Perspectives on Low-Mass Star Formation

Shantanu Basu
Department of Physics and Astronomy, The University of Western Ontario, London, Canada.

Abstract

I review some recent work on low-mass star formation, with an emphasis on theory, basic principles, and unresolved questions. Star formation is both a gravitational fragmentation problem as well as an accretion problem. Molecular cloud structure can be understood as a fragmentation process driven by the interplay of turbulence, magnetic fields, and gravity (acting on either a dynamical or ambipolar-diffusion time scale). This results in a natural way to understand filamentary structure as magnetic ribbons that have an apparent width that scales differently than the Jeans length. Recent work also shows that stellar mass accretion through a disk is episodic. We show through numerical simulations that bursts of FU Ori type may be clustered, since the clump that accretes to the center is tidally sheared apart in its last stage of infall. Finally, we utilize a simplified model of stellar mass accretion and accretion termination to derive an analytic form for the initial mass function that has a lognormal-like body and a power-law tail. This scenario is consistent with an expectation of a larger number of substellar objects than may have been previously detected.

2. Fragmentation of Clouds: Magnetic Ribbon Model

Recent years have seen a renewed interest in filamentary structures in molecular clouds, thanks to the Herschel Space Observatory observations of dust emission from molecular clouds (André et al. 2010). These observations reveal a filamentary network of dust emission that is present in both star-forming and non-star-forming clouds. This implies that the initial structure of molecular clouds may be an imprint of initial (likely turbulent) conditions and exists before self-gravity of the cloud can make a major impact and lead to star formation. Furthermore, observations of a handful of molecular clouds in the Gould Belt have found that the average projected lateral width of the filamentary structures are clustered around 0.1 pc, even though the mean column density of the filaments vary by at least two orders of magnitude.

A mean width of filaments that clusters around ~ 0.1 pc is surprising because it is not consistent with expectations based on either self-gravitating equilibria or gravity-driven collapse. In either case a central flat region (or FWHM) is essentially the hydrodynamic Jeans scale evaluated at the central density. This means that its width \( a \sim c_s^2/(G\Sigma_c) \propto \Sigma_c^{-1} \) where \( c_s \) is the isothermal sound speed and \( \Sigma_c \) is the central column density. How are we to understand this result? On one hand it could be some kind of observational bias. However, the resolution of Herschel is about 0.01 pc at the distance of the Gould Belt clouds so we can rule out beam smearing. It is possible that the averaging technique can converge to a narrow range of mean widths even if the filaments intrinsically have a wide range of widths along their spine (Panopoulou et al. 2017). One may even think of the filaments as an ensemble of collapsing cores that have narrow FWHM and wider regions that are not collapsing. What explains the widths of the non-collapsing regions? This is probably an imprint of the filament formation process.

In Auddy et al. (2016) we proposed that the filaments are actually magnetic ribbons, part of the scenario of dynamically-oscillating molecular clouds supported by magnetic fields due to a large-scale subcritical mass-to-flux ratio. In this scenario, molecular clouds are supported by magnetic fields, and the initial structure is inherited from initial conditions. If the initial condi-
tions are turbulent, perhaps inherited from a larger scale turbulent cascade, then filamentary structure is naturally generated. These filaments differ from those in cosmological simulations that are driven purely by the gravity of the dark matter and collapse on a dynamical time. Instead, these are quasi-equilibrium filaments (really ribbons, with preferential flattening in the direction of the mean magnetic field) that are in approximate force balance between turbulent ram pressure and the pressure and tension of the magnetic field. Since the mass-to-flux ratio is subcritical, the ribbon cannot collapse in the flux-freezing limit, and rebounds when the magnetic pressure equals the ram pressure. If the initial turbulent compression occurs on a characteristic scale \( L_0 \), Auddy et al. (2016) show that the equilibrium lateral thickness of the resulting ribbon is

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L = L_0 \left[ 2 \left( \frac{v_0}{v_{A0}} \right)^2 + 1 \right]^{-1},
\]

where \( v_0 \) is the nonlinear flow speed and \( v_{A0} \) is the background Alfvén speed. This thickness depends on \( L_0 \) but is independent of density, unlike the Jeans scale. However, the ribbon is expected to be flattened preferentially along the mean magnetic field direction and have a thickness \( H = c_s/\sqrt{2\pi G \rho} \) that is comparable to the Jeans length. In this model we ignore turbulent pressure effects in the direction of the magnetic field. Kudoh & Basu (2003, 2006). Figure 4 shows a schematic picture of the ribbon formation, with a turbulent flow that is in the plane perpendicular to a mean magnetic field along which the cloud is flattened. An ensemble of such ribbons will be observed at a random set of viewing angles, each with a unique projected width and line-of-sight column density. Figure 2 shows the result of a synthetic set of projected widths generated for a random distribution of viewing angles.

The magnetic ribbon scenario can explain why the observed widths can: (1) cluster around an approximately fixed width, since they are quasi-equilibrium objects and not on a one way path of collapse; (2) why the widths are not wholly different that the Jeans length, since one dimension has that width; (3) why the observed polarization patterns imply a large scale magnetic field perpendicular to the filament. However, an explanation for a preferred wavelength \( L_0 \) for the background turbulence, of order 1 pc, remains an open issue.

3. Disk Accretion: Migrating Embryo Model

Detailed self-consistent simulations of the formation of circumstellar disks from their parent cores and their further evolution shows that the mass accretion rate \( \dot{M} \) at small scales near the star can differ considerably from the mass infall rate onto the disk. In a series of papers (Vorobyov & Basu, 2005, 2006, 2010, 2015) we have shown that \( \dot{M} \) in the disk is episodic and characterized by bursts with \( \geq 10^{-4} \dot{M}_\odot \) yr\(^{-1} \) that result from gravitational instability. The instability leads to fragmentation and the migration of the fragments to the protostar. The recurrent gravitational instability occurs while there is significant envelope accretion onto the disk, which can temporarily reduce the Toomre \( Q \) parameter to be less than the critical value. This paradigm has become the standard one for early disk accretion, as the mean and median luminosity of protostars in star-forming regions are lower by about an order of magnitude than predicted from the standard spherical accretion models (Evans et al., 2009). This so-called “luminosity problem” can be resolved by episodic accretion coupled with a slowly declining mean accretion rate (Dunham & Vorobyov, 2012).

Figure 3 shows the time evolution of \( \dot{M} \) at both an inner radius (black solid lines) and an outer radius (red dashed lines) characteristic of envelope infall, in three models with different initial core masses \( M_{\text{core}} \) as labeled. The main elements of stellar mass accretion are evident in these plots. The low mass model with \( M_{\text{core}} = 0.3 \, M_\odot \) illustrates all the phases. The \( \dot{M} \) near the center rapidly rises to a value \( \sim c_s^3/G \) upon the formation of a first hydrostatic core, where \( c_s \) is the isothermal sound speed. Subsequently there is a smooth accretion until the formation of a centrifugal disk. Although this occurs \( \sim 10^4 \) yr after the formation of the first core, this is a model dependent effect. The central sink cell sets the time for the start of disk accretion, since the centrifugal radius of infalling mass shells must reach the sink cell radius of 6 AU for a disk to form in the simulation. Higher resolution but one-dimensional simulations that also include non-ideal magnetohydrodynamics (Dapp & Basu, 2010, 2012) show that a disk actually forms immediately after the formation of a stellar core. All three panels of Figure 3 shows that the disk accretion has a baseline rate that is well below the rate of infall onto the disk but is punctuated by bursts that temporarily increase \( \dot{M} \) by one to two or more orders of magnitude. This burst mode of accretion continues until the envelope accretion, which is a declining function of time due to a finite mass reservoir, drops to negligible values. The top panel of
Figure 1. Formation of a magnetic ribbon under the influence of ram pressure and the magnetic field. The cloud is flattened along the mean magnetic field direction and the compression is in one dimension in the perpendicular plane. The thick black arrow points to an observer located at a random orientation.

Figure 2. Observed ribbon width $L_{\text{obs}}$ vs. observed column density $N_{\text{obs}}$. Each blue dot corresponds to a magnetic ribbon with intrinsic column density $N$ and observing angle $\theta$ chosen randomly. The black dashed line is the mean ribbon width for the entire range of values of $N_{\text{obs}}$. The black dotted line is the width when the ribbon is viewed at $\theta = 0^\circ$. The blue dotted-dashed line is the width for the side on view $\theta = 90^\circ$. 
Figure 4 shows that the disk accretion continues after this time in a power-law manner. This later evolution of $\dot{M}$ is set by internal transport mechanisms of the disk, mainly gravitational torques arising from persistent nonaxisymmetric structure (Vorobyov & Basu, 2007). The dependence $\dot{M} \propto t^{-n}$ with $n \approx 1$ is indicative of a self-similar solution (Lin & Pringle, 1987; DeSouza & Basu, 2017). The models with greater values of $M_{\text{core}}$ have not yet settled into the self-similar regime during the times shown, as the envelope infall continues for a longer time. The mass dependence of the rate of decline of the disk accretion rate is an important observable and merits a careful comparison with models. Within the first $\sim$ Myr of accretion, the objects with greater mass, accreting from more massive envelopes, will show a more rapid decrease of mass accretion rate than lower mass accretors. This is because the more massive object’s accretion rate is still set by the envelope accretion rate onto the disk, while the lower mass object may have ended its phase of envelope-driven accretion and already settled into self-similar disk accretion. At later times, it is possible that $\dot{M}$ may decline more rapidly for the low mass objects, as inferred in one observational study (Manara et al., 2012), due to photoevaporation of the inner disk due to x-ray and UV stellar flux (Ercolano et al., 2014).

An interesting new prediction based on high-resolution modeling (Vorobyov & Basu, 2015) was that a mass accretion burst of FU Ori magnitude could actually occur with a series of secondary bursts. This is due to the physics of clump infall that leads to the burst. In the late stages of infall to the center, the clump can be sheared apart and include secondary fragments. The mass infall can occur in the form of a clustered burst. Figure 4 shows the late stages of infall of a clump as it approaches the center. A clustered burst has very recently been confirmed in the FU Ori object V346 Orion Nebula Cluster (Drass et al., 2016).

4. Stellar and Substellar Masses: MLP distribution

Despite claims that the observed core mass function (CMF) may be the explanation for the stellar (and substellar) initial mass function (IMF), there are roadblocks to the idea of a simple one-to-one mapping of the CMF to the IMF. The discovery of an ever growing set of substellar objects, down to as low as $\lesssim 10^{-2} M_\odot$, for example by (Drass et al., 2016), imply that direct collapse scenario would have to produce extremely low mass collapsing cores. The mean Jeans mass in a molecular cloud is already as high as $\approx 10 M_\odot$.

In the accretion scenario, there is still a CMF but it is not fundamentally important to determining the IMF. The exact shape and mean value of a CMF depends on a variety of physical factors as well as the observational technique and definition of core boundaries. The CMF will inevitably be drawn toward a lognormal distribution due to the multiple effects of turbulence, magnetic fields, gravity, and temperature fluctuations. However, it need not be the cause of the IMF, which may also resemble a lognormal for statistical reasons having to do with the Central Limit Theorem.

An attractive scenario is to think of star formation as a killed accretion process. Since a protostellar seed or first hydrostatic core starts with a very low mass $\lesssim 10^{-2} M_\odot$ (Larson, 1969), the formation of substellar and stellar mass objects can be thought of as arising from a combination of mass accretion and a mechanism for termination of the accretion. Accretion termination can arise from a variety of effects, including ejection from a multiple system of proto-objects in a disk (Basu & Vorobyov, 2012), outflows from the protostar, and sweeping away of molecular cloud gas by feedback from a nearby high-mass star. If the distribution of accretion stopping times is $\delta t = e^{-\delta t}$, representing equally likely stopping (ELS) in equal time intervals, and the mass growth law is exponential, i.e., $dm/dt = \gamma m$, then the resulting normalized pdf for masses after accretion termination is

$$f(m) = \frac{\alpha}{2} \exp \left[ \alpha \mu_0 + \alpha^2 \sigma_0^2 / 2 \right] m^{-1-\alpha} \times \text{erfc} \left[ 1 \sqrt{2} \left( \alpha \sigma_0 - \ln m - \mu_0 \right) / \sigma_0 \right].$$

Here $\mu_0$ and $\sigma_0$ are the mean and dispersion of a starting lognormal distribution of masses which then undergo accretion growth, and $\alpha = \delta / \gamma$ is the dimensionless ratio of “death” rate to “growth” rate of protostars. The exponential growth law of protostars is an approximation to a two-stage process where we envision that the early stage accretion rate is nearly constant but later needs to increase rapidly if massive stars are to be formed. This is because of the relatively small age spread of stars in young clusters containing stars of widely varying masses (Myers & Fuller, 1993).

This modified lognormal power-law (MLP) model hypothesizes that the initial distribution of accreting protostellar seed masses is lognormal. However, a lognormal of very small dispersion $\sigma$ approaches a delta function, and we may also think of the initial distribution as being essentially a delta function at the mass of the first hydrostatic cores, $\sim 10^{-2} M_\odot$. This interpretation is aided by a newly derived mass function of the Orion Nebula Cluster (Drass et al., 2016). Their fit of a lognormal to the low mass data yields parameters...
Figure 3. Mass accretion rates versus time for models with three different initial core masses, as labeled. The black solid lines are the accretion rates at the inner sink cell (at radius 6 AU) and the red dashed lines are the envelope infall rates measured at 2000 AU. The arrows in the top panel mark the formation of the first hydrostatic core and the disk.
that imply that the mode of the density function is $\simeq 0.03 \, M_\odot$.

5. Magnetic Fields

The SFDE conference had a special session on magnetic fields and important points about the observability of magnetic fields were discussed. Why are magnetic fields important to star formation studies? The most important potential role of magnetic fields would be to ensure the observed low efficiency of star formation. This would primarily require that the mass-to-flux ratio in much of the cloud volume is subcritical. So far there is no equivocal direct evidence of this, as magnetic field detections are difficult enough in dense regions let alone in the low density regions of clouds. A strong magnetic field could also explain features like the magnetic ribbons described in this paper, and the striations that are observed perpendicular to large filaments (Tritsis & Tassis, 2016). They could also provide a conduit for rapidly spreading kinetic energy throughout the cloud (Kudoh & Basu, 2003; Wang et al., 2010). Neutral-ion slip must exist in molecular clouds since the neutrals cannot feel any Lorentz force but for a collisional interaction with ions that requires a relative drift between the two species. Is it worthwhile to look for direct evidence of neutral-ion drift? Observational comparison of individual neutral and ionic species line widths can be problematic due to their differing (and uncertain) critical densities and optical depths. It is even more problematic to interpret any alleged systematic difference in the neutral and ion line widths based on a linear theory of Alfvén waves in a uniform non-gravitating medium (Li & Houde, 2008). Since self-gravity is important in molecular clouds, particularly in clumps and cores, there should be a systematically greater line width of neutrals than ions due to unresolved gravitationally-driven ambipolar diffusion. This effect is typically only a fraction of the sound speed on a core scale. However, there is the possibility of high resolution observations of the protostellar collapse zone revealing an ambipolar diffusion shock at a typical distance $\sim 10^3$ AU from a young stellar object (Li & McKee, 1996; Contopoulos et al., 1998). In this region, the neutral infall motions are supersonic and the neutral-ion drift speed is also supersonic. The infall of neutrals, let alone ions, within an expansion wave (Shu, 1977), has yet to be characterized observationally and compared to theoretical models.

6. Final Thoughts

How is the research field of star formation faring? We have been encouraged by the organizers to express our opinions. All areas of human activity follow trends,
Figure 5. Comparison of a lognormal density function with the MLP density function. The lognormal has parameters $\mu = -1.5$ and $\sigma = 0.5$ with an MLP function that results from the growth of masses that start from the same lognormal function. The MLP parameters are $\mu_0 = -1.5$, $\sigma_0 = 0.5$, and $\alpha = 1$.

Figure 6. The MLP function with parameters $\mu_0 = -2.404$, $\sigma_0 = 1.044$, and $\alpha = 1.396$, overlaid with histogram values for random samples drawn from the distribution with different sizes $N$ as labeled. All histograms are binned in increments $\Delta \log m = 0.2$, where $m$ is in units of $M_\odot$. The analytic function is plotted as $m f(m)$ where $f(m)$ is the density function, and the histogram is the fractional number in each bin divided by $\Delta \ln m$. 
and this field is no exception. In the 1980s the hot topic was the singular isothermal sphere, the 1990s saw the development of models with magnetic fields and then turbulence, the 2000s saw a resurgence of interest in the Bonnor-Ebert sphere and the core mass function, and the 2010s have focused a lot on filamentary structure. The field may have settled into chasing “rabbits” and we appear to be in a quiescent era of progress while the bursts of activity are happening in related areas of planetary and substellar objects or the application of star formation (e.g., star formation rate history and IMF) to the extragalactic and high redshift universe. Population III star formation may become a hot topic depending on the findings of the James Webb Space Telescope (JWST).

There are still many outlets for research in star formation studies. Although the core subject of molecular cloud structure may have stalled in my opinion, the big outstanding question is still to be solved. Can magnetic fields or turbulence enforce a very low efficiency of star formation in molecular clouds? If the former then we need to find evidence of subcritical mass-to-flux ratio in cloud envelopes. If the latter then we need to identify drivers of turbulence, either on the large scale or through stellar feedback. New high resolution observations that reveal ribbon-like structure or striations are interesting in my view insofar as they can help distinguish between scenarios, e.g., magnetically-dominated or not.

Stellar mass accretion is an interesting area with much theoretical and observational development in the last decade. The episodic accretion paradigm is now firmly established, and can be further explored with the Atacama Large Millimeter/submillimeter Array (ALMA) disk observations and the upcoming JWST ability to identify numerous low mass and substellar objects. Even the IMF may be understood as essentially an accretion process, and accretion models like the MLP can be constrained by new observations of the substellar and low mass IMF.

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References

André, P., Men’shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102
Auddy, S., Basu, S., & Kudoh, T. 2016, ApJ, 831, 46