Perspective

Star Formation and Gravitational Collapse

by Steven W. Stahler

1 Two Routes to Collapse

The central process in star formation is gravitational collapse. After so many decades of exploration by theorists, in studies ranging from analytical to semi-analytical to full-blown simulations, is there anything left to say on the subject? Yes! In the realm of low-mass stars, observations are now revealing the physical and chemical structure of dense cores prior to collapse. Indeed, an evolutionary sequence of starless cores is emerging (Keto & Caselli 2008), although the elapsed time for each phase is poorly known. For massive stars, the observations are much sparser, but we have at least identified the entities – infrared dark clouds – responsible for spawning these objects (Carey et al. 1998). In both cases, we are now confronting an issue more subtle than collapse itself, and that is its onset. It is time to take stock of the theoretical situation.

I will focus here on low-mass star formation, and first pose the broadest question of all. How does a molecular cloud arrive at the point where it undergoes gravitational collapse? Quite generally, there are two possibilities, depending on how rapidly the cloud changes *prior* to collapse. In the "slow" route, the object gradually accrues mass from its environment. At first, whatever internal pressure is available (thermal, turbulent, magnetic) successfully counteracts self-gravity. Thus, the cloud evolves through a sequence of equilibrium states. Eventually, it gains enough mass to tip over the edge into collapse. The buildup period is, by hypothesis, long compared to the eventual collapse time.

In contrast, this buildup time is relatively brief in the "fast" route. Here, mass gathers together quickly, i.e., a pre-existing, diffuse configuration is suddenly compressed. The self-gravity of this material is too great for any countervailing pressure gradient. Gravitational collapse thus occurs promptly, immediately following the initial compression. If the total mass is large enough, the object breaks apart even as it is collapsing. This is the traditional picture of fragmentation, an idea invoked by several generations of theorists (Hoyle 1953; Low & Lynden-Bell 1976), and now being resurrected in large-scale simulations of cluster formation (e.g., MacLow & Klessen 2004).

A succinct, if rather technical, way of distinguishing the two routes is through the dynamical state of the cloud just before it collapses. A cloud evolving along the slow route passes through stable configurations in near force balance between self-gravity and pressure. The cloud may undergo oscillations as it grows (Keto et al. 2006). Just before collapse, the configuration is "marginally stable." Its fundamental mode of oscillation has zero (or nearly zero) frequency, meaning that restoring forces act very weakly and slowly to rectify any impressed disturbance.

In contrast, a cloud that collapses via the fast route is never in equilibrium. Just before the collapse, self-gravity is stronger than the outward pressure gradient. It is this substantial force imbalance that drives both prompt collapse and fragmentation, should the latter occur. Note that neither scenario postulates, as the immediate pre-collapse states, *unstable* equilibria. These are configurations that are in temporary force balance, but depart from that condition immediately upon being perturbed.

2 Splitting the Difference

In principle, one should examine carefully the physical conditions and processes in the interstellar medium to decide which route to collapse best describes reality. However, the actual course of research in this branch of astrophysics, as in any other, has not been this straightforward. The very first numerical simulation of cloud collapse leading to the birth of a low-mass star was that of Larson (1969). This pioneering work actually predated the discovery of molecular clouds. Lacking any empirical guide, Larson chose a collapse model and initial conditions based on computational feasibility and physical plausibility. The first issue constrained him to adopt a spherical cloud, which he endowed with a spatially uniform temperature. He also gave the cloud a uniform density initially. For its starting radius, he chose the largest value that led to continuing collapse, as opposed to an early bounce.

An isothermal cloud with uniform density has no internal pressure gradient. Thus, Larson's initial state was far out of force balance. In this sense, he was simulating a collapse that could only have been achieved via the fast route, although he certainly did not characterize his model this way. Rather, he selected his pre-collapse cloud to be barely capable of collapse, just the state of affairs in a slow buildup. But he also knew that, if he started with an *exact* equilibrium state, the model cloud would just sit there on the computer. He therefore compromised, selecting an initial state that was marginally prone to deep collapse, but still able to evolve dynamically.

The years subsequent to Larson's simulation witnessed a complete transformation of the observational landscape. Key was the identification of dense cores as the sites of low-mass starbirth (Beichman et al. 1986). By every empirical measure, these objects are in dynamical equilibrium before they produce stars. Here, the balance is between self-gravity and a combination of thermal and magnetic pressure, with turbulence playing a measurable, but relatively minor role (Barranco & Goodman 1998). Larson's original intuition was fully justified, and it would seem that the slow route to collapse is the one occurring in nature. This conclusion is reinforced once we consider alternate scenarios. In regions of active, low-mass star formation, like those in Taurus, Lupus, or Chamaeleon, there are no massive stars generating HII regions or supernova shocks to compress pre-existing gas.

These considerations notwithstanding, the many collapse simulations following Larson continued to adopt a hybrid set of initial conditions. As one example, the influential study of Foster & Chevalier (1993) began with a marginally stable, isothermal sphere, but with its density everywhere enhanced to a degree that ensured collapse. Since the origin of dense cores themselves was not at issue, no one attempted to justify these conditions as being the natural product of earlier evolution. Indeed, they are not. It is more straightforward to simulate on the computer a fully dynamical, as opposed to a quasi-static, process, and only the former route was explored.

3 Dense Core Dynamics

The most exciting development in low-mass star formation since the identification of dense cores has been the discovery of their internal motion. Cores that contain very young stars do not differ in their gross properties from those still lacking them. However, if the idea of gravitational collapse is at all correct, then the deep interiors of these objects must be very different indeed. This interior gas should be streaming toward the star at high speed. Detecting this motion requires spectroscopic observations, specifically of molecular lines that are sufficiently optically thin to penetrate to the central regions of the core. After years of effort by several groups, the appropriate transitions were found and the so-called "infall signature" was established (for a review, see Evans 2003). This is a line profile exhibiting a blueward asymmetry, often with a central, self-absorption dip. The two rightmost panels of Figure 1 show profiles for dense cores containing infrared sources. The inward speeds matching these profiles, as determined from a simple, two-slab model, are a few tenths of the dense core's sound speed. Despite the nomenclature, the infall signature is actually signifying bulk, *subsonic contraction*, in these and many other cases.

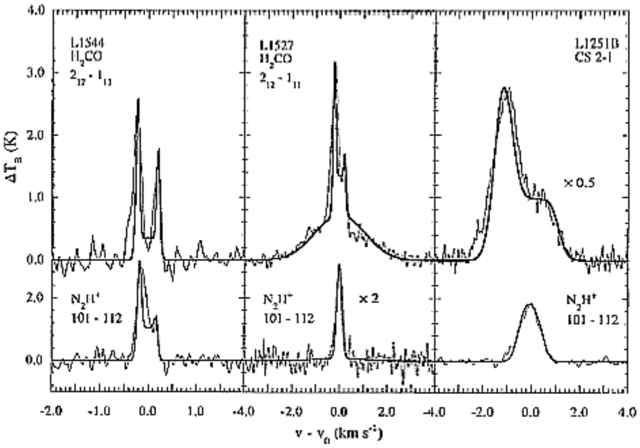

Figure 1: Line profiles of three dense cores, with the various molecules and transitions indicated. The leftmost panel shows data for a starless core. while the other two cores harbor infrared sources. From Myers et al (1996).

But this is not the full story. Further probing has by now uncovered true supersonic motion within the deeper interiors of a number of cores containing stars (e.g., Gregersen et al. 1997; Belloche et al. 2002). These interior velocities are at most a few times the ambient sound speed. However, there can be little doubt that higher speeds are to be found even closer to the young star, and the essential point has been established. The collapse of molecular clouds is not just theoretical speculation, but a reality.

Even as theorists collectively breathe a sigh of relief, we must note that the observations bring additional news of a more troubling nature. First is the fact that many dense cores *without internal stars* are also contracting; the left-hand panel of Figure 1 is an example. What is going on? A closer look at the data offers both clarification and a degree of comfort. I mentioned earlier that starless cores lie along an evolutionary sequence. At one end of the spectrum are those of the lowest density contrast, while at the other are cores of relatively high density that seem truly poised to collapse. It is only the latter that exhibit the spectroscopic infall signature, and their inferred, interior velocity is everywhere subsonic. This is indeed comforting news, although the driving force of the subsonic contraction is a matter of some debate. I shall return to that issue toward the end of this piece.

The second surprise concerns the physical extent of supersonic motion in dense cores containing stars. In all studies that have obtained at least a rudimentary velocity profile, it is apparent that the sonic transition occurs extremely close to the star. For example, Belloche et al (2002) find this point to be less than 0.007 pc from the center of the IRAM 4191 core, which has a total radius ten times larger. Shirley et al. (2002) have noted that, within the region of free-fall collapse, the spherically averaged density should vary as $r^{-3/2}$. Their submillimeter continuum mapping of five, nearly spherical dense cores with embedded stars reveals a steeper (r^{-2}) profile throughout the interiors; the transition to the flatter one associated with collapse occurs too deep for them to detect.

4 Extending the Models

The observations show that the region of true supersonic collapse, as opposed to static equilibrium or subsonic contraction, is confined to a region just outside the star. This is troubling because all theoretical collapse simulations to date find pervasive and vigorous inward motion *even before the star forms.* In the calculation of Foster & Chevalier (1993), the innermost 44 percent of the mass has supersonic velocity at the instant the central star first appears. This fraction grows as the stellar mass increases.

Part of the underlying problem is the historical tendency to treat collapse in isolation. Recently, theorists have begun extending their models to cover the earlier evolution leading up to this event, i.e., the formation of the dense cores themselves. Within the fast picture, I noted earlier the large-scale cluster simulations. In the usual procedure, a box of gas is stirred up, imitating the turbulence observed in the larger clouds harboring dense cores. A steady state is eventually reached, in which the total energy dissipation rate matches the input power driving the turbulence. Only at this point does the simulator switch on self-gravity, and the densest substructures promptly collapse. In their shapes and masses, these objects can resemble real cores to a striking degree (Offner & Krumholz 2009; Schmidt et al. 2010). Similar agreement, however, has not been demonstrated for their internal velocity structure.

We therefore turn once more to the slow route. Within this context, are dense cores actually created by turbulent flows? Gong & Ostriker (2009) addressed this question via direct simulation. They built up the core through a converging, supersonic flow, taken to be spherically symmetric. At first, the core was a growing, nearly hydrostatic structure inside a bounding accretion shock front. With increasing self-gravity, however, both the core and even the shock itself began to move inward supersonically. At the instant of star formation, the interior velocity was almost entirely supersonic. Gong & Ostriker (2011) later relaxed the assumption of spherical symmetry and adopted a planar supersonic flow, obtaining essentially the same result for the core evolution.

Observations do show clearly that gas velocity outside the dense core boundary is supersonic (Pineda et al. 2010). Perhaps, however, the velocity vectors are randomly oriented, and it is an inward, subsonic drift that actually builds up the object. Walsh et al. (2006), among others, have presented evidence for such widespread drift from spectroscopic mapping. Motivated by such considerations, Motahareh Mohammadpour and I recently simulated the buildup and collapse of a spherical core through subsonic inflow. We gave the core a constant radius of 0.05 pc and let gas flow across this boundary at fixed density and a speed 0.2 times the sound speed of 0.2 km s^{-1}. In this way, we hoped to avoid pervasive, supersonic velocities prior to star formation.

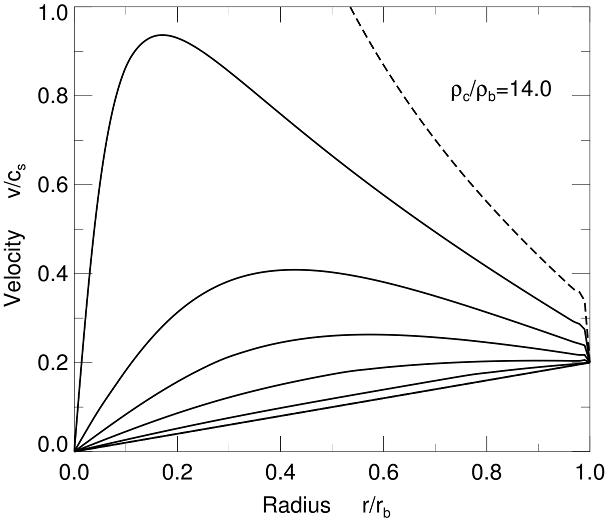

Figure 2: Evolution of the velocity profile for a cloud undergoing subsonic mass accretion. The velocity and radius are displayed in units of the sound speed and the fixed boundary radius, respectively. All curves are separated by equal time intervals, and the final, dashed one corresponds to a time of 3×10^5 yr, soon after the star forms. From Mohammadpour & Stahler (2013).

Figure 2 shows the velocity evolution in a typical run. For most of its prestellar life, the core evolves through near-equilibrium states. Inevitably, however, the interior velocity becomes supersonic. The region of supersonic flow then spreads rapidly outward. By the time the star has built up its full mass, the sonic transition radius is almost halfway to the core boundary. This result still violates the admittedly limited observations available.

5 Magnetic Mediation

There is another reason to be suspicious of the theoretical models. As gas rushes inward supersonically, it builds up the star's mass over a period short compared to the core's initial free-fall collapse time. This "accretion spike," which has been obtained in all spherical simulations, creates a much higher *luminosity* in the star than is observed for low-mass, embedded sources (see the original discussion in Kenyon et al. 1990).

Vorobyov & Basu (2010) found, again through simulations, that infalling matter can be hung up for an extended time in the star's surrounding disk, effectively postponing the accretion spike. For simplicity, they modeled the entire dense core as a thin sheet; we await a more complete calculation to corroborate their intriguing result. Recall that a typical disk radius is 100 AU, or 0.001 pc. My own feeling is that, once a substantial part of the cloud is in vigorous motion, a lot of energy will be released at the star, regardless of the details on such a relatively tiny scale. Something is preventing supersonic cloud motion over a large volume of the dense core.

The obvious culprit here is the interstellar magnetic field, which penetrates the interiors of all cores. Within the slow picture, the core's gravitational contraction causes field lines to bow inward and crowd together. The resulting buildup in magnetic tension and pressure does not halt contraction, since gas still creeps across field lines in the process known as ambipolar diffusion. Ciolek & Mouschovias (1995) tracked this motion numerically, and found drift speeds lower than the observed ones we have cited. Such disagreement has led some to dismiss ambipolar diffusion as a mediating influence. The simulation, however, again modeled the cloud as a thin sheet, so this negative conclusion is premature. In a semi-analytic, spherical calculation, Stahler & Yen (2009) showed how self-gravity eventually accelerates the flow in a marginally stable core to full collapse, generating along the way subsonic speeds just at the level observed. This is an encouraging result, but their study included no magnetic forces.

The next major step in theory will be a three-dimensional, or at least axisymmetric, model of a slowly growing, magnetized dense core. Pending this development, researchers are already confronting the issue of magnetic support in a less detailed, global manner that is amenable to observational check. Define a nondimensional quantity λ by

$$\lambda = \frac{2\,\pi\,G^{1/2}\,M}{\Phi}\,. \tag{1}$$

Here M and Φ are, respectively, the core's mass and the total magnetic flux penetrating it. The definition in equation (1) has historical roots. Nakano & Nakamura (1978) showed that a self-gravitating slab, infinite in extent and threaded vertically by a magnetic field, is supported against radially inward collapse only if $\lambda < 1$. Now the line-of sight field is observable spectroscopically through the Zeeman effect. After making a reasonable correction for projection, it is therefore feasible to obtain both Φ and λ. Of course, real dense cores are not infinite slabs, so we need to be cautious when interpreting the results.

Crutcher (2012) has collated a large number of Zeeman measurements, and concludes that $\lambda \approx 2 - 3$ for dense cores. This global finding means, in essence, that a typical core's total magnetic energy is less than its thermal or gravitational potential energy. It does *not* mean that magnetic forces are dynamically unimportant now or in the core's previous history. Only the more complete evolutionary model will tell us if the field can keep all velocities properly subsonic until the star forms, and restrict the spread of collapse thereafter.

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