VIII - SYMPOSIUM SUMMARY

Symposium Summary: Fragmentation and Star Formation in Molecular Clouds:

A.E. Glassgold
New York University
New York, NY 10463, U.S.A.

This Symposium on fragmentation and star formation has dealt with the heart of the study of molecular clouds, which is how they form stars. This problem is one of the most profound and challenging problems in all of astrophysics. The complexity of the interstellar medium adds to its difficulty and we cannot expect a quick and easy solution. Nonetheless, the reports presented at this Symposium indicate that substantial progress is being made in this field.

The basis for current research in star formation has been developed over several decades. During the 1980s, large scale surveys with the mm lines of CO (see, e.g., the reviews by Thaddeus 1990, Scoville and Sandars 1988) have determined the distribution of the molecular gas near the plane of the Milky Way and how that gas is made up of giant molecular cloud complexes. The unusual properties of the immediate neighborhoods of recently formed stars were also elucidated. Of particular interest in connection with low-mass star formation has been the systematic investigation of the properties of the cores of dark clouds (e.g., Myers 1988). Near infrared studies of molecular clouds have provided a powerful method for detecting the young stellar objects ("YSOs") embedded in molecular clouds. The IRAS satellite has been particularly useful here because of its all-sky coverage. Another striking discovery of the last decade was the detection of powerful molecular outflows around YSOs (reviewed by Lada 1985). The outflows were a surprise in view of the widely held belief that star formation involves gravitational collapse.

The measurement of the magnetic field strength and direction is one of the most important goals of research in the interstellar medium. Magnetic fields almost certainly control many aspects of the structure and dynamics of

E. Falgarone et al. (eds.), Fragmentation of Molecular Clouds and Star Formation, 379–386.

molecular clouds and the formation of stars. Perhaps the main point to be drawn from Heiles' Symposium review (Heiles 1990) is that we seem to be finally emerging from a long developmental period, characterized by fairly uncertain results, to one where reliable but limited measurements of the parallel component of the magnetic field are now becoming available. For example, there is now good evidence for a square root dependence of the field on the density. Another obvious conclusion is that there are tremendous opportunities here for additional observational programs.

Many diverse observations of low-mass star formation have been integrated into a coherent conceptual framework by the theory of star formation developed by Shu and his collaborators (reviewed by Shu, Adams, and Lizano 1987, Lada and Shu 1990). The theory starts from the idea that the cores are in a quasi-equilibrium state with magnetic fields balancing gravity. Gravitational collapse does not occur until the field (slowly) slips away by ambipolar diffusion and becomes decoupled from the bulk of the gas. The collapse then proceeds from inside out at the sound speed, with the infalling gas spiraling inward through a disk onto the protostar. The corotation of the young protostar with the disk at essentially breakup speed leads to the generation by magnetic stresses of a fast wind that emanates from the equatorial regions of the protostar. The wind is fast (of order 100 km s^{-1}) and neutral and powers dramatic events far from the protostar (100-1000 AU) in directions perpendicular of the accretion disk. In addition to its unified conceptual basis, the theory makes predictions that can be tested observationally. Although not discussed extensively at the Symposium, the record so far is very promising. For example, Evans (Evans and Lada 1990) showed that the theory can account for the broad infrared spectrum of protostellar sources (Adams, Lada, and Shu 1987) and for the large scale density distribution of the infalling matter. A review of the current situation is given by Lada and Shu (1990).

A basic objective of current observational studies of star formation that was discussed at length at the Symposium is to relate the properties of the molecular gas in star-forming regions to the distribution of protostars and other YSOs. The basic tools are molecular line maps of the gas and near infrared imaging of the embedded sources, e.g., with the new array cameras. On the largest scales, the line surveys are now emphasizing the study of individual cloud complexes. The idea is to obtain the internal physical properties of complexes on all scales, starting from the largest (the size of the complex, 10-100 pc) down to the smallest generally accessible with current techniques (~ 0.01 pc). The probing of the internal structure requires telescopes with suitable spatial resolution and a multi-transition analysis. One of the molecules now in vogue for probing the higher density regions is CS, which is assumed to have a constant abundance (independent of region) ~ 10^{-9}.

Striking results of this type of research were reported in the review talks by Myers (1990) and Evans and Lada (1990), who reported in-depth comparison of the core and YSO populations in different cloud complexes. By studying six nearby complexes, Myers and his collaborators are able to demonstrate systematic progressions in core and YSO properties with complex mass, e.g., an increase in the number of stars formed and in the probability for forming a massive star. Lada (Evans and Lada 1990) discussed the differences between the Taurus and Ophiuchus complexes. Not only is Ophiuchus more efficient at star formation, but the process seems to be more localized. The observations in Orion (Lada 1990) illustrate star formation in clusters. Lada also discussed the observational problems in determining the mass distributions of the cores and of newly formed stars. The hope is to definitively determine these distributions in nearby complexes and thus understand the basis for the initial mass function (Larson 1990). Perhaps the main, interim conclusion from these studies is that the molecular line and near infrared mapping of clouds have matured to the point where quantitative analyses of the star-forming regions are possible.

A closely related topic is the small scale structure of the interstellar medium and its connection with star formation. Small scale observations of molecular gas are now being made with angular resolutions of a few arc seconds, using existing mm interferometers. At the distance of the nearby cloud complexes, this corresponds to a spatial scale of the order of 6×10^{15} cm (0.002 pc or 500 AU). It is common to observe blobs of this size in star-forming regions with aspect ratios of a few. Although symptomatic of the dynamics of star formation, the blobs by themselves do not provide direct evidence of "thin accretion disks", as sometimes claimed, although we all suspect if not believe that such disks exist. Detailed modeling of multi-wavelength observations are considerably more convincing, as in the study of L1151-IRS5 (Keene 1990, Keene and Masson 1990).

The many new results on gas structure and YSOs represent a new stage in the observational study of star formation that will be significantly enhanced by the expansion of existing interferometer capabilities and infrared imaging in the next few years. In this context, it was entirely appropriate that some aspects of the methodologies of this research were discussed critically throughout the Symposium and in a panel discussion on fragmentation. For example, the selection and substantiation of high gas density (molecular line) tracers were hotly debated. Many observational studies tacitly assume that particular species measure the local volume density, but examples of contradictory and misleading information were cited as well as cases of close agreement between different tracers. It is obvious that proposed density tracers should not be overly sensitive to temperature and chemical effects. Until a badly needed calibration of the most useful molecular lines is effected, mapping of gas structure will have to be made in several lines, chosen so that the same angular resolution and sensitivity limits are achieved. It would also be desirable to model the local physical conditions, but this requires determining the kinetic temperature as well as the density. Considering the intrinsic inhomogeneous nature of the clouds, this may require a larger measure of faith in current radiation transfer techniques than they deserve. Theoretical work on this problem is badly needed.

Related questions on the interpretation of the measurements were raised but not pursued at length, For example, results of intercomparisons between gas and YSO distributions are expressed in terms of the "star formation efficiency", usually defined as the fraction of a region's gas that has been converted to stars. We can see that this definition is rather tricky when we consider that both distributions (gas and stars) are inhomogeneous in space and time. In particular, observed correlations between neighboring cloud cores and YSOs refer to different times so that, within the relevant time difference, the gas will have been perturbed by the newly formed stars. A related issue is the connection between fragmentation, conventionally viewed as a dynamical process, and the observations of clumpy molecular gas and star formation reported at the Symposium. Theories of cloud fragmentation (and growth) have to make specific predictions about cloud condensations, including their spatial correlations, that can be tested observationally.

It was completely appropriate that interstellar turbulence should occupy a prominent place on the program of the Symposium. I was particularly impressed by the stimulating report of Falgarone and Phillips (1990) on the possible connection between the extended wings, observed in molecular line shapes measured with high signal to noise, and the structure functions in the statistical theory of turbulence. In particular, they ascribe the wings to the phenomenon of "intermittency", familiar in laboratory and atmospheric turbulence. The existence of the these wings in regions without molecular outflows has been known for some time but Falgarone and Phillips are the first to examine them in a systematic fashion. Additional observational tests and theoretical underpinning have to be made before their interpretation can be accepted as definitive. Also, other theoretical interpretations will have to judged inferior. Elmegreen (1990) presented an interesting explanation of the roughly constant ratio of the wing to core widths (about 3) in terms of the nonlinear interaction of MHD waves.

The poster paper by O'Dell (1990) on measurements of spatial fluctuations of line emission from HII regions highlighted the long history of interstellar turbulence (see, also, O'Dell and Castaneda 1987). At the 1955 "Symposium on The Dynamics of Cosmic Clouds", Courtes (1955) presented evidence for the Kolmogorov scaling relation, $v_l \sim l^{1/3}$, near Lambda Orionis and a steeper law for the Orion Nebula. O'Dell's modern results for a variety of Galactic HII regions lead to line width - size correlation with an exponent of 1/4, whereas the molecular cloud exponent is close to 1/2. Understanding this difference would appear to be an important goal for the theory of interstellar turbulence. Moreover, O'Dell's measurements refer to the neutral transition regions of HII regions as well as to the ionized gas; both are intimately related to the subjects of star formation and cloud fragmentation.

An intriguing result discussed by Falgarone (1990) is that the fractal dimensions of interstellar clouds, determined on different scales with different lines, is the same (1.4). The significance of this result is unclear. It suggests that the physics of the boundaries is independent of scale. One must ask, however, how common or easy is it to achieve the dimension 1.4. It remains to be seen whether the fractal dimension provides the key to understanding the small scale structure of interstellar clouds.

Although fully developed, incompressible turbulence, the source of many of the most useful concepts in turbulence, shouldn't apply to the interstellar medium (see e.g., Larson 1980, Scalo 1988), some of the concepts (such as scaling) are very useful. The powerful observational techniques now available for studying the interstellar medium should make it possible to test the applicability of turbulence to the problem of interstellar clouds and star formation.

Except for a very elegant review of the chemistry of "translucent" clouds by Black (1990), there were few reports on (or relevant to) realistic chemical modeling of the inhomogeneous clouds found in nature. Indeed the most stimulating reports on interstellar chemistry came from the observers. For example, Joncas (1990) and Feldt and Wendker (1990) described HI measurements of molecular clouds that are informative on the H_2-H transition regions of molecular clouds. Stutzki (1990) described the status of modeling the more familiar CO-C-C^+ transition regions, in the context of further observations of the CO/HII interface observed edge on in M17. In order to account for the CI emission, a strongly clumped model of the cloud has been introduced which permits diffusion of UV radiation into an inter-clump medium, thus enabling each clump to have its own photodissociation region. However, certain aspects of the model are troubling, in particular the very large clump-interclump density contrast ($\sim 10^2$) and the failure to explain the observed emission in the J = 7-6 line of CO. High spatial resolution maps of the M17SW cloud core reveal about 200 high density clumps and provide important structural information for future modeling of this situation (Stutzki and Gusten 1990).

A novel chemical point was made by Boulanger (1990) on the basis of observations of rapid, (small-scale) fluctuations in the 12/100 micron IRAS colors. His interpretation is that there are large changes in the amount of carbon in small particles (or large molecules), presumably produced by rapid cycling of material between dense and diffuse phases. Important modifications in the thermal and chemical properties of the interstellar medium are implied and, presumably, subject to observational tests.

One of the problems in developing more realistic chemical models is the sheer technical difficulty in capturing the essence of real (inhomogeneous and evolving) clouds. Of course, many informative and useful programs have been developed that deal effectively with either the chemical, thermal, or radiative-transfer aspects of interstellar clouds, but rarely with more than one of these essential ingredients. Almost always, the geometry is grossly oversimplified and steady-state is sometimes assumed without justification; real clouds seldom resemble a sphere or a slab and are likely to be variable temporally. In this context, it was refreshing to see the promising approach adopted in the poster paper by Keto, Lattanzio, and Monaghan (1990). They modeled the observations of the ring of star formation observed in W49A (Welch et al. 1987) with a 3-d hydrodynamics code that does include some chemistry, thermal effects, and radiative transfer. Similarly, some of the problems with shock models discussed by Draine (1990) may be overcome by abandoning planar shocks and considering instead bow shocks (Smith et al. 1990).

Certainly chemical modeling of fragmenting and star-forming regions of interstellar clouds is important. At the empirical level, it is crucial to know whether a molecule used for mapping is chemically active and whether its abundance is sensitive to local physical conditions. It is also generally accepted that the chemistry determines the abundances of the coolants and of the ions that couple the gas to the magnetic field. Of course chemistry includes the solid as well as the gas phase. The criticality of the chemistry of dust for understanding the infrared radiation of star-forming clouds is also widely recognized. For these and other reasons, it is important that interstellar chemistry becomes better integrated into general research on star formation.

It is usual in a conference summary to identify or suggest important problems for future research, a custom that I find difficult to follow. However, the Symposium did give me the sense that this field is in the process of transition in which the remarkable discoveries of the last decade are being extended by greatly improved technical capabilities, such as interferometers, infrared array cameras and, hopefully, new space observations at far infrared and submm wavelengths. In other words, areas of research on star formation that will be important in the next several years have been identified and are being pursued vigorously. These include the improved measurements of magnetic fields, systematic studies of the properties of star-forming cores and young stellar objects, and the probing of the actual star-forming entities e.g., the infalling cloud, the accretion disk, and the various outflow components, on ever decreasing size scales.

This does not mean that we are close to understanding even a small fraction of the complex of problems that make up the subject of star formation. The Symposium focused on the particularly difficult, basic problem of the small scale structure of interstellar clouds and its relation to star formation. This subject is of course related to more global ones such as the formation and evolution of the giant molecular cloud complexes. Although many good qualitative ideas were discussed, our understanding of this subject needs to become more quantitative and, eventually, organized according to some general principles. Perhaps the concepts and methods developed in the study of turbulent fluids will be useful. Certainly, the Symposium did an excellent job in giving a current account of the complex of challenging issues and of some methods that should help us understand the subject better.

On behalf of all the participants, I would like to thank Edith Falgarone and the members of the Scientific Organizing Committee for arranging a truly stimulating meeting. The beauty of the city and the surrounding areas made Grenoble an ideal meeting place. Many hanks are also due the Local Organizing Committee and, particularly, the excellent supporting staff, for all their generous help and hospitality. On a personal note, I would also like to thank the organizers, for making it possible for me to return to Grenoble and to participate in the Symposium, and NASA (Grant NAGE-630) for additional support.

References

Adams, F.C., Lada, C.J., and Shu, F.H. 1987, Ap.J. 312, 836.
Black, J.H. 1990, this meeting.
Boulanger, F. 1990, this meeting.
Courtes, G. 1955, in "Gas Dynamics of Cosmic Clouds", (Interscience, 1955), p.131.
Draine, B.T. 1990, this meeting.
Elmegreen, B.G., 1990, this meeting.
Evans, N.J. II and Lada, E.A., 1990, this meeting.
Falgarone, E., 1990, this meeting.
Falgarone, E. and Phillips, T.G., 1990, this meeting.
Feldt, C. and Wendker, H.J. 1990, this meeting.
Heiles, C. 1990, this meeting.
Joncas, G. 1990, this meeting.
Keene, J. 1990, this meeting.
Keene and Masson, C.R. 1990, Ap.J. 355, 635.
Keto, E.R., Lattanzio, J.C., and Monaghan, J.J. (1990), this meeting.
Lada, E.A. 1990, thesis, Univ. of Texas.
Lada, C.J. 1985, Ann. Rev. Astr. and Ap., 23, 267.
Lada, C.L. and Shu, F.H. 1990, Science, 248, 564.
Larson, R.B. 1990, this meeting.
Larson, R.B. 1980, M.N.R.A.S. 186, 479.
Myers, P.C., 1988, in "Interstellar Processes", Eds. D.J. Hollenbach and H.A. Thronson, (Reidel), p.71.
Myers, P.C., 1990, this meeting.
O'Dell, C.R. and O. Castaneda, O. 1987, Ap.J. 317, 686.
O'Dell, C.R. 1990, this meeting.
Scalo, J.M. 1988, in "Interstellar Processes", Eds. D.J. Hollenbach and H.A. Thronson, (Reidel), p.349.
Shu, F.H., Adams, F., and Lizano, S. 1987, Ann. Rev. Astr. and Ap., 255, 23.
Smith, M.D., Brand, P.W.J.L., and Moorhouse, A. 1990, this meeting.
Stutzki , J. 1990, this meeting
Stutzki , J. and Gusten, R. 1990, Ap.J. 356, 513.
Thaddeus, P. 1990, this meeting.
Welch, W.J. et al., 1987, Science 238, 1550.