Perspective

The Myth of Fragmentation

by Steven W. Stahler

1 An Attractive Idea

All students and researchers in star formation have encountered the concept of fragmentation, the breakup of relatively large, self-gravitating entities into smaller ones. The idea figures prominently in studies ranging from molecular cloud dynamics to the evolution of circumstellar disks. Fragmentation, in one of its variants, often forms the intellectual backbone of these investigations. This is an unfortunate situation that has impeded progress in our field for many years. In my opinion, there is no evidence, either from observation or theory, that fragmentation actually occurs, at least within the realm of star formation. It is time that we move beyond this outdated notion to a picture that more plausibly describes astrophysical reality. I cannot yet discern every feature of the new landscape. Instead I will try to sketch its topography, indicating directions for future research that I hope will prove useful.

Fragmentation is an old idea, and an understandably attractive one. As we survey the interstellar medium, looking for the precursors to stars, we find, in descending order of size: giant molecular complexes, clumps within these complexes, relatively tiny dense cores embedded within clumps, and finally stars themselves. Surely, these objects must be related. A grand idea, easy to grasp and sweeping in scope, is that this observed morphological sequence of gaseous bodies also represents a temporal sequence. Giant complexes break into clumps, which in turn break into dense cores, and so on.

This is the "top-down" view of star formation, and it still dominates present-day thinking. Whatever, its basic, intuitive appeal, the idea suffers from an equally basic problem. On its own, an object does not spontaneously break apart into denser fragments. At each stage in the putative hierarchical process, the parent body can only fragment if it is significantly out of force balance. Self-gravity, which causes fragments to congeal, must be stronger than any combination of forces supporting the body.

How does this force imbalance arise? The only possibility that has ever been offered is that the object is assembled quickly, before it has time to contract. Once in place, the overly massive body collapses inward and breaks apart. The earlier process of rapid gas accumulation is rarely described explicitly (for one such attempt, see Ballesteros-Paredes et al 1999), much less justified empirically. But in the absence of other explanations, such early condensation must be present implicitly in *all* simulations that start with full collapse.

Now gravitational collapse certainly occurs when a dense core spawns an individual protostar. However, the dense core does not begin out of force balance, but close to it, and the result is a star, not a collection of fragments. More generally, it is implausible that rapid coalescence followed by fragmenting collapse plays a dominant role in all the multi-scale phenomena associated with star formation.

I have just sketched out both a big idea, and what I view as the major problem with that idea. To clarify things further, let me now consider two specific examples, areas where fragmentation is currently thought to occur, and where it has led to serious conceptual difficulty. The parent objects of interest will be giant molecular clouds and the dense cores that form binary stars. In both cases, I will argue that the object does not dynamically fragment.

2 Molecular Clouds

For many years, theorists have been simulating the collapse and fragmentation of molecular clouds, using ever faster computers and incorporating a growing list of physical effects. These calculations are the most ambitious in the field. Not only do researchers hope to explain the structure of clouds themselves, but even the basic properties of the stars they create, including the initial mass function.

All simulations are done in a computational box of fixed size. Thus, they represent a *portion* of a much larger cloud. In addition, researchers endow the gas with some degree of random, turbulent motion from the start. This latter ingredient of the simulations reflects the observed fact that all molecular clouds larger than dense cores have molecular emission lines of superthermal width. We have known for decades that the corresponding speeds are virial, based on the clouds masses and sizes (Larson 1981). Moreover, the

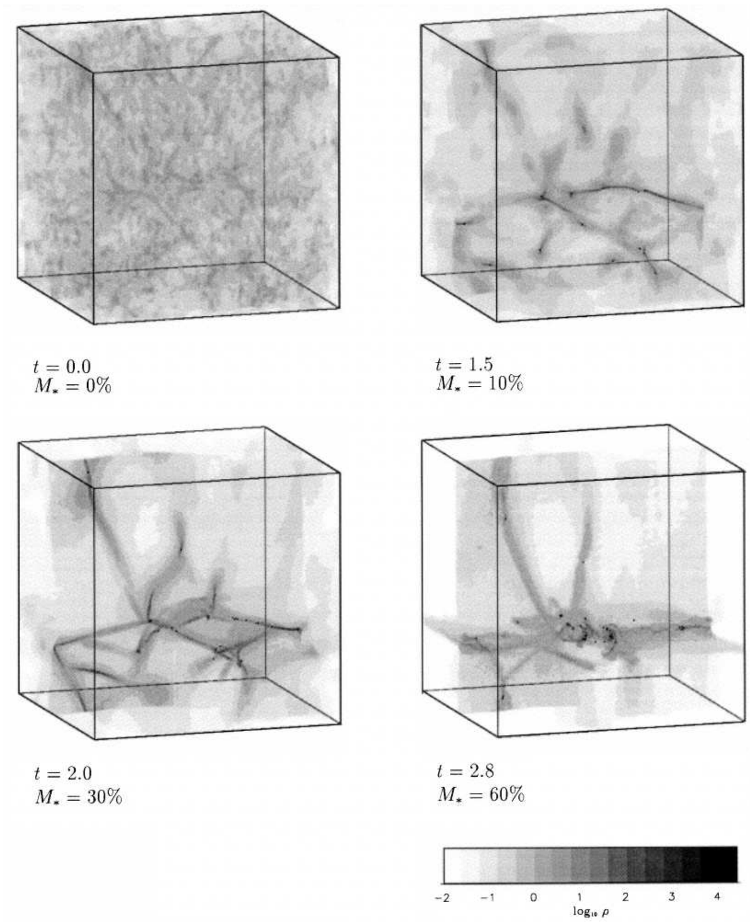

Figure 1: Evolution of the density distribution in a computational box representing a portion of a molecular cloud. The gas initially has no internal velocity, but a Gaussian pattern of density perturbations. Soon, the velocity everywhere grows and clumps arise. From Klessen & Burkert (2000).

speed in one patch of a cloud is correlated with that in a neighboring patch (Heyer & Brunt 2004).

These are both important, solidly established facts. Beyond them, we still have little direct evidence either for the physical origin of the turbulence (see Dobbs et al 2014 for a discussion) or for the actual spatial pattern of this motion within any cloud. The numerical techniques employed to simulate turbulence are artificial means for obtaining the requisite velocities, methods that happen to be the most easy to implement on the computer.

What happens in these simulations can be broadly summarized. At $t = 0$, the gas begins to collapse inward and fragment. The fragments are much smaller than the full computational volume. They also have a far higher density than the original gas. Density is enhanced when oppositely directed turbulent streams collide and shock. If the post-shock gas is also cold enough, it further collapses under the influence of self-gravity. Eventually, isolated regions are created which are so compact that they are counted as stars, although the computed density at this point is still far less than that of an actual star (see Fig. 1).

The parent clouds in these simulations are either initially far out of force balance, or else quickly become so. In some experiments, the total kinetic energy in turbulent motion, plus the relatively tiny energy in microscopic thermal motion, is far less than the bulk gravitational energy from the start (Klessen & Burkert 2000). In others, the kinetic and potential energies are comparable at first (Bate et al 2003). It makes little practical difference, since the kinetic energy is lost in shocks within a single crossing time. Even if the turbulence is continually driven throughout the collapse, the outcome is essentially the same (Klessen 2001). Most of the kinetic energy vanishes so quickly that there is soon relatively little diffuse gas subjected to the driving. The bulk of the gas goes into headlong collapse and fragmentation.

Researchers are busy adding more features to these simulations. For example, it is technically challenging to treat in detail the trapping of any magnetic field threading the parent cloud. One might also desire a more refined treatment of the effects of winds being driven by the stars created. Over and above these details, one should ask if this general picture, obtained consistently by many calculations, is a realistic description of how molecular clouds actually evolve.

I don't believe it is. Since each simulation tracks only a small portion of the entire cloud, it is legitimate to ask what might be happening in other portions. Yet another standard technique in the simulations is to employ periodic boundary conditions at all faces of the computational box. In effect, one is assuming that all neighboring portions of the parent cloud evolve identically to the one being examined, which is collapsing on the fastest possible (dynamical) time scale. As indicated earlier, there is no firm understanding, backed by observations, of how the extended cloud arrived at such a state. It is equally difficult to entertain the alternative view, that one portion evolves quickly, while its surrounding environment does not.

A key hypothesis here is that clumps within clouds are generated through shocks. In principle, one could test this idea by searching for the emission lines from relatively low-velocity shocks (e.g., Kaufman & Neufeld 1996). I hope such a search will be done, but I would not bet on its success. All self-gravitating clouds are observed to be clumpy, and it is unlikely that we happen to be observing them just after they formed via rapid coalescence. More probably, they were born with a clumpy morphology. Why this should be so is an interesting question, and one that could be answered by theory.

As for the clouds' turbulence, Larson's original observation of virial velocities continues to indicate that self-gravity is the driving mechanism. But what, more precisely, is the causal link between gravity and turbulence? Suppose the clumps are relatively stable and long-lived. Then their slow contraction could release energy to power turbulence. If this picture is valid, then simulations modeling small portions of a cloud cannot capture it. And if the clump is not just a transient entity, then the current numerical prescription for simulating turbulence through randomly stirring gas creates too much dissipation. Somehow, the clump undergoes a more organized kind of internal churning, in which shocks are the exception rather than the rule. Even the most simplified account of such dynamics would represent a major step forward.

3 Binary Stars

How binary stars form is a venerable question that first exercised physicists and mathematicians over a century ago, and is still a mystery today. The early idea that a star rotating fast enough would split into two was refuted in the 1980s (Durisen et al 1986). Simulations demonstrated that a rapidly rotating body sheds angular momentum in a pair of trailing spiraling arms. Another influential idea was that binaries form through gravitational capture. We now understand that capture can occur, but only in very dense stellar environments, where energy is either transferred to a nearby third body (e.g., Terlevich 1987), or else dissipated via tidal interaction of the two stars in question, as originally proposed by Fabian et al (1975) for globular clusters. How binaries arise in the sparser regions of low-mass star formation remains the outstanding issue.

The two leading models at present both invoke fragmentation of a dense core. Like all fragmentation schemes, these require the parent body to be out of force balance. Equivalently, the body's actual mass must exceed its Jeans mass, where the latter is calculated for the density and the effective temperature associated with the combined forces of mechanical support. A convenient and sensible rule of thumb, corroborated by decades of simulations, is that each body produces roughly N_J fragments, where N_J is the number of Jeans masses at the start of collapse. For a dense core to produce a binary, and no other stars, via this route, we need $N_J = 2$. That is, the parent cloud has too much self-gravity, but not to a large degree.

In the *turbulent fragmentation* picture, the dense core is initially spherical and non-rotating, but contains a certain amount of turbulence. Usually, the total energy in turbulence is assumed to be relatively small, consistent with observations of dense cores (Goodman et al 1998). This internal, random motion is generated numerically in just the same way as in the simulated collapse of much larger molecular clouds.

Goodwin et al (2004) endowed their spherical core with a Plummer density profile, an analytic prescription that describes fairly well the observations of more concentrated (protostellar) starless cores. Since the Plummer sphere is not a solution for the equations of hydrostatic equilibrium, the cloud immediately collapses to a flattened, more compact structure. This entity draws in turbulent eddies and thereby acquires a net rotation. Eventually, it grows spiral arms that may or may not fragment, depending on the detailed properties of the imposed velocity field. A higher degree of initial turbulence generally yields a larger number of fragments (Fig. 2). No one has suggested how the slightly overmassive cloud might arise in the first place.

Another approach has been to posit non-turbulent, spherical clouds, as long as they start with some bulk rotation. These models exemplify *rotational fragmentation.* Machida et al (2008) employ such an initial state, giving it the Bonnor-Ebert density profile. This is an exact solution for a (non-rotating) isothermal equilibrium. However, since fragmentation requires the configuration to collapse fully from the start, the authors increased the initial density everywhere by a certain amount, typically 10 percent. They further added a bar-like perturbation of the density in order to promote breakup. The cloud again collapsed promptly to a flattened structure near the center of the computational domain, and fragmentation came from the breakup of either a ring- or bar-like structure. Arreaga-Garcia et al (2010) have presented a similar model, including the bar-like perturbation, but with an initial Plummer density profile.

These examples suffice to show that there is no unique way to implement the requirement that $N_J = 2$. A range of initial cloud states will collapse and break up into two or more stable fragments. The exact route for this breakup differs from one model to the next. Of course, we are still a long way from being able to account for the rich observations of young binary stars (Reipurth et al 2014). To tie theory and observation together, a more fruitful approach might be to start from the empirical properties of dense cores that have produced embedded pairs of stars. Is it possible to explain these observations without invoking the artificial condition that the cloud be in full collapse from the start?

The observed shapes of dense cores are two-dimensional projections, and it requires statistical analysis to infer their underlying, three-dimensional structure. Such analysis has long indicated that the cores are elongated, prolate objects (Ryden 1996). For a time, this inference met with some resistance. The issue has now been settled with the finding that cores often reside within larger filaments, in which case their long axes align with that of these parent structures (e.g., Tafalla & Hacar 2015). It is no longer tenable that the cores are flattened structures viewed nearly edge on; they are indeed prolate, like the filaments themselves. Note finally that when a dense core contains a primitive binary, consisting of two Class 0 sources, the stars similarly align with the core's central axis (see Fig. 3). These embedded stars, not yet gravitationally bound to each other, must have formed along that axis.

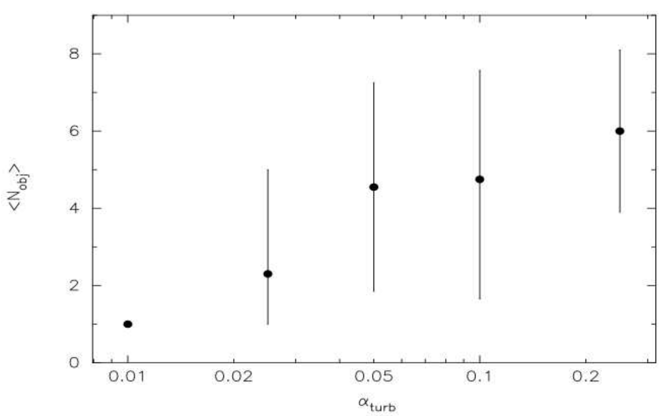

Figure 2: The number of fragments produced by a collapsing cloud, as a function of the degree of initially imposed turbulence. The amount of turbulence is expressed as $\alpha_{\rm turb}$, the ratio of the initial turbulent kinetic energy to the gravitational potential energy of the cloud. From Goodwin et al (2004).

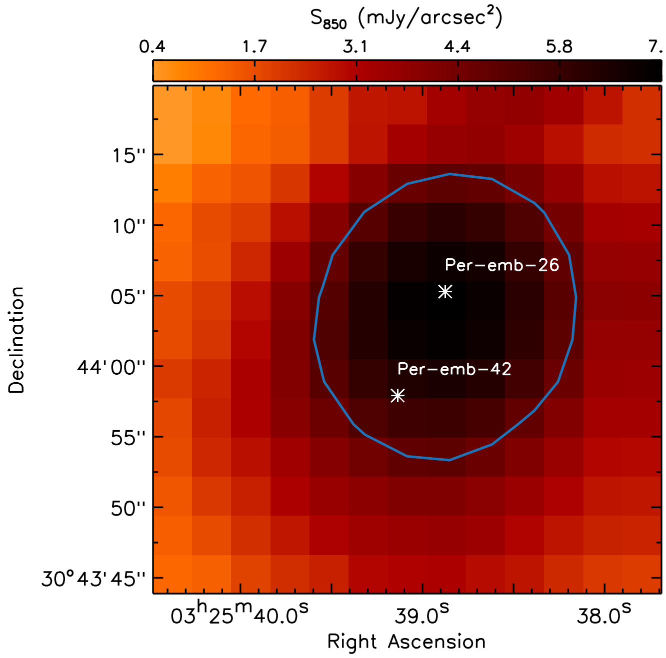

Figure 3: The dense core L1448-C in Perseus, along with its embedded binary (Sadavoy & Stahler, in preparation). Shown is a SCUBA-2 850 μm map from the initial release of the JCMT Gould Belt Survey (Chun-Yuan Chen et al. 2016). The binary is from the VANDAM radio survey of Tobin et al (2016).

Returning to filaments, it is found that some have relatively smooth interior densities; they contain no cores. Both the lengths and diameters of these barren filamants are similar to those with cores; they simply have less internal mass (Arzoumanian et al 2014). It thus appears that the origin of binaries is closely linked to that of dense cores themselves. Cores seem to accumulate inside each filament as it accretes gas from the outside. As the elongated core grows in mass, it often develops a density concentration at both ends. These concentrations become more pronounced until they eventually collapse to form stellar binaries. At first, the stars are bound only to the host core, but they gradually drift together as their winds dissipate the parent cloud. In this "bottom-up" picture, the collapse of the cloud is the end result of a quasi-static evolutionary process, and is not present at the start.

4 Summary

The idea that the precursors to stars fragment hierarchically traces its origin to the very early work of Hoyle (1953), written in an era long before detailed theoretical calculations in star formation. The situation today is entirely different. The vast majority of theoretical studies consist of computationally intensive simulations that supply a flood of numerical results. Moreover, since fragmentation requires an actively collapsing body, even slight differences of initial conditions often lead to qualitatively different outcomes. Supplied with robust, often publicly accessible, computer codes, researchers have delivered a steady stream of fragmentation studies for two decades.

It may be, however, that we are being dazzled, if not blinded, by the very power of our technical tools. We believe in just those processes which computers track most easily. These are fully dynamical situations, in which fluid elements cross a significant portion of the numerical grid in a practical, computable time. In the evolutionary processes we have considered, this restricted perspective translates into the stipulation that the parent body be in full collapse from the start. The difficulty is in specifying plausible conditions leading to this circumstance. Mass must be accrued quickly. If it gathers together slowly, the parent body will eventually collapse, but without fragmenting. This slow, bottom-up route is still largely unexplored.

Fragmentation is a big idea that is supposed to apply to a broad range of size scales and physical conditions. It will not be replaced by another overarching scheme, but by a variety of models that apply to specific problems. Full collapse and fragmentation can often yield interesting structure, but we should not be content with such an account. The slow route is ultimately more promising.

A final case in point is the cloud filaments that often contain dense cores. It is not difficult to obtain filaments through a simulation of cloud collapse (e.g., Peters et al 2012). Moving beyond such calculations means finding circumstances under which filaments appear, gather mass, and condense within a slowly evolving cloud interior. Any such investigation, if it is to be more than schematic, will ultimately be numerical. But the qualitative result to be sought is a gentler, less dynamic evolution. A new generation of models is needed, and it will be exciting to see them arriving on the scene.

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