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MASSIVE STAR FORMATION

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ABSTRACT

Several topics in massive star formation are discussed. These include chemical markers of the evolutionary state of massive protostellar cores, kinematic evidence for gravitational collapse, and studies of massive star formation in different environments.

INTRODUCTION

While understanding of low-mass star formation advanced significantly in the past decade, it has proven more difficult to make progress in the study of high-mass star formation. In part this is because massive stars are less common and evolve more quickly, resulting in smaller samples of nearby objects. The large distances to typical massive star-forming regions result in poor spatial resolution, a problem exacerbated by the tendency for massive stars to form in clusters, and in high extinction, making coordinated optical studies difficult. Also, massive stars have high luminosities and ionizing fluxes and powerful winds which disrupt the morphology, kinematics, and chemistry of the ambient gas that formed the stars. On the other hand, the higher temperatures and larger column densities provide a variety of diagnostic probes that are beginning to be understood. Similarly, the availability of embedded luminous continuum sources permits absorption studies which can disentangle the kinematics. Perhaps most important, massive star formation can be observed in a wide range of Galactic and extragalactic environments, which may ultimately lead to an understanding of processes of broader astrophysical interest, such as the factors determining the high-mass IMF and star formation rate.

ABUNDANCE VARIATIONS AND CHEMICAL MARKERS

Interferometric maps of massive star-forming regions generally reveal large variations in the emission distribution of different molecular species. This is most obvious in the Orion-KL region (e.g. see Yamamoto, Mikami, and Saito; Saito *et al.*; Minh and Ohishi; in this volume), and much of this is due to abundance variations. Classification into several components (e.g. hot-core, compact ridge, plateau), although useful, clearly oversimplifies the chemistry. Many of the abundance variations can be attributed to the changing conditions during the evolution of a massive star. For example, the enhancement of NH_3 and various deuterated species in the hot-core (e.g. Walmsley *et al.* 1987; Plambeck *et al.* 1987) is explained as the result of grain chemistry during an earlier, cooler epoch when many molecules were depleted on to grains mantles, followed by evaporation upon ignition of a luminous star (Brown, Millar, and Charnley 1988). The emergence of an outflow has a further dramatic effect on sulfur and silicon chemistry (Blake *et al.* 1987; Yamamoto *et al.*, this volume). These evolutionary effects are illustrated by a comparison of Orion-KL and the star-forming region 1.5′ to the south, Orion-S. Maps of Orion-S with the BIMA array by McMullin, Mundy, and Blake (1992) indicate different distributions for the various species, as in Orion-KL. However, the relative abundances are quite different from Orion-KL, which they interpret as evidence that Orion-S is at an early evolutionary stage. In particular, the weakness of SO_2 emission and the compactness of SiO emission suggest an outflow in an early stage. In contrast to Orion-KL where many species have enhanced abundances in the dust continuum peak (the hot-core), in Orion-S abundances appear low at the position of the dust continuum peak. They argue that here molecules are depleted on to grains, also indicative of an early, cool evolutionary stage.

Another object in which molecular depletion may have been observed is NGC 2024, where several condensations are observed that are more prominent in maps of dust continuum emission than in line emission (Mezger *et al.* 1992; Mauersberger *et al.* 1992). The dust in some of these cores is claimed to be cold (10–22 K), which would argue that these are protostellar cores prior to the emergence of a luminosity source. However, observations of substantially warmer molecular emission have caused these claims to be disputed (Moore and Chandler 1989; Schulz *et al.* 1991; Ho *et al.*, this volume). Moreover, the proposed protostellar cores do not dominate the continuum flux at any wavelength, and the derived cool temperatures depend on an assumed dust emissivity (e.g. Moore and Chandler). On the other hand, the molecular observations may not probe the interior of the cores, particularly since the molecules may be depleted. Since models indicate variations among molecules in the amount of depletion, and, except at very high depletions, the abundances of some species may actually be enhanced, interferometric observations of a variety of tracers would be useful (e.g. Walmsley and Schilke 1992).

Determination of the spectral dependence of the dust emissivity is clearly essential to determine dust temperatures in these cores, and also to provide a reliable column density indicator. Currently, there are large variations in the derived dust emissivity, even for a specific region such as Orion-KL (e.g. Wright *et al.* 1992; Murata *et al.* 1992; Sandell, this volume). Wright *et al.* argue that the emissivity varies between dust cores in this region, but this depends on the assumption that each core can be characterized by a single temperature, which seems unlikely. Probably the best prospect for obtaining the spectral index is to make observations with the same interferometer at widely separated frequencies in the 3 mm window. The ratio of the fluxes emitted at 75 and 110 GHz changes by $\sim$50% for a change of one in the dust emissivity exponent, whereas at these frequencies the temperature dependence for $T > 10$ K is negligible. Also, maps can be obtained at similar resolution, calibration uncertainties are minimized, and high optical depths are less likely to be a problem.

EVIDENCE FOR GRAVITATIONAL INFALL

The definitive evidence for a massive protostar would be unambiguous detection of the kinematic signature of accreting gas. This has proven elusive because the collapse velocities are relatively small compared to other motions, except close to the star where the mass involved is small. After a luminous hydrostatic core forms, there is a continuum source, permitting high-resolution (i.e. interferometric) absorption studies to differentiate between infalling and outflowing gas. At submillimeter wavelengths, heated dust grains near the star could provide the continuum source; at radio wavelengths ultracompact HII regions supply the beacon.

Absorption components, predominantly redshifted, have been detected in an increasing number of sources. On the largest scale, redshifted HCO^+ absorption has been detected in W49 and W51, two of the most luminous star-forming complexes in the Galaxy (Welch *et al.* 1987; Rudolph *et al.* 1990). Unrelated foreground gas can be ruled out, which means that gas in these complexes is moving inward toward the HII regions, requiring either large-scale gravitational collapse or the collision of two clouds. The absorption profiles can be fit by models of inside-out collapse (Shu 1977) using masses obtained independently. For example, in W49 50,000 $M_\odot$ is inferred from the HCO^+ luminosity and from the apparent rotation of the ring of HII regions; a similar velocity gradient is also seen in molecular emission (Miyawaki, Hayashi, and Hasegawa, this conference). Miyawaki *et al.* conclude that SiO emission is in a shell around source *G* in W49, and from the absence of redshifted emission argue that the material is infalling, deriving an accretion rate similar to that inferred by Welch *et al.*, although they suggest a different center. They propose that the SiO abundance is enhanced by the accretion shock rather than the usual outflow shock. The alternative is that there are two colliding clouds (Miyawaki *et al.* 1986). Although the 13–16 km s^{-1} velocity difference between the two components is large compared to the typical velocity dispersion of GMCs, cloud-cloud collisions of this magnitude are predicted in the spiral arms of the Galaxy (Roberts and Stewart 1987). Moreover, the unusually large luminosities of W49 and W51 and the near-simultaneous formation of a large number of massive stars distributed over several parsecs might be explained by an unusually high-speed cloud collision. In addition, striking evidence suggesting the collision of two clouds at a relative speed of 30 km s^{-1} producing the 65 km s^{-1} star-forming core in Sgr B2 has been presented (Miyawaki *et al.*, this volume); redshifted absorption is also present in Sgr B2. Regardless of which view is correct, the redshifted absorption lines clearly implicate a large-scale dynamical event leading to the formation of the most massive clusters.

Redshifted absorption consistent with infall is also found toward smaller complexes with masses in the range 100–1000 $M_\odot$, such as G10.6−0.4, W3OH, G34.3+0.2, G45.47+0.05, and G5.89−0.39 (Ho and Haschick 1986; Keto *et al.* 1987; Carral and Welch 1992; Cesaroni *et al.* 1992; Wilner, Foster, and Murata, this volume). On a smaller scale, involving a single star prior to the emergence of an HII region, observations at Nobeyama by Nakamura *et al.* (1991) are consistent with a rotating, infalling accretion disk; the inferred accretion luminosity and the observed bolometric luminosity are both $\sim 10^4$ $L_\odot$. Further observations of other tracers in this source are clearly warranted.

ROTATION AND CIRCUMSTELLAR DISKS

Although there are examples of possible large-scale rotation (e.g. Murata 1990), and striking evidence for ring-shaped molecular features (e.g. Hayashi and Murata 1992; Kawabe *et al.* 1992a), there are few proposed cases of rotationally-supported cores (i.e. disks) on scales larger then ~1000 AU. This implies that angular momentum redistribution must be efficient, presumably by magnetic fields. The recent observation of NGC 2071 interpreted as a counterrotating core by Kawabe *et al.* (1992b) is particularly interesting because this is predicted by magnetic-braking models.

Circumstellar disks, common among forming low-mass stars, can also be found around high-mass stars. The best example is the Orion SiO maser source. Observations of the SiO $v = 1$, $J = 1 - 0$ maser show two clusters of spots separated by about 0.15″ (Plambeck, Wright, and Carlstrom 1990). The polarization and kinematics fit a disk model with Keplerian rotation and decelerating outflow in which the masers are 40–80 AU from the star; presumably the SiO emission originates in an interface region between the circumstellar disk and the outflowing wind. Recent Nobeyama maps by Morita *et al.* (1992) of the SiO $J = 1 - 0$ maser emission from both the $v = 1$ and $v = 2$ levels show a similar distribution of spots, with some differences as expected for a non-stationary, inhomogeneous disk. Morita *et al.* also determined that the SiO masers in W51 and Sgr B2 coincide with the H_2O maser and NH_3 hot-cores in these sources to better than 1″. They calculate that the probability that an evolved stellar SiO maser is located in a 1″ radius region is $\sim 10^{-6}$, and since there are now three examples, contrary to recent suggestions (e.g. Gezari 1992) these SiO masers probe protostellar environments. Gezari (1992) has found that the infrared source IRc2, long thought to be the primary source of luminosity and outflow in Orion-KL, is offset to the north by 0.8″ from the SiO maser; this suggests that the infrared emission is affected by extinction. There is also considerable evidence for a circumstellar disk surrounding MWC 349, a massive star of uncertain evolutionary status. Most recently, Planesas, Martín-Pintado, and Serabyn (1992) have determined the relative positions of the H30α maser features at 232 GHz with the OVRO interferometer. The masers originate in two regions separated by 80 AU (0.065″). They conclude that the source of the ionized gas producing the masers is a neutral circumstellar disk.

EVOLUTION OF MASSIVE CORES

One of the reasons circumstellar disks are important is they may help explain the long lifetimes derived for ultracompact (UC) HII regions. Because 15% of all OB stars are found in the UC HII stage, this stage must last more than 100,000 yr, much longer than the 1000 yr lifetime obtained from the sound-crossing time (Wood and Churchwell 1989). One elegant explanation for the long lifetimes is that the ionized gas is in a shell around a bubble inflated by a stellar wind and confined by the ram pressure of the ambient gas as the star moves through the medium — i.e. the ionized gas is in a bow shock, which can last as long as there are clumps of density $\sim 10^5$ cm^{-3} to move through (Van Buren *et al.* 1990). The bow shock picture almost certainly applies to some UC HII regions, since molecular line studies have confirmed that they are generally associated with gas clouds of sufficient density (Churchwell, Walmsley, and Cesaroni 1990), OB stars have powerful winds throughout their lifetimes, and some of them are likely moving at supersonic speeds. The main uncertainty is the velocity dispersion of these nascent OB stars; it appears unlikely this is large enough to account for all UC HII regions. Circumstellar disks may account for the long lifetimes of some, as suggested by Vogel, Genzel, and Palmer (1987) to explain the large number of UC HII regions in Sgr B2. Recently, Hollenbach (1992) has modeled circumstellar disks in the stellar wind and ionizing environment of massive stars and finds that these disks can last long enough to help explain the longevity of UC HII regions.

The large number of UC HII regions demands that most are relatively old; which are the youngest ones? Most UC HII regions have associated warm NH_3 at moderate column densities and water masers (Churchwell *et al.* 1990). But only two of the 16 UC HII regions with the strongest (2,2) NH_3 emission have large NH_3 column densities comparable to the Orion hot-core (Cesaroni, Walmsley, and Churchwell 1992). It appears that the number of hot-cores is even smaller than the number of warm massive dust cores seen at millimeter wavelengths. For example, in Sgr B2 there are ~20 UC HII regions (Gaume and Claussen 1990). Most are not associated with the two 3000–9000 dust cores observed at 1 mm at OVRO (Lis *et al.* 1992) or with dense ($n \approx 10^7$ cm^{-3}) gas, consistent with the idea that most of the ionized regions are more evolved and are examples of bow shocks or circumstellar disks. Although the two massive dust cores have comparable luminosities, the northern core has a NH_3 abundance 100 times larger, comparable to the Orion hot-core; several observations suggest that it is the less evolved of the two (Vogel *et al.* 1987; Sutton *et al.* 1991). The grain-mantle chemistry models predict large NH_3 and deuterated molecule enhancements immediately following the emergence of a luminous protostar, both of which are observed (Jacq *et al.* 1990; Peng, Vogel, and Carlstrom 1993). It appears, therefore, that large NH_3 and other hot-core enhancements are markers of the earliest stages following the ignition of a luminous protostar, that the dense (10^7 cm^{-3}) gas is dispersed in at most a few 10^4 yr, and that the grain-mantle abundance enhancements are largely erased in an even shorter time.

STAR FORMATION IN DIFFERENT ENVIRONMENTS

In contrast to low-mass star formation, for which studies are limited by sensitivity to relatively nearby regions, massive star formation can be studied in a variety of locations in the Galaxy and even in external galaxies. Ultimately, this can lead to an understanding of the environmental factors and physical processes important in determining the IMF and star formation rate. The outer Galaxy and local environments are quite different; for example, the molecular clouds are more sparsely distributed, and the cosmic ray flux and metallicity are lower. This may affect star formation: Fich and Terebey (1992) claim that the IMF is steeper in the outer Galaxy. A better understanding of star formation in the outer Galaxy may yield an understanding of the physical reasons for the empirical success of the Kennicutt (1989) gas surface-density threshold for massive star formation, which predicts the outer cutoff in massive star formation in the disks of galaxies. A central question is whether star formation is inhibited by large-scale processes that determine the formation of GMC complexes, or on a smaller scale in the formation of protostellar cores. CO emission has been detected at galactocentric distances as large as 28 kpc (Digel *et al.* 1993). The star-forming cores can be studied in the outer Galaxy using mm-wave interferometry. Several regions are been studied by de Geus *et al.* (1993) with the BIMA array. CO and CS studies at a spatial resolution comparable to the Bell Labs surveys of Orion are in progress to compare clump properties, such as relative frequency of high density cores.

At the opposite Galactic extreme, within a few hundred parsecs of the Galactic center the temperatures, linewidths, densities, and pressures of the GMCs are much greater than for local GMCs (e.g. Bally *et al.* 1988). Cloud-cloud collisions, such as suggested for Sgr B2 by Miyawaki *et al.* (this volume), are likely to be more important. Despite these differences, most of the signposts of massive star formation are present, such as all types of masers and chemical enhancements similar to Orion. There are some differences in molecular abundances, but at least some of these can be understood as the result of the different elemental and physical conditions (e.g. Peng, Vogel, and Carlstrom 1993).

Significant advantages are realized by studying massive star formation in nearby galaxies. In the Galaxy, optical studies of the resulting stars are complicated by extinction in the plane. In other galaxies, it is not necessary to use a rotation curve or assume that kinematic perturbations such as density wave streaming are negligible. Consequently, the location of a cloud is clearly established, such as whether it is in a spiral arm or in a region of high metallicity. Ordinary GMCs, similar to Orion, have been resolved in M31 and M33 (Vogel, Boulanger, and Ball 1987; Wilson and Scoville 1990). The most extensive work has been by Wilson, who has detected 38 GMCs in M33 with the OVRO array and has also done optical photometry of OB associations (Wilson and Scoville 1990; Regan and Wilson 1993). Remarkably, with the speed and sensitivity of the expanded arrays, properties of GMCs will be determined for Local Group galaxies for samples of hundreds of clouds, similar to the number of clouds in Galactic plane surveys. Most of the key properties (e.g. size, luminosity, line width) can be determined for the same mass range of clouds that populate the Galactic plane surveys; this is possible because a large region (10^5 kpc^2) can be surveyed at 10 pc resolution in Local Group galaxies within the field of view of the primary beam.

Even in more distant galaxies where ordinary GMCs are difficult to resolve, interferometric observations are useful for understanding larger-scale processes important in massive star formation. For example, the question of whether spiral arms trigger star formation remains surprisingly controversial (e.g. Adler *et al.* 1992; Rand and Kulkarni 1992). Rand and Kulkarni, with high-resolution CO maps of M51, find an enhanced star formation efficiency in the arms, and conclude that this can be explained by application of the Kennicutt (1989) surface-density threshold. The most enhanced star formation efficiency appears to occur near corotation, where the density-wave streaming motions and hence the compression are low; however, Vogel *et al.* (1993) propose that this may also be explained by the Kennicutt criterion because CO maps (e.g. Nakai *et al.* 1991) show that a large amount of molecular gas has pooled near corotation.

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DISCUSSION

P.T.P. Ho It may be difficult to see disks around massive stars because of the luminous output of central star. Therefore, often, there is not enough dynamic range to see both a massive star and a faint disk in the dust continuum. Spectral lines would be a better way?

S. Vogel Yes, such as the SiO maser observations.

T. Henning Have you any evidence for dusty disk-like structures around O stars?

S. Vogel There is no clear evidence for such dusty disks around the very massive stars. One reason may be the dynamic range of the observations.

M. Hayashi I think inside-out collapse is a well accepted idea for low mass star formation where star formation starts from gravitationally stable cloud cores. But in the case of massive star formation it is not necessary. Is there any direct evidence of suggesting inside-out collapse for W49 or W51, and so on?
I mean the initial massive cloud core may not be gravitationally stable.

S. Vogel Yes. Massive stars have already formed on the inside of many large clouds, as indicated by the presence of ultracompact HII regions. As I discussed, in a number of cases, such as W49 and W51, redshifted absorption lines are detected, which can be explained if the outer parts of the cloud are now collapsing.

H. Zinnecker Just a comment: I'd like to point out that beside the Hollenback analytical theory on the photoevaporation of circumsteller disks around massive stars there is also a radiative hydrodynamical simulation of the same phenomenon by H.W. Yorke (Proc. 1992 Madison conference on "Massive Stars")

T. Hasegawa I would like to point out that the apparently short but actually long lifetime of compact HII regions in the case of ones in massive molecular cloud cores (containing $\gtrsim 10^3$ $M_\odot$ can be simply explained by the large mass accretion rate($\gtrsim 10^{-2}$ $M_\odot yr^{-1}$) alone

S. Vogel I agree that same HII regions can be confined by this process.