DISCUSSION FOLLOWING REVIEW BY J. LEQUEUX

Fragmentation, collapse and turbulence.

FIELD: In view of the fact that you did not have time to cover all your material, can you go back over some of the points? In particular, what is the evidence for the fragmentation of molecular clouds?

LEQUEUX: The evidence for fragmentation is indirect. There is evidence for clumpiness in molecular clouds coming from a study of CS and NH_3 lines. Roughly speaking, CS lines are saturated and their excitation (and brightness) temperature should not be very much smaller than the kinetic temperature. However the antenna temperatures measured are obviously much smaller, suggesting beam dilution and clumpiness. The situation with the NH_3 lines is similar.

SOLOMON: The low intensity and high optical depths of the $^{12}C^{32}S$ lines do not necessarily indicate that the material is clumpy, although that is a possible interpretation. The observed intensities and optical depths can result from line formation. At densities in a homogeneous cloud where CO emission will be thermalized ($n(H_2) \simeq 3 \times 10^3$ or $10^4 cm^{-3}$), CS emission will have about 1/10 the intensity of CO, even though the CS may be optically thick. This is a result of the large dipole moment and therefore fast decay rate of the CS molecule. The lower intensity of high dipole moment molecules (even if $\tau > 1$) such as CS, HCN can be explained by radiative transfer models as the effect of photon trapping and is not in itself proof of strong clumping.

GLASSGOLD: What do you mean by observing fragmentation, in particular, what sizes and masses do you have in mind? Perhaps, I really have in the back of my own mind whether it requires interferometric observations.

LEQUEUX: The present resolution of molecular observations is about 1 arc minute corresponding to 0.15 pc at the distance of the Orion cloud. With a density $n(H_2) \simeq 10^5 cm^{-3}$ this corresponds to more than 10 $M_\odot$. Thus we do not see in most cases solar-mass fragments, and higher resolution observations are required.

MOUSCHOVIAS: Regarding models for explaining the large linewidths in molecular clouds, I would like to point out that the conclusion of Arons and Max (Ap.J.196, L77) was that hydromagnetic waves may account for the observed linewidths but only if the wavelength is comparable to the size of the cloud. This is not a wave but a large-scale oscillation. I had earlier suggested (unpublished thesis work) that a self-gravitating, magnetic cloud could oscillate about a stable equilibrium configuration with a supersonic but subalfvénic velocity field. These oscillations do not dissipate easily. I suggest that this possibility be considered in more detail.

WERNER: Observations of density gradients may be another way of determining whether a cloud is collapsing. This can be done more readily by observing thermal emission from the dust in such a cloud, which is optically thin, than by observations of the optically thick gas. Some initial results (Westbrook et al., Ap.J. 209, 94, 1976) on the 1mm emission from dust in molecular clouds have been interpreted as showing that the density gradients in the centre of these regions are consistent with those expected from collapse models.

MESTEL: In the cases where rotational velocities are not unambiguously observed: if it is postulated that the clouds form not conserving their angular momentum, but remembering the angular velocity of the local galactic rotation, would the consequent rotational velocity be observable?

LEQUEUX: Certainly not. From Oort's constant A of 15 km s^{-1} kpc^{-1} a cloud of 5 pc radius would have a peripheral rotation velocity of $\lesssim 0.1$ km s^{-1} if conserving angular velocity.

C.J. CESARSKY: In the turbulent models where cold blobs are floating in a hot interblob medium: is it not the case that the blobs would be dissipated by thermal conduction?

LITVAK: I would like to make a few corrections to an otherwise fine review. Line shapes: It is possible to obtain good agreement of line profiles with CO data e.g. for ORI A and 5gr B2, as was done by a student, D. Cook. However, the isotopic abundances are non-terrestrial but agree with the results of Wannier, Penzias, etc.
Microturbulence: The data seem to indicate microturbulence with some mean flow of collapse that is only somewhat supersonic, if the small shift between peaks of ^{12}CO and ^{13}CO is to be interpreted as such. The gravitational energy could be the source of energy since the free-fall velocity is of the same order of magnitude. The mean flow would feed the turbulence and the collapse would be slower than free-fall.
1720 MHz OH: Neither experiment nor theory have given collision cross-sections, so that hard conclusions about collisional pumping of OH can not be drawn. Other mechanisms can give 1720 MHz emission. It is a question of the observed power as to which mechanism is important.

LARSON: Some of the controversy over whether the kinematics of dense clouds are dominated by collapse or turbulence may result from the use of over-idealized collapse models, which assume spherical symmetry and purely radial motion. Some recent attempts to simulate 3-dimensional collapse, upon which I shall report later, indicate that if the size of a cloud exceeds the Jeans length, the cloud fragments into a number of lumps which rapidly become very centrally condensed. Thereafter the large scale dynamics is dominated by the random motions of the lumps, as in a cluster of stars, and the system might appear turbulent to a radio observer. It is possible to have a situation where the cloud as a whole contracts only slowly or even expands, being supported by a combination of rotation and random motions, while collapse continues on smaller scales within the individual condensations. This more complicated collapse scenario may reconcile some of the seemingly contradictory arguments for large scale collapse vs. turbulent motions; both may well be possible. The problem of rapid dissipation of supersonic motions is made less severe by the fact that the lumps become highly concentrated, and the importance of collisions is correspondingly reduced.

FIELD: Your model of clumpiness is quite interesting. It suggests a pause in the overall collapse analogous to virialization in stellar clusters. But how, in view of the fact that the free-fall time within each blob is shorter than that of the cloud as a whole, do you explain the persistence of gaseous blobs over a time equal to, or greater than, the dynamical time of the cloud?

LARSON: It is indeed true that within the dense lumps the collapse time is short, and stellar objects rapidly form within them. However, these stellar objects are surrounded by extended envelopes from which they continue to accrete matter for a more extended period of time. Thus small scale collapse, in the sense of an accretion process, can continue as long as there is a significant amount of more diffuse gas remaining to be accreted (or until infall is halted by stellar winds or other effects).

McCREA: As regards the random motion of the blobs, their behaviour as statistical kinetic motion on a large scale may be regarded as adiabatic. So the compression of clouds as a whole will tend to drive the random motions, i.e. some of the energy of the flow that produces the compression will go into these motions.

ZUCKERMAN: Regarding the question of fragmentation of molecular clouds, there is clear evidence from the molecular data for fragments of mass $\sim 1000\ M_\odot$ separated by ~1 pc: the beamwidths of existing radio telescopes are sufficiently small (~ 1') to easily resolve such condensations. The existence of fragmentation or clumpiness on a much smaller scale must be investigated more indirectly. NH_3 observations by some MIT and Berkeley radio astronomers have been interpreted by them to indicate that the Orion molecular cloud is clumpy although other interpretations might be possible. The model for Herbig-Haro objects suggested by Strom et al. also suggests clumpy clouds with many holes and tunnels.

PENZIAS: Discussions of condensations in molecular clouds must include the scale size. While there is clear evidence for structure on a scale greater than the resolution of our radio-telescopes in the nearest clouds,

~0.1 pc, any viable theory of line formation by supersonic turbulence must involve condensations on a very much smaller scale. This is because the smoothness of the observed spectral line shapes requires a large number of condensations within the antenna beam, if relative motions are chaotic. There are serious theoretical problems associated with the existence of such postulated objects, such as the lack of a high pressure "inter-blob" medium required to prevent their dissipation. We ought to remember, however, that photographs of nearby obscured objects often show dust features as small as a few milliparsecs. Observations of NH_3 lines from the well-known molecular sources yield highly saturated (determined from hyperfine intensity ratios), but very weak, spectra. Because the transitions have rather long radiative lifetimes, the collision rates deduced from other molecular lines, e.g. CS, ought to yield very strong NH_3 excitation. This apparent paradox has led several workers to suggest that the NH_3 only fills a small portion of the antenna beam. Obviously, such a model would fit in well with some small scale structure pictures, if in fact the NH_3 emission comes from the same region as the CS.

LADA: I would like to make a few comments concerning fragmentation in molecular clouds. First, in M17 the observed sizes of the fragments vary from about 3 to 13 pc in diameter through the cloud. The masses of these fragments are very large, about $10^5 M_\odot$. Secondly, fragmentation of molecular clouds into fragments of a few parsecs in size with densities of 10^4 cm^{-3} and masses of $\sim 10^3 M_\odot$ seems to be a common characteristic of a molecular cloud whether or not O-B stars are being formed within it.

KUIPER: You have addressed the question of the formation of typical CO line shapes with widths up to 10km/s. I believe that in considering this question you cannot ignore the CO line wings in Orion as a special case that is of no interest to the larger question. I would argue this on philosophical grounds, in that whatever dynamical process is occurring in the cloud, it very likely peaks at the Kleinmann-Low nebula, and also on observational grounds, in that the CO profile is not composed of two distinct features, like a spike and a plateau, but forms one continuous shape from its peak until the wings disappear in the noise. In fact, it is possible that these wings provide us with an observational connection to the evidence of the H_2O masers, as discussed by Morris, and by Heckman and Sullivan.

SCHATZMAN: Can you comment on the fact that the microscopic kinetic temperature and the radiation temperature is the same?

LEQUEUX: In a very optically thick cloud, the inside is isolated from the external world and the second principle of thermodynamics tells that all the temperatures should be the same. This thermalisation by radiation trapping is indeed confirmed by numerical radiative transfer calculations.

MESTEL: I think that gravitational energy can and will feed the turbulence. But there is the difficulty that the characteristic time of decay of the turbulence by cascade into smaller and smaller scales is (by analogy with ordinary hydro-dynamic turbulence) of the order of the turn-over time of the largest-scale motions. If the turbulence is strong enough to be dynamically significant, it will therefore tend to decay in something like the free-fall time. I think the moral is that we need much more sophisticated studies of these dynamical problems. Further, in a diffuse cloud, the time of heat loss is much shorter than any dynamical time, so that heat of dissipation will be rapidly radiated away.

Maser sources associated with star formation

HABING: In discussing the information about stellar formation processes that one can extract from masers, you mention very accurate position measurements. I agree with that point. However, one should not forget about the velocity information that one can derive and that also may be very useful for understanding the overall process.

ROBINSON: In May 1976 a four-station VLBI experiment at 22 GHz was carried out by Batchelor, Jauncey, Johnston, Knowles, Kostenko, Matveyenko, Schilizzi, etc. Their results on W 49 are qualitatively different from previous VLBI results. Previously there has been a single hot-spot corresponding to each radial velocity feature on the H_2O profile. The results of the USSR-Australia-USA VLBI experiment in May appear to require several hot-spots with the same velocity. This would support the global maser model (with several coherent amplification paths through a large cloud) rather than the local model.

WELCH: In addition to our measurement of absolute H_2O maser positions in W3(OH) which were summarized by Dr. Lequeux, we have also measured absolute H_2O positions in about a dozen other regions. The positional accuracy is between $0\overset{''}{.}1$ and $0\overset{''}{.}5$. In every case, the H_2O maser does not coincide with any compact HII region in the field.

STROM: It is well known that dark cloud complexes curtain young stellar objects such as T Tau stars and H-H objects. Currently we believe that these objects have strong mass outflows (10^{-6}-10^{-9} $M_\odot yr^{-1}$, outflow velocities $\simeq$ 200 km s^{-1}). What evidence is there, either from observations of maser sources (or other molecular lines) for possible interactions between the stellar winds and the dark cloud material?

LEQUEUX: The difference in velocity between T Tau stars or H-H objects and the associated masers might be an indication of such an interaction. The large velocity spread observed in several H_2O maser groups like that in W49 might also be due to stellar winds. I am not able however to comment quantitatively on the effects of such winds on the dark cloud material.

ZUCKERMAN: Dr. Strom has asked if there is evidence from the maser results of an interaction of stellar winds (at velocities of about 100 km s^{-1}) with the molecular clouds. Although most H_2O maser sources show rather simple spectra with only a few features at small velocities, there are some H_2O maser sources that contain many features spread over a large velocity range. Because this spread is much greater than say twice the sound speed in the ionized gas it appears that stellar winds are the most likely acceleration mechanism for such high velocity gas. (Dr. M. Morris has argued for this view in Ap.J. 210, 100). In addition, from an examination of the published literature on H_2O masers and associated radio continuum sources, I believe, that for the class of sources with large velocity spreads, the H_2O features lie parallel to and probably just outside of ionization fronts. (The same remark does not hold for the simple low-velocity H_2O sources). High velocity H_2O sources that lie parallel to ionization fronts include Orion A and Sgr B2 and probably W49 and W51. Continuum aperture synthesis and H_2O interferometry on additional sources will be required to confirm or deny the generality of this suggestion.

ROBINSON: Mention has been made of the high velocity components in the W49 water vapour maser, which are separated by up to 200 km s^{-1} from the main part of the H_2O emission profile. Goss et al. (MNRAS 174, 541, 1976) have found high velocity components in about seven other H_2O masers, but in these the velocity shift is typically 50 km s^{-1}. They have recently found another case, where the velocity shift is 100 km s^{-1}. These high velocities could well be associated with a stellar wind.

HUGHES: Our recent unpublished observation of the 22GHz H_2O line profiles from W3 show that a very broadband emission underlies the narrow band intense emission features. The narrow band features may vary, but they appear to be confined to velocities enclosed by the broadband component. This suggests that H_2O is contained in a comparatively large cloud and that the intense maser emission is seen from regions where the velocity along a line of sight is constant.

ROBINSON: Is the very high maser luminosity in W49 dependent on assumptions about the linear size of the W49 emitting regions? In the global model the total luminosity might be reduced by a high degree of beaming.

LEQUEUX: Of course you are right. Beaming effects can reduce the calculated luminosity significantly.

LADA: I would like to make a comment concerning the relative orientation of H_2O masers and compact continuum sources and the large scale sequential progression of visible subgroups in the same star-forming complex. In the model of Elmegreen and Lada, we can only say that massive stars will form in a thin layer between an ionization front and a shock front moving into the cloud away from the most recently found OB stars in the association. However, we do not have enough information, either observational or theoretical, to enable us to determine exactly what happens within this star-forming layer. This depends on the details of the final collapse of the layer, a problem unfortunately beyond the scope of present-day theory. Thus within the narrow layer itself one cannot predict the relative orientations of H_2O masers, IR sources, OH masers or compact continuum sources.

SCALISE: Wide range spectra (±140 km s^{-1}) of H_2O maser sources (W49, W51, G331.5-0.1, Orion) are obtained weekly at Itapetinga Radio Observatory (Sao Paulo, Brazil) since February 1976. The variability of each feature is studied in order to see if they are correlated, indicating a common centre of excitation, or if they vary independently, especially in the case of extreme velocity features.

BOOTH: From the interferometric maps of H_2O and OH one sees that spectral features are clumped spatially in regions with dimensions approximately one tenth of the overall spread of the source. It would be interesting to look at the variable features with the interferometer maps in mind to see if clumped features vary together.

ENCRENAZ: Could you please summarize the situation for the two other molecules which are masing: SiO (silicon monoxyde) and CH_3OH (methyl alcohol) and in particular emphasize their relation to protostars?

ZUCKERMAN: Dr. Encrenaz has asked about the relationship between SiO masers and regions of star formation. So far, at least, there is not much overlap since almost all known SiO maser sources are associated with evolved stars. The only exceptions are, possibly, objects like VY CMa which have been suggested by some to be pre- rather than post-main sequence objects and the Orion Nebula SiO maser. Dr. Snyder and co-workers have suggested that the Orion SiO maser is due to a post-main sequence star buried in the molecular cloud in or near the Kleinmann-Low Nebula. Based on the far-infrared luminosity of the K-L cluster it seems that such a star would then be $\gtrsim 10^7$ years old. Orion would then represent an apparently unique case where an old star is located very close to a young star cluster. The alternative possibility that the Orion SiO maser is supported by inflow onto or outflow from a pre-main sequence object also requires that Orion be unique. The relatively small variation of the Orion SiO maser intensity with time suggests that it might be of a different nature than the SiO masers associated with evolved stars.

LEQUEUX: CH_3OH masers have not been observed as extensively as the others. The most important results obtained recently seem to me the observation of correlated variations by Barrett et al. (1975) (see the review paper) and the lack of VLBI detections of such masers, indicating that their sizes are rather large compared to OH and H_2O masers.

MORRIS: Two other interstellar molecules which probably show weak maser action are HC_3N and HC_5N. At least the J=1→0 transitions (and perhaps a few higher ones) of both molecules are much more intense relative to higher-lying lines than can be accounted for without maser amplification. Other evidence exists to support this hypothesis.
The observations of more than 10 galactic water maser sources having high velocity features seem to rule out the possibility that each maser feature is associated with a separate protostellar condensation. This is because of the large masses required to bind a group of objects having such a velocity dispersion. Rather, in many of these cases, acceleration of the masering gas by an intense stellar wind from an O star is a more plausible explanation. My recent observations extend the total radial velocity range of H_2O maser emission in W49N to 530 km s^{-1}, in W51 to 180 km s^{-1}, and in Sgr B2 to 140 km s^{-1}. Of the mechanisms conceived to-date, acceleration by a stellar wind appears to be the only hope for explaining such velocities. Only in Sgr B2 is the cloud mass perhaps large enough to bind discrete objects having the observed velocity dispersion.

HUGHES: H85 α recombination line observations of W3(OH) (Hughes & Viner, Ap.J. 204, 55, 1976) show that the velocity of the compact HII region is -54 km s^{-1} in comparison with the surrounding medium which moves with -41 km s^{-1}. Since the sound speed in the latter is about 1 km s^{-1}, a shock wave will be set up and could be the reason for the H_2O and OH masers. The H_2O can be produced at the apex of the shock and the OH further back along the bow-wave. If the more recent observations by Welch place the OH regions close to an edge of the HII region, then this suggests an alternative place for formation, namely the turbulent region near to a tail shock. The stand-off distance of the H_2O maser is about 15,000 A.U., and is likely to be produced by a magneto-hydrodynamic shock, especially so if the large suggested magnetic field of ∿5 mG is associated with the region.

LADA: What is the sense of the velocity difference between the compact continuum source and the surrounding medium? Is the compact HII region approaching us relative to the cloud?

HUGHES: The compact HII region (-54 km s^{-1}) is approaching us relative to the molecular cloud (-48 km s^{-1}) which in turn is approaching us relative to the low emission HII (-41.6 km s^{-1}), which we interpret as a weakly-ionized HII cloud.

PISMIS: My comment concerns the optical HII region in W3. Perhaps I can add further information to the velocity field of that region. Several Fabry-Perot interferograms in the Hαline have yielded a gradual variation of the average radial velocity towards the north and north-east. The velocity is -41 km s^{-1} at the brightest position of the HII region attaining a value of -46 km s^{-1} in the northern part of the HII complex. A report on these observations is in preparation.

MORRIS: Maser emission from water vapor has been seen in the direction of a few Herbig-Haro objects and can perhaps aid in determining their nature. The most spectacularly varying H_2O source known appears to be associated with HH-11 (Lo, Morris, Moran and Haschick, Ap.J. 204, L 21, 1976). Noticeable intensity variations can occur from day-to-day, and in a several-month interval, activity has been observed over a 40 km s^{-1} radial velocity range on the blueshifted side of the underlying molecular cloud velocity. The interpretation offered by Lo et al. is basically one in which a stellar wind from an HH star or HH object is interacting with and accelerating neutral gas from the surrounding molecular cloud. The H_2O emission could thus arise in the accelerated region of interaction. I would like to remark that this interpretation is completely analogous to the stellar wind acceleration mechanism suggested to account for high-velocity H_2O maser emission from the vicinity of HII regions such as W49N, W51, and many others. We therefore have an indication of a phenomenon that may be responsible for a significant fraction of the H_2O masers that are found in regions of active or recent star formation.

BOOTH: Rieu and I have observed OH emission in the direction of a group of H-H objects using the Effelsberg 100m radio telescope. Here there seems to be a background OH cloud since there is emission between the objects. Perhaps the H_2O is formed more efficiently close to the Herbig-Haro objects or perhaps its maser pump is more efficient.

CASWELL: Attention has been drawn to a number of H_2O masers where there are no associated OH masers. It seems very likely that this is largely a problem of sensitivity limits. For example, the Brazilian group recently discovered new H_2O masers which apparently had no nearby OH masers. In observations made at Parkes we have now found weak 18 cm main line OH masers at the position of four of these H_2O masers.

BAUDRY: This is a comment on Morris's previous comment about the acceleration mechanism of the water sources in W49N. The supernova blastwave hypothesis cannot be definitely ruled out in W49N until we have checked for possible changes in the total size of the emitting H_2O region.