DISCUSSION FOLLOWING REVIEW BY L. MESTEL

Magnetic fields, angular momentum and fragmentation of clouds

PENZIAS: Can you estimate the wavelength and velocity amplitude distribution of the Alfvén waves which you suggest to brake the angular momentum of the cloud? As you know, molecular clouds are generally observed to have highly supersonic velocity widths, usually much larger than any rotation velocities, whose origin has been suggested to have some relation to magnetohydrodynamics by Arons and Max (Ap.J. 196, L77, 1975).

MESTEL: The Alfvén waves I deal with have wavelengths and amplitudes determined by the shears that develop as a rotating cloud contracts. I don't think that they have anything to do with the Arons-Max waves. My waves may describe the process by which the molecular clouds have been relieved of the angular momentum that would otherwise be observable as a rotational velocity.

MOUSCHOVIAS: In response to Dr. Penzias question, whether large velocities seen in molecular clouds can be accounted for by hydromagnetic waves, I refer to my comment during the first day of this Symposium. The answer is no; but large-scale oscillations about a stable equilibrium state in the presence of a magnetic field may, possibly, account for the large linewidths.

BODENHEIMER: I would like to make three comments. First, the theory of fragmentation as outlined by you relies strongly on the assumption that the fragment mass is close to the Jeans mass for a given T, ρ. Recent three-dimensional numerical hydrodynamic calculations indicate that fragmentation occurs in the rotating rings that are formed in the interiors of assumed axisymmetric collapsing clouds. The radius for such a fragment can be considerably smaller than the Jeans radius for a given fragment mass. This question will be discussed further this afternoon.
Secondly, you mentioned that if the magnetic field can remove angular momentum efficiently enough to keep the angular velocity constant during an increase of density of a factor of 50, then further contraction with conservation of angular momentum can occur without difficulty all the way to densities characteristic of pre-main-sequence equilibrium stars. Under these circumstances I suggest that the angular momentum problem has been solved too well. Most main-sequence stars near solar type have been found to be members of binary systems. I maintain that although the magnetic field may play an important role in the removal of angular momentum during star formation, the transfer of angular momentum from spin to orbital motion must also be important in the resolution of the "angular momentum problem".
Thirdly, concerning the question of the minimum fragment mass, the studies that you referred to, all assume that fragmentation ceases when the fragment becomes optically thick, since beyond that point $\gamma \to 5/3$ and the

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Jeans mass increases with increasing density. In fact, once the temperature exceeds about 80K the rotational levels of molecular Hydrogen are excited and γ is no longer 5/3 but close to 1.4. Therefore the Jeans mass increases, but rather slowly. Once the temperature reaches about 1800K, the molecular Hydrogen dissociates, resulting in a γ considerably less than 4/3 over an increase of several orders of magnitude in density. Thus in the late stages of collapse, the Jeans mass decreases again, and a rough calculation shows that the minimum fragment mass is reduced by a factor of 3 or 4 from the value of .007 $M_\odot$ that has been previously quoted.

MESTEL: In response to your second comment, I do not envisage that magnetic coupling between a fragment and the background galactic material will persist indefinitely. I expect magnetic braking to be sharply reduced once the field of a fragment has detached; however, redistribution of angular momentum within the fragment can assist the next stage of break-up. Such a hierarchical process will automatically yield binary systems.

MAEDER: How does the time scale for collapse of a cloud change due to the magnetic field and to rotation, relative to the free-fall time?

MESTEL: If the cloud mass exceeds a critical mass M_c for its magnetic flux, then the time of collapse of a non-rotating cloud will be the free-fall time with a magnetically-diluted gravitational constant - essentially $(\varepsilon G\rho)^{-\frac{1}{2}}$, where $\varepsilon < 1$. Unless the mass is very close to M_c, this will be hardly different from the non-magnetic case. If the cloud is rotating, we need a definitive estimate for the efficiency of angular momentum transport by the magnetic stresses. It may be that in some cases the rotation is kept well below the centrifugal balance limit, in which case the collapse time is again near the free-fall value. If magnetic braking is less efficient, contraction will be determined by the braking rate, yielding a time-scale rather longer than free-fall.

McNALLY: May I ask you to comment on the observation that interstellar gas clouds are elongated parallel to the galactic plane but yet the rotation vector does not seem to be aligned to the direction of galactic rotation?

MESTEL: Couldn't this be due just to the differential galactic rotation?

SILK: Although the characteristic minimum fragmentation mass of about 0.01 $M_\odot$ is insensitive to temperature (and also to opacity), it may yield a severe underestimate if a more realistic dynamical framework is used than provided by a spherically symmetric model. For example, a small degree of initial oblateness will result in larger minimum mass fragments, when opacity first becomes appreciable for the fragments. The reason for this is that at a given density (specified by the opacity condition) a uniform spheroid is collapsing more rapidly than a sphere.

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Fragments of critical Jeans mass can first achieve appreciable opacity at a low density and higher temperature. I estimate that reasonable initial conditions could yield estimates of the minimum mass as high as 0.1 $M_\odot$ (and even 1 $M_\odot$).

MOUSCHOVIAS: The problems that conservations of angular momentum and magnetic flux pose for the theoretical understanding of single-star formation have been stated clearly by Dr. Mestel. I intend to propose a resolution of these two problems in a way that deviates qualitatively at some crucial points from the one proposed by Dr. Mestel.
It is well known that the angular momentum in the orbital motion of a binary star system is larger by a few orders of magnitude than the spin angular momentum of each of its components. It is therefore more appropriate to ask: can a binary star system form through fragmentation of a blob of typical interstellar density (say, 15 cm^{-3}) that rotates only once per galactic rotation? The answer is no: the resulting "binary" would have a separation of 1.3 pc and its orbital period would be 10^8 years! This problem cannot be bypassed by forming many star systems while putting most of the angular momentum in the rotation of the resulting stellar cluster. As far as I know, open clusters do not exhibit any rotation. Altogher then, it follows that most of the angular momentum of the parent blob must be dissipated in order for stars to form. I shall now outline a scenario for star formation.
(1) Since the magnetic energy of a typical H I cloud is comparable with its thermal energy but two orders of magnitude larger than its gravitational and rotational energies, it follows that collapse will be initiated through a rise in the intercloud pressure.
(2) The contraction of the cloud proceeds at a constant angular velocity - not a constant angular momentum. This is so because the observed parameters of the interstellar medium indicate that magnetic braking is very efficient. For example, I calculate that the characteristic time for the dissipation of an H I cloud's angular momentum is less than or equal to 5 x 10^7 years. For the dense cores of molecular clouds, this time is less than 2 x 10^6 years. It would be erroneous to compare these timescales with the corresponding free-fall times. As I stated above, most H I clouds are not even self-gravitating - let aside collapsing. Free-fall is irrelevant even for the molecular clouds because of the retarding effect of the magnetic field (see step 4 below). During this phase of contraction the magnetic and gravitational energies of the cloud increase, respectively, as $R^{-(1-\varepsilon)}$ and $R^{-(1+\delta)}$, where ε and δ are small positive constants accounting for flattening along field lines and for the development of a central condensation. For isothermal contraction, of course the thermal energy remains constant. The crucial point is that the rotational kinetic energy decreases as R^2. This is the phase during which most of the angular momentum of the cloud is lost.
I should, perhaps, translate my last sentence into Dr. Strom's language for his benefit. Is he here? Oh, good! Yesterday he spoke of "cosmic conception" and other such things that I dare not repeat. What I am saying is that the ... ceremony which precedes conception is a ...

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tricky business that in fact may hold the key to the answers of many a problem ... This ceremony, I may add, is quite ... stimulating, both from a theoretical and a practical (I should not say observational) point of view...

(3) Contraction continues with the gravitational forces taking over when the magnitude of the cloud's gravitational energy becomes comparable to its magnetic energy. Conversion of atomic to molecular Hydrogen may occur when the density is high enough, and collapse receives a boost by the resulting reduction in the sound speed.

(4) The outer envelope of the cloud is left behind because the tension of the field lines (which thread both the cloud and the intercloud medium and are frozen in the matter) overwhelms the gravitational forces. I have shown elsewhere (1976, Ap.J. 207, 141) that, in this region, the ratio of the magnetic tension and the gravitational force increases upon contraction.

(5) The core of the cloud continues to contract (the tension of the field lines is small there). Fragmentation may take place due to flattening, as described ten years ago by Dr. Mestel.

(6) When the core becomes dense enough, the magnetic field is expelled by ambipolar diffusion (see below).

(7) Further contraction proceeds at a constant angular momentum and a small magnetic energy.

(8) There is a one-to-one correspondence between the density (n_{cr}) at which the magnetic field decouples from the matter and the periods of the resulting binary stars. If n_{cr} is large enough, single stars can form.

Let us now ask: how can we account for the observed periods of binary stars (roughly, 10 hours to 100 years), at which density should the magnetic field decouple from the matter? I calculate that $n_{cr} \simeq 7.5 \times 10^3 - 2.2 \times 10^6$ cm^{-3} (the largest density corresponds to the shortest period, and vice-versa). The important question now is: does the magnetic field have enough time to decouple from the matter at the above densities? I find that the ambipolar diffusion time, τ_B, corresponding to the density range deduced above, is $\tau_B \simeq 8.8 \times 10^5 - 3.9 \times 10^7$ yrs. Since the spiral density wave theory allows a time of 3×10^7 years within which star formation must take place (otherwise, young stars would be seen too far downstream from a galactic shock; see Roberts, 1969, Ap.J. 158, 123), all is well for us.

Let me conclude with the remark that the single mechanism which I have outlined accounts for the periods (and separations) of all binary stars. We need not appeal to different mechanisms for the formation of spectroscopic binaries on the one hand and wide visual binaries on the other. The recent observations by Abt and Levy (1976, Ap.J. Suppl. Ser. 30, 273) on the multiplicity among solar-type stars indicate that there is a single maximum in the period distribution for the 88 available systems. This suggests that indeed a single mechanism is responsible for their formation.

MESTEL: I agree that the outer parts of the flattened cloud will be prevented from contracting by the field, essentially because there is not enough cool gas available in these regions to yield a large enough gravitational force density. I think you will find this implicit in the earlier, partly intuitive studies. Provided the cloud is more massive than the critical $M_c(F)$, then the inner parts will contract substantially. With the field frozen in, there will result a domain within the cloud in which nearly radial field lines pinch an equatorial zone of cold gas, with the consequences outlined in my report. However, if the flux-loss becomes "fast" before the field has suffered much distortion, then of course the scenario will be very different.

HERBIG: The orbital angular momentum vectors of binary stars are said to be distributed in random directions with respect to the galactic plane. Is this compatible with your ideas?

MOUSCHOVIAS: Yes, as far as I can say, without having done the detailed calculation of how magnetic torques alter the direction of the angular momentum vector when it is oriented at some angle with respect to the magnetic field. Let me remind you that the interstellar magnetic field is not oriented exactly parallel to the galactic plane, as the optical polarization observations of Mathewson and Ford (1970) show; there are arches of field lines rising high above the galactic plane. This may have something to do with the final orientation of the angular momentum vector of a binary system. As another possibility, gravitational encounters between cluster members may randomize the angular momenta of the binaries.

APPENZELLER: How reliable are the present estimates of the density at which ambipolar diffusion becomes important in view of the uncertainties of the ionizing radiation field in interstellar space?

MESTEL: I feel that there is enough uncertainty for theoretical workers to be justified in keeping this density as a parameter that can be varied within reasonable limits.

C.J. CESARSKY: Dr. Mestel said that ambipolar diffusion could become important at densities $\gtrsim 10^4$ cm^{-3}. It is difficult to decide exactly when it is important, as we do not know well the degree of ionization of the clouds, or the contraction times. I wonder if observations of strong magnetic fields (a few milligauss) in some objects could not help to put an upper limit to the rate of decay of the magnetic field due to ambipolar diffusion.

MOUSCHOVIAS: In the absence of ambipolar diffusion the magnetic field scales according to what has been referred to as "the usual law", $B = 3\, n_H^{2/3}$, where B is in microGauss and n_H is in cm^{-3}. My rigorous calculations (Ap.J. 207, 141, 1976) show that instead we have $B = 3\, n_H^k$ with $k < 2/3$. This is crucial for fragmentation which cannot occur if $k = 2/3$. A likely range of k is $1/3 \lesssim k \lesssim 1/2$. A theoretical lower

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limit on k does not exist; it must be set by observations. There is an observation by Heiles et al. attempting to measure the Zeeman effect in the recombination lines of Hydrogen in compact HII regions. If I remember correctly, they put upper limits of about 200-300 microGauss. For the densities which are presumed to be common in compact HII regions, the above upper limits on B are consistent with the theoretical result $1/3 \lesssim k \lesssim 1/2$.

LEQUEUX: The most convincing determinations of magnetic fields inside molecular clouds seem to me (see my review paper):
(1) an upper limit of 50μG obtained by observation of the Zeeman splitting of OH lines in the ρ Oph cloud by Crutcher et al. (1975); however the density (perhaps 10^3 cm^{-3}) is not really known.
(2) values of 3 - 9 mG in several 1720 MHz OH masers, obtained in VLBI-Zeeman observations by Lo et al. (1975). Since the density cannot be larger than $10^{5-6}cm^{-3}$ (if not the maser would be quenched) this suggests a value of $k \simeq 3/5$, only slightly smaller than 2/3.

McCREA: The basic principles of star formation appear to be:
(a) Compression, as such, of cloud material does not help in general. Consider the simplest case of compression of a cloud in one dimension. The ratio of Jeans length to the cloud width increases as compression proceeds, so that the formation of gravitational condensations actually becomes more difficult as the material becomes more compressed.
(b) Accumulation of cloud material is in general needed. If two clouds collide at supersonic speed then a layer of material of a particular density of growing thickness is formed; when the thickness has grown sufficiently, it exceeds the Jeans length for the material, and gravitational condensations can occur.
(c) Supersonic motion is in general essential. This seems to be effectively the only means for producing in practice the required accumulation of material.
Examples of the application of the principle are the floccule theory and the model for galaxy-formation that I mentioned before. Also the principle accounts for the significance of shocks as repeatedly illustrated during this Symposium.

ELMEGREEN: I would like to point out that the model of star formation by Elmegreen and Lada is entirely consistent with Dr. McCrea's remark. In fact, the requirement of "accumulation" is the reason we believe that the successive generations of OB stars will be separated in both age and distance; that is, the shocked layer must accumulate to a critical column density before it becomes gravitationally unstable to transverse perturbations. Otherwise, the appearance of OB "sub-groups" within a large association would be unlikely, according to our theory.

MOUSCHOVIAS: Most references to shocks were made for Mach numbers between 2 and 3. Wouldn't a reasonable magnetic field prevent the formation of such shocks except in special cases?

ELMEGREEN: The advantage of star formation in large molecular clouds is that one can always find a part of the shock wave which moves parallel to the magnetic field, for which magnetic inhibition to star formation is least severe.

THOMPSON: What provides the shock for the first star formation? Can supermassive stars form without shocks?

McCREA: I suggest that galaxies were formed by the collision of very large clouds (about the epoch of "recombination" of the big-bang model universe). If so they provide the most direct illustration of the principle I have proposed. (According to my model, the first condensations in the sense of the pri.ciple would have been of globular-cluster size, the next would have been massive temporary stars, and after that the first stars as we know them).

MESTEL: I am not quarrelling with what you are saying; however, one must consider clouds in which the temperature is low enough for the classical Jeans length to be much less than the radius, but where fragmentation is prevented by the frozen in magnetic field. After collapse down the field, fragmentation can occur: the mass required by the mass-flux relation for a sub-condensation to form is agglomerated by the motion down the field. This is a situation in which one-dimensional collapse is absolutely crucial for fragmentation.

FIELD: Perhaps I have forgotten the physics, but as I remember it, the one-dimensional compression of a disk of matter induces gravitational instability for waves travelling along the disk even though it does not do so for waves perpendicular to the disk.

McCREA: I said only that compression alone does not help in general. It is, of course, possible to think of any number of particular cases where compression can be made to help.

WOODWARD: While we are discussing the means of lighting cigars and of producing a first generation of stars, I would like to point out that star formation from cloud implosion driven by a spiral wave shock can fill the bill. This mechanism demands no immediate stellar predecessors, but of course the disk stars of a galaxy must already exist in order to generate the spiral wave. Recent calculations of long-term evolution of imploding clouds indicates that this mechanism can both produce the required cigar-shaped cloud and "light it" as well. Such a cigar-shaped cloud would have to be much denser on the upstream end and would have a velocity gradient along it. The cigar shape is produced by a dense compressed cloud with gas expanding away from it in the downstream direction after the original cloud has been completely flattened upon entering a spiral arm. Stars which may form in the dense end of the cloud will eventually be left behind as the cloud is blown away by the shocked intercloud wind. Then, as before, a second generation of stars may be formed by gravitational collapse of a clump within the dense end of the cloud. This second generation may still form without any help from the interaction of the first generation with the cloud. Thus, although the second generation of stars may owe its existence to the first, this conclusion cannot be drawn from the fact of its existence alone. A detailed comparison of the importance of compression of the cloud due to the intercloud wind and due to its interaction with the newly-formed stars should be made.

BASTIEN: I want to raise an old question related to fragmentation: the problem of statistical fluctuations. A perfect gas has fluctuations in the number density given by $\langle \delta n^2 \rangle^{\frac{1}{2}} = n^{\frac{1}{2}}$. These fluctuations are known to be insufficient to produce condensations large enough to grow. But Saslaw has studied again the question in three papers (M.N.R.A.S. 141, 1, 1968; 143, 437, 1969; 147, 253, 1970) including the effect of gravitation on the thermodynamics. His main result is that the fluctuations are of order unit and occur on scales of the order of the Jeans length. These could indeed develop and produce the fragmentation we want. Hence, the problem of fluctuations is still open and is a possible alternative to formation of dense clouds by shocks.

CUDABACK: There is hope for measurements at 10μ wavelength with 0".01 resolution in a few years. This will give information on a late stage of the fragmentation, when the fragments begin to look like stars. It probably is possible to achieve resolution better than 1" at 350μ wavelength with the same instrument.

Minimum Jeans mass and initial mass function of stars

LYNDEN-BELL: I would like to comment on the masses of the smallest fragments that can form in a cloud. The last fragmentation is given by three conditions:
(1) The mass and radius are given by Jeans's criterion
(2) The fragment is just optically thick ($\tau \simeq 1$)
(3) Since optical thickness is only just achieved, the rate of pdV work is (still) balanced by the rate of radiative heat losses.
Using reasonable values of the dust opacity we find fragments of mass $0.007 M_\odot$ at temperatures near 10K and densities near $n(H) = 10^{10}\,cm^{-3}$.

SILK: Dr. Lynden-Bell has provided an admirable introduction to the remarks I wish to make concerning opacity-limited fragmentation. I address myself to the question of the possible development of an initial mass function in this general scenario and I focus on the role of opacity and cooling, primarily due to dust grains, in the final stages of fragmentation of an isothermally collapsing molecular cloud. In a general situation, the density distribution will be inhomogeneous, and fragments of mass comparable to, or larger than, the Jeans mass may form. The Jeans mass decreases with increasing density throughout the isothermal regime. [....]. When the density achieves a sufficiently high value,

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Jeans mass fragments become opaque, can no longer radiate freely, and any further sub-fragmentation ceases. Estimates of the minimum fragment mass range from 0.007 $M_\odot$ in a spherical collapse model (Lynden-Bell) to 0.1 $M_\odot$ or greater when oblate spheroidal collapse models are studied. However it cannot be overemphasized that this type of argument only yields a lower limit to the resulting fragment masses. Many processes could conceivably determine or affect the resulting initial mass function (e.g. accretion, fragment collisions, disk formation and instability).
I wish to describe here a highly simplified model that offers some prospect of obtaining a universal initial mass function. Consider the cloud when the first opaque fragments (of mass M_{min}) form. This will occur at a stage when the bulk of the cloud is still at a much lower density, because of the extremely non-homologous nature of realistic collapse models. A sizeable fraction of the energy liberated by these first fragments will be trapped within the cloud. When sufficient of these fragments have begun to collapse, this energy input (produced over a time-scale short compared to the collapse of the more diffuse gas) can affect the thermal balance of the rest of the cloud. Now M_{min} depends sensitively on the temperature T and will therefore increase as the cloud becomes hotter. Since the protostellar energy output of a collapsing fragment also depends strongly on its mass, this scenario therefore suggests a negative feedback mechanism whereby a reduced frequency of more massive fragments is formed. [....]
This model, which is evidently of a statistical nature since the increments in T may not be continuous, yields a mass function of the form $dN/dM \propto M^{-\beta}$, where $\beta = 2 + \delta(2 + \delta)^{-1}$ and δ is a parameter that expresses the temperature dependence of the Planck-mean grain absorption efficiency in terms of a power-law fit over a specified temperature range. For $\delta \simeq 1$ (ice mantle grains below 50K) the mass function closely resembles the Salpeter function but other values of δ also give quite satisfactory results because the mass function is not very sensitive to the precise value adopted for δ.
Parenthetically, I mention that other modes of energy input, e.g. dynamical dissipation or protostellar winds can yield a similar result. An interesting difference is that dynamical dissipation directly heats the gas while the grains provide the cooling, thereby eventually providing a possible decoupling between gas and grain temperatures. One can show that this effect introduces a strong sensitivity of fragment mass to grain temperature, and could lead to a steepening of the predicted mass spectrum at the high mass end.
Finally, I will summarize some observational implications of my model for the initial mass function. Opacity-limited fragmentation suggests that smaller stars form first. The low mass cut-off is very sensitive to temperature; thus hotter regions (e.g. molecular clouds near HII regions) may contain a deficiency of less massive stars. On the other hand, the feed-back mechanism I have described may be quite inefficient under certain circumstances (e.g. if the efficiency of formation of the first generation of fragments is low), and could lead to an initial mass function lacking in massive stars.

WHITWORTH: The optical depth required for the fragment to heat up is not unity. If you take the cloud to be collapsing in free-fall and calculate the rate at which heat is being generated and must be disposed of, then you find that this heat can be disposed of until the optical depth is very much higher (say 10^6!). This must spoil your power law.

SILK: The optical depth is not precisely unity, but it need not be very large (certainly less than 10) before the radiation is effectively trapped and effective heating occurs. Detailed computations of the radiative transfer problem by Low and Lynden-Bell indicate that the critical optical depth in a uniform spherical fragment dominated by dust cooling and dust opacity is about 3. I should emphasize that these are optical depths, not in the visual, but in the far-infrared, using the Planck mean absorption coefficient appropriate to the temperature of the cold fragments we are considering.

WHITWORTH: If magnetic and/or centrifugal processes assume an important role, then the rate of collapse - and hence the rate of heating - are decreased. As a consequence, the optical depth is required to be greater before this heat cannot escape.

SILK: Comparison of the collapse rate of a uniform pressure-free rotating spheroid with that of a sphere at the same density indicates that the former system is collapsing more rapidly (in the sense that d log ρ/dt is larger). A similar remark applies to the case of oblate collapse.

MICHEL: How sensitive is the value of the exponent in the mass distribution function to the optical grain properties in your fragmentation model? The optical properties of grains in the far-infrared may vary by an order of magnitude from the values usually quoted in the literature (cf. Drapatz and Michel, Mitt. Astron. Ges. 1976).

SILK: I have fitted Planck mean emissivities for a wide range of possible grain models, including graphite, olivine, and ice-mantle grains. I found that the exponent of a power-law fit to the temperature dependence of the Planck mean absorption efficiency ranged from approximately 1 to 4 for different materials and temperature ranges. The corresponding range in β is from 2.33 to 2.67. This result is for spherical grain models. I have also looked into the possible effect of non-spherical grains, which generally yield an increased absorptivity per unit mass. This latter effect is small for dielectric materials, but can be large for graphite grains. Again, I think that the sensitivity of my result to more realistic grain models is probably small. This is because the exponent of the derived mass function is principally dependent on the strongly mass-dependent energy input to the cloud from newly fragmented protostars.

SOLOMON: You are assuming that the gas and dust are thermally coupled.

This will be approximately true at densities greater than 10^6 cm^{-3}. Of course the gas contains most of the thermal energy and the cooling and heating of the gas may effect your results.

LYNDEN-BELL: I don't think that the densities of last fragmentation are dependent on details. Our T-ρ relationship is defined by $\tau_{dust} = 1$ through a Jeans mass and the value of the mass defines the density completely.

SCHATZMANN: There is great ingenuity in the way you obtain the mass spectrum. However, as far as I know there are about half a dozen ways of reproducing the observed mass spectrum. I would like to say that obtaining the proper mass spectrum is not a proof.

Observations of magnetic fields related to star formation

VRBA: I would like to report on observations which Dr. Steve Strom and I undertook in order to investigate the magnetic field structures of several massive dark cloud complexes. These were obtained by measurement of the broadband visual linear polarization of the light of stars seen shining through the peripheries of the clouds. The clouds chosen for observation were required to be both nearby ($\lesssim$500 pc) and at high galactic latitude to minimize the effects of foreground and background interstellar matter.
We have assumed that the polarizations we observe are due to alignment of cloud grains by the same mechanism which operates in the general interstellar medium. In this case the polarization directions are in the same direction as that of the magnetic field. We have checked this assumption by measuring polarizations of stars near to several of the dark clouds but whose light only passes through normal interstellar material. In each case the sense of alignment has been the same.
In the Rho Ophiuchi (Barnard 42) cloud, there is considerable scatter in the amounts and position angles of polarization in the western region of the cloud where most of the mass of the cloud and a large embedded stellar complex are located (Vrba, Strom, Strom and Grasdalen, Ap.J. 197, 77, 1975). However along the two streamers extending to the east of the cloud the polarization vector are large ($\lesssim$ 12%) and are aligned with the streamers. A number of features of this cloud are identical with the observationable consequences predicted by Woodward's (Ap.J. 207, 484, 1976) model of a cloud hit by a shock wave:
(1) Star formation occurs in a concentrated region in a much more extensive cloud. The location of such a region in the Rho Ophiuchi cloud indicates that the shock front velocity must have been to northeast.
(2) A magnetic field which is present must be parallel to the shock velocity otherwise star formation cannot proceed. Our observations of the streamer region and of stars some distance from the cloud indicate this is so.
(3) While the main mass of the cloud remains relatively stationary, some mass will be lost in the downstream direction. This would explain the

streamers seen in the downstream direction for a shock velocity to the Northeast. Furthermore, ^{12}CO observations obtained for us by Drs. R. Loren and C. Gottlieb indicate that there is a radial velocity difference between the streamer and main cloud which indicates an age for the streamer consistent with the age of bright stars in the main cloud (5-7 x 10^6 yrs).

From this picture it is not likely that magnetic fields played a major role in the evolution of the cloud. However, this possibility should not be ruled out until magnetic field strengths are measured. For example, even for kinetic temperatures as low as 5 K thermal pressures alone are sufficient to prevent collapse of the streamers. Thus, a strong magnetic field permeating the streamers could force gas to be squeezed out along the field lines and could reproduce the ^{12}CO velocity structure in the streamers.

The polarization data for the R Corona Austrina dark cloud are exactly like those expected for a Parker instability as predicted by Field (1970, in "Dark Nebulae, Globules and Protostars", ed. B.T. Lynds, Un. of Arizona Press):

(1) The polarization vectors are smooth and follow closely the edges of the cloud.

(2) The only sharp twist in the field occurs in the region of the cloud closest to the galactic plane (magnetic well region).

(3) The magnetic well contains the highest obscuration of the cloud and is the only region where limited star formation has occurred (Vrba, Strom, and Strom, Astr.J. 81, 317, 1976).

From these considerations it is likely that magnetic fields played an important part in the evolution of this cloud. Moreover, from radial velocity maps and the fact that very little star formation has occurred in this massive cloud it is unlikely that the cloud has undergone a general collapse. However, thermal and kinetic pressures are not large enough to have prevented a collapse. Thus, another pressure such as a strong magnetic field needs to be invoked. Similar polarization structures have also been noted for the Alpha Perseus star cluster by Appenzeller (1971, Astr.Ap.12, 313) and Markkanen (1977, in press).

The polarization data for the Lynds 1630 cloud is rather incomplete but does show a definite radial geometry. At the focus of this geometry is an OH/H_2O maser and the centre of the embedded stellar cluster discovered by Strom, Strom and Vrba (1976, Astr.J. 81, 308). The radial polarization pattern is that expected when a Parker instability is viewed end on and the fraction of the cloud which has turned into stars is not inconsistent with that found for the R Corona Austrina cloud.

The polarization structure for Lynds 1450 (NGC 1333) shows a bimodal distribution of position angles one angle dominating the southwestern region of the cloud and another angle the northwestern. Loren (1976, Ap.J. 209, 466) has convincingly shown this complex to be the result of a two-cloud collision with the northwestern and the southwestern region seen at different radial velocities. Thus, it is most likely that the polarization structure seen is a result of the superposition of the magnetic field structures of the parts of the two clouds which have not yet

collided.
Magnetic fields are not expected to play a significant role in this evolutionary scenario. The strip of visible stars, Herbig-Haro objects and CS and H_2CO emission peaks represent star formation which is a significant fraction of the total mass of the two clouds and suggests that cloud-cloud collisions are an efficient process in forming stars.
The polarization structure seen for Lynds 1551 (the HL and XZ Taurus cloud) shows an extremely smooth field which permeates the entire cloud. At the distance of the cloud the polarization observed must be completely due to aligned cloud material. It is not surprising that little evidence for star formation has been noted for this cloud since such a field structure would indicate that the cloud has not collapsed. It is likely that the magnetic field helped prevent the collapse.

Cloud	Most likely evolutionary scenario	ESF
R Cr A	Parker instability (B field very important)	8×10^{-4}
L 1551	Uniform field prevents collapse (B field very important)	0.03
L 1630	Parker instability seen end-on (B field may be important)	0.04
ρ Oph	Shock-initiated star formation (B field probably not important)	0.14
NGC 1333	Cloud collision (B field not important)	0.19

In the Table above I give the most likely scenario for the evolution of the clouds to their present morphology and the efficiency of star formation (ESF) which is defined as ESF = $M_{stars} / (M_{gas} + M_{stars})$. M_{stars} has been estimated by correcting for the undetected faint portion of the luminosity function for the Rho Ophiuchi and L1630 clouds, by normalization to the Salpeter initial luminosity function while for the other clouds no correction has been applied since it is likely that all embedded sources were detected. It was assumed that each star has a mass of $2M_\odot$. The mass of the clouds were estimated by the ^{12}CO observation of various authors. ESF must be considered as only a schematic number since there are very large errors associated with each of these masses. The Table shows that for cloud evolutionary scenarios for which magnetic fields play a role ESF is low. However, where dynamic pressures are important the ability to form stars is much greater. This trend is independent of cloud mass.

MARKKANEN: It was pointed out by Appenzeller that there should be a magnetic pocket in the area of the α Per association. He had made polarization observations of bright stars only, and there were no observations in the most crucial area. I have made observations of about

90 additional stars.
In the area we look perpendicularly through the galactic magnetic field, and the undisturbed field seems to run at an inclination of about 20^0 to the galactic plane. The polarization observations show evidence of a magnetic pocket. The work is at a preliminary state but there seems to be a correlation between the amount of polarization and reddening which means that the stars are in a dust cloud. When the spatial distribution of the stars is taken into account it seems that the stars that are falling towards the galactic plane through the pocket, are leaving the dust cloud behind.

WHITWORTH: The Davis-Greenstein alignment mechanism, apart from imposing severe constraints on the structure and strength of the magnetic field, and the susceptibility of the grain material, require that the grain temperature be a factor $\gtrsim 3$ smaller than the gas kinetic temperature. I should like to suggest an alternative alignment mechanism which might operate, namely supersonic streaming of the dust with respect to the gas. The required streaming direction would be perpendicular to the proposed magnetic field; thus perhaps at right angles to a shock front, or radial to a source of radiation pressure. I think it is dangerous to assume that the polarization vectors map out the magnetic field in all cases.

SPITZER: I would like to point out that according to recent work by Purcell a difference of grain and gas temperature no longer seems necessary for magnetic alignment of grains. Purcell has shown that the rotational angular velocity of grains tends to be much increased over its thermal value by an effect which he calls "spin-up"; for example, the formation of H_2 molecules at a number of "active sites" on the grain surface produces a net unbalanced torque as the newly formed molecules come off the grain with appreciable velocities, and this torque produces a very rapid rotation of the grains.

ENCRENAZ: I do not think that you are looking deep inside the cloud with your polarization measurements. In the case of HD 147889, A_V is at most 3 mag. compared to more than 20 mag. through the cloud.

APPENZELLER: A few years ago I checked through all available polarimetric observations of regions of recent star formation in order to find evidence for Parker's instability. I found the observations in all cases to be at least compatible with the field structure predicted by Parker. However, the interpretation of the observations is reliable only in those cases where we are looking approximately perpendicular to the undisturbed field. If we are, e.g. looking along the (undisturbed) lines of force, we always get a radial orientation of the electric vectors regardless of the existence or non-existence of a magnetic pocket.

LOREN: Mapping of the dense core of the R CrA molecular cloud with the neutral molecules CS, HCN and H_2CO, which require $\sim 10^5$ cm^{-3} for substantial excitation, it is found that each has a similar distribution. The distribution of column density of these molecules is highly elongated with a ratio of major to minor axis of 3 : 1. The major axis of this dense core lies parallel to Vrba and Strom's polarization vectors. There is no evidence of any difference of velocity across this dense core of greater than 0.7 km s^{-1}. This elongated core is perpendicular to the galactic plane and thus the elongation is not due to shear of the galactic rotation. Thus the dominance of the magnetic field in controlling the shape of the cloud holds up to higher densities.

STROM: Measurements of p/A_V (an indication of alignment efficiency) suggests that p/A_V decreases as A_V increases. The range of A_V values studied are $1 \lesssim A_V \lesssim 20$ mag.

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