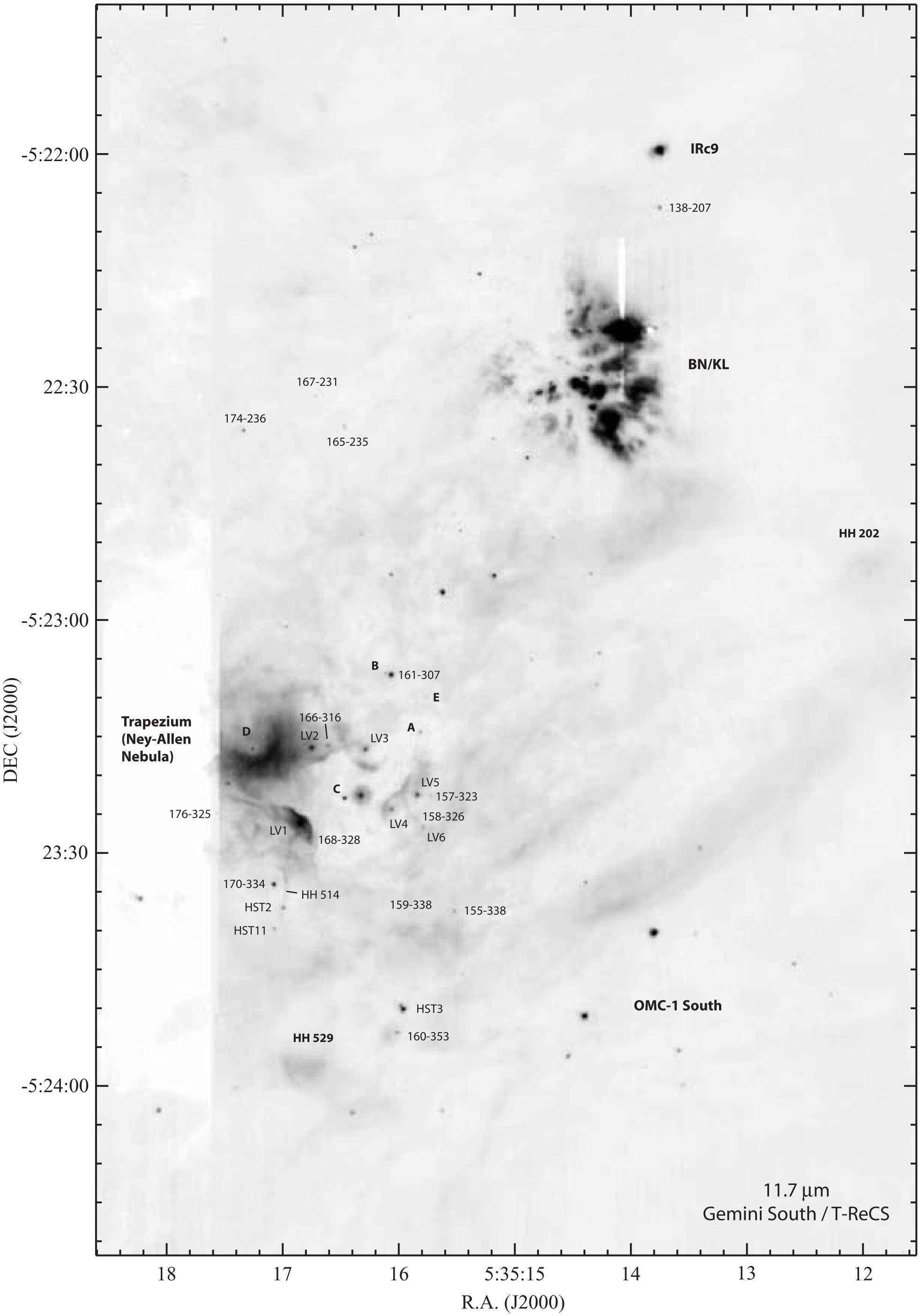

Figure 1. OMC-1, OMC-1S, and Trapezium at 11.7 μm. Obtained with the TReCS instrument on Gemini South (Smith *et al.* 2005).