Session 5: Ending the symposium

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W-J. de-Wit, F. Palla and M. Robberto touring Acireale

M. Sewilo, S. Komugi and T. Pillai receive the prize for the best posters; behind M. Felli and E. Churchwell

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Massive Star Birth: A Crossroads of Astrophysics
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Summary Talk I – Natal molecular clouds: Summary and perspectives

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Abstract. I describe some common themes that emerged from the meeting, ending with some thoughts on connecting our studies with those of other galaxies.

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1. Introduction

This summary focuses on the molecular cloud stage of star formation, leaving studies of the stars themselves to the summary by Peter Conti and most discussion of clusters to the summary by Hans Zinnecker. Even with this restriction of topic, I have space to mention only a subset of the many excellent talks. The talks at this symposium demonstrated the considerable progress that has been made since the last meeting on the topic in Boulder. I have organized this summary into 6 themes that emerged from the meeting in my view.

2. Tracers

One theme that has been emerging in recent years is the fickleness of tracers, and this theme was covered well during the meeting. No single observational technique traces faithfully the physical properties that we wish to constrain. Each tracer is limited in dynamical range and each depends on more than one physical property. There is an intricate interplay between gas, ice, and dust; we will not understand the physics of star formation without understanding the chemistry of interstellar molecular clouds, including the changes to the dust opacities when they become coated with ice.

Molecular lines, vital for studies of dynamics, are particularly sensitive to chemical changes as well as to density, temperature, and column density. This was nicely illustrated by Garay in a slide showing maps of 7 molecular lines and the dust continuum emission toward S255, a source with two peaks in dust emission. Some molecules showed stronger lines toward the northern peak, some toward the southern peak, and some equally toward both peaks. While some of these differences can be caused by the different sensitivity to physical conditions, some of them must be due to chemical differences.

Studies of low-mass regions have revealed clearly the role of freeze-out of gas-phase molecules onto dust grains in cold regions. Alves reminded us of this with a slide showing dust extinction, dust emission, and $C^{18}O$ emission toward a cold globule. While the two tracers of dust column density roughly agreed in showing a centrally peaked distribution, the $C^{18}O$ emission showed a hole at the center of a ring. The utility of widely-used CO isotopologues as tracers of gas column density clearly fails completely in cold, dense regions because the molecules have frozen onto dust grains.

Palumbo reminded us that we have direct evidence for the frozen species from the rich infrared absorption spectra toward massive protostars. CO absorption features are seen, reflecting the freeze-out of the most abundant (other than H_2) gas-phase species. Many other species are also seen as ice features, some forming from reactions on the grain surface. These deep absorptions will modify the extinction law in the 3 to 20 micron region as well, affecting the use of extinction to probe column density in very opaque regions. Palumbo also reported on laboratory work that shows how irradiation can drive reactions among the ices, producing different species. When these new species evaporate because of heating by the forming star, they form the complex molecules associated with hot cores, as reviewed by van der Tak. Greater awareness of these complex interplays was evident in many talks at this meeting.

3. Morphology

Bearing in mind the warnings about tracers, certain morphological regularities emerged from many of the talks. It seems that material passes through many shapes on its way to becoming a spherical star. Images of tracers primarily of column density revealed many examples of filamentary structure. Long, sinuous, dark regions were apparent in maps of extinction tracers. Maps of dust emission also showed many filaments, but they also revealed more spherical lumps spaced along them. These more spherical regions were often the site of star formation, as shown by Menten, Pillai, and others. It may still be reasonable to model the initial collapse process in a spherical geometry.

The spherical geometry is very unlikely to apply during the whole process, as rotation is very likely to produce a disk. Indeed, it is hard to see how very massive stars can be formed without disks, which can minimize the problem of radiation pressure. Evidence for disks around forming massive stars has been difficult to obtain, in contrast to their well-established presence around low-mass stars. Zhang reviewed the techniques used to search for disks around massive stars, including kinematic evidence for rotation, but he also noted the difficulty of sorting out rotation from infall and outflow, all of which may be present simultaneously. Many of the inferred disks are quite large and massive compared to the mass of the central star, suggesting that disk instabilities may be common. For the most massive stars, the disks may be more like tori. Chini and others showed images of disk-like morphology in extinction studies, but these were larger than expected for Keplerian disks. Some may be shadows cast by smaller disks and some may be transitional regions from the infalling envelope to the rotational disks. Whatever the final explanation, these objects will be prime targets for further studies. While it seemed for a time that methanol masers might be good tracers of rotational disks, evidence presented by De Buizer and others indicates that the masers originate in outflows.

While the existence of disks around forming massive stars is still observationally challenging, it is clear that massive stars have an impact on the disks of low-mass stars around them. Williams presented detections of the proplyds in Orion at millimeter wavelengths. Most lacked enough mass to form solar systems, probably because of disk erosion by radiation from the massive stars in Orion.

4. Initial Conditions

Perhaps the greatest progress since the Boulder meeting was made in this area. Massive stars generally form in a cluster with a total mass of hundreds to thousands of solar masses. We see massive, dense molecular cores forming these clusters, but very little information was available until recently on the precursors of these regions, the massive equivalent of the "Pre-Protostellar Cores" that have been identified for low-mass star formation. Indeed, at the Boulder meeting, I could make a reasonable prediction for what such cores *should* look like, but when it came to describing actual observations, I was only able to put up a blank slide.

That situation has changed dramatically with the study of Infrared Dark Clouds (IRDCs) seen in the MSX survey at mid-infrared wavelengths, as described by Menten and others. These have provided good hunting grounds for the earliest stages, though many have some evidence for on-going star formation. Garay showed that one may also find these by larger maps of regions around star-forming cores. One dramatic example of an isolated massive core was shown, but 90% are found within larger, less dense molecular clouds.

A new generation of bolometer arrays has enabled large-scale surveys for massive dense cores, as demonstrated by the MAMBO-2 maps of Cygnus X presented by Motte. Unbiased surveys will be needed to address lifetimes for the different evolutionary phases. The GLIMPSE survey with Spitzer, reported by Indebetouw, is such a survey of the inner Galaxy in the infrared. In addition to the many sources of emission, the GLIMPSE images show IRDCs in many directions, providing more candidates for follow-up studies of millimeter-wave dust continuum emission.

Another exciting development has been the detection of signatures of inflow in massive star forming cores. While a few examples of likely inflow had been identified in interferometric studies, surveys for line profiles indicative of inflow have only recently begun to appear. They show that a substantial fraction of massive cores show the blue profile that has been taken to be indicative of inflow in low-mass cores (Wu & Evans 2003, Fuller *et al.* 2005). Models with inflow can be fitted to some of these lines, as discussed by Y. Wu at this meeting.

5. Life Cycle: Birth to Death

Massive stars have a much more dramatic effect on their surroundings than do low mass stars, so we can expect the formation of massive stars to involve complex feedback effects. Bally reminded us that massive stars regulate the interstellar medium, driving a complex Galactic ecology.

Shepherd and Pudritz covered the observational and theoretical work on the evolution of outflows from massive stars. The observations suggest an evolution from collimated to wide-angle flows as a star grows in mass. Shepherd reminded us that a young O star can look like a B star before it accretes its final mass, and the outflow morphology may trace this evolution. Some beautiful VLBA data was presented by Torrelles, showing how maser proper motions can trace the outflow on tiny angular scales. In one striking image, we saw how two nearby outflows differ: one drives a collimated flow and the other a more spherical flow. Evidence of more explosive phenomena was presented by Rodriguez, who showed the images of the $\sim$1000 year old Orion outflow with an energy of 4×10^{47} ergs.

Another highlight of the meeting were the talks on X-ray emission from regions of massive star formation. Brandl showed how the cavities in the molecular gas around massive clusters are filled with hot, X-ray emitting gas.

6. Formation Mechanisms

One of the foremost questions in the field of star formation is what controls the tempo and mode of star formation. The discovery of molecular clouds provided the long-sought formation sites for stars, but it soon became clear that free-fall collapse of all the molecular clouds in the Galaxy would produce a star formation rate similar to that of a starburst galaxy. The process of star formation in our own Galaxy must be inherently inefficient at the level of the molecular cloud. Later studies showed that it is quite efficient at the level of the dense molecular core, so the control of the star formation rate occurs in the process of forming dense cores within clouds. In our Galaxy, this process is inefficient, with only a few percent of the molecular cloud forming dense cores. The outstanding question for 30 years has been *why* it is inefficient. The leading contenders are turbulence and magnetic fields. Crutcher reported on progress in measuring magnetic fields in molecular clouds. These studies reveal that, within uncertainties, most clouds are near the critical mass to flux ratio. Clouds below this ratio may be supported by magnetic fields. Finding a way to measure this ratio in the dense cores would be very important.

Surveys of the millimeter and submillimeter continuum emission toward nearby molecular clouds confirm the picture that only a small fraction of the cloud mass is contained in dense cores (Johnstone *et al.* 2004, Hatchell *et al.* 2005, Enoch *et al.* 2005, Young *et al.* 2005). This picture then predicts that the youngest stars in a cloud should be highly concentrated, a prediction readily tested by Spitzer. Megeath reported that Orion A and B clouds (L1641 and L1630) have both clustered and distributed populations. Further study is needed to find out if the distributed population is systematically older. If so, they may have wandered from their more clustered birthplaces.

Barbosa & Figer (2004) collected from a variety of people their top ten questions about massive stars. From my reading of that collection, the most common question was this: what is the basic formation mechanism for massive stars? There are two leading contenders. At the time of the Boulder meeting, these went by the names of "accretion" or "mergers"; by the time of this meeting, these had morphed into "turbulent cores" versus "coalescence". These options are also tied up with different computational techniques (AMR versus SPH) and issues of the equation of state. We can think of these as "low-mass star formation on steroids" (turbulent cores) versus "unrestrained capitalism" (coalescence).

Cesaroni suggested an outline of massive star formation that looked similar to that of low mass star formation, with the essential addition of fragmentation to form many stars. Krumholz presented beautiful new calculations of this scenario, in which disks form, outflows develop, and a massive star forms. Bonnell countered with an attractive movie showing the unrestrained competition of sink particles for the remaining SPH particles, leading to runaway growth of the most massive star. While the audience was duly impressed with both of these calculations, questioning revealed that the most massive stars actually formed in these calculations were more like B or late O stars.

The challenge remains: can anyone form a star with 100 solar masses? Tan took up the challenge for the turbulent core team, saying "Yes, it can be scaled up to 100 solar masses." Bonnell suggested that mergers of already massive stars may be needed to make the most massive ones. While we can expect this debate to resume at the next massive star meeting, Rodriguez offered tantalizing evidence for close encounters of massive stars in Orion. He related the explosive outflow to a close encounter 500 years ago of BN and source I, which are moving in opposite directions. While a close encounter is not a merger, this evidence does suggest that close interactions can be common.

7. Connecting to galaxy formation

I did not have time for this in my talk, but I will slip it in here. Kennicutt challenged us on the first day of the meeting to extend the theme of "crossroads" into the issues of star formation in galaxies. This charge is indeed timely as progress on the formation of both stars and galaxies is rapid. The origin of galaxies, long subject to archaeological studies (extremely metal-poor stars, stellar populations in nearby galaxies, ...), is becoming amenable to direct, look-back observations. Meanwhile, as this conference has demonstrated, star formation studies in our Galaxy are moving beyond case studies to systematic surveys that are clarifying the central role of the massive, dense core (also refered to as the "maternities" by Garay) as the fundamental unit of cluster formation. Extreme clusters near the Galactic Center provide local examples of nuclear star formation, as discussed by Morris. Johnson described studies of super star clusters in nearby galaxies that are still embedded and compared their properties to those of embedded clusters in our Galaxy. Theoretical work on cluster formation is progressing nicely, though questions remain. These developments argue persuasively for a meeting of students of the Galaxy with the extragalactic gang at the crossroads of star formation.

Kennicutt plotted star formation surface density versus total star formation rate for a large number of galaxies, showing a broad correlation, but scatter in both axes of 6 to 7 orders of magnitude. Understanding these features will require the combined efforts of experts on galaxy dynamics and star formation.

The discovery of many submillimeter galaxies, which lie at the extreme of star formation rates (Chapman *et al.* 2005), provides an avenue for progress. The properties of these submillimeter galaxies bear a resemblance to the conditions in massive dense cores in our Galaxy, showing similar values of the ratio of infrared luminosity to dust mass (Mueller *et al.* 2002). This similarity has been strengthened by the detection of high-excitation molecular emission in many distant starbursts, as reviewed recently by Solomon & Vanden Bout (2005). Studies of high excitation molecules in massive, dense Galactic cores indicated similar ratios of far-infrared luminosity to the mass of the dense gas (Shirley *et al.* 2003).

One problem has been that different dense gas tracers were used in the extragalactic (HCN) and Galactic (CS) studies. Recent studies of HCN toward Galactic dense cores have solved that problem (Wu *et al.* 2005), and the results are striking. Above a threshold level of either far-infrared luminosity or HCN luminosity, the mean ratio of these two quantities in Galactic cores is the same as that in extreme starbursts. The threshold value is roughly what is needed for a full sampling of the IMF. This result suggests that we may be able to understand extreme starbursts, the likely precursors of modern-day elliptical galaxies, in terms of the properties of nearby dense cores, which are accessible to detailed study.

8. Conclusions

The study of massive star formation is thriving, with major progress on understanding the uses and limitations of different tracers, the evolution of morphology, initial conditions, Galactic ecology, and formation mechanisms. The time is right for a major effort to meet extragalactic astronomers at the crossroads of star formation.

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References

Barbosa, C. & Figer, D. 2004 astro-ph/0408941
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005 *Ap. J.* 622, 772
Enoch, M. L. *et al.* 2005 *Ap. J.* in prep.
Fuller, G. A., Williams, S. J., & Sridharan, T. K. 2005 *Astr. Ap.* in press
Hatchell, J., Richer, J. S., Fuller, G. A., Qualtrough, C. J., Ladd, E. F., & Chandler, C. J. 2005 *Astr. Ap.* in press (astro-ph/0505444)
Johnstone, D., Di Francesco, J., & Kirk, H. 2004, *Ap. J. (Letters)* 611, L45
Mueller, K. E., Shirley, Y. L., Evans, N. J., & Jacobson, H. R. 2002 *Ap. J. Supp.* 143, 469
Shirley, Y. L., Evans, N. J., Young, K. E., Knez, C., & Jaffe, D. T. 2003 *Ap. J. Supp.* 149, 375
Solomon, P. M., & Vanden Bout, P. A. 2005, *ARAA* in press
Wu, J., & Evans, N. J. 2003, *Ap. J. (Letters)* 592, L79
Wu, J., *et al.* 2005, *Ap. J.* in prep.
Young, K., *et al.* 2005 *Ap. J.* in prep.

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