What Radio Astronomy Tells Us About
Massive Star Formation

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While great progress has been made in the last decade in our understanding of the earliest stages of low mass star formation, the earliest stages of high mass star formation are still poorly understood. Considerable observational and theoretical effort has been made, but the relative rarity, short lifetime and dense clustering of massive protostars have made the task of developing an evolutionary sequence for massive star formation difficult. For example, Shepherd & Churchwell (1996) have shown that a significant fraction of young massive stars experience molecular outflows, and the work of Cesaroni et al. (1998) and others has pinpointed the hot cores in molecular clouds that are likely to be the location of the youngest massive protostars.

Much of this ongoing work has made it clear that in order to explore the earliest phases of massive star formation, radio wavelength investigations are not only desirable, but indispensable. The host molecular clouds of the youngest massive star clusters are dense and optically thick. The W49A region is a representative example: almost the entire region is obscured optically, and only some of the peripheral sources are visible in the near infrared (Conti & Blum 2001). One of the few windows that we do have into such dense cloud cores is at centimeter and millimeter wavelengths, and since the Galaxy’s youngest, most luminous massive star forming regions are distant (W49A: 11.5 kpc; Sgr B2: 8.5 kpc), subarcsecond angular resolution is needed to probe the emission on relevant spatial scales.

Some of the observational clues gathered in the past five years concerning the earliest stages of massive star formation are the extreme physical parameters of the ultracompact (UC) HII regions found in dense cloud cores like W49A and Sgr B2. Emission measures of 1010 pc cm-6 and electron densities of 106 cm-3 are not uncommon in the ultracompact sources detected in these two regions (e.g. De Pree et al. 1998; De Pree et al. 2000). What is becoming clear is that the ultracompact regions of ionized gas that we detect in regions like W49A are not simply small versions of the HII regions described in such classic texts as Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Osterbrock, 1989), but comprise a unique class of objects.

Early efforts to characterize UC HII regions culminated at the end of the 1980s and early 1990s with the surveys of Wood & Churchwell (1989), and Kurtz et al. (1994), in which snapshot observations of large numbers of HII regions (~75 sources in each survey) were used to tabulate their morphology and physical parameters. A large fraction of sources were found to have cometary morphologies, and as a result, there was considerable effort towards the development of a “cometary bow shock” model (e.g. Mac-Low et al. 1991). The cometary model proposed that the observed cometary structures arose from the motion of the host star and its HII region through
the parent molecular cloud, and that this shock served to confine
the UC HII region and keep it from expanding as an overpressured
source would naturally tend to do. Our recent multi-frequency,
multi-configuration observations of the W49A, Sgr B2 and several
other Galactic regions have been made in order to probe the physical
parameters and morphologies of an equally large number of UC HII
regions within only a few massive star clusters, with the addition of
radio recombination line (RRL) spectroscopy. Early results in the
W49A and Sgr B2 regions indicate that the cometary morphology is
relatively uncommon, with a large fraction of sources appearing to
have asymmetrically bright shells or rings on the smallest scales, and
bipolar lobes on larger scales. The prevalence of small-scale shells and
bipolar morphologies suggests that at least in the youngest sources,
circumstellar material might be distributed equatorially, and be related
to the accretion process. We are beginning the process of modeling the
early evolution of UC HII regions in dense environments with the new
distribution of morphologies as a motivator.

We have recently obtained ultra-high-resolution observations of both
the millimeter continuum and the H52a spectral line (Wilner et al.
2001; De Pree et al. 2000) in W49A. These observations and others
have indicated the existence of a new subclass of sources within the
UC HII region category. De Pree et al. (1996) and Jaffe & Martin-
Pintado (2000) have identified a number of sources that have very
broad radio recombination lines (DV > 50 km s⁻¹), and continuum
spectral indices (Su ~ ua, 0.6 < a < 1.0) that rise monotonically. These
spectral indices rise up to the highest frequencies detected (1 mm
in the case of some of the regions in W49A), and their values indicate that the rise is not due to the presence
of dust, which would cause the index to increase much more steeply. At 7 mm, the recombination lines are
not significantly biased by opacity or pressure effects and can
provide accurate velocities and linewidths for comparison with
molecular line data.

Jaffe & Martin-Pintado (2000) have called these sources broad
line recombination objects (BLROs). It is possible that BRLOs
represent the earliest stage of the evolution of UC HII regions,
and might be transitional objects that link hot cores to UC
HII regions. We hope to extend our high frequency line and
continuum work in the coming year to the massive star-forming
region W51. Rising spectral indices (indicative of ionized
winds), shell-like and bipolar morphologies, molecular outflows
and broad radio recombination lines all point, perhaps, to the
presence of accretion disks early in the massive star formation
process. Molecular line observations made with the Atacama
Large Millimeter Array (ALMA), once operational, will be able
to detect the presence of such disks.

Figure 3. The W49A B and D regions as imaged
at 7 mm with the VLA. Insets show the integrated
H52α radio recombination line toward sources B1
and D. A combination of imaging spectroscopy
and multi-frequency observations to determine
continuum spectral indices can effectively identify
the youngest of the UC HII regions in a massive
star forming cluster.