Annu. Rev. Astron. Astrophys. 2002. 40:27–62
doi: 10.1146/annurev.astro.40.060401.093845


# Ultra-Compact HII Regions and Massive Star Formation

Ed Churchwell
*Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, Wisconsin 53706-1582; email: churchwell@astro.wisc.edu*



**Key Words** prestellar cores, hot cores, accretion disks, bipolar outflows

■ **Abstract** This review discusses three main topics: evolution to the ultra-compact (UC) state; the properties of UC HII regions and their environments; and UC HII regions as probes of Galactic structure. The evolution to UC HII regions begins in giant molecular clouds that provide the natal material for prestellar cores that evolve into hot cores, the precursors of UC HII regions. The properties of each evolutionary phase are reviewed, with particular emphasis on those of hot cores. The observed properties of UC HII regions and their environments are summarized with emphasis on the physical processes that may produce the observed properties. The final section summarizes the use of UC HII regions as probes of Galactic structure: in particular, the Galactic population and distribution of newly formed massive stars, the location of spiral arms, and the average galactocentric temperature and abundance gradients.

## INTRODUCTION

Ultra-compact (UC) HII regions are manifestations of newly formed massive stars that are still embedded in their natal molecular clouds. Dust in the molecular cloud core renders UC HII regions observable only at radio, submillimeter, and infrared wavelengths. Hofner et al. (2002) showed that deeply embedded stars in the W3 massive star formation complex can be detected via hard X-rays ($\geq$2.5 kev), including the detection of the apparent ionizing stars of the compact HII regions in W3. At this stage, the central ionizing star of a UC HII region is believed to have ceased accreting matter and to have settled down for a short lifetime on the main sequence. During the main sequence lifetime of the central star, its HII region will evolve from a deeply embedded UC state to a much larger, uncloaked, classical nebula. As the name suggests, UC HII regions are small (diameters $\leq 10^{17}$ cm), very dense (typically $\geq 10^4$ cm$^{-3}$), and bright (emission measures $>10^7$ pc cm$^{-6}$). They are among the brightest and most luminous objects in the Galaxy at 100 $\mu$m because of their warm dust envelopes that convert the entire stellar luminosity to far infrared radiation. Typically the infrared emission peaks at $\sim$100 $\mu$m and is $\sim$3 to 4 orders of magnitude above the free-free emission at this wavelength. To be detectable at radio wavelengths, the luminosity of UC

HII regions must be equivalent to a B3 or hotter main sequence star. At mid-infrared wavelengths where warm circumstellar dust, stellar photospheres, and nebular fine structure lines are bright, it will be possible to detect even cooler, less luminous, embedded, newly formed stars using sensitive modern facilities such as the Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA). At wavelengths shorter than $\sim 2\ \mu$m, detection of the ionizing star in most UC HII regions is difficult to impossible because the dust cocoon becomes optically thick.

The study of O stars and their associated HII regions inherently concerns the nature of massive star formation and the impact of newly formed massive stars on their environments. UC HII regions represent a key stage in the development of massive stars. This is the period between the rapid accretion phase of star formation, when the central protostar is being formed, and the period when the UC phase gives way to a larger, more diffuse, less obscured HII region either by destruction of the natal molecular core or by moving out of the core. UC HII regions provide a way to study the process of formation and early evolution of massive stars and the environments in which this occurs. They also have high luminosities and thus are important probes of global properties of the Galaxy because with modern facilities they can be detected throughout the entire Galaxy. They have been used to confirm the electron temperature and metallicity gradients in the Galaxy, establish the scale height in Galactic latitude and angular distribution in longitude of O stars in the Galaxy, infer the fraction of O stars that are obscured at visible wavelengths in their natal cocoons, and estimate the contribution of hot O and B stars to the radiant and mechanical energy budget of the Galaxy. Several reviews that address various aspects of UC HII regions are contained in the recently published compendium *Protostars and Planets IV*; the reviews in Parts I, II, and IV are of particular relevance to massive star formation and UC HII regions. The extensive reviews by Garay & Lizano (1999) and Churchwell (1999) summarize the state of our understanding of UC HII regions up to 1999.

This review concentrates on the evolution leading to UC HII regions (below), the physical properties and nature of UC HII regions as presently understood "UC HII Regions", and the Galactic population and distribution of UC HII regions "Galactic Population and Distribution".



## EVOLUTION TO THE ULTRACOMPACT STATE

### The Natal Material

UC HII regions do not represent the earliest stage of massive star formation, as is often claimed. The story of their origin begins much earlier in the dense cores of giant molecular clouds (GMCs). The clumpy structure of GMCs has been referred to as clumps and cores by Blitz and coworkers (Blitz 1991, Blitz & Williams 1999, and others), as fractal by Bazell & Désert (1988), Scalo (1990), and Falgarone et al. (1991), and as turbulent structures by Vázquez-Semadeni et al. (2000 and references therein). The structure of GMCs appear to be self-similar over a very wide range of sizes and masses (Williams et al. 2000 and references therein). The clumps in which massive stars and their associated lower mass cluster stars form can be quite massive (up to several thousand solar masses). Typically only those with mass $\geq$300–500 $M_\odot$ are gravitationally bound and produce stars; those below $\sim$300 $M_\odot$ are not bound (Blitz 1991). The most massive clumps ($>10^3$–$10^4$ $M_\odot$) contain most of the mass in GMCs, and they provide the natal material for the formation of stellar clusters (Blitz 1991, Blitz & Williams 1999). Cores are the substructure of clumps; they are smaller, denser, and have lower mass (a few tens of solar masses) than clumps. Cores are the sites of individual star formation within clumps. Crutcher (1999) found that the supersonic motions in molecular clouds are about equal to the Alfvén speeds and suggested that the supersonic motions are magneto hydrodynamic (MHD) waves. The magnetic energy in cores appears to be close to but slightly less than the gravitational energy (Crutcher 2001), so magnetic fields alone probably cannot prevent gravitational collapse.

The origin of the stellar initial mass function (IMF) is a fundamental unsolved problem in star formation. To first approximation, the IMF appears to be universal, independent of abundance differences in the Milky Way and in neighboring galaxies (Massey 1999, Massey & Hunter 1998, Meyer et al. 2000, Kroupa 2001). Several hypotheses have been proposed to explain the observed stellar IMF, some of which are, the mass spectrum produced by cloud fragmentation; the impact of the initial stars on the structure of the local interstellar medium (ISM); the fractal structure of molecular clouds; the MHD wave patterns in molecular clouds; shock patterns produced by cloud-cloud collisions, etc. Blitz & Williams (1999) and Williams et al. (2000) have postulated that the IMF is determined by the mass spectrum of the natal molecular cloud well before star formation begins. This would imply that the mass spectrum of the molecular cores out of which stars form have an approximate Salpeter slope ($dN/d \ln M \propto M^{-\alpha}$ where $\alpha \sim 1.35$). It is interesting that the mass spectra of embedded molecular cores in $\rho$ Oph (Motte et al. 1998) and in Serpens (Testi & Sargent 1998) have slopes $\alpha > 1.1$, quite close to the Salpeter value. This is consistent with the hypothesis that the stellar IMF could be determined by the structure of the natal cloud prior to star formation activity but not sufficient for a proof (Meyer et al. 2000).

Why do cores become gravitationally unstable and begin to collapse? Myers & Fuller (1992) and others have called attention to the importance of nonthermal motions (mostly turbulence) in molecular cores. Turbulent dissipation seems to occur on shorter timescales than the gravitational free-fall time (Vázquez-Semadeni et al. 2000 and references therein). However, recent simulations by Cho et al. (J. Cho, A. Lazarian, E.T. Vishniac, submitted) find weak coupling between wave packets traveling in the direction of magnetic field lines, resulting in a slower decay of turbulent motions than reported by Vázquez-Semadeni et al. (2000). In the absence of either continuous mechanical energy injection and/or strong magnetic fields, short dissipation times would lead to wholesale cloud collapse.

Myers & Lazarian (1998), Nakano (1998), Williams & Myers (2000), and Williams (2001) have proposed the interesting hypothesis that turbulent cooling flows in molecular clouds may initiate collapse by producing low pressure regions that can be compressed by nearby high pressure regions. From an analysis of line dispersions toward several molecular cores, Williams & Myers (2000) found that inward motions predominate in quiescent cores (i.e., those with the narrowest line widths), while in cores with the largest dispersions the motions are primarily outward. Williams (2001) suggests that in regions of high pressure (where turbulent motions are large), matter flows outward to regions of lower pressure, and in regions of low pressure (where turbulent motions have dissipated), matter flows inward. In regions of low turbulence (low pressure), gravity plus external pressure may initiate collapse. In this picture, the turbulent structure of molecular cores plays a critical role in the initiation of star formation. It also requires that turbulent structure in molecular clumps produce an approximate Salpeter stellar mass spectrum—an issue that remains to be determined.



## Prestellar Cores

Prestellar cores (PSCs) are the earliest identifiable stage of a star in the process of forming. They are dense, gravitationally bound, molecular cloudlets that are undergoing quasistatic gravitational contraction. Formation of PSCs may be the most poorly understood stage of massive star formation (Garay & Lizano 1999). PSCs have not yet formed a central protostar and therefore will not appear as near-infrared (near-IR) ($\lambda \leq 2\ \mu$m) point sources. They are also generally optically thick at these wavelengths. Because PSCs are only heated by the ambient interstellar UV radiation field, they have temperatures of only 10–20 K, and their spectral energy distributions (SEDs) peak in the far infrared at $\sim$200 $\mu$m, as illustrated in Figure 1 by the low-mass PSC in L1544. Due to their low temperatures, PSCs can be detected at 4–8 $\mu$m in absorption against the bright Galactic plane background emission (Bacmann et al. 1998). At far-IR and sub-mm wavelengths ($\lambda > 150\ \mu$m) (Ward-Thompson et al. 1994, Launhardt & Henning 1997, André et al. 1996, Ward-Thompson & André 1998) they can be detected in emission. PSCs can also be detected in the rotational lines of CO and other molecules.

Proof that a cloudlet is a PSC requires molecular line measurements that show the characteristics of infall. Zhou et al. (1993) and Ward-Thompson et al. (1996) have demonstrated this toward B335 and NGC 1333-IRAS2, respectively. However, both of these clouds have already formed a protostar at their core. Lee et al. (1999), Gregersen et al. (2000), and Gregersen & Evans (2000) have identified over a dozen PSC candidates with infall signatures. Claims for other PSCs have been based on indirect arguments such as high densities, $L_{bol}$ too low to be consistent with an accreting protostar, low temperatures (indicating no internal heating), masses approximately virial, no IR point source detected in the cloudlet, etc. This is rapidly changing with the efforts to detect infall by Myers, Evans, and their coworkers.

The distribution of $H_2$ column density with radius is an indicator of the support mechanism(s) of PSCs, which also has consequences for the process of star formation. For example, the "inside-out" collapse model of Shu (1977), Shu et al. (1987),

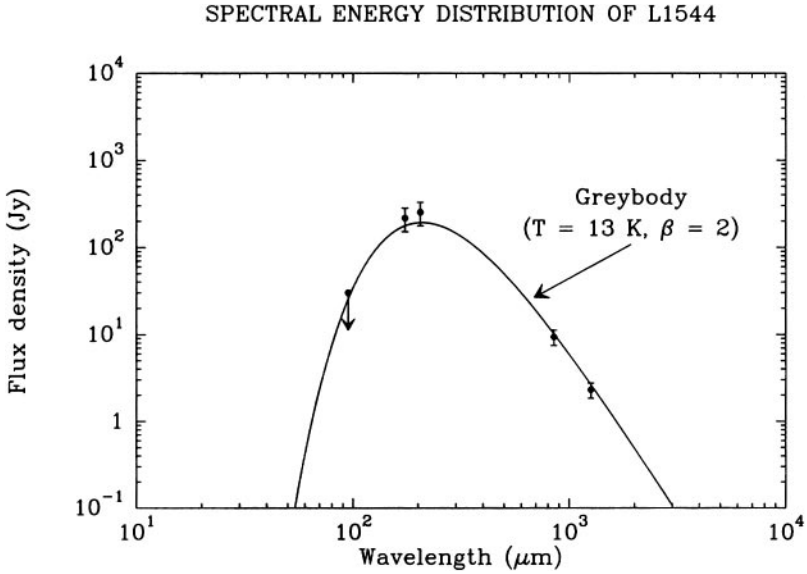


**Figure 1** The spectral energy distribution of the prestellar core in L1544 from Bacmann et al. (1998). A greybody model of temperature 13 K (solid curve) is superimposed on the observed data points.

and Shu et al. (2000) predicts a power law distribution, $N_{H_2} \propto r^{-2}$, consistent with an isothermal sphere for the protostellar precursor cloud. Ward-Thompson et al. (1994), André et al. (1996), and Bacmann et al. (1998) have found PSC column density profiles to be approximately flat near the center and to approach $N_{H_2} \sim r^{-2}$ toward the outer boundaries. They argue that the observed profiles are consistent with magnetically supported clouds undergoing ambipolar diffusion. It is worth noting that the derived density profiles require several uncertain assumptions or extrapolations that could significantly alter the results. Also, the timescale for star formation via ambipolar diffusion seems to be too long (Lee & Myers 1998, Jijina et al. 1999).

The study of PSCs is still in its infancy, and much more work will be required to obtain a better understanding of them. PSCs probably do not remain in this state for more than about $10^6$ years (Ward-Thompson et al. 1994, Fuller & Myers 1987) and therefore are rather rare and difficult to find. All PSCs detected so far are low-mass cloudlets that will give rise to low-mass stars. PSCs that produce massive stars have not been unambiguously identified, although one suspects that they may be among the more compact objects detected by Egan et al. (1998). The densities, sizes, and masses of the objects reported by Egan et al. (1998) are in the right range to give rise to massive stars and their associated lower-mass cluster members (Carey et al. 1998).

## Hot Cores: Precursors to UC HII Regions

Hot cores (HCs) have been defined by Kurtz et al. (2000) as compact (diameters $\leq$0.1 pc), dense ($n_{H_2} \geq 10^7$ cm$^{-3}$), and warm (T $\geq$ 100 K) molecular cloud cores that have large molecular line optical depths and high line-brightness temperatures when resolved. This observationally based definition of HCs is broad enough to apply to any hot, dust/molecular gas–enshrouded object such as UC HII regions, evolved hot stars that have moved into a dense molecular cloud, or massive protostars still undergoing rapid accretion. In this section, I consider only the class of hot cores containing rapidly accreting, massive protostars. These are the precursors of UC HII regions, which I refer to as PUCHs (precursors of UC HIIs). PUCHs are internally heated by the central massive protostar plus any associated lower-mass cluster members. They are likely to be surrounded by an equatorial accretion disk and a massive bipolar outflow along their spin axes. Their outflow masses, momenta, and kinetic energies are much larger than those of low-mass protostars, and they are generally poorly collimated relative to those associated with low-mass stars. Because of rapid accretion, the protostar does not produce a detectable HII region, even though it has a large UV photon flux. PUCH lifetimes are quite short, typically $\leq 10^5$ yr.

The above statements implicitly assume that massive stars are formed via accretion of ambient interstellar matter through an equatorial disk. This assumption has been questioned by Bonnell et al. (1998) and Stahler et al. (2000) who have suggested that massive stars (M > 10 $M_\odot$) may be formed via coalescence of intermediate mass protostars. This hypothesis is supported by the central location of the most massive stars in young open clusters and the high stellar density of many open clusters, such as the Orion cluster whose mean stellar separation is less than the Jeans length for any reasonable initial natal cloud temperature. The coalescence hypothesis for massive star formation, in fact, is likely to be even more effective than argued by Bonnell et al. (1998) if three-body interactions had been included in which a bound binary pair of protostars interact with a third member of a forming stellar cluster. Models including such interactions have not been published but clearly need to be done. It is entirely possible that massive stars could be formed both by accretion and coalescence in the same cluster. The presence of massive bipolar molecular outflows (and reported detection of equatorial accretion disks toward a few objects) provide strong arguments in favor of formation via accretion, but there are equally strong arguments for the coalescence hypothesis. In much of the discussion of hot cores below, it is assumed that accretion produces massive stars. However, one should be aware that coalescence may be an important formation mechanism of massive stars.

TEMPERATURE STRUCTURE Wolfire & Churchwell (1994) investigated the temperature structure of dust cocoons enshrouding UC HII regions for a range of different dust properties, cocoon density profiles, and stellar radiation fields. The temperature structure of these models is likely to apply to any type of hot star or protostar whose UV radiation is absorbed by a large circumstellar dust cocoon such as PUCHs. Wolfire & Churchwell (1994) found that the temperature profiles can generally be described by four zones around the central heat source. A central dust evacuated cavity around the ionizing star or protostar exists where the temperatures are higher than the dust sublimation temperature. Their models and others (e.g., Chini et al. 1987) indicate that the inner dust radius is generally substantially larger than the dust sublimation radius, probably owing to stellar winds and radiation pressure. A thin inner dust shell exposed to direct stellar UV radiation declines in average dust temperature with distance from the central protostar as $\overline{T}_d \propto e^{-\tau_{UV}}$, where $\tau_{\rm UV}$(r) is the optical depth at UV wavelengths to the stellar radiation field at distance $r$ from the protostar. Most of the decrease in dust temperature can occur in this thin shell. At radii beyond where direct and scattered stellar UV radiation has been absorbed in the inner shell, the dust is heated by NIR radiation from hot dust at the inner edge of the shell. Due to dilution of this emission, the mean dust temperature, $\overline{T}_d$, declines with radius as $\overline{T}_d \propto r^{-\alpha}$, where $\alpha \approx 2/(\beta + 4)$ and $\beta$ is the index of the FIR dust opacity ($K_\lambda \propto \lambda^{-\beta}$). At distances where extinction of the NIR emission of the inner shell becomes important, the temperature profiles become slightly steeper than $r^{-\alpha}$. Figure 2 shows the calculated temperature profile

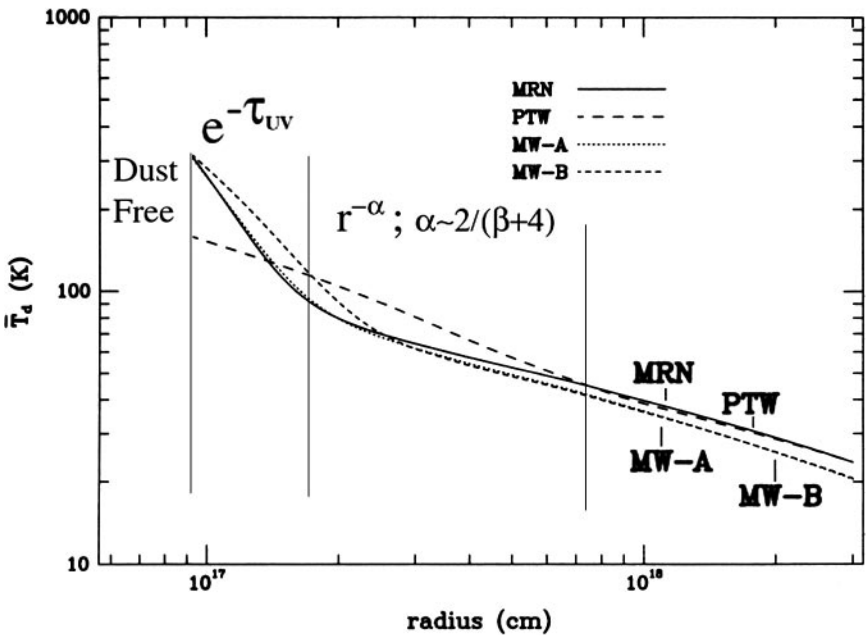


**Figure 2** The calculated average dust temperature with distance from an O6 star for four different dust models from Wolfire & Churchwell (1994). Three different temperature zones are indicted by vertical lines.

of a UC HII region ionized by an O6 star from Wolfire & Churchwell (1994). This model and others (e.g., Chini et al. 1987) imply that dust hotter than ~100 K occupies a very small fraction (a few percent) of the volume of the dust envelope; most of the dust is well below 100 K, with average values of ~30 K. Thus PUCHs and UC HII regions are expected to be brightest at about 100 $\mu$m, at which most of the emission escapes.

SPECTRAL ENERGY DISTRIBUTIONS The IR/sub-mm SEDs of PUCHs are likely to be quite similar to those of UC HII regions. The primary differences are the locations of the stellar wind terminal shock and the radius of the dust sublimation temperature. The large infall rates will push both boundaries closer to the protostar than would otherwise be the case. A central dust-free cavity must exist around the rapidly accreting protostar of a PUCH because its large luminosity will heat the dust to temperatures well above the sublimation temperature. For example, for $L \geq 10^4$ $L_\odot$, even graphite dust would be destroyed at radii less than ~850 solar radii; for $L = 10^5$ $L_\odot$, the sublimation radius becomes ~2700 $R_\odot$ or about 12.5 AU. Dust may exist inside the dust-free cavity in a dense, self-protective accretion disk and thereby provide some NIR emission from this region. Because of the temperature gradient with radius, the SEDs are broader than single temperture Planck functions. Osorio et al. (1999) have modeled four hot molecular cores with rapidly accreting massive protostars at their centers and found that the observed SEDs are better fit by envelopes with singular logatropic spheres ($\rho(r) \propto r^{-1}$) than singular isothermal spheres ($\rho(r) \propto r^{-2}$). Their model fits to the SEDs, and temperature distributions of four PUCHs are shown in Figure 3. These are, as expected, essentially identical to the SEDs of UC HII regions. One implication is that the radius of the wind terminal shock, the dust sublimation temperature, and the accretion disk are so small relative to the extent of the dust envelope that they make essentially no impact on the emergent spectrum. Osorio et al. (1999) also find that accretion provides the dominant source of luminosity at this stage of evolution.

RADIO FREE-FREE EMISSION PUCHs are not expected to produce a detectable HII region, even though the central protostar produces a large UV photon flux, because these photons cannot travel far from the protostar before being absorbed by infalling matter. The result is a small Strömgren sphere around the central protostar. The critical mass infall rate at which all the stellar UV photons are absorbed by the infalling material is

$$\dot{M}_{crit} = \left[\frac{4\pi m_H^2 G L_{UV}^* M^*}{\alpha(2)}\right]^{1/2} \qquad (1)$$

(Walmsley 1995), where $m_H$ is the mass of hydrogen, $\alpha(2)$ is the hydrogen recombination coefficient to all levels except $n = 1$, G is the gravitational constant, $L^*_{UV}$ is the protostellar ionizing photon flux, and $M^*$ is the mass of the central protostar. In Figure 4, log ($\dot{M}_{crit}$) versus $T_{eff}$ (or spectral type) for main sequence O stars is plotted using the stellar data ($M^*$ and $L^*_{UV}$) from Vacca et al. (1996). One sees

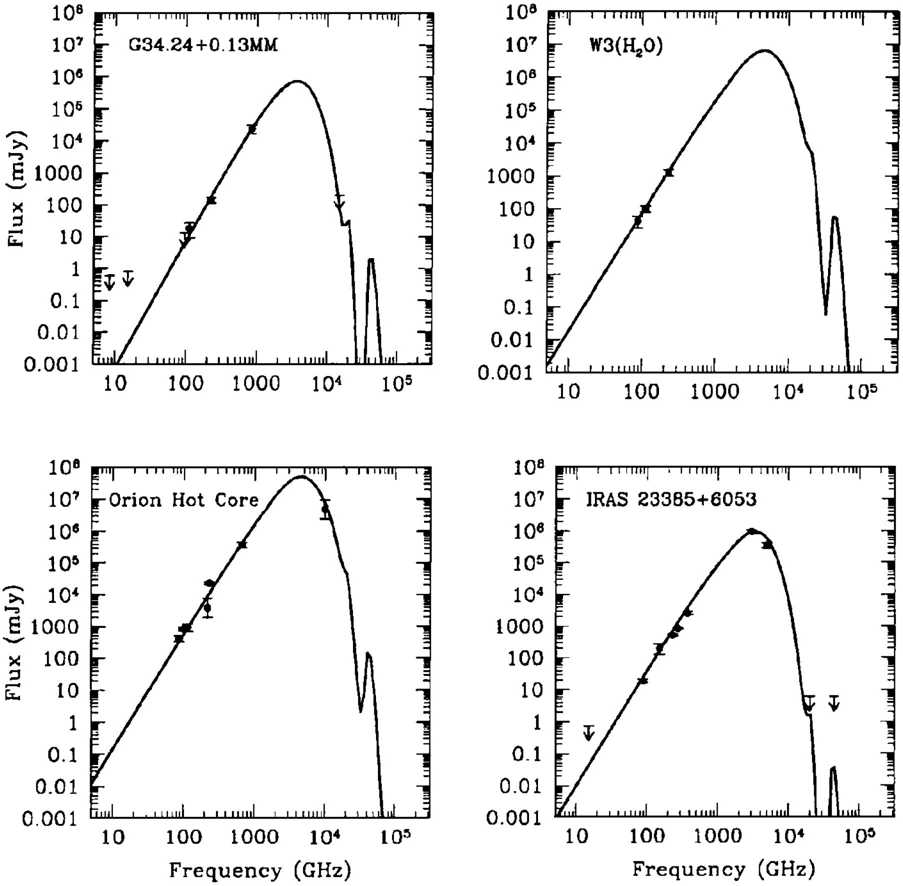


**Figure 3** The SEDs of four hot cores with model fits to the observed data points from Osorio et al. (1999). These are very similar to those of UC HII regions.

from Figure 4 that for O4 to B0 main sequence stars, a critical mass infall rate of only $10^{-4}$ to $10^{-5}$ solar masses per year, respectively, is adequate to quench the circumstellar HII. The mass infall rate around massive protostars in their rapid accretion phase is likely to be $\sim 10^{-3}$ solar masses per year, or a factor of 10–100 times the critical infall rate. Thus, it is reasonable to expect that a HC harboring a massive protostar at its center, even if it is very luminous, will not have detectable radio free–free emission. It is important to note, however, that there will be a small dust-evacuated cavity around luminous protostars undergoing rapid accretion with radius $R_c$ in which hydrogen will also be ionized. Temperatures will be larger than the dust sublimation temperature for $R_c \leq (L_*/4\pi\sigma T^4)^{1/2}$, where $T$ is the dust sublimation temperature. For $L_* = 10^5\ L_\odot$, $R_c \leq 12$ AU. This is still too small and probably optically thick to be detected by current instrumentation.

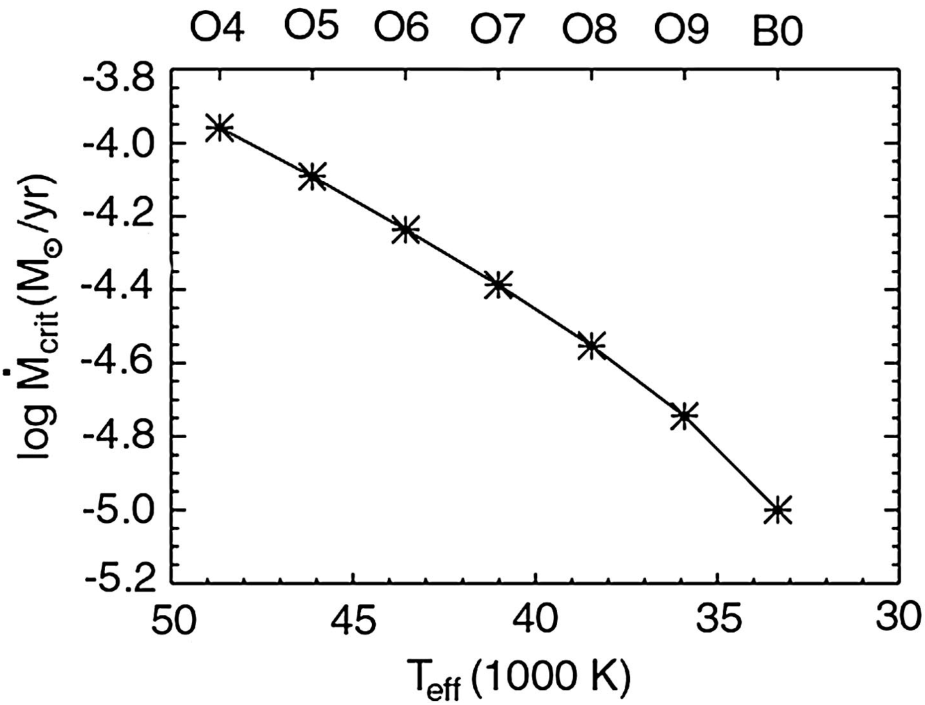


**Figure 4** The critical mass infall rate that will absorb all stellar UV photons as a function of effective temperature (or spectral type). The stellar properties of Vacca et al. (1996) are assumed and the relation of Walmsley (1995) is plotted.



What is the evidence that massive protostars have such high accretion rates and short lifetimes? Several arguments lead us to this conclusion. First, the Kelvin-Helmholtz timescale, which is a strict lower limit on the time to produce a star of a given mass, is only a few thousand years for a 30 solar mass star. These short timescales require accretion rates of $\dot{M}_{acc} \approx M_*/\Delta t \leq 10^{-2}$ solar masses per year. A more accurate estimate of the timescale may be obtained using the properties of molecular outflows associated with massive star formation. Molecular outflows driven by massive protostars have dynamical ages of a few times $10^4$ years, masses of a few tens to a couple of hundred solar masses, and mass outflow rates ranging from $10^{-0.6}$ to a few times $10^{-2.0}$ solar masses per year with a typical value of $\sim 10^{-3}$ solar masses per year (see Churchwell 1997). Presumably the mass accretion rate has to be somewhat larger than the outflow rate because some of the mass must go into building the star. Taking the conservative approximation that $\dot{M}_{acc} > \dot{M}_{out} \approx 10^{-3}$ solar masses per year requires that the timescale for massive star formation is in the range of a few times $10^4$ to a few times $10^5$ yr. These arguments require both a high mass accretion rate and a short timescale for massive star formation, neither of which is particularly surprising because gravitational processes occur more rapidly in deeper gravitational potentials. Recent evolution models of star formation by Behrend & Maeder (2001) using mass-dependent accretion rates (increasing with increasing stellar mass) find that the average mass accretion timescale for formation of stars from 8 to 80 solar masses is $\sim 3 \times 10^5$ yr independent of the mass. They also find that low-mass stars form first and massive stars later using current best IMF models. A further argument for short PUCH lifetimes has been proposed by Wilner et al. (2001). They find about half as many PUCHs as UC HII regions in the giant massive star formation region W49 and suggest that the average PUCH lifetime may be about half that of UC HII regions.

OUTFLOWS AND ACCRETION DISKS If massive stars form by accretion of ambient gas, then PUCHs must experience a period of rapid accretion accompanied by an equatorial accretion disk and a massive bipolar outflow normal to the disk according to the standard paradigm. Observational evidence for accretion disks around massive protostars exists for only a very few objects; Garay & Lizano (1999) list eight objects in their Table 3. A more recent reference for G192.16 − 3.82 is Shepherd et al. (2001). Accretion disks in massive star formation regions are very difficult to detect because of their large distances, the brightness of the central protostar, and the difficulty of distinguishing a possible disk from the dense, hot, circumstellar environment of the natal hot core. The natal core is bright and may have large velocity gradients other than Keplerian motions. The protostars with detected accretion disks have masses ranging from 10 to 370 $M_{\odot}$, radii from $<$500 to $10^4$ AU, and all of them have observed outflows (Garay & Lizano 1999). High resolution observations of methanol masers by Norris et al. (1993, 1998) and Phillips et al. (1998) have been interpreted to originate in accretion disks, but this hypothesis is not universally accepted.

Molecular outflows have been observed toward numerous massive star formation regions (see Shepherd & Churchwell 1996, Ridge 2000). The molecular outflows from massive protostars have very large masses, mass fluxes, momenta, and mechanical luminosities (Churchwell 1997, Ridge 2000). They are also not as well collimated as those from low-mass protostars (see the closest one in Figure 7). There is a tight correlation between the outflow mass flux, $\dot{M}_{out}$, and the bolometric luminosity of protostars that holds over at least six orders of magnitude in $L_{bol}$ from 1 to $\sim 10^6$ $L_{\odot}$ (see Cabrit & Bertout 1992, Shepherd & Churchwell 1996, Churchwell 1999 and references therein). Figure 5 shows a recent version of this relation with additional data from Henning et al. (2000). The continuity of the $\dot{M}_{out}$-$L_{bol}$ relation has been used to argue that the formation of massive stars is simply an extension of the process of low-mass star formation to more massive stars. This seems unlikely for several reasons. Since the luminosity is a reflection of the mass of the central protostar and the mass determines the gravitational potential that governs the rate of accretion and other processes associated with star formation, it is not surprising that a continuous $\dot{M}_{out}$-$L_{bol}$ relationship holds for all stellar luminosities. This correlation may have nothing to do with the actual

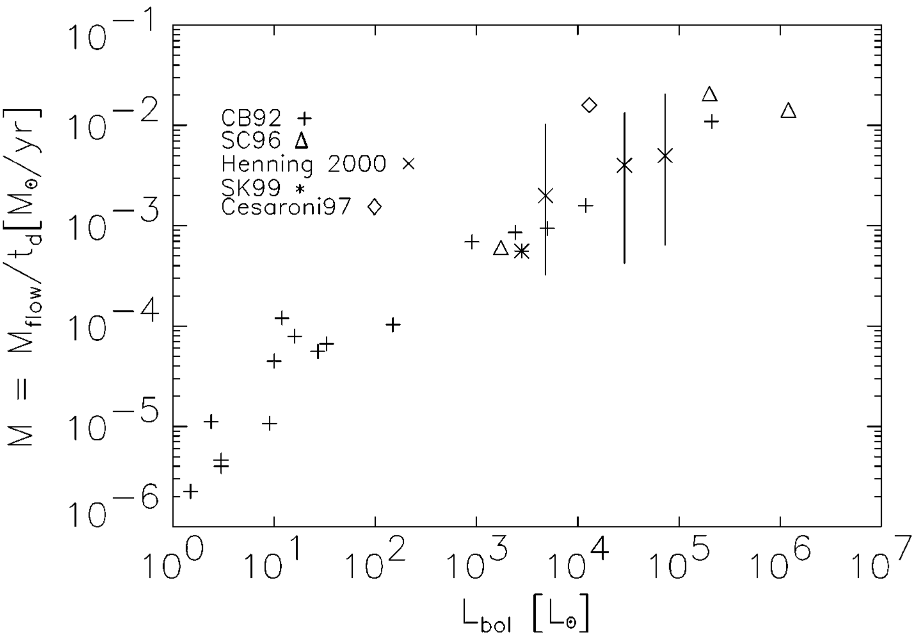


**Figure 5** The mass outflow rate of bipolar molecular outflows driven by protostars of bolometric luminosity ranging from 1 to $10^6\ M_\odot\ yr^{-1}$. Data for this plot were assembled from Cabrit & Bertout (1992), Shepherd & Churchwell (1996), Henning et al. (2000), Cesaroni et al. (1997), and Shepherd & Kurtz (1999).



process of star formation but may simply reflect the central role gravity plays in star formation. Ridge (2000) finds that the mass and luminosity of outflows suffer from Malmquist bias. She argues that since more luminous protostars are embedded in more massive HCs, the mass in outflows only reflects the amount of material available in the HC. She concludes that "the outflow dynamics may tell us nothing about the mechanism that generated the flow, only that they have propagated through more material" (Ridge 2000). The sources with the highest luminosities in Figure 5 are unlikely to suffer Malmquist bias, as they could be detected at much greater distances, although the lower luminosity sources may well suffer such an effect. The $\dot{M}_{out}$-$L_{bol}$ relationship has been used to infer $L_{bol}$ for the central protostar from measured $\dot{M}_{out}$ values. However, most recently Beuther et al. (2001) found that the relation shown in Figure 5 only represents an upper envelope for $\log(L_{bol} > 3.5)$. This calls into question the determination of $L_{bol}$ for massive protostars using the $\dot{M}_{out}$-$L_{bol}$ relationship.

BIPOLAR MOLECULAR OUTFLOWS Bipolar outflows provide a mechanism for accretion disks to shed angular momentum, thereby permitting matter in the disk to migrate to the central protostar. Since bipolar outflows appear to be intrinsic to the process of star formation, it is essential to understand them as a step toward understanding star formation. Unfortunately, there is no generally accepted theory for how tens to hundreds of solar masses of cold molecular gas can be accelerated and collimated on short timescales while matter is simultaneously rapidly accreting onto the protostar. The X-wind theory of Shu and coworkers (Shu et al. 1988, 1994, 2000) and other theories that invoke magnetic fields to redirect and collimate outflows were developed for low-mass protostars that involve small masses and probably are not applicable to massive outflows.

Massive outflows have some general properties that have to be explained by any successful theory of their origin. One, they are not well collimated relative to those associated with low-mass protostars. Two, most of the mass in the outflows have velocities of only a few tens of km $s^{-1}$, not hundreds. The outflow observed by Henning et al. (2000) toward IRAS12091-6129 is typical of the low collimation, low outflow velocities, and large outflow masses found in massive star formation regions. This outflow is shown in Figure 6. Three, the Orion IRc2 outflow shown in Figure 7, (Subaru Telescope Facility) appears to originate from a surface much larger than a star, the opening angle is quite wide, and the outflow working surface is jagged (i.e., does not act like a smooth piston on the ambient medium). The large surface of origin, wide opening angle, and low outflow velocities suggest that much of the outflow material must have been accelerated outward at fairly large distances from the protostar where the escape velocity is commensurate with the flow velocities.

We know that radiation alone cannot drive the outflows because the radiation momentum flux is small relative to that in the outflow $L^*/c \ll \dot{M}_f \mathrm{v}_f$, where f refers to the outflow. Additional driving mechanisms could be protostellar winds and/or rotation perhaps combined with a magnetic field and gravity. However, the physics of how bipolar molecular outflows are driven and collimated are not understood. There must be either an additional component of force normal to the disk, such as a disk wind, and/or a radiation field produced by a hot, shocked disk surface (as postulated by Neufeld & Hollenbach 1994, 1996). Perhaps magnetic fields normal to the disk play a role in aligning and redirecting infalling material outward along the spin axis. The poor collimation of the outflows, however, is not a good sign for magnetic alignment. Larson (2002) has postulated that tidal torques could play an important role in redistributing angular momentum during the process of massive star formation.

Although there is considerable uncertainty in the determination of outflow masses (see Ridge 2000), all investigators find very large outflow masses associated with massive protostars. This presents an interesting and unsolved problem. Churchwell (1997) noted that the outflow masses are generally greater than the inferred mass of the protostar that drives them, sometimes by a factor of ∼8. He examined four mechanisms that may explain the large outflow masses and concluded that neither accumulated stellar winds nor broad piston-like outflow working surfaces are likely to be able to account for the observations. Turbulent entrainment of ambient HC gas may be able to account for a few solar masses of material,

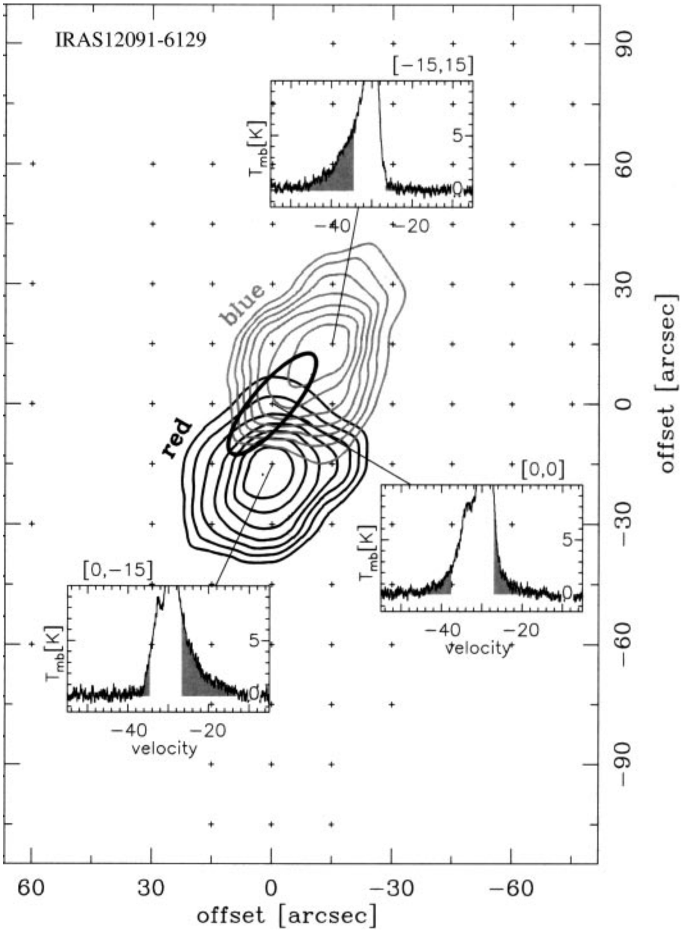


**Figure 6** The CO outflow presumably driven by the FIR source IRAS12091-6129 from Henning et al. (2000). This figure illustrates three general properties of outflows driven by massive protostars: low outflow speeds, poor collimation, and large masses. The arbitrary cutoff velocities (shaded regions in the spectra) for the outflow also illustrate why outflow masses are uncertain and different authors disagree on the estimated masses.

but the entrainment efficiency appears to be too small to account for tens of solar masses. Churchwell (1997) concluded that the most likely mechanism is infalling material that is somehow diverted out again along the protostellar spin axis. An interesting implication of this scenario is that only a small fraction of the infalling matter actually reaches the central protostar; most is blown back out into the hot core. This would also imply that for a hot core to produce a star of a given mass, it would have to have an initial mass many times the mass of the most massive star in an OB cluster. Thus to form a 50 solar mass star, it may require a molecular clump of several thousand solar masses. Such clumps are rare and may be a primary reason why O stars are rare. A possible way to save the entrainment idea is by magneto-turbulent entrainment. The advantage of magneto-hydrodynamic entrainment is that it operates at Alfvén speeds, about a factor of 10 larger than the sound speed in hot cores. This is about the factor needed to account for the measured outflow masses. Observational support for this mechanism does not exist at this time.



### Hyper-Compact HII Regions

A growing number of super compact and super dense objects have been discovered mostly at millimeter wavelengths (see the compilation of Johnson et al. 1998). They are typically about 10 times smaller and 100 times denser than UC HII regions. They are generally very weak or not detected at cm wavelengths, but their flux densities increase roughly proportional to frequency at mm wavelengths. Several have been observed in hydrogen radio recombination lines (H42$\alpha$ to H66$\alpha$) and found to have astonishingly broad linewidths (FWHM $\sim$ 50 to 180 km s$^{-1}$); typical HII linewidths are $\sim$30 km s$^{-1}$. The nature of these objects is not understood: Neither the spectral indices nor the broad lines, nor their origin have adequate explanations. Hofner et al. (1996) reproduced the spectral index of G9.62E with a partially ionized stellar wind; unfortunately, no radio recombination lines exist for this source. With the exception of G25.5 + 0.2, all the known hyper-compact HII regions are located in massive star formation complexes. It is tempting to speculate that these objects may possibly be massive protostars near the end of their rapid accretion stage and are in the process of producing a detectable HII region. They are so dense that they are optically thick at cm wavelengths and only become detectable at mm wavelengths. The broad linewidths could be produced by ionized bipolar outflows that drive the observed molecular outflows associated with accretion. Other scenarios have been postulated, but at this point too little information is available to decide among them. G25.5 + 0.2 appears to be an evolved object (Subrahmanyan et al. 1993). Much more intensive study will be required before a better understanding of these objects emerges.

## UC HII REGIONS

Massive stars begin burning hydrogen well before they reach the main sequence (i.e., while they are still accreting matter; see Bernasconi & Maeder 1996). However, they probably do not form detectable UC HII regions until they have ceased most accretion for the reasons given above (see Radio Free-Free Emission). Thus, we should expect that the ionizing star of a UC HII region is on the main sequence, no longer accreting significant (if any) mass, and basically obeys the statistical relations found for optically visible O stars such as the mass-luminosity relation ($L \propto M^3$) and mass loss rate ($\dot{M} \propto L^{1.7}$).

## The Ionized Gas

MORPHOLOGIES AND LIFETIMES UC HII regions have only a few recurring morphological types, which Wood & Churchwell (1989a) classified as cometary, core-halo, shell, and irregular and multiple peaked structures. An additional type, not included in the Wood & Churchwell (1989a) survey, is bipolar HII regions that comprise a very small number of objects: NGC7538 IRS1 (Campbell 1984, Turner & Matthews 1984), NGC6334A (Rodríguez et al. 1988), G45.48 + 0.13 (Garay et al. 1993), W49A-A (De Pree et al. 1997), and K3-50A (De Pree et al. 1994). S106 also has a bipolar morphology, but it is too large to qualify as a UC HII region. The bipolar nebulae have broad radio recombination lines, strong velocity gradients along the bipolar axes, and an hourglass shape when projected on the sky. Radio images shown in Figure 8 illustrate the four morphological types that have some degree of symmetry.



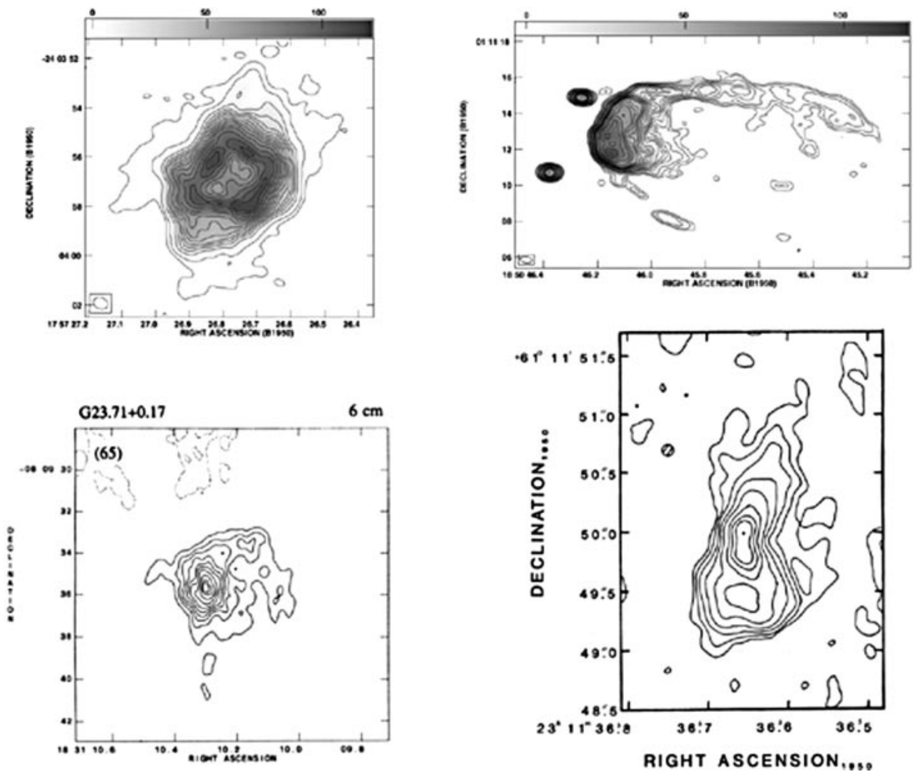


**Figure 8** Examples of UC HII morphological types. Top left: G5.89 − 0.39, a shell-like structure. Top right: G34.26 + 0.15, a cometary nebula. Lower left: G23.71 + 0.17 from Wood & Churchwell (1989a), a core/halo morphology. Lower right: NGC7538 IRS1 from Campbell (1984), a bipolar nebula.

How do we explain the small number of morphological types, and how they are formed? The morphology of a UC HII region is a complicated function of its age, the dynamics of both the ionized and molecular gas, the density structure of the local ambient ISM, and the motion of the HII region relative to the ambient medium. Because the morphology depends on so many factors, it has not been easy to isolate the primary mechanism(s) that determine the morphology and maintain UC HII regions in a compact state for periods up to $\sim 10^5$ years (see "Galactic Population and Distribution" below). The morphology and lifetime in the UC state are related, and any successful theory that explains the morphology must also account for the long dwell time in the compact state. Churchwell (1999) discussed six proposed hypotheses to explain either the long lifetimes of UC HII regions (required to account for their large number) or their morphologies. These are champagne flow or blister models; infall models; photo-evaporating disks; pressure-confined nebulae; stellar wind–supported bow shocks; and mass-loaded stellar winds. Except for the bow shock hypothesis, each of the other hypotheses either addresses a particular morphology or the long lifetime issue but not both. The bow shock hypothesis can explain the long lifetimes and cometary, core/halo, and shell morphologies, but it does involve fine-tuning the ambient density, stellar velocity through the molecular core, and the aspect angle of observation to account for a given morphology and lifetime. Churchwell (1999) concluded that all the above hypotheses may be valid at different evolutionary stages in the lifetime of a UC HII region. For example, a champagne flow is likely to occur as a star exits its natal molecular cloud, photo-evaporating disks are likely to occur as long as a disk exists around a massive protostar, and if ambient pressure is greater than that of the UC HII region, it will provide confinement. Each of the hypotheses predicts different kinematics of the ionized gas, so they can be tested by observing high resolution velocity distributions of the gas via radio recombination lines and/or IR fine structure lines. Using high spatial resolution images of radio recombination lines toward the cometary UC HII region G29.96 – 0.02, Afflerbach et al. (1994) concluded that the distribution of line velocities and widths was consistent with a bow shock model. Using long slit echelle spectra of the Br$\gamma$ line toward G29.96 – 0.02, Lumsden & Hoare (1996) concluded that the distribution of line velocities was inconsistent with the bow shock model and generally consistent with a champagne flow. This illustrates the difficulty of distinguishing between various models and the importance of obtaining more high-quality data.

LOW-DENSITY EXTENDED HALOS Interferometric observations with lower resolution (i.e., sensitive to larger spatial structures) than the surveys of Wood & Churchwell (1989a) and Kurtz et al. (1994) show that many UC HII regions are surrounded by extended lower density ionized halos (Garay et al. 1993, Koo et al. 1996, Kurtz et al. 1999, Kim & Koo 2001). This is illustrated in Figure 9 from Kurtz et al. (1999). The panels from bottom to top are in order of increasing resolution and decreasing sensitivity to extended emission. The ratio of halo to core luminosities ranges from 10 to 20 with a mean of $\sim$15 (S. Kurtz, private

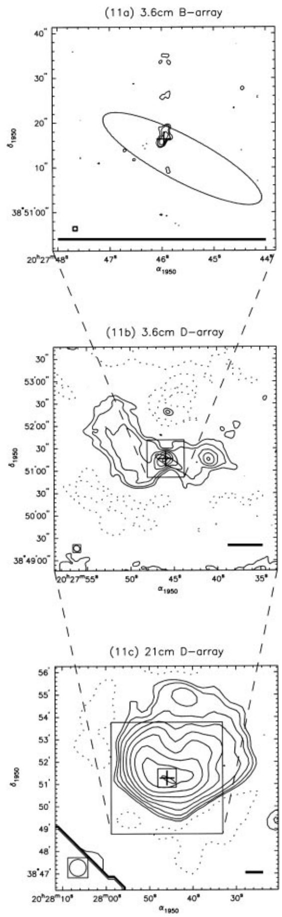


**Figure 9** A montage of images of G77.9 − 0.0 obtained with different resolutions by Kurtz et al. (1999). This illustrates the extended halo that becomes quite apparent at lower spatial resolutions. Note the change in scale and field of view from bottom to top.



communication). Thus, the energy flux from the halos is quite large relative to that of the small UC HII cores. This clearly requires ionization by a cluster of hot stars because the energies are generally larger than that expected from single stars. Extended low-density gas associated with UC HII regions is also required to explain the detection of FIR fine structure emission lines of $O^{++}$, $N^{++}$, $N^{+}$, and $S^{++}$ (Martín-Hernández et al. 2002, and references therein). Extended, lower-density, ionized hydrogen surrounding UC HII regions supposedly deeply embedded in dense molecular hydrogen cores does not easily fit the standard picture. Kim & Koo (2001) have suggested that extended halos can be understood in terms of a champagne flow combined with the clumpy structure of the molecular core. A clumpy structure of the molecular core would permit ionizing radiation to penetrate further from the protostar than in a uniform medium. Kim & Koo's idea also requires that the UC HII regions be located near the boundary of their natal molecular core. Is this reasonable for the majority of massive protostars? If UC HII regions are substantially older than their diameters suggest based on classical Strömgren theory, this could well be true. It would also be consistent with the bow shock model of UC HII regions, which predicts that they convert to champagne-type flows as they exit their natal molecular core. Formation of a halo during the bow shock phase is unlikely because existing bow shock models predict that the ionization fronts are trapped behind the bow shock and would therefore prevent formation of a halo in all directions except the tail. The proposed Kim & Koo (2001) model is shown in Figure 10. Kim & Koo (2001) have suggested that the existence of extended halos could also resolve the lifetime problem of UC HII regions. However, it is also possible that the halos are formed on or near light travel timescales. If champagne flows

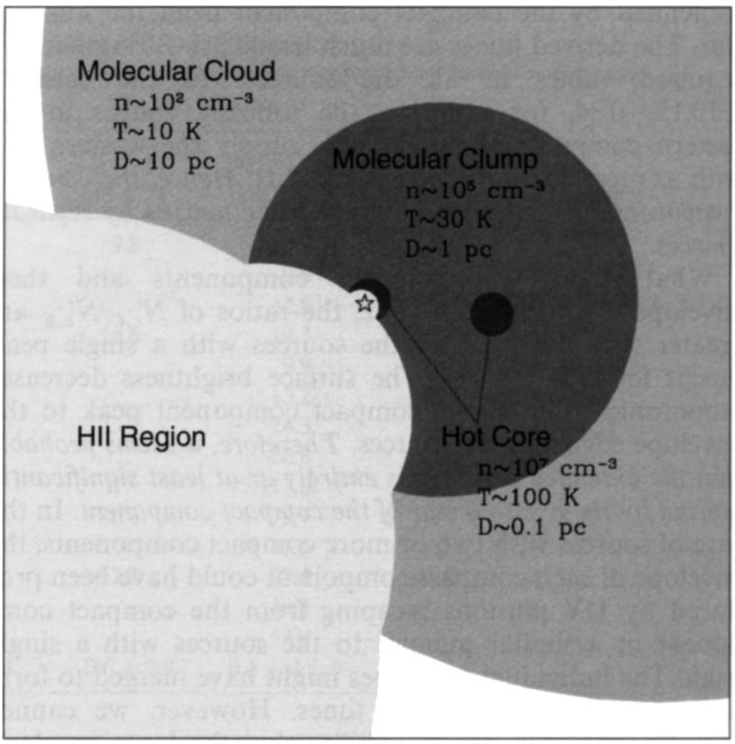


**Figure 10** The Kim & Koo (2001) proposed model for extended halos associated with UC HII regions. This model requires the ionizing star to be located near the boundary of the hot natal molecular core and molecular clump.

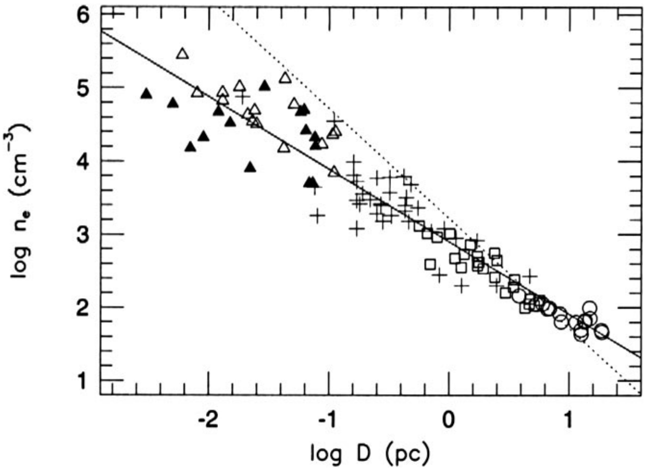


**Figure 11** The electron density-size relation from Kim & Koo (2001). The dashed curve is the $D^{-3/2}$ relation expected for a spherical, uniform density nebula, and the solid curve is a least squares fit to the data points.

combined with clumpy molecular cores is the correct model, then this should be reflected in the morphology of the halos. The data so far available are not able to resolve this issue.

THE ELECTRON DENSITY-SIZE RELATION Garay & Lizano (1999) and Kim & Koo (2001) have compiled the rms electron densities of HII regions ranging in diameter from 0.004 to 5 pc and found that $n_e$ is approximately inversely proportional to the diameter. The Kim & Koo (2001) relation is shown in Figure 11. For a uniform-density nebula, the density should scale with diameter as $D^{-3/2}$. Garay & Lizano (1999) suggested that the observed shallower slope can be explained if UC HII regions are ionized by stars with lower luminosities than those ionizing more extended HII regions. This is not a compelling explanation because many UC HII regions are known to require $\geq$ the maximum UV photon flux that a single star can produce for its IR luminosity (Kurtz et al. 1994). Kim & Koo (2001) suggest that the more compact HII regions are located in denser parts of molecular cores, which results in proportionally smaller HII regions. The expectation of a $D^{-3/2}$ dependence is for a uniform, homogeneous medium. Natal molecular cloud cores are likely to be anything but uniform and homogeneous. It is interesting that Figure 11 implies that the column density of $H^+$ is $\sim 3 \times 10^{21}$ cm$^{-2}$ for all D, implying $A_V$(dust) $\sim 3 \times 10^{21}(R/5.8 \times 10^{21}) \sim 1.7$ ($R = A_V/E_{B\text{-}V}$); $\tau_V$(dust) $\sim$1.5; $\tau_{912A}$(dust) $\sim$ 8; and $\tau_{912A}$(dust absorption) $\sim$ 5. This implies that ionization of extended halos requires both a clumpy medium and the destruction of dust in the interclump medium. Models need to be calculated that include stellar winds and a clumpy ambient medium into which the HII region is expanding.

## The Warm Dust Cocoons

UC HII regions heat the dust in their natal molecular cores out to large radii, causing them to be among the most luminous objects in our galaxy at far infrared wavelengths. The association of UC HII regions with luminous far infrared emission combined with obscuration of UC HII regions at visible and even NIR wavelengths leads to the conclusion that UC HII regions are embedded in their natal molecular cloud cores. The infrared SEDs of UC HII regions have been modeled by several groups (Chini et al. 1986, Hoare et al. 1988, Churchwell et al. 1990, Wolfire & Churchwell 1994). The predictions of these models have been reviewed by Churchwell (1991, 1999), and further discussion of them is not pursued here. The above models all assume a spherical, homogeneous medium. More sophisticated models should include a clumpy medium, nonspherical geometry, and the possible effects of remnant accretion disks.

## The Molecular Environment

The molecular cores in which UC HII regions reside have rich molecular spectra. The spectra indicate a large variety of molecular species and isotopic substitutions as well as a wide range of excitation conditions. Molecular spectra provide a rich energy level structure and a wide range of excitation energies from which physical properties such as the distributions of density, temperature, and gas kinematics can be derived. They can also be used to probe the cosmic ray ionization rate and magnetic field strengths in dense, hot cores surrounding UC HII regions and in massive star formation clouds with hundreds of magnitudes of extinction.

PHYSICAL PROPERTIES Wood & Churchwell (1989a) postulated that UC HII regions are deeply embedded in their natal molecular clouds, based on their coincidence with strong IR emission and small sizes, both indirect inferences. This was put on firmer ground by Churchwell et al. (1990), who observed 84 UC HII regions and found that ~70% of the sample had $NH_3$(1,1) and/or $H_2O$ maser emission. Following this, a series of papers were published to establish the physical properties of the molecular clouds in which UC HII regions are formed. Churchwell et al. (1991) found from $^{13}$CO, CS, and $CH_3CN$ that the molecular clouds have large column densities ($\geq 5 \times 10^{23}$ cm$^{-2}$), are hot ($\geq$100 K), dense ($\geq 10^5$ cm$^{-3}$), and lie within a few tenths of a pc of the ionizing star. Cesaroni et al. (1991a) confirmed these properties from $C^{34}S$ and showed that cloud masses determined assuming virial equilibrium, statistical equilibrium analyses, and CS column densities (all of which depend on distance to different powers) give about the same mass. They found cloud masses of ~2000 $M_\odot$ and diameters of ~0.4 pc. Cesaroni et al. (1991b) used observed inversion transitions of $NH_3$ from (1,1) to (5,5) inclusive to model the excitation of $NH_3$ associated with 16 UC HII regions. They found column densities in the range N($H_2$) ~ $10^{23}$–$10^{24}$ cm$^{-2}$, densities n($H_2$) ~ $10^5$–$10^6$ cm$^{-3}$, kinetic temperatures 100–200 K, diameters of ~0.4 pc, and virial masses ~100 to 2000 $M_\odot$. High resolution VLA observations by Cesaroni et al. (1994) of the

$NH_3$(4,4) emission toward G9.62, G10.47, G29.96, and G31.41 showed that the natal molecular clouds contain hot, compact $NH_3$ clumps located close to the UC HII regions. The $NH_3$ clumps are small ($\leq$0.1 pc), dense ($\sim 10^7$ cm$^{-3}$), massive ($\sim$100 $M_\odot$), and luminous ($10^4$–$10^6$ $L_\odot$). They suggested that these luminous clumps may be the sites of newly emerging young massive stars; their spatial coincidence with water masers gives further support to this hypothesis. Cesaroni et al. (1994) also pointed out what they referred to as a "luminosity paradox" in which the luminosity (for spherical clouds) inferred from the $NH_3$ excitation analysis was about an order of magnitude larger than the luminosity obtained from the observed FIR flux densities. In a follow-up study with even higher spatial resolution (0.4″), Cesaroni et al. (1998) were able to resolve the $NH_3$ clumps for the first time and derive the velocity structure and temperature gradients across them. They found that $T(r) \propto r^{-3/4}$ and that the only way the temperature gradients could be satisfactorily modeled was with disk-like (oblate) clumps. Using oblate clumps rather than spheres in combination with the temperature gradients also resolved the luminosity paradox so that the luminosities inferred from the $NH_3$ temperature structure and from FIR fluxes are in agreement.

In summary, the natal clouds that harbor UC HII regions are small ($\leq$0.5 pc), dense (typically $>10^5$ cm$^{-3}$), hot (100–200 K), luminous ($10^4$–$10^6$ $L_\odot$), and massive (up to several $\times 10^3$ $M_\odot$). They are clumpy, with clumps of diameter $\sim$0.1 pc, mass $\sim$100 $M_\odot$, and densities of $\sim 10^7$ cm$^{-3}$ located near the embedded UC HII region. The clumps are enhanced in $NH_3/H_2$ abundance by $\geq$100 over that in quiescent molecular clouds. This enhancement is believed to be due to evaporation of ice mantles on grains in the neighborhood of the UC HII regions.

CHEMISTRY The chemistry of massive star formation regions (hot cores or HCs) has been recently reviewed by Ohishi (1997), van Dishoeck & van der Tak (2000), and Millar (2000). Detailed, high spatial, and spectral resolution studies show that there are few generalizations one can make about the chemistry in HCs. There are large relative abundance variations among HCs and large variations in distribution of different species within a given HC (van Dishoeck 2001 and references therein). Perhaps the main generalizations are that grain surface chemistry appears to play a critical role in establishing relative abundances; photochemistry and shock chemistry are likely to be important at different evolutionary phases and locations within a HC; and the chemistry is almost certainly time-dependent. The current chemical evolution paradigm involves formation of icy grain mantles by accretion of gas-phase atoms and molecules during the prestellar phase of cloud evolution, followed by grain-surface chemistry and evaporation of ices as the protostar begins to heat its environment. The evaporated molecules provide reactants for a high-temperature gas-phase chemistry, which can produce complex saturated organic molecules (Charnley et al. 1992, 1995; Millar 1997; van Dishoeck 2001). Understanding the evolution of HCs depends on establishing their ages. The relative abundances of certain species such as $CH_3OCH_3/CH_3OH$ and others that show strong variations with time in chemical models may provide chemical clocks that will determine ages.

An example of the relative abundances of molecular species in HCs containing UC HII regions is provided by the work of Hatchell et al. (1998) who used the James Clark Maxwell Telescope (JCMT) to obtain spectra in the 230 GHz and 345 GHz bands of 14 UC HII regions previously shown to have high excitation $NH_3$ and $CH_3CN$ emission. They found that the number of transitions varied by a factor of 20 between sources. Half of the sources showed only a few lines, the carriers of which were $C^{17}O$, $C^{18}O$, SO, $C^{34}S$, and $CH_3OH$. In the other half of their sample (the line rich sources), they detected over 150 lines, many of which were from high excitation lines of some of the more complex interstellar molecules such as $HCOOCH_3$, $C_2H_5CN$, and $CH_3CCH$. They found that the line rich sources require hot, dense, compact cores surrounded by an ambient cloud consisting of less dense, cooler gas. The molecular cores are $<0.1$ pc in size, with densities of $\sim10^8$ cm$^{-3}$ and temperatures $>80$ K. The line poor sources could be modeled with a temperature of 20–30 K, density of $10^5$ cm$^{-3}$, and no hot core. The hot cores in the line rich sources have sizes about equivalent to their UC HII regions. In the line poor sources, it is unclear how $NH_3$ and $CH_3CN$ can achieve high excitation if temperatures and densities are as low as claimed. Is it possible that the difference between the line poor and line rich sources is mainly an evolutionary one in which the line poor sources have mostly destroyed their molecular cocoons and are now surrounded by a small amount of molecular gas that can produce only weak lines of a few impervious molecules?

MASERS Molecular masers are very bright and ubiquitous in the vicinity of UC HII regions and MSF regions. The most widespread masers associated with MSF regions are $H_2O$, OH, and $CH_3OH$; $H_2CO$ and $NH_3$ have been detected toward fewer sources and only in a few transitions. The presence of protostars or newly formed massive stars provides photons and heat, both of which are probably necessary to main population inversion depending on the molecule. Masers are distinguishable from nonmasering clouds by brightness, temperature, size, temporal variability, polarization, number of spectral features, and line width. Masers are generally confined to very dense ($10^6$–$10^9$ cm$^{-3}$), small (a few tens of AUs) clumps, which makes them excellent probes of the kinematics and physical properties of MSF regions on scale sizes that are otherwise very difficult or impossible to observe directly.

$H_2O$ masers are signposts of massive star formation; Churchwell et al. (1990) detected $H_2O$ masers toward 67% of about 100 observed UC HII regions. $H_2O$ masers occur in small clusters with extents of $\sim$10–100 AU. Their spectra usually show many velocity components spread over velocities of $\sim$50 to $>$100 km s$^{-1}$, and their luminosities are proportional to the integrated far infrared luminosity of the SFR (Moran 1990, Palagi et al. 1993). Precisely what dynamical features of massive star formation regions are probed by $H_2O$ masers has been a topic of considerable debate. VLBI measurements of Genzel et al. (1981), Reid et al. (1988), Bloemhof et al. (1992) and others indicate that the $H_2O$ masers are expanding away from the center in several MSF regions. Torrelles et al. (1996, 1997, 1998a,b) find that $H_2O$ masers trace both molecular outflows and accretion disks (perpendicular to the molecular outflow). Because of the high excitation of the 1.3 cm $H_2O$ maser

(>600 K above ground), it is generally believed that shocks are probably required to achieve the temperatures and densities necessary to produce the observed $H_2O$ masers. In the case of outflows or expanding shells, these would occur at the interface of the outflow and the ambient medium. In accretion disks, they could be produced by infalling matter onto the disk.

The 1665 and 1667 MHz OH masers are closely associated with star formation and UC HII regions. Individual velocity components have sizes of $\sim 10^{14}$ cm and are distributed over regions of $\sim 10^{16}$ cm (about the radius of typical UC HII regions). The origin of OH masers in MSF regions is uncertain. Garay et al. (1985) have suggested that OH masers lie in an accreting envelope outside the advancing ionization front of the HII region. Bloemhof et al. (1992) have interpreted their proper motion measurements of OH masers toward W3(OH) as an expanding shell between the shock front and the ionization front of the HII region.

Methanol masers have been observed in many transitions toward massive star formation regions (see Garay & Lizano 1999 for an enumeration of the observed maser transitions). As with $H_2O$ and OH masers, it is not clear if methanol masers probe exclusively outflows, accretion disks, or advancing shock fronts. Claims have been made for each in different sources. The $NH_3$ and $H_2CO$ masers have not been observed in as many sources as the other masers, and general conclusions about their properties cannot be made.

Based on the typical relative positions of the masers with each other and with radio continuum contours, several investigators have postulated that $H_2O$, $CH_3OH$, and OH masers appear at different evolutionary stages of star formation (see the summary of Garay & Lizano 1999). They and others suggest that $H_2O$ masers appear in the earliest stages of massive star formation during the rapid accretion phase. $CH_3OH$ masers appear later during the period when the emerging protostar forms a detectable UC HII region, and OH masers appear last in a compressed, possibly infalling, circumnebular shell. These masers fade away as the UC HII region evolves into a diffuse HII region (Codella et al. 1994). Although compelling because of its simplicity and potential for establishing relative ages, this scenerio is based on shaky age determinations. Also, numerous examples are known where all three masers are observed in what appears to be the same star formation region.

## GALACTIC POPULATION AND DISTRIBUTION

If the number, spatial distribution, and ages of newly formed O stars in the Galaxy were known, they would permit a direct determination of the current rate of massive star formation in the Galaxy (independent of uncertainties in the IMF of O stars), provide estimates of the mechanical and radiative energy and momentum input to molecular clouds, allow a determination of the contribution of massive stars to the global energetics of the Galaxy, show the locations of massive star formation relative to spiral arms, and delineate the spiral structure of the Galaxy. To estimate the contribution of O stars to the global energetics, we must know what fraction of the total O star population resides in molecular clouds hidden from optical and UV observations. Distances are required to use O stars as tracers of galactic structure.

## The Distribution and Number of UC HII Regions

Estimates of the number and distribution of O stars in the Milky Way have been made by Wood & Churchwell (1989b), Hughes & McLeod (1989), Zoonematkermani et al. (1990), White et al. (1991), Helfand et al. (1992), and Becker et al. (1994). All the above groups used far infrared (FIR) colors from the Infrared Astronomical Satellite (IRAS) Point Source Catalog to select HII regions. All the above groups found close to the same far infrared colors for galactic HII regions, including UC HIIs. The small differences in the precise color boundaries chosen, in the lower limit to the flux density for a given wavelength band, and whether the IRAS source coincides with a radio source are the basic reasons why each group gets somewhat different numbers of HII regions and different scale heights in Galactic latitude. Hughes & McLeod (1989) used optical HII regions to establish IRAS colors [$\log(S_{25\,\mu m}/S_{12\,\mu m}) \geq 0.4$ and $\log(S_{60\,\mu m}/S_{25\,\mu m}) \geq 0.25$] and found $\sim$2300 HII region candidates lying between $\pm 3^0$ in Galactic latitude. Wood & Churchwell (1989b) used selection criteria $S_{12\,\mu m}$ and $S_{25\,\mu m} \geq 10$ Jy, $\log(S_{60\,\mu m}/S_{12\,\mu m}) \geq 1.30$, and $\log(S_{25\,\mu m}/S_{12\,\mu m}) \geq 0.57$, based on the colors of radio-identified UC HII regions. They identified $\sim$1650 UC HII region candidates in the Galaxy with a scale height of $0.6^0 \pm 0.05^0$ in latitude, corresponding to about 90pc at a distance of 8.5 kpc. They also showed that most UC HII region candidates lie in quadrants I and IV of the Galactic plane. White et al. (1991), Helfand et al. (1992), and Becker et al. (1994) derived IRAS colors based on the coincidence of IRAS point sources with identified thermal radio sources. They identified all together <1000 candidate UC HII regions in the fraction of the Galactic plane observable with the VLA. They find the distribution in latitude to have a full-width at half-maximum (FWHM) $\sim 15'$ [a factor of 0.4 times that found by Wood & Churchwell (1989b)], which implies a latitude scale height for O stars of only 36 pc at a distance of 8.5 kpc. They argue that the sample of Wood & Churchwell (1989b) is contaminated by UC HII regions ionized by B stars, which have a wider latitude distribution than O stars. Both estimates imply that O stars are very tightly confined to the Galactic plane with a rapidly declining chance of finding young massive stars more than a few tens of parsecs from the plane. Also, O stars are far more likely to be found in the inner galaxy than outside the solar circle. The concentration of UC HII regions to the Galactic plane and to the inner Galaxy is illustrated by the FIR color–selected plot of candidate UC HII regions shown in Figure 12 [taken from Wood & Churchwell (1989b)]. This has implications both for massive star formation and the location of luminous UV energy sources in the Galaxy. In particular, the conditions required to form massive stars are far more likely to occur at midplane in the Galaxy than at latitudes only a few parsecs above or below it. The distribution of UC HII candidates and molecular gas, as traced by CO, are very similar as illustrated in Figure 13 taken from Wood & Churchwell (1989b).

All attempts to obtain the number of newly formed O stars (represented by UC HII regions) using IRAS colors find about $2000 \pm 40\%$ integrated over the entire Galactic plane. Wood & Churchwell (1989b) found that about 10% of all O stars within about 2.5 kpc of the Sun are in the ultracompact state. Assuming that

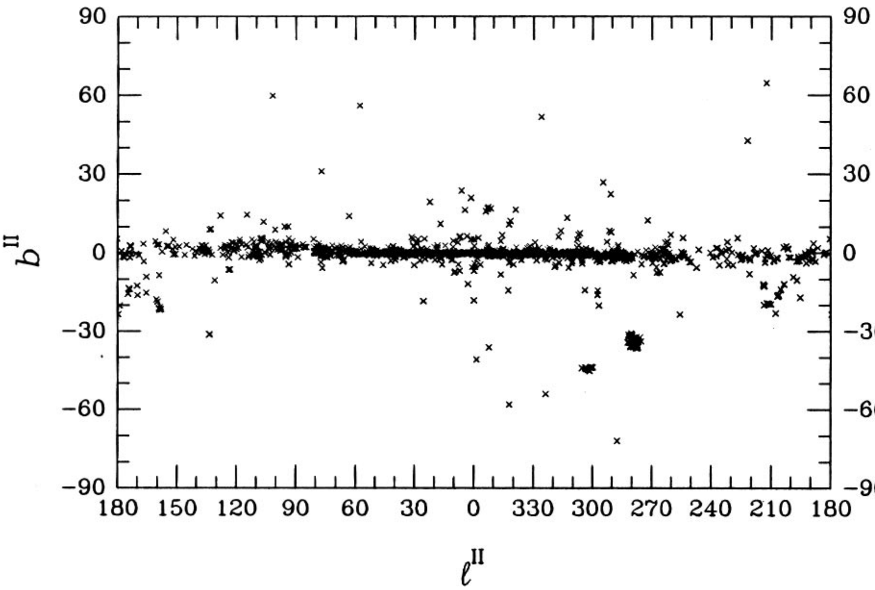


**Figure 12** The distribution in Galactic coordinates of all candidate UC HII regions selected from the IRAS Point Source Catalog according to the FIR color-color criteria of Wood & Churchwell (1989b). Note the tight confinement to the Galactic plane, the crowding in the inner galaxy, and the conspicuousness of the LMC and SMC.



this percentage is about constant over the Galactic disk, this implies that the total number of O stars in the Galaxy is about 20,000 ± 80% (including generous errors introduced by assumptions). Wood & Churchwell (1989b) estimated that O stars have an average integrated luminosity of $\sim 10^9\ L_\odot$ or ~30% of the FIR luminosity of molecular clouds and ~8% of the FIR luminosity of the entire Galaxy (Sodroski 1988), hardly a dominant contribution to the total luminosity of the Galaxy. However, the above estimates are likely to be substantially increased by 2MASS and SIRTF surveys, which will go much deeper and have better spatial resolution than IRAS. The fraction of O stars with nebulae in the UC state is also an indication of the fraction of the time that they remain in the UC state. Wood & Churchwell (1989b) estimated that UC HII regions have typical lifetimes of about $10^5$ years. This is substantially longer than the sound crossing time and the timescale predicted by classical Strömgren theory in the absence of significant confining pressure. This dilemma was discussed above ("Morphologies and Lifetimes") and is often referred to as the lifetime problem.

All the above attempts to determine the population and angular distribution of O stars in the Galaxy suffer from the poor spatial resolution and limited sensitivity of IRAS. Higher spatial resolution and better sensitivity will more precisely define the IR colors and better determine the total number of O stars in the Galaxy. With

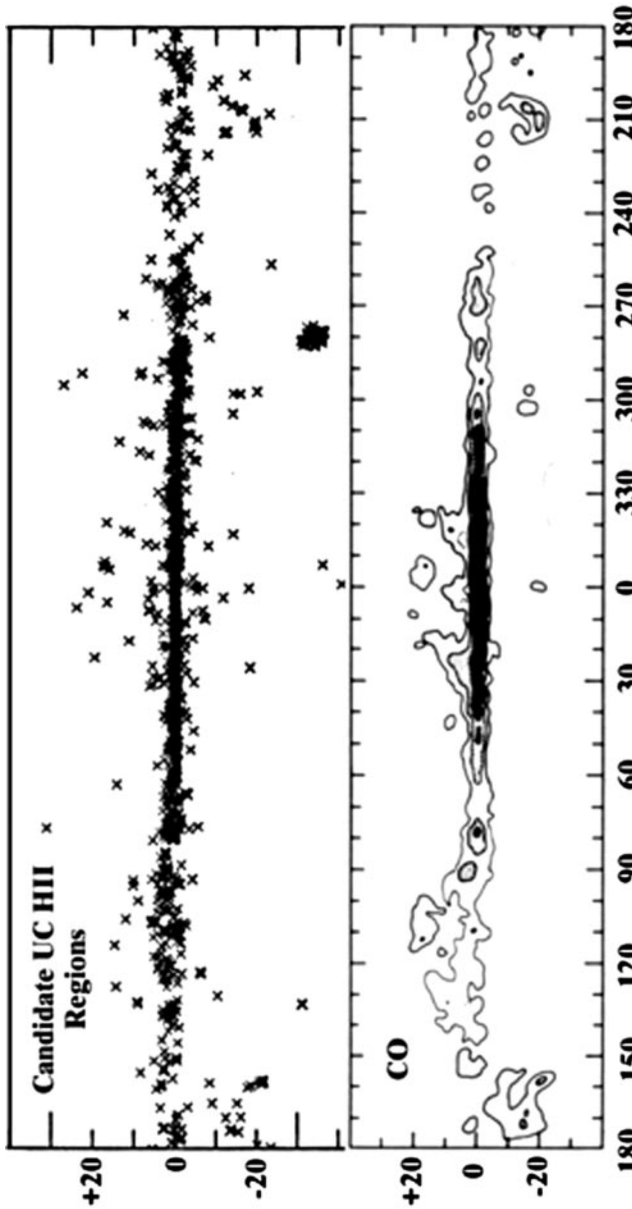


**Figure 13** A comparison of the distributions of UC HII regions from Wood & Churchwell (1989b) and CO emission from Dame et al. (1987). This visually demonstrates the close association of molecular gas and young massive stars.

18″ spatial resolution, the Mid-Course Space Experiment (MSX) can take a large step in this direction. However, both the 2 Micron All Sky Survey (2MASS) and the Space Infrared Telescope Facility Infrared Array Camera (SIRTF/IRAC) will achieve more than two orders of magnitude greater sensitivity and spatial resolution than IRAS. The combination of 2MASS and SIRTF surveys are expected to fine-tune the infrared (NIR-MIR) colors of O and B stars (including embedded ones) and detect all those not confused or hidden by background emission. Together these two large databases should resolve many of the remaining questions related to the number, distribution, formation rate, and energetics of massive stars in the Galaxy.

## Spiral Structure Using UC HII Regions

Spiral arms in other galaxies are defined by the distribution of O stars; thus we expect one of the best tracers of spiral arms in our Galaxy to be newly formed O stars or their HII regions. As early as 1952, Morgan et al. (1952) reported evidence for two and possibly three spiral arms in the solar neighborhood using optically visible HII regions. More recent attempts to determine the spiral arms of the Galaxy by using HII regions as tracers were Georgelin & Georgelin (1976), who used visible, evolved HII regions, and Kurtz et al. (1994), who used radio-detected UC HII regions. Both of these were of limited success in delineating the Galaxy's spiral structure; without lines drawn to guide the eye, different observers could have easily drawn quite different spiral arms. Kurtz et al. (1994) postulated that the combination of near/far distance ambiguities in the inner Galaxy plus peculiar motions masked the spiral arm structure. Recently, Araya et al. (2001) measured both radio recombination line emission and $H_2CO$ in absorption toward 21 selected UC HII regions using the Arecibo 305 m telescope. The velocity of the recombination line established the velocity of the UC HII region, and the pattern of $H_2CO$ absorption velocities was used to resolve the distance ambiguity for each source. With this limited number of UC HII regions, they found surprisingly good agreement with previous spiral arm determinations. This is illustrated in Figure 14. The accuracy of this picture will be tested when more sources are measured using this promising technique.

## Galactic Temperature and Abundance Gradients

The mean electron temperatures of evolved Galactic HII regions depend on their galactocentric distance, $D_G$, in the sense that temperatures increase with $D_G$ (Churchwell & Walmsley 1975, Shaver et al. 1983, and others). This has been interpreted to imply a corresponding gradient in metallicity because metals provide the primary coolants of HII regions and determine their equilibrium temperatures. In a classical paper by Shaver et al. (1983), the relationship between metal abundances and mean temperatures of HII regions was quantified by determining both metal abundances and temperatures independently for a large number of evolved HII regions whose distances were well known.

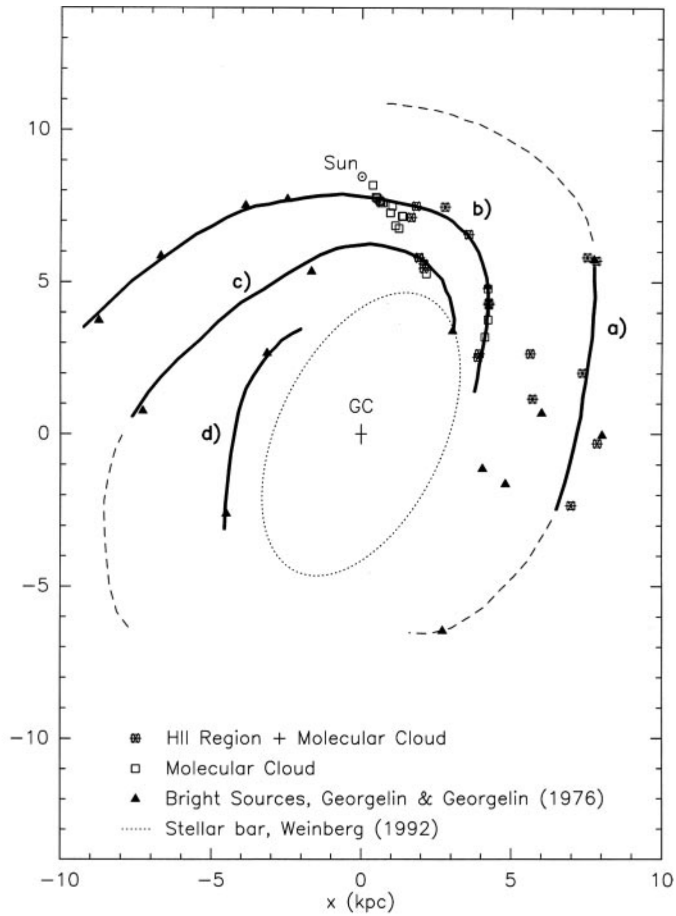


**Figure 14** The spiral arms suggested by Georgelin & Georgelin (1976) (solid curves) with the distribution of UC HII regions from Araya et al. (2001). With the exception of two points that fall between arms *a* and *b*, the UC HII regions trace quite closely the end portions of arms *a*, *b*, and *c*.



UC HII regions have very recently ionized their natal molecular cores and provide an opportunity to determine if the abundances and electron temperatures in these rather special regions of the interstellar medium are similar to those of evolved HII regions (where the gas and dust have been exposed to UV radiation for long periods and probably mixed with ambient diffuse interstellar matter). Afflerbach et al. (1996) made such a test by using high spatial resolution observations in the radio recombination lines H42$\alpha$, H66$\alpha$, H76$\alpha$, and H93$\alpha$ toward 17 UC HII regions distributed in galactocentric radius from 4 kpc to 11 kpc. Nonlocal thermodynamic equilibrium (NonLTE) models were calculated for all nebulae from which electron temperatures and densities were derived. They found that the electron temperature increases with $D_G$ as $T_e(K) = (5540 \pm 390) + (320 \pm 64) D_G(kpc)$ with a correlation coefficient of 0.82. The data with the linear least squares fit superimposed is shown in Figure 15. Also shown for comparison is the Shaver et al. (1983) fit to their diffuse HII data. The Afflerbach et al. (1996) $T_e$ values are on average about



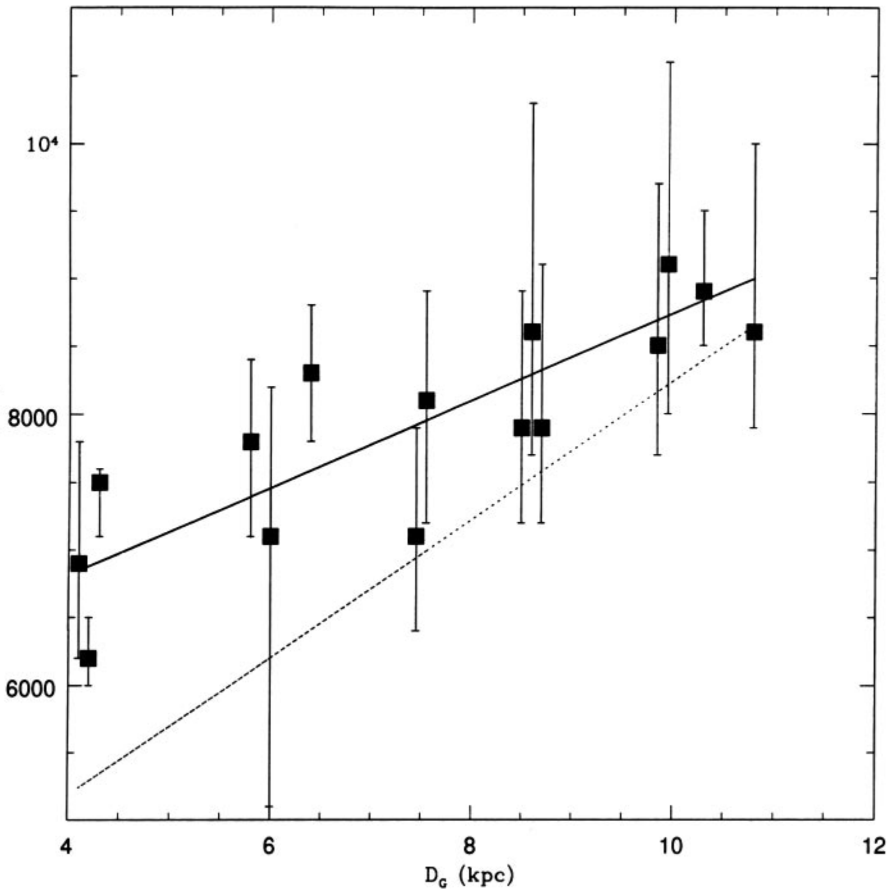


**Figure 15** The galactocentric electron temperature gradient derived for UC HII regions by Afflerbach et al. (1996) using non-LTE analyses of radio recombination line observations. The dashed curve is the gradient found by Shaver et al. (1983) from diffuse optically visible HII regions. The solid curve is the least squares fit to the UC HII data. The systematically higher temperatures of UC HII regions than of diffuse HII regions is consistent with collisional quenching of coolants in UC HII regions.

1500 K higher than those of Shaver et al. (1983); this is entirely consistent with increased collisional quenching of the coolants in UC HII regions. From the $T_e$-$D_G$ relation, Afflerbach et al. (1996) inferred a Galactic O/H abundance gradient of the form

$$\frac{d(O/H)}{dD_G} = -0.047 \pm 0.009\ dex\ \mathrm{kpc}^{-1},$$

which is about the same as found by Shaver et al. (1983) using optical line observations of diffuse HII regions. This is also in reasonable agreement with galactocentric abundance gradients derived from far infrared fine structure line observations of Lester et al. (1987), Simpson et al. (1995), Afflerbach et al. (1997), and Rudolph et al. (1997). The far infrared fine structure and radio recombination line data together indicate that (1) the mean temperatures of UC HII regions systematically increase with $D_G$ by about 300 K per kpc; (2) the average abundances of O, N, and S decrease with $D_G$ by ∼0.065 dex per kpc in UC HII regions; and (3) the abundances in UC HII regions are about the same as those in classical diffuse HII regions at the same galactocentric distance, which indicates that the abundances (gas plus dust) in natal molecular cloud cores must also have the same abundance gradient as other constituents of the interstellar medium.



## SUMMARY AND FUTURE PROSPECTS

A brief summary is given of our present understanding of the evolution to the UC HII region state. This is based on observationally identified properties of giant molecular clouds that provide the natal material for prestellar cores, which are the precursors of hot cores that probably produce hypercompact HII regions postulated to quickly evolve into UC HII regions. The properties of hot cores were emphasized because most is known about this stage of evolution. The stages about which least is known are prestellar cores and hypercompact HII regions. Both these stages of evolution are expected to be very short and the number of objects in each state is therefore expected to be very small. In fact, no prestellar core that will produce an O star is known. The discussion of prestellar cores is based on the properties of low-mass star forming prestellar cores.

The properties of UC HII regions and their associated molecular and dust environments are discussed in some detail. It is argued that the limited number of observed morphological types and the lifetime of UC HII regions are related and that any theory that can account for their morphologies must also account for their extended lifetimes. The existence of extended halos around UC HII regions requires either a very clumpy molecular core or a modification of our present picture of UC HII regions with sharply truncated boundaries. An electron density-size relation is one in which $n_e \propto D^{-1}$ exists for HII regions with diameters from 0.004 pc to 5 pc. Uniform density, spherical HII regions are expected to scale as $D^{-3/2}$. The shallower dependence on size is not understood, but it is suggested that departures from uniform density, nonspherical morphologies, and ionizing stars that have strong winds probably play a role. The $n_e \alpha D^{-1}$ relation implies $H^+$ column density of about $3 \times 10^{21}$ $cm^{-2}$, independent of diameter. We also infer that dust must be destroyed in the interclump gas in UC HII regions to be consistent with observed ionized halos. The properties of the warm dust cocoons and molecular cores that enshroud UC HII regions were briefly discussed, including the chemistry and maser emission in the hot environments around UC HII regions.

Finally, the use of UC HII regions as probes of global properties of the Galaxy was summarized. In particular, the distribution of UC HII regions in the Galaxy and implications for the UV and kinetic energy contributions to the interstellar medium in the Galaxy were reviewed. The attempts to determine spiral structure as well as temperature and abundance gradients in the Galaxy were also discussed.

All evolutionary stages preceding the UC state are not well understood, and future efforts are likely to concentrate on these, especially prestellar cores and hypercompact HII regions. The physics of how massive bipolar outflows are driven and collimated is basically still a mystery and needs much more observational and theoretical attention. The same can be said for the interdependence of accretion disks and outflows. No viable theoretical models of massive star formation are available that can account for all the observed properties of the early evolutionary stages of massive star formation. Higher resolution and more sensitive observations of the thermal dust emission, ionized gas, and associated molecular gas are also needed to better constrain models. New facilities that can provide incisive observational constraints are the Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy (SOFIA), the Submillimeter Array (SMA), the Atacama Large Millimeter Array (ALMA), the Square Kilometer Array (SKA), the Combined Array for Research in Millimeter-Wave Astronomy (CARMA), the Large Millimeter Telescope (LMT), and the Chandra X-Ray Observatory (CHANDRA). Although there is still much to be done before massive star formation will be understood, the future looks quite promising with the array of facilities currently online or under construction.



## ACKNOWLEDGMENTS

I am indebted to all my coworkers who have contributed to much of the work reported here and from whom I have learned so much; in particular, Malcolm Walmsley, Riccardo Cesaroni, Doug Wood, Peter Hofner, Stan Kurtz, Deborah Shepherd, Andrew Afflerbach, Jerry Acord, Christer Watson, and Marta Sewilo. I also thank John Mathis, who gave critical comments on the manuscript; I have benefited greatly from his deep understanding of this subject. I am indebted to Christer Watson for help with some of the figures. Finally, figures were taken from several sources authored by numerous people to whom I am indebted for giving permission to reproduce images. This review was supported in part by NSF grant AST-9986548.

**The *Annual Review of Astronomy and Astrophysics* is online at http://astro.annualreviews.org**



## LITERATURE CITED


Afflerbach A, Churchwell E, Acord JM, Hofner P, Kurtz S, DePree CG. 1996. *Ap. J. Suppl.* 106:423–46

Afflerbach A, Churchwell E, Hofner P, Kurtz S. 1994. *Ap. J.* 437:697–704

Afflerbach A, Churchwell E, Werner MW. 1997. *Ap. J.* 478:190–205

André P, Ward-Thompson D, Motte F. 1996. *Astron. Astrophys.* 314:625–35

Araya E, Hofner P, Churchwell E, Kurtz S. 2002. *Ap. J. Suppl.* 138:63–74

Bacmann A, André P, Abergel A, Puget J-L, Bontemps S, et al. 1998. In *The Universe as Seen by ISO*, ed. P Cox, MF Kessler, pp. 467–70. Noordwijk, The Netherlands: ESA

Bazell D, Désert FX. 1988. *Ap. J.* 333:353–58

Becker RH, White RL, Helfand DJ, Zoonematkermani S. 1994. *Ap. J. Suppl.* 91:347–87

Behrend R, Maeder A. 2001. *Astron. Astrophys.* 373:190–98

Bernasconi PA, Maeder A. 1996. *Astron. Astrophys.* 307:829–39

Beuther H, Schilke P, Walmsley CM, Sridharan TK, Wyrowski F, Menten KM. 2001. In *Massive Star Birth*, ed. P Crowther, ASP Conf. Ser. In press

Blitz L. 1991. In *The Physics of Star Formation and Early Evolution*, NATO Sci. Ser., ed. CJ Lada, ND Kylafis, 342:3–33

Blitz L, Williams JP. 1999. In *The Origin of Stars and Planetary Systems*, NATO Sci. Ser., ed. CJ Lada, ND Kylafis, 540:3–28

Bloemhof EE, Reid MJ, Moran JM. 1992. *Ap. J.* 397:500–19

Bonnell IA, Bate MR, Zinnecker H. 1998. *MNRAS* 295:93–102

Cabrit S, Bertout C. 1992. *Astron. Astrophys.* 26:274–84

Campbell B. 1984. *Ap J.* 282:L27–30

Carey SJ, Clark FO, Egan M, Price SD, Shipman RF, Kuchar TA. 1998. *Ap. J.* 508:721–28

Cesaroni R, Churchwell E, Hofner P, Walmsley CM, Kurtz S. 1994. *Astron. Astrophys.* 288:903–20

Cesaroni R, Felli M, Testi L, Walmsley CM, Olmi L. 1997. *Astron. Astrophys.* 325:725–44

Cesaroni R, Hofner P, Walmsley CM, Churchwell E. 1998. *Astron. Astrophys.* 331:709–725

Cesaroni R, Walmsley CM, Churchwell E. 1991b. *Astron. Astrophys.* 256:618–30

Cesaroni R, Walmsley CM, Kömpe C, Churchwell E. 1991a. *Astron. Astrophys.* 252:278–90

Charnley SB, Kress ME, Tielens AGGM, Millar TJ. 1995. *Ap. J.* 448:232–39

Charnley SB, Tielens AGGM, Millar TJ. 1992. *Ap. J.* 399:L71–74

Chini R, Krügel E, Kreysa E. 1986. *Astron. Astrophys.* 167:315–24

Chini R, Krügel E, Wargau W. 1987. *Astron. Astrophys.* 181:378–82

Churchwell E. 1991. In *The Physics of Star Formation and Early Stellar Evolution*, ed. CJ Lada, ND Kylafis, pp. 221–68. Dordrecht: The Netherlands: Kluwer

Churchwell E. 1997. *Ap. J. Lett.* 479:L59–61

Churchwell E. 1999. In *The Origin of Stars and Planetary Systems*, ed. CJ Lada, ND Kylafis, pp. 515–52. Dordrecht: The Netherlands: Kluwer

Churchwell E, Walmsley CM. 1975. *Astron. Astrophys.* 38:451–54

Churchwell E, Walmsley CM, Cesaroni R. 1990. *Acta Astron. Sinica.* 83:119–44

Churchwell E, Walmsley CM, Wood DOS. 1991. *Astron. Astrophys.* 253:541–56

Churchwell E, Wolfire M, Wood DOS. 1990. *Ap. J.* 354:247–61

Codella C, Felli M, Natale V, Palagi F, Palla F. 1994. *Astron. Astrophys.* 291:261–70

Crutcher RM. 1999. *Ap. J.* 520:706–13

Crutcher RM. 2001. In *Massive Star Birth*, ed. P Crowther. *ASP Conf. Ser.* In press
Dame TM, Ungerechts H, Cohen RS, de Geus EJ, Grenier IA, et al. 1987. *Ap. J.* 322:706–20
De Pree CG, Mehringer DM, Goss WM. 1997. *Ap. J.* 482:307–33
De Pree CG, Goss WM, Palmer P, Rubin RH. 1994. *Ap. J.* 428:670–79
Egan MP, Shipman RF, Price SD, Carey SJ, Clark FO, Cohen M. 1998. *Ap. J.* 494:L199–202
Falgarone E, Phillips TG, Walker CK. 1991. *Ap. J.* 378:186–201
Fuller GA, Myers PC. 1987. In *Physical Processes in Interstellar Clouds*, ed. M Scholer, pp. 137–60. Dordrecht: Reidel
Garay G, Lizano S. 1999. *Publ. Astron. Soc. Pac.* 111:1049–87
Garay G, Reid MJ, Moran JM. 1985. *Ap. J.* 289:681–97
Garay G, Rodríguez LF, Moran JM, Churchwell E. 1993. *Ap. J.* 418:368–85
Genzel R, Reid MJ, Moran JM, Downes D. 1981. *Ap. J.* 244:884–902
Georgelin YM, Georgelin YP. 1976. *Astron. Astrophys.* 49:57–79
Gregersen EM, Evans NJ II. 2000. *Ap. J.* 538:260–67
Gregersen EM, Evans NJ II, Mardones D, Myers PC. 2000. *Ap. J.* 533: 440–53
Hatchell J, Thompson MA, Millar TJ, MacDonald GH. 1998. *Astron. Astrophys. Suppl.* 133:29–49
Helfand DJ, Zoonematkermani S, Becker RH, White RL. 1992. *Ap. J. Suppl.* 80:211–55
Henning TH, Schreyer K, Launhardt R, Burkert A. 2000. *Astron. Astrophys.* 353:211–26
Hoare MG, Glencross WM, Roche PF, Clegg RES. 1988. In *Dust in the Universe*, ed. ME Bailey, DA Williams, pp. 107–11. Cambridge, UK: Cambridge Univ. Press
Hofner P, Delgado H, Whitney B, Churchwell E. 2002. *Ap. J.* In press
Hofner P, Kurtz S, Churchwell E, Walmsley CM, Cesaroni R. 1996. *Ap. J.* 460:359–71
Hughes VA, McLeod GC. 1989. *Astron. J.* 97:786–800
Jijina J, Myers PC, Adams FC. 1999. *Ap. J. Suppl.* 125:161–236
Johnson C, De Pree C, Goss WM. 1998. *Ap. J.* 500:302–10
Kim K-T, Koo B-C. 2001. *Ap. J.* 549:979–96
Koo B-C, Kim K-T, Lee H-G, Yun M-S, Ho PT. 1996. *Ap. J.* 456:662–76
Kroupa P. 2001. *MNRAS* 322:231–46
Kurtz S, Cesaroni R, Churchwell E, Hofner P, Walmsley CM. 2000. See Mannings et al. 2000, pp. 299–326
Kurtz S, Churchwell E, Wood DOS. 1994. *Ap. J. Suppl.* 91:659–712
Kurtz SE, Watson AM, Hofner P, Otte B. 1999. *Ap. J.* 514:232–48
Larson RB. 2002. *MNRAS.* In press
Launhardt R, Henning Th. 1997. *Astron. Astrophys.* 326:329–46
Lumsden SL, Hoare MG. 1996. *Ap. J.* 464:272–85
Lee CW, Myers PC. 1998. *Ap. J. Suppl.* 123:233–50
Lee CW, Myers PC, Taffalla M. 1999. *Ap. J.* 526:788–805
Lester DF, Dinerstein HL, Werner MW, Watson DM, Genzel R, Storey JWV. 1987. *Ap. J.* 320:573–85
Mannings V, Boss AP, Russell SS, eds. *Protostars and Planets IV*. Tucson: Univ. Ariz. Press
Martín-Hernández NL, Peeters E, Morisset C, Tielens AGGM, Cox P, et al. 2002. *Astron. Astrophys.* 381:606–27
Massey P. 1999. *IAU Cir. Symp. #190*, ed. Y-H Chu, N Suntzeff, J Hesser et al., pp. 173–80
Massey P, Hunter DA. 1998. *Ap. J.* 493:180–94
Meyer MR, Adams FC, Hillenbrand LA, Carpenter JM, Larson RB. 2000. See Mannings et al. 2000, pp. 121–49
Millar TJ. 1997. In *Molecules in Astrophysics: Probes and Processes, IAU Cir. Symp.*, ed. EF van Dishoeck, 178:75–88
Millar TJ. 2000. In *Science with the Atacama Large Millimeter Array*, ASP Conf. Ser., ed. A Wootten. In press
Moran JM. 1990. In *Molecular Astrophysics*, ed. T Hartquist, pp. 397–423. Cambridge, MA: Cambridge Univ. Press

Morgan WW, Sharpless S, Osterbrock D. 1952. *Astron. J.* 57:3

Motte F, André P, Neri R. 1998. *Astron. Astrophys.* 336:150–72

Myers PC, Fuller GA. 1992. *Ap. J.* 396:631–42

Myers PC, Lazarian A. 1998. *Ap. J.* 507:L157–60

Nakano T. 1998. *Ap. J.* 494:587–604

Neufeld DA, Hollenbach DJ. 1994. *Ap. J.* 428:170–85

Neufeld DA, Hollenbach DJ. 1996. *Ap. J.* 471:L45–48

Norris RP, Byleveld SE, Diamond PJ, Ellingsen SP, Ferris RH, et al. 1998. *Ap. J.* 508:275–85

Norris RP, Whiteoak JB, Caswell JL, Wieringa MH, Gough RG. 1993. *Ap. J.* 412:222–32

Ohishi M. 1997. In *Molecules in Astrophysics: Probes and Processes. IAU Cir. Symp. 178*, ed. EF van Dishoeck, pp. 61–74. Dordrecht: Kluwer

Osorio M, Lizano S, D'Alessio P. 1999. *Ap. J.* 525:808–20

Palagi F, Cesaroni R, Comoretto G, Felli M, Natale V. 1993. *Astron. Astrophys. Suppl.* 101:153–93

Phillips CJ, Byleveld SE, Ellingsen SP, McCulloch PM. 1998. *MNRAS* 300:1131–57

Reid MJ, Schneps MH, Moran JM, Gwinn CR, Genzel R, et al. 1988. *Ap. J.* 330:809–16

Ridge NA. 2000. *The dynamics of outflows from young stellar objects*. PhD thesis. John Moores Univ. Liverpool, UK

Rodríguez LF, Cantó J, Moran JM. 1988. *Ap. J.* 333:801–5

Rudolph AL, Simpson JP, Haas MR, Erickson EF, Fich M. 1997. *Ap. J.* 489:94–101

Scalo J. 1990. In *Physical Processes in Fragmentation and Star Formation*, ed. R Capuzzi-Dolcetta C Chiosi, A Di Fazio, et al., pp. 151–76. Dordrecht: Kluwer

Shaver PA, McGee RX, Newton LN, Danks AC, Pottash SR. 1983. *MNRAS* 204:53–112

Shepherd D, Churchwell E. 1996. *Ap. J.* 472:225–39

Shepherd D, Claussen MJ, Kurtz SE. 2001. *Science* 292:1513–18

Shepherd DS, Kurtz SE. 1999. *Ap. J.* 523:690–700

Shu FH, Lizano S, Ruden SP, Nagita J. 1988. *Ap. J.* 328:L19–23

Shu FH, Nagita J, Ostriker E, Wilkin F, Ruden S, Lizano S. 1994. *Ap. J.* 429:781–96

Shu FH, Najita JR, Shang H, Li Z-Y. 2000. See Mannings et al. 2000, pp. 789–813

Simpson JP, Colgan SWJ, Rubin RH, Erickson EF, Haas MR. 1995. *Ap. J.* 444:721–38

Sodroski TJ. 1988. *The galactic large-scale far-infrared emission observed by IRAS: implications for the morphology, physical conditions, and energetics of dust in the interstellar medium.* PhD thesis, Univ. Maryland

Stahler SW, Palla F, Ho PTP. 2000. See Mannings et al. 2000, pp. 327–51

Subrahmanyan R, Ekers R, Wilson W, Goss WM, Allen D. 1993. *MNRAS* 263:868–74

Testi L, Sargent AI. 1998. *Ap. J. Lett.* 508:L91–94

Torrelles JM, Gómez JF, Garay G, Rodriguez LF, Curiel S, Cohen RJ, Ho PTP. 1998b. *Ap. J.* 509:262–69

Torrelles JM, Gómez JF, Rodriguez LF, Curiel S, Anglada G, Ho PTP. 1998a. *Ap. J.* 505:756–65

Torrelles JM, Gómez JF, Rodriguez LF, Curiel S, Ho PTP, Garay G. 1996. *Ap. J.* 457:L107–11

Torrelles JM, Gómez JF, Rodriguez LF, Ho PTP, Curiel S, Vázquez R. 1997. *Ap. J.* 489:744–52

Turner BE, Matthews HE. 1984. *Ap. J.* 277:164–80

Vacca WD, Garmany CD, Shull JM. 1996. *Ap. J.* 460:914–31

van Dishoeck EF. 2001. In *Galactic Structure, Stars and the Interstellar Medium*, ASP Conf. Ser., ed. CE Woodward, MD Bicay, JM Shull, 231:244–64

van Dishoeck EF, van der Tak FFS. 2000. In *Astrochemistry: from Molecular Clouds to Planetary Systems*, IAU Symp., ed. YC Minh, EF van Dishoeck. 197:97–112

Vázquez-Semadeni E, Ostriker EC, Passot T,

Gammie CF, Stone JM. 2000. See Mannings et al. 2000, pp. 3–28
Walmsley CM. 1995. *Rev. Mex. Astron. Astrofis. Ser. de Conf.* 1:137–48
Ward-Thompson D, André P. 1998. In *The Universe as Seen by ISO*, ed. P Cox, MF Kessler, pp. 463–66. Noordwijk, The Neth.: ESA
Ward-Thompson D, Buckley HD, Greaves JS, Holland WS, André P. 1996. *MNRAS* 281: L53–56
Ward-Thompson D, Scott PF, Hills RE, André P. 1994. *MNRAS* 268:276–90
White RL, Becker RH, Helfand DJ. 1991. *Astron. J.* 371:148–62
Williams JP. 2001. In *Massive Star Birth*, ed. P Crowther. *ASP Conf. Ser.*: In press
Williams JP, Blitz L, Mc Kee CF. 2000. See Mannings et al. 2000, pp. 97–120
Williams JP, Myers PC. 2000. *Ap. J.* 537:891–903
Wilner DJ, DePree CG, Welch WJ, Goss WM. 2001. *Ap. J. Lett.* 550:L81–85
Wolfire MG, Churchwell E. 1994. *Ap. J.* 427: 889–97
Wood DOS, Churchwell E. 1989a. *Ap. J. Suppl.* 69:831–95
Wood DOS, Churchwell E. 1989b. *Ap. J.* 340: 265–72
Zhou S, Evans NJ II, Kömpe C, Walmsley CM. 1993. *Ap. J.* 404:232–46
Zoonematkermani S, Helfand DJ, Becker RH, White RL, Perley RA. 1990. *Ap. J. Suppl.* 74:181–224

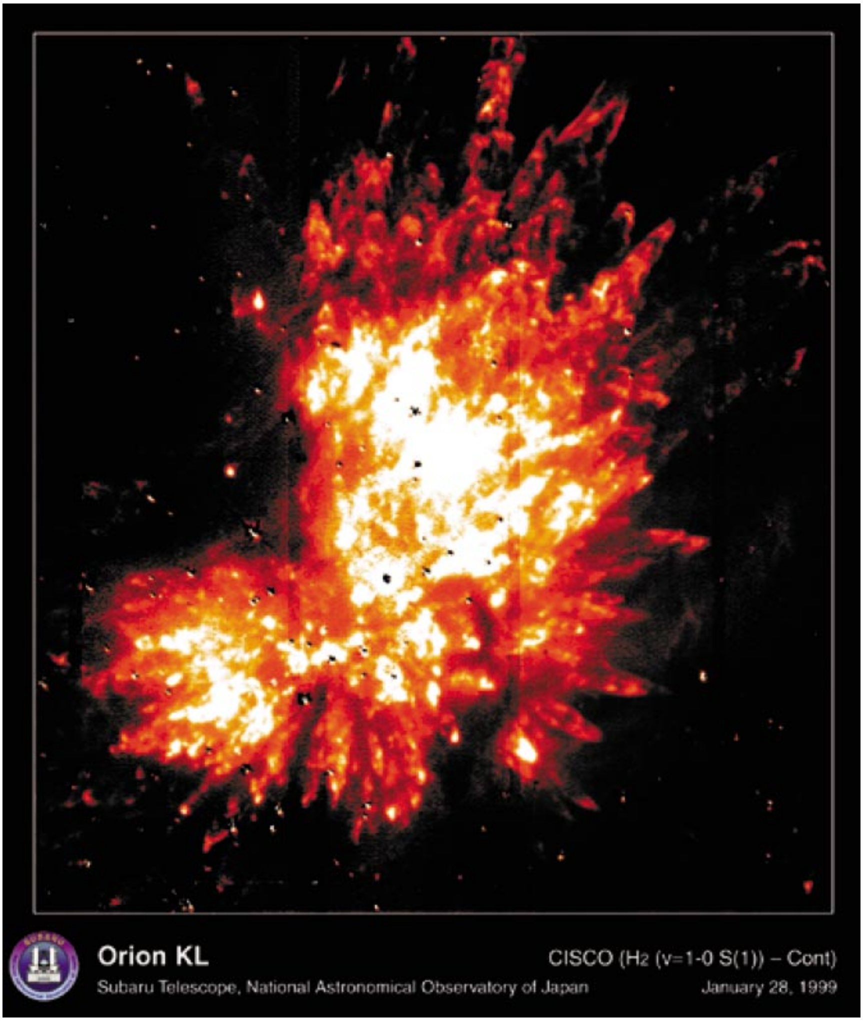


**Figure 7** The outflow in Orion IRc2 in $H_2$ emission courtesy the Subaru Telescope. Note the poor collimation of the outflow, the fact that it does not appear to originate at a point, and the jaggedness (bow shocks) at the ends of the outflow.

Annual Review of Astronomy and Astrophysics
Volume 40, 2002

# CONTENTS

ERRATA

An online log of corrections to *Annual Review of Astronomy and Astrophysics* chapters (if any, 1997 to the present) may be found at http://astro.annualreviews.org/errata.shtml