STAR FORMATION IN MOLECULAR CLOUDS

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ABSTRACT. We examine how star formation occurs in the Galaxy and come to the following conclusions. (1) The distribution of newly-born stars in the Galaxy depends on the origin of giant-molecular-cloud complexes. For individual complexes, we favor the mechanism of Parker's instability behind galactic shocks. The production of "supercomplexes" may require the mediation of Jeans instability in the interstellar gas. (2) Magnetic fields help to support the clumps of molecular gas making up a complex against gravitational collapse. On a timescale of 10^7 years, these fields slip by ambipolar diffusion relative to the neutral gas, leading to the formation of dense cloud cores. This timescale is the expected spread in ages of stars born in any clump. (3) When the cores undergo gravitational collapse, they usually give rise to low-mass stars on a timescale of 10^5 years. (4) What shuts off the accretion flow and determines the mass of a new star is the onset of a powerful stellar wind. The ultimate source of energy for driving this wind in low-mass stars is the release of the energy of differential rotation acquired during the protostellar phase of evolution. The release is triggered by the entire protostar being driven convectively unstable when deuterium burning turns on.

INTRODUCTION

The problem of star formation in spiral galaxies attracts a diverse group of workers, because the phenomenon spans at least twelve orders of magnitude in length scale. In this paper, I shall comment on a selected list of physical events that allow a galaxy of size 10^{23} cm to give birth to a star of size 10^{11} cm.

THE ORIGIN OF MOLECULAR-CLOUD COMPLEXES

It is widely believed that the bulk of star formation today takes place in giant-molecular-cloud complexes. The empirical evidence is consistent with the interpretation that, once we have a molecular cloud of sufficient mass, no external inducement is needed to yield stars.

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All we need to do is wait (on the order of 10^7 years according to the estimates of Mathewson, van der Kruit, and Brouw 1972). Moreover, once OB stars appear, the destruction of a molecular cloud also seems secure. Again, we just have to wait (on the order of 3 x 10^7 years according to the estimates of Bash, Green, and Peters 1977, and Blaauw 1985).

The first problem of star formation reduces, therefore, to the origin of giant molecular clouds. In particular, why should they aggregate along long spiral features, many kiloparsecs in length (Dame et al. 1985, Stark 1985)? And why should they gather in "supercomplexes" (complexes of complexes), tens of millions of $M_\odot$ in mass (Allen and Goss 1979, Elmegreen and Elmegreen 1983)?

These questions pose severe difficulties for the picture of stochastic self-propagating star formation (SSPSF). The issue, as Seiden (1983) has himself emphasized recently, is not how to induce star formation, but how to induce molecular-cloud formation. What is the PHYSICS in SSPSF that allows a giant molecular cloud here to induce the formation of a giant molecular cloud there, a few hundred parsecs away, much less many kiloparsecs away?

In density-wave theory, the answer is simple: the concentration of giant molecular clouds along long spiral fronts is organized by galactic shocks (Fujimoto 1966, Roberts 1969). In particular, even if molecular clouds of 10^5-10^6 $M_\odot$ do not exist in the interarm regions, they can form by the triggering of Parker's (1966) instability behind galactic shocks (Mouschovias, Shu, and Woodward 1974; Blitz and Shu 1980; Giz and Shu 1983). This proposal is well known; here, let me simply reiterate two points. First, no one has found any plausible way to prevent the instability, either by geometrical arrangement (Parker 1967), or by differential rotation (Shu 1974), or by tangled magnetic fields (Zweibel and Kulsrud 1975). Second, the buckling of the field lines and the escape of cosmic-ray particles to the elevated portions yield a natural account for the thin and thick disks in the nonthermal radio-continuum emission of external galaxies (Mathewson, van der Kruit, and Brouw 1972; Beck and Reich 1985).

The agglomeration of molecular clouds into "supercomplexes" also seems to have a convenient explanation within the context of density-wave theory. Length scales of roughly a kiloparsec or more and mass scales of 10^7-10^8 $M_\odot$ appear automatically, if the interstellar gas behind galactic shocks is Jeans-unstable (Elmegreen 1979, Cowie 1981, Jog and Solomon 1983, Elmegreen and Elmegreen 1983).

THE ORIGIN OF MOLECULAR-CLOUD CORES

Observed at high enough angular resolution, completely mapped giant molecular clouds break up into many clumps, each of which may contain several thousand $M_\odot$ and which move randomly with respect to each other at roughly the virial speeds appropriate to the complex (Sargent 1977; Blitz 1978; Solomon, Scoville, and Sanders 1979). The clumps themselves are probably supported against their internal gravity by a combination

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of magnetic fields (Mouschovias 1976) and turbulence (Larson 1981). The turbulent velocity fields can often be attributed to driving by stellar winds from newly-formed stars. The youngest of these stars are often found in the densest portions (the cores) of a clump (see the review of Wynn-Williams 1982).

Since gravitational contraction has never been documented for any molecular-cloud complex, or even for a single clump, it is tempting to speculate that star formation requires only the collapse of the dense cores. The second problem of star formation reduces, therefore, to the question of the origin of molecular cloud cores. This question, I believe, also has a simple answer. Once we have a molecular clump, supported against its self-gravity at least in part by magnetic fields, the production of dense cores is inexorable. We only have to wait.

Wait for what? Wait for the magnetic field to leak out by ambipolar diffusion (Mestel and Spitzer 1956, Nakano 1981, Mouschovias 1981). This leakage is inevitable, because magnetic fields can provide only indirect support of the neutral gas. It is the ions and electrons which are tied to the field lines and feel their stresses; they transmit the stresses to the neutrals via frictional coupling (through ion-neutral collisions), but this friction requires there to be slip of ions (and field) relative to the neutrals. As the field slips out and the medium becomes less elastic, the level of turbulence which can be sustained presumably also drops. Thus, the self-gravity of a clump tends automatically to produce concentrated cores where the neutrals have pulled past the magnetic field embedded in the less dense background of the envelope. Simple one-dimensional calculations give the timescale of core formation as roughly 10^7 years (see fig. 5 of Shu 1983). Preliminary analysis of more realistic cloud geometries and field configurations (Lizano-Soberon and Shu 1984) suggest that the cores try to acquire $1/r^2$ density profiles (singular isothermal spheres).

This picture for the formation of molecular-cloud cores is attractive from three observational viewpoints. First, radio studies of ammonia in molecular-cloud cores find many quiet cases where the line shapes are consistent with the cores being in hydrostatic equilibrium (at an "equivalent temperature" that includes some "subsonic turbulence") or, at most, in an early stage of gravitational collapse (Myers and Benson 1983). Although Myers and Benson analyzed their data in terms of <u>bounded</u> isothermal spheres (see fig. 3 of their paper), in fact the correlation they find for the average density divided by the "equivalent temperature" plotted versus size is consistent with all their cores being singular isothermal spheres (where $\bar{n}/T_{eq} \propto 1/R^2$). Second, a timescale of core formation of roughly 10^7 years would explain the spread in the ages of the T Tauri stars which have recently formed from the same regions (Cohen and Kuhi 1979). Third, the gravitational collapse of singular isothermal spheres (Shu 1977) with the "equivalent temperature" characteristic of Myers and Benson's observations would lead to a typical protostellar accretion rate $\dot{M} = 10^{-5}\ M_\odot/\mathrm{yr}$, a value which Stahler, Shu, and Taam (1980) advocate as required to explain the locations of T Tauri stars in the Hertzsprung-Russell diagrams constructed by Cohen and Kuhi (1979, see also Stahler 1983).

THE ORIGIN OF STELLAR MASSES

If the above interpretation is correct, then we need to revise conventional ideas concerning how the masses of forming stars arise. It does not happen because the accretion process runs out of gas; there is no clean separation of the mass which forms the core and the mass of the envelope around it. The masses derived from the ammonia observations refer to a certain sensitivity level; going to lower density contours would almost certainly produce larger masses. And if we consider the molecular clump as a whole, then we have much more gas than is needed to form any conventional star. Why does the protostellar buildup process usually halt after only a solar mass, or less, of gas has been used up? Observations suggest the reversal of the accretion flow by the onset of a powerful stellar wind.

What is the basic energy source for driving this wind? From studies of the collapse of a model for a rotating molecular-cloud core plus its envelope (Terebey, Shu, and Cassen 1983), we find that a significant fraction of the gravitational binding energy of a protostar may be stored in the form of differential rotation of the protostar. If this store of mechanical energy can be tapped with reasonable efficiency and on a timescale short in comparison with the accretion timescale to drive a stellar wind, then there would be ample power to reverse the accretion flow.

What triggers the sudden release of stored rotational energy? In a low-mass star, it may be the dynamo action initiated when the differentially rotating star is driven convectively unstable by the onset of deuterium burning (see fig. 6 of Stahler, Shu, and Taam 1980 for a calculation of the latter process in a nonrotating context). The strong magnetic fields generated and twisted in this fashion would buoy up to the surface, ultimately driving the activity that astronomers have long associated with young stellar objects of low mass (Herbig 1962; Kuhi 1964; Strom, Strom, and Grasdalen 1975). It is interesting to note that, when T Tauri stars first appear as visible objects (after the onset of a wind that has reversed the accretion flow and swept clear the surrounding gas and dust), they are indeed completely convective (Cohen and Kuhi 1979), and their "birthline" lies close to the locus for the onset of deuterium burning (see Stahler 1983 for a different interpretation).

From this viewpoint, a T Tauri star ends with the mass that it does, because that is the mass it acquires (at an accretion rate of roughly 10^{-5} $M_{\odot}$/yr) before its interior temperature rises high enough to ignite deuterium. Differences in the masses of T Tauri stars then occur, because this condition is reached at different stages in the accretion flows of collapsing molecular-cloud cores of different "equivalent temperatures," angular rotation rates, magnetic fluxes, etc.

The above scenario cannot explain the formation of high-mass stars. It is quite possible that the production of high-mass stars requires exceptional circumstances (say, the additional compression provided by clump-clump collisions or other violent events), and therefore constitutes a separate mode of star formation from that of low-mass stars.

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DISCUSSION

B.G. Elmegreen: I believe that the physics of long-range propagating star formation is beginning to be understood in some detail. One mechanism is for an OB association to pressurize the surrounding interstellar medium, thereby causing a large shell to be swept up. If this shell moves fast enough when the pressure goes away and the shell enters the snowplough phase, then the shell will be able to collapse gravitationally along its periphery before it erodes. The growth of gravitational instabilities in expanding, sheared shells is being studied now. The preliminary results explain well the positions, ages and velocities of the large star-formation sites (the Orion, Perseus and Sco-Cen associations) that occur along the periphery of the expanding Lindblad ring.

Shu: I hope these physical calculations are fed back into the computer simulations.

V. Radhakrishnan: In this picture there is no connection whatever with magnetic fields associated with stars, and with the fields in the original gas from which the stars condensed.

Shu: That's right.

B.F. Burke: Garcia Barreto has recently determined the local magnetic-field values at several places in a star-forming region. The Zeeman effect in the OH-maser complex W3OH was measured for 6 different Zeeman pairs with secure identification. The spots are scattered over the entire complex, a linear spread of about 2000 AU, and all values of B are remarkably similar, ranging from 5.2 to 6.7 milligauss, all pointing in the same direction. This shows that the field is well-ordered, with a magnetic pressure entirely comparable to the local gas pressure.

Shu: That's fine. The magnetic fields, if they are to play a role, must be dynamically significant.

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