

# The Earliest Stages of Star and Planet Formation: Core Collapse, and the Formation of Disks and Outflows

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The formation of stars and planets are connected through disks. Our theoretical understanding of disk formation has undergone drastic changes in recent years, and we are on the brink of a revolution in disk observation enabled by ALMA. Large rotationally supported circumstellar disks, although common around more evolved young stellar objects, are rarely detected during the earliest, “Class 0” phase; a few excellent candidates have been discovered recently around both low- and high-mass protostars though. In this early phase, prominent outflows are ubiquitously observed; they are expected to be associated with at least small magnetized disks. Whether the paucity of large Keplerian disks is due to observational challenges or intrinsically different properties of the youngest disks is unclear. In this review we focus on the observations and theory of the formation of early disks and outflows, and their connections with the first phases of planet formation. Disk formation — once thought to be a simple consequence of the conservation of angular momentum during hydrodynamic core collapse — is far more subtle in magnetized gas. In this case, the rotation can be strongly magnetically braked. Indeed, both analytic arguments and numerical simulations have shown that disk formation is suppressed in the strict ideal magnetohydrodynamic (MHD) limit for the observed level of core magnetization. We review what is known about this “magnetic braking catastrophe”, possible ways to resolve it, and the current status of early disk observations. Possible resolutions include non-ideal MHD effects (ambipolar diffusion, Ohmic dissipation and Hall effect), magnetic interchange instability in the inner part of protostellar accretion flow, turbulence, misalignment between the magnetic field and rotation axis, and depletion of the slowly rotating envelope by outflow stripping or accretion. Outflows are also intimately linked to disk formation; they are a natural product of magnetic fields and rotation and are important signposts of star formation. We review new developments on early outflow generation since PPV. The properties of early disks and outflows are a key component of planet formation in its early stages and we review these major connections.

## 1. Overview

This review focuses on the earliest stages of star and planet formation, with an emphasis on the origins of early disks and outflows, and conditions that characterize the earliest stages of planet formation.

The importance of disks is obvious. They are the

birthplace of planets, including those in our solar system. Nearly 1000 exoplanets have been discovered to date (<http://exoplanet.eu>; see the chapters by Chabrier et al. and Helled et al. in this volume). The prevalence of planets indicates that disks must be common at least at some point in time around Sun-like stars. Observations show that this is

indeed the case.

Direct evidence for circumstellar disks around young stellar objects first came from the HST observations of the so-called Orion “proplyds” (O’Dell & Wen 1992; McCaughrean & O’Dell 1996), where the disks are seen in silhouette against the bright background. More recently, with the advent of millimeter and sub-millimeter arrays, there is now clear evidence from molecular line observations that some protoplanetary disks have Keplerian velocity fields, indicating rotational support (e.g., ALMA observations of TW Hydra; see § 2 on observations of early disks). Indirect evidence, such as protostellar outflows and infrared excess in spectral energy distribution, indicates that the majority, if not all, low-mass, Sun-like stars pass through a stage with disks, in agreement with the common occurrence of exoplanets.

Theoretically, disk formation — once thought to be a trivial consequence of the conservation of angular momentum during hydrodynamic core collapse — is far more subtle in magnetized gas. In the latter case, the rotation can be strongly magnetically braked. Indeed, disk formation is suppressed in the strict ideal MHD limit for the observed level of core magnetization; the angular momentum of the idealized collapsing core is nearly completely removed by magnetic braking close to the central object. How is this resolved?

We review what is known about this so-called “magnetic braking catastrophe” and its possible resolutions (§ 3). Important processes to be discussed include non-ideal MHD effects (ambipolar diffusion, Ohmic dissipation and Hall effect), magnetic interchange instability in the inner part of protostellar accretion flow, turbulence, misalignment between the magnetic field and rotation axis, and depletion of the slowly rotating envelope by outflow stripping or accretion. We then turn to a discussion of the launch of the earliest outflows, and show that two aspects of such outflows — the outer magnetic “tower” and the inner centrifugally driven disk wind that have dominated much of the discussion and theory of early outflows, are actually two regimes of the same unified MHD theory (§ 4). In § 5, we discuss the earliest phases of planet formation in such disks which are likely quite massive and affected by the angular momentum transport via both strong spiral waves and powerful outflows. We synthesize the results in § 6.

## 2. Observations

### 2.1. Dense Cores

Dense cores are the basic units for the formation of at least low-mass stars. Their properties determine the characteristics of the disk, outflow and planets—the byproducts of the star formation process. Particularly important for the formation of the outflow and disk (and its embedded planets) are the core rotation rate and magnetic field strength. We begin our discussion of observations with these two key quantities, before moving on to early outflows and disks.

Rotation rate is typically inferred from the velocity gra-

dient measured across a dense core (Goodman et al. 1993; Caselli et al. 2002). Whether the gradient traces true rotation or not is still under debate (Bergin & Tafalla 2007; Dib et al. 2010). For example, infall along a filament can mimic rotation signature (Tobin et al. 2012a; for synthetic line emission maps from filament accretion and their interpretation, see also Smith et al. 2012, 2013). If the gradient does trace rotation, then the rotational energy of the core would typically be a few percent of the gravitational energy. Such a rotation would not be fast enough to prevent the dense core from gravitational collapse. It is, however, more than enough to form a large,  $10^2$  AU-sized circumstellar disk, if angular momentum is conserved during the core collapse.

Magnetic fields are observed in the interstellar medium on a wide range of scales (see chapter by H.-B. Li et al. in this volume). Their dynamical importance relative to gravity is usually measured by the ratio of the mass of a region to the magnetic flux threading the region. On the core scale, the field strength was characterized by Troland & Crutcher (2008), who carried out an OH Zeeman survey of a sample of dense cores in nearby dark clouds. They inferred a median value  $\lambda_{los} \approx 4.8$  for the dimensionless mass-to-flux ratio (in units of the critical value  $[2\pi G^{1/2}]^{-1}$ , Nakano & Nakamura 1978). Geometric corrections should reduce the ratio to a typical value of  $\lambda \approx 2$  (Crutcher 2012). It corresponds to a ratio of magnetic to gravitational energy of tens of percent, since the ratio is given roughly by  $\lambda^{-2}$ . Such a field is not strong enough to prevent the core from collapsing into stars. It is, however, strong enough to dominate the rotation in terms of energy and, therefore, is expected to strongly affect disk formation (§ 3).

### 2.2. Early Outflows

Jets and outflows are observed during the formation of stars over the whole stellar spectrum, from brown dwarfs (e.g., Whelan et al. 2005, 2012) to high-mass stars (e.g., Motogi et al. 2013; Carrasco-González et al. 2010; Qiu et al. 2011, 2008, 2007; Zhang et al. 2007), strongly indicating a universal launching mechanism at work (see § 4 and also chapter by Frank et al. in this volume).

Young brown dwarfs have optical forbidden line spectra similar to those of low-mass young stars that are indicative of outflows (Whelan et al. 2005, 2006). The inferred outflow speeds of order 40–80 km s<sup>-1</sup> are somewhat lower than those of young stars (Whelan et al. 2007; Joergens et al. 2013). Whelan et al. (2012) suggest that brown dwarf outflows can be collimated and episodic, just as their low-mass star counterparts. There is some indication that the ratio of outflow and accretion rates,  $\dot{M}_{out}/\dot{M}_{accr}$ , is higher for young brown dwarf and very-low mass stars (Comerón et al. 2003; Whelan et al. 2009; Bacciotti et al. 2011) than for the classical T-Tauri stars (e.g., Hartigan et al. 1995; Sicilia-Aguilar et al. 2010; Fang et al. 2009; Ray et al. 2007). Whether this is generally true remains to be established.

Since planetary systems like the Jovian system with its

Galilean moons are thought to be built up from planetary sub-disks (Mohanty et al. 2007), one would naturally expect them to launch outflows as well (see e.g., Machida et al. 2006; Liu & Schneider 2009). There is, however, no direct observational evidence yet for such circum-planetary disk-driven outflows.

At the other end of the mass spectrum, there is now evidence that outflows around young massive stars can be highly collimated, even at relative late evolutionary stages (e.g., Carrasco-González et al. 2010; Rodríguez et al. 2012; Chibueze et al. 2012; Palau et al. 2013). For example, interferometric observations reveal that the young, luminous ( $\sim 10^5 L_\odot$ ), object IRAS 19520+2759 drives a well collimated CO outflow, with a collimation factor of 5.7 (Palau et al. 2013). It appears to have evolved beyond a central B-type object, but still drives a collimated outflow, in contrast with the expectation that massive YSO outflows decollimate as they evolve in time (Beuther & Shepherd 2005). Interestingly, an HII region has yet to develop in this source. It may be quenched by protostellar accretion flow (Keto 2002, 2003; Peters et al. 2010, 2011) or absent because the central stellar object is puffed up by rapid accretion (and thus not hot enough at surface to produce ionizing radiation; Hosokawa et al. 2010).

### 2.3. Early Disks

From an observational point of view, the key question to address is when rotationally supported circumstellar disks are first established and become observable. It is clear that, after approximately 0.5 Myr (Evans et al. 2009), gaseous Keplerian (protoplanetary) disks are present on the scales of  $\sim 100$ –500 AU around both low- and intermediate-mass stars (“T Tauri” and “Herbig Ae” stars, respectively — or Class II young stellar objects; see Dutrey et al. 2007). Whether they are present at earlier times requires high-resolution studies of the youngest protostars, e.g., Class 0 and Class I objects.

One way to constrain the process of disk formation is to study the rotation rates on difference scales (see the caveats in inferring rotation rate in § 2.1). From larger to smaller scales, a clear progression in kinematics is evident (Fig. 1; reproduced from Belloche 2013): at large distances from the central protostar and in prestellar cores, the specific angular momentum decreases rapidly toward smaller radii, implying that the angular velocity is roughly constant (e.g., Goodman et al. 1993; Belloche et al. 2002). Observations of objects in relatively late stages of evolution suggest that the specific angular momentum tends to a constant value ( $v_{\text{rot}} \propto r^{-1}$ ) between  $\sim 10^2$  and  $10^4$  AU, as expected from conservation of angular momentum under infall. A rotationally supported disk is expected to show increasing specific angular momentum as function of radius (Keplerian rotation,  $v_{\text{rot}} \propto r^{-0.5}$ ). To characterize the properties of disks being formed, the task at hand is to search for the location where the latter two regimes, Keplerian disk with  $v_{\text{rot}} \propto r^{-0.5}$  and the infalling envelope with  $v_{\text{rot}} \propto r^{-1}$ ,

separate.

#### 2.3.1. Techniques

Observationally the main challenge in revealing the earliest stages of the circumstellar disks is the presence of the larger scale protostellar envelopes during the Class 0 and I stages, which reprocess most of the emission from the central protostellar object itself at shorter wavelengths and easily dominate the total flux at longer wavelengths. The key observational tools at different wavelength regimes are (for convenience we define the near-infrared as  $\lambda < 3 \mu\text{m}$ , mid-infrared as  $3 \mu\text{m} < \lambda < 50 \mu\text{m}$ , far-infrared as  $50 \mu\text{m} < \lambda < 250 \mu\text{m}$ , (sub)millimeter as  $250 \mu\text{m} < \lambda < 4 \text{mm}$ ):

**Mid-infrared:** at mid-infrared wavelengths the observational signatures of young stars are dominated by the balance between the presence of warm dust and degree of extinction on small-scales — and in particular, highly sensitive observations with the *Spitzer Space Telescope* in 2003–2009 have been instrumental in this field. One of the key results relevant to disk formation during the embedded stages is that simple infalling envelope profiles (e.g.  $\rho \propto r^{-2}$  or  $r^{-1.5}$ ) cannot extend unmodified to  $\lesssim$  few hundred AU scales (Jørgensen et al. 2005b; Enoch et al. 2009): the embedded protostars are brighter in the mid-infrared than expected from such profiles, which can for example be explained if the envelope is flattened or has a cavity on small scales. Indeed, extinction maps reveal that protostellar environments are complex on  $10^3$  AU scales (Tobin et al. 2010) and in some cases show asymmetric and filamentary structures that complicate the canonical picture of formation of stars from the collapse of relatively spherical dense cores.

**Far-infrared:** at far-infrared wavelengths the continuum emission comes mainly from thermal dust grains with temperatures of a few tens of K. This wavelength range is accessible almost exclusively from space only. Consequently, observatories such as the Infrared Space Observatory (ISO) and Herschel Space Observatory (Pilbratt et al. 2010) have been the main tools for characterizing protostars there. At the time of writing, surveys from the Herschel Space Observatory are starting to produce large samples of deeply embedded protostellar cores that can be followed up by other instruments. The observations at far-infrared wavelengths provide important information about the peak of the luminosity of the embedded protostars and the distribution of low surface brightness dust — but due to the limitation in angular resolution less information on the few hundred AU scales of disks around more evolved YSOs.

**(Sub)millimeter:** the (sub)millimeter wavelengths provide a unique window on the thermal radiation from the

cooler dust grains on small scales (André et al. 1993; Chandler & Richer 2000). Aperture synthesis observations at these wavelengths resolve scales down to  $\sim 100$  AU or better in nearby star forming regions. The flux from the thermal dust continuum emission is strongly increasing with frequency  $\nu$  as  $F_\nu \propto \nu^2$  or steeper, making these wavelengths ideally suited for detecting dense structures while discriminating from possible free-free emission. Likewise the high spectral resolution for a wide range of molecular rotational transitions can be tailored to study the structure (e.g., temperature and kinematics) of the different components in the protostellar systems (Jørgensen et al. 2005a).

### 2.3.2. Millimeter Continuum Surveys

The main observational tool for understanding disk formation is millimeter surveys using aperture synthesis technique that probe how the matter is distributed on the few hundred AU scales. The use of such a technique to address this question goes back to Keene & Masson (1990) and Terebey et al. (1993) with the first larger arcsecond scale surveys appearing in the early 2000s (e.g., Looney et al. 2000) and detailed radiative transfer modeling appearing about the same time (e.g. Hogerheijde & Sandell 2000; Harvey et al. 2003; Looney et al. 2003; Jørgensen et al. 2004, 2005a).

The general conclusion from these studies is that, in most cases, both the large- and small-scale continuum emission cannot be reproduced by a single analytical model of a simple, axisymmetric envelope. In some cases, e.g., Brown et al. (2000); Jørgensen et al. (2005a); Enoch et al. (2009), these structures are well resolved on a few hundred AU scales. Some noteworthy counter-examples where no additional dust continuum components are required include L483 (Jørgensen 2004), L723 (Girart et al. 2009) and three of the nine Class 0 protostars in Serpens surveyed by Enoch et al. (2011). Typically the masses for individual objects derived in these studies agree well with each other once similar dust opacities and temperatures are adopted. Jørgensen et al. (2009) compared the dust components for a sample of 18 embedded Class 0 and I protostars and did not find an increase in mass of the modeled compact component with bolometric temperature as one might expect from the growth of Keplerian disks. Jørgensen et al. (2009) suggested that this could reflect the presence of the rapid formation of disk-like structure around the most deeply embedded protostars, although the exact kinematics of those around the most deeply embedded (Class 0) sources were unclear. An unbiased survey of embedded protostars in Serpens with envelope masses larger than  $0.25 M_\odot$  and luminosities larger than  $0.05 L_\odot$  by Enoch et al. (2011) finds similar masses for the compact structures around the sources in that sample. Generally these masses are found to be small relative to the larger scale envelopes in the Class 0 stage on 10,000 AU scales — but still typically one to two orders of magnitude larger than the mass on similar, few

hundred AU, scales extrapolated from the envelope.

Still, the continuum observations do not provide an unambiguous answer to what these compact components represent. By the Class I stage some become the Keplerian disks surrounding the protostars. The compact components around the Class 0 protostars could be the precursors to these Keplerian disks. However, it is unlikely that such massive rotationally supported disks could be stably supported given the expected low stellar mass for the Class 0 protostars: they should be prone to fragmentation (see § 5).

An alternative explanation for the compact dust emission detected in interferometric continuum observations may be the presence of “pseudo-disks”. In the presence of magnetic fields, torsional Alfvén waves in twisted field lines carry away angular momentum, preventing the otherwise natural formation of large rotationally supported disks. However, strong magnetic pinching forces deflect infalling gas toward the equatorial plane to form a flattened structure—the “pseudo-disk” (Galli & Shu 1993; Allen et al. 2003; Fromang et al. 2006). Unlike Keplerian disks observed at later stages, this flattened inner envelope is not supported by rotational motions, but can be partially supported by magnetic fields. Observationally disentangling disks and pseudo-disks is of paramount importance since accretion onto the protostar proceeds very differently through a rotationally-supported disk or a magnetically-induced pseudo-disk.

Maury et al. (2010) compared the results from an IRAM Plateau de Bure study of five Class 0 to synthetic model images from three numerical simulations — in particular focusing on binarity and structure down to scales of  $\sim 50$  AU. The comparison shows that magnetized models of protostar formation including pseudo-disks agree better with the observations than, e.g., pure hydrodynamical simulation in the case of no initial perturbation or turbulence. With turbulence, magnetized models can produce small disks ( $\sim 100$  AU) (Seifried et al. 2013), which might still be compatible with Maury et al. (2010)’s observations. The compact continuum components could also represent the “magnetic walls” modeled by Tassis & Mouschovias (2005), although in some sources excess unresolved emission remains unaccounted for in this model (Chiang et al. 2008).

### 2.3.3. Kinematics

A number of more evolved Class I young stellar objects show velocity gradients that are well fitted by Keplerian profile (e.g., Brinch et al. 2007; Lommen et al. 2008; Jørgensen et al. 2009) (see also Harsono et al. 2013, and Lee 2011 for evidence of Keplerian disks around Class I object TMC1A and HH 111, respectively). Generally the problem in studying the kinematics on disk scales in embedded protostars is that many of the traditional line tracers are optically thick in the larger scale envelope. Jørgensen et al. (2009), for example, showed that the emission from the (sub)millimeter transitions of  $\text{HCO}^+$  would be optically thick on scales of  $\sim 100$  AU for envelopes with masses

larger than  $0.1 M_{\odot}$ . An alternative is to trace less abundant isotopologues. Recently one embedded protostar, L1527, was found to show Keplerian rotation in  $^{13}\text{CO}/\text{C}^{18}\text{O}$  2–1 (Tobin et al. 2012b, see also Murillo et al. 2013 for VLA1623A); this result was subsequently strengthened by ALMA observations (N. Ohashi, priv. comm., see also <http://www.almasc.org/upload/presentations/DC-05.pdf>). Another example of Keplerian motions is found in the protostellar binary L1551-NE (a borderline Class 0/I source), in  $^{13}\text{CO}/\text{C}^{18}\text{O}$  2–1 (Takakuwa et al. 2012). Large circumstellar disks are inferred around a number of high-mass young stellar objects, including G31.41+0.31 (Cesaroni et al. 1994), IRAS 20126+4104 (Cesaroni et al. 1997), IRAS 18089-1732 (Beuther et al. 2004), IRAS 16547-4247 (Franco-Hernández et al. 2009) and IRAS 18162-2048 (Fernández-López et al. 2011). Whether they are rotationally supported remains uncertain.

Brinch et al. (2009) investigated the dynamics of the deeply embedded protostar NGC 1333-IRAS2A in subarc-second resolution observations of HCN (4–3) and the same line of its isotopologue  $\text{H}^{13}\text{CN}$ . Through detailed line radiative transfer modeling they showed that the  $\sim 300$  AU compact structure seen in dust continuum was in fact dominated by infall rather than rotation.

Pineda et al. (2012) presented some of the first ALMA observations of the deeply embedded protostellar binary IRAS 16293-2422. These sensitive observations revealed a velocity gradient across one component in the binary, IRAS16293A, in lines of the complex organic molecule methyl formate. However, this velocity gradient does not reflect Keplerian rotation and does not require a central mass beyond the envelope mass enclosed on the same scale. This is also true for the less dense gas traced by lines of the rare  $\text{C}^{17}\text{O}$  and  $\text{C}^{34}\text{S}$  isotopologues in extended Submillimeter Array (eSMA) observations ( $0.5''$  resolution; Favre et al. 2014).

The above observations paint a picture of complex structure of the material on small scales around low-mass protostellar systems. They raise a number of important potential implications, which we discuss next.

## 2.4. Implications and Outlook

### 2.4.1. Protostellar Mass Evolution

An important constraint on the evolution of protostars is how the bulk mass is transported and accreted from the larger scales through the circumstellar disks onto the central stars (§ 5). An important diagnostic from the above observations is to compare the disk masses — either from dust continuum or line observations (taking into account the caveats about the dust properties and/or chemistry) to stellar masses inferred, e.g., from the disk dynamical profiles. Jørgensen et al. (2009) compared these quantities for a sample of predominantly Class I young stellar objects with well-established disks: an updated version of this figure including recent measurements of dynamical masses for additional sources (Tobin et al. 2012b; Takakuwa et al. 2012) is

shown in Fig. 2. These measurements are compared to standard semi-analytic models for collapsing rotating protostars (Visser et al. 2009): these models typically underestimate the stellar masses relative to the disk masses. These simple models of collapse of largely spherical cores are likely inapplicable on larger scales where filamentary structures are sometimes observed (Tobin et al. 2010; Lee et al. 2012). Still, this comparison illustrates a potential avenue to explore when observations of a large sample of embedded protostars become available in the ALMA era; it provides direct measures of the accretion rates that more sophisticated numerical simulations need to reproduce.

### 2.4.2. Grain growth

Multi-wavelength continuum observations in the millimeter and submillimeter are also interesting for studying the grain properties close to the newly formed protostars. In more evolved circumstellar disks a flattened slope of the spectral energy distribution at millimeter or longer wavelengths is taken as evidence that significant grain growth has taken place (see, e.g., Natta et al. 2007 for a review). On larger scales of protostellar envelope where the continuum emission is optically thin, ISM-like dust would result in submillimeter spectral slopes of 3.5–4. The more compact dust components observed at few hundred AU scales have lower spectral indices of 2.5–3.0 (Jørgensen et al. 2007; Kwon et al. 2009; Chiang et al. 2012), either indicating that some growth of dust grains to millimeter sizes has occurred or that the compact components are optically thick. At least in a few cases where the dust emission is clearly resolved the inferred spectral slopes are in agreement with those observed for more evolved T Tauri stars, indicating that dust rapidly grows to millimeter sizes (Ricci et al. 2010). Assessing the occurrence of grain growth during the embedded stages is important for not only understanding the formation of the seeds for planetesimals (§ 5), but also evaluating the non-ideal MHD effects in magnetized core collapse and disk formation, since they depend on the ionization level, which in turn is strongly affected by the grain size distribution (§ 3).

### 2.4.3. Chemistry

The presence of disk-like structures on hundred AU scales may also have important implications for the chemistry in those regions. The presence of a disk may change the temperature, allowing molecules to freeze-out again which would otherwise stay in the gas-phase. Water and its isotopologues are a particularly clear example of these effects: for example in observations of the  $\text{H}_2^{18}\text{O}$  isotopologue toward the centers of a small sample of Class 0 protostars, Jørgensen & van Dishoeck (2010) and Persson et al. (2012) found lower  $\text{H}_2\text{O}$  abundances than expected in the typical gas-phase, consistent with a picture in which a significant fraction of the material at scales  $\lesssim 100$  AU has temperatures lower than  $\sim 100$  K. This complicates the interpretation of the chemistry throughout the envelope. For example,

it makes extrapolations of envelope physical and abundance structures from larger scales invalid (Visser et al. 2013). An ongoing challenge is to better constrain the physical structure of the protostellar envelopes and disks on these scales. This must be done before significant progress can be made on understanding the initial conditions for chemical evolution in protoplanetary disks. The challenge is even more formidable for massive stars, although Isokoski et al. (2013) did not find any chemical differentiation between massive stars with and without disk-like structures.

#### 2.4.4. Linking Observations and Theory

Observations suggest that, in principle, there is typically more than enough angular momentum on the core scale to form large,  $10^2$  AU scale rotationally supported disks. The common presence of fast jets around deeply embedded protostars implies that the formation of such disks has begun early in the process of star formation. There is, however, currently little direct evidence that large, well-developed, Keplerian disks are prevalent around Class 0 protostars, as one may naively expect based on angular momentum conservation during hydrodynamic core collapse. The paucity of large, early disks indicates that disk formation is not as straightforward as generally expected. The most likely reason is that star-forming cores are observed to be significantly magnetized, and magnetic fields are known to interact strongly with rotation. They greatly affect, perhaps even control, disk formation, as we show next.

### 3. Theory of Magnetized Disk Formation

How disks form has been a long-standing theoretical problem in star formation. Early work on this topic was reviewed by Bodenheimer (1995) and Boss (1998). Both reviews listed a number of unsolved problems. Topping both lists was the effect of the magnetic field, which turns out to present a formidable obstacle to disk formation. Substantial progress has been made in recent years in overcoming this obstacle, especially through Ohmic dissipation, field-rotation misalignment, and turbulence. This progress will be summarized below.

#### 3.1. Magnetic Braking Catastrophe in Ideal MHD Limit

The basic difficulty with disk formation in magnetized dense cores can be illustrated using analytic arguments in the strict ideal MHD limit where the magnetic field lines are perfectly frozen into the core material. In this limit, as a finite amount of mass is accreted onto the central object (the protostar), a finite amount of magnetic flux will be dragged into the object as well. The magnetic flux accumulated at the center forms a magnetic split monopole, with the field lines fanning out radially (Galli et al. 2006; see the sketch in their Fig. 1). As a result, the magnetic field strength increases rapidly with decreasing distance to the center, as  $B \propto r^{-2}$ . The magnetic energy density, which is proportional to the field strength squared, increases with

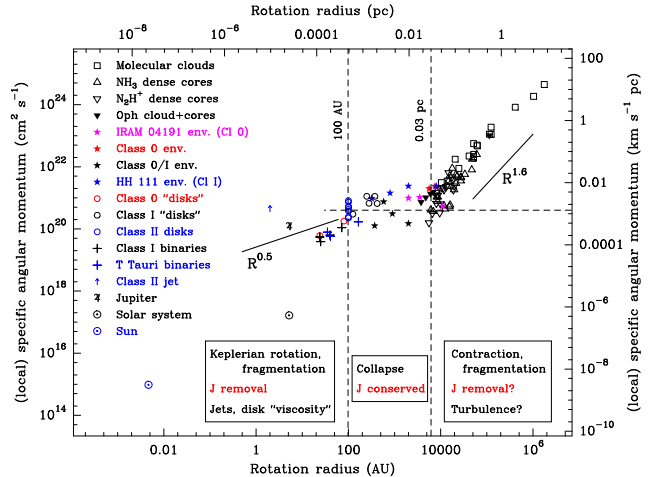


Fig. 1.— Progression of specific angular momentum as function of scale and/or evolutionary stage of young stellar objects. Figure from Belloche (2013).

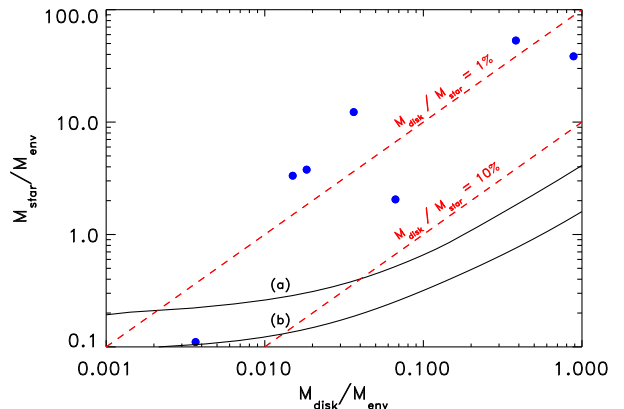


Fig. 2.— Updated version of Fig. 18 from Jørgensen et al. (2009). Predicted stellar mass,  $M_{\text{star}}$ , vs. disk mass,  $M_{\text{disk}}$ , both measured relative to the envelope mass  $M_{\text{env}}$  in the models of Visser et al. (2009) with  $\Omega_0 = 10^{-14} \text{ s}^{-1}$  and  $c_s$  of (a)  $0.19 \text{ km s}^{-1}$  and (b)  $0.26 \text{ km s}^{-1}$  (solid lines). The sources for which stellar, disk and envelope masses are measured are shown with blue dots (Jørgensen et al. 2009; Takakuwa et al. 2012; Tobin et al. 2012b). Finally, the dashed lines indicate  $M_{\text{disk}}/M_{\text{star}}$  ratios of 1% (upper) and 10% (lower).

decreasing radius even more rapidly, as  $E_B \propto r^{-4}$ . This increase is faster than, for example, the energy density of the accretion flow, which can be estimated approximately from spherical free-fall collapse as  $E_{\text{ff}} \propto r^{-5/2}$ . As the infalling material approaches the central object, it will become completely dominated by the magnetic field sooner or later. The strong magnetic field at small radii is able to remove all of the angular momentum in the collapsing flow, leading to the so-called “magnetic braking catastrophe” for disk formation (Galli et al. 2006). The braking occurs naturally in a magnetized collapsing core, because the faster rotating matter that has already collapsed closer to the rotation axis remains connected to the more slowly rotating material at larger (cylindrical) distances through field lines. The differential rotation generates a fieldline twist that brakes the rotation of the inner, faster rotating part and transports its angular momentum outward (see Mouschovias & Paleologou 1979, 1980 for analytic illustrations of magnetic braking).

The catastrophic braking of disks in magnetized dense cores in the ideal MHD limit was also found in many numerical as well as semi-analytic calculations. Krasnopolsky & Königl (2002) were the first to show semi-analytically, using the so-called “thin-disk” approximation, that the formation of rotationally supported disks (RSDs hereafter) can be suppressed if the efficiency of magnetic braking is large enough. However, the braking efficiency was parametrized rather than computed self-consistently. Similarly, Dapp & Basu (2010) and Dapp et al. (2012) demonstrated that, in the absence of any magnetic diffusivity, a magnetic split-monopole is produced at the center and RSD formation is suppressed, again under the thin-disk approximation.

Indirect evidence for potential difficulty with disk formation in ideal MHD simulations came from Tomisaka (2000), who studied the (2D) collapse of a rotating, magnetized dense core using a nested grid under the assumption of axisymmetry. He found that, while there is little magnetic braking during the phase of runaway core collapse leading up to the formation of a central object, once an outflow is launched, the specific angular momentum of the material at the highest densities is reduced by a large factor (up to  $\sim 10^4$ ) from the initial value. The severity of the magnetic braking and its deleterious effect on disk formation were not fully appreciated until Allen et al. (2003) explicitly demonstrated that the formation of a large, numerically resolvable, rotationally supported disk was completely suppressed in 2D by a moderately strong magnetic field (corresponding to a dimensionless mass-to-flux ratio  $\lambda$  of several) in an initially self-similar, rotating, magnetized, singular isothermal toroid (Li & Shu 1996). They identified two key ingredients behind the efficient braking during the accretion phase: (1) concentration of the field lines at small radii by the collapsing flow, which increases the field strength, and (2) the fanning out of field lines due to equatorial pinching, which increases the lever arm for magnetic braking.

The catastrophic braking that prevents the formation of RSDs during the protostellar accretion phase has been con-

firmed in several subsequent 2D and 3D ideal MHD simulations (Mellon & Li 2008; Hennebelle & Fromang 2008; Duffin & Pudritz 2009; Seifried et al. 2012; Santos-Lima et al. 2012). Mellon & Li (2008), in particular, formulated the disk formation problem in the same way as Allen et al. (2003), by adopting a self-similar rotating, magnetized, singular isothermal toroid as the initial configuration. Although idealized, the adopted initial configuration has the advantage that the subsequent core collapse should remain self-similar. The self-similarity provides a useful check on the correctness of the numerically obtained solution. They found that the disk formation was suppressed by a field as weak as  $\lambda = 13.3$ .

Hennebelle & Fromang (2008) carried out 3D simulations of the collapse of a rotating dense core of uniform density and magnetic field into the protostellar accretion phase using an ideal MHD AMR code (RAMSES). They found that the formation of a RSD is suppressed as long as  $\lambda$  is of order 5 or less. However, the  $\lambda = 5$  case in Price & Bate’s (2007) SPMHD simulations appears to have formed a small disk (judging from the column density distribution). It is unclear whether the disk is rotationally supported or not, since the disk rotation rate was not given in the paper. Furthermore, contrary to the grid-based simulations, there appears little, if any, outflow driven by twisted field lines in the SPH simulations, indicating that the efficiency of magnetic braking is underestimated (prominent outflows are produced, however, in other SPMHD simulations, e.g., Bürzle et al. 2011 and Price et al. 2012). Another apparently discrepant result is that of Machida et al. (2011). They managed to form a large,  $10^2$ -AU scale, rotationally supported disk for a very strongly magnetized core of  $\lambda = 1$  even in the ideal MHD limit (their Model 4) using a nested grid and sink particle. This contradicts the results from other simulations and semi-analytic calculations.

To summarize, both numerical simulations and analytic arguments support the notion that, in the ideal MHD limit, catastrophic braking makes it difficult to form rotationally supported disks in (laminar) dense cores magnetized to a realistic level (with a typical  $\lambda$  of a few). In what follows, we will explore the potential resolutions that have been proposed in the literature to date.

### 3.2. Non-ideal MHD Effects

Dense cores of molecular clouds are lightly ionized (with a typical electron fractional abundance of order  $10^{-7}$ ; Bergin & Tafalla 2007). As such, the magnetic field is not expected to be perfectly frozen into the bulk neutral material. There are three well known non-ideal MHD effects that can in principle break the flux-freezing condition that lies at the heart of the magnetic braking catastrophe in the strict ideal MHD limit. They are ambipolar diffusion, the Hall effect, and Ohmic dissipation (see Armitage 2011 for a review). Roughly speaking, in the simplest case of an electron-ion-neutral medium, both ions and electrons are well tied to the magnetic field in the ambipolar diffusion

regime. In the Hall regime, electrons remain well tied to the field, but not ions. At the highest densities, both electrons and ions are knocked off the field lines by collisions before they finish a complete gyration; in such a case, Ohmic dissipation dominates. This simple picture is complicated by dust grains, whose size distribution in dense cores is relatively uncertain (see § 2.4), but which can become the dominant charge carriers. Under typical cloud conditions, ambipolar diffusion dominates over the other two effects at densities typical of cores (e.g., Nakano et al. 2002, Kunz & Mouschovias 2010). It is the most widely studied non-ideal MHD effect in the context of core formation and evolution in the so-called “standard” picture of low-mass star formation out of magnetically supported clouds (Nakano 1984; Shu et al. 1987; Mouschovias & Ciolek 1999). It is the effect that we will first concentrate on.

Ambipolar diffusion enables the magnetic field lines that are tied to the ions to drift relative to the bulk neutral material. In the context of disk formation, its most important effect is to redistribute the magnetic flux that would have been dragged into the central object in the ideal MHD limit to a circumstellar region where the magnetic field strength is greatly enhanced (Li & McKee 1996). Indeed, the enhanced circumstellar magnetic field is strong enough to drive a hydromagnetic shock into the protostellar accretion flow (Li & McKee 1996; Ciolek & Königl 1998; Contopoulos et al. 1998; Krasnopolsky & Königl 2002; Tassis & Mouschovias 2007; Dapp et al. 2012). Krasnopolsky & Königl (2002) showed semi-analytically, using the 1D thin-disk approximation, that disk formation may be suppressed in the strongly magnetized post-shock region if the magnetic braking is efficient enough. The braking efficiency, parametrized in Krasnopolsky & Königl (2002), was computed self-consistently in the 2D (axisymmetric) simulations of Mellon & Li (2009), which were performed under the usual assumption of ion density proportional to the square root of neutral density. 3D simulations of AD were performed by Duffin & Pudritz (2009) using a specially developed, single fluid AMR code (Duffin & Pudritz 2008) as well as by a two fluid SPH code (Hosking & Whitworth 2004). Mellon & Li (2009) found that ambipolar diffusion does not weaken the magnetic braking enough to allow rotationally supported disks to form for realistic levels of cloud core magnetization and cosmic ray ionization rate. In many cases, the magnetic braking is even enhanced. These findings were strengthened by Li et al. (2011), who computed the ion density self-consistently using the simplified chemical network of Nakano and collaborators (Nakano et al. 2002; Nishi et al. 1991) that includes dust grains. An example of their simulations is shown in Fig. 3. It shows clearly the rapid slowdown of the infalling material near the ambipolar diffusion-induced shock (located at a radius  $\sim 10^{15}$  cm in this particular example) and the nearly complete braking of the rotation in the post-shock region, which prevents the formation of a RSD. The suppression of RSD is also evident from the fast, supersonic infall close to the central object. We should note that RSD formation may still

be possible if the cosmic ray ionization rate can be reduced well below the canonical value of  $10^{-17} \text{ s}^{-1}$  (Mellon & Li 2009), through for example the magnetic mirroring effect, which may turn a large fraction of the incoming cosmic rays back before they reach the disk-forming region (Padovani et al. 2013).

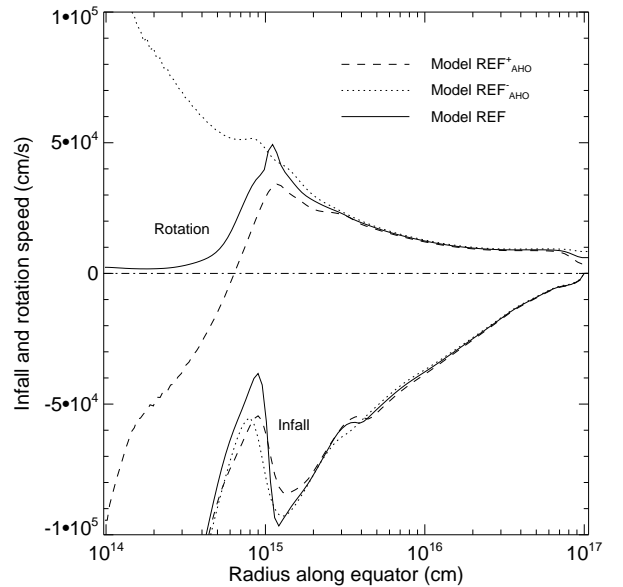


Fig. 3.— Infall and rotation speeds along the equatorial plane of a collapsing rotating, magnetized dense core during the protostellar mass accretion phase for three representative models of Li et al. (2011). Model REF (solid lines) includes only ambipolar diffusion, whereas the other two include all three non-ideal MHD effects, especially the Hall effect. The initial magnetic field and rotation axis are in the same direction in one model (REF<sup>+</sup>, dashed lines) and in opposite directions in the other (REF<sup>-</sup>, dotted).

As the density increases, the Hall effect tends to become more important (the exact density for this to happen depends on the grain size distribution). It is less explored than ambipolar diffusion in the star formation literature. A unique feature of this effect is that it can actively increase the angular momentum of a collapsing, magnetized flow through the so-called “Hall spin-up” (Wardle & Ng 1999). In the simplest case of electron-ion-neutral fluid, the spin-up is caused by the current carriers (the electrons) moving in the azimuthal direction, generating a magnetic torque through field twisting; the toroidal current is produced by gravitational collapse, which drags the poloidal field into a pinched, hourglass-like configuration. The Hall spin-up was studied numerically by Krasnopolsky et al. (2011) and semi-analytically by Braiding & Wardle (2012a,b). Krasnopolsky et al. (2011) showed that a rotationally supported disk can form even in an initially *non-rotating* core, provided that the Hall coefficient is large enough. Interestingly, when the direction of the initial mag-



netic field in the core is flipped, the disk rotation is reversed. This reversal of rotation is also evident in Fig. 3, where the Hall effect spins up the nearly non-rotating material in the post-AD shock region to highly supersonic speeds, but in different directions depending on the field orientation. The Hall effect, although dynamically significant, does not appear capable of forming a rotationally supported disk under typical dense core conditions according to Li et al. (2011). This inability is illustrated in Fig. 3, where the equatorial material collapses supersonically on the  $10^2$ -AU scale even when the Hall effect is present.

Ohmic dissipation becomes the dominant nonideal MHD effects at high densities (e.g., Nakano et al. 2002). It has been investigated by different groups in connection with disk formation. Shu et al. (2006) studied semi-analytically the effects of a spatially uniform resistivity on the magnetic field structure during the protostellar mass accretion phase. They found that, close to the central object, the magnetic field decouples from the collapsing material and becomes more or less uniform. They suggested that a rotationally supported disk may form in the decoupled region, especially if the resistivity is higher than the classic (microscopic) value. This suggestion was confirmed by Krasnopolsky et al. (2010; see also Santos-Lima et al. 2012), who found numerically that a large,  $10^2$ -AU-scale, Keplerian disk can form around a  $0.5 M_{\odot}$  star, provided that the resistivity is of order  $10^{19} \text{ cm}^2 \text{ s}^{-1}$  or more; such a resistivity is significantly higher than the classic (microscopic) value over most of the density range relevant to disk formation.

Machida & Matsumoto (2011) and Machida et al. (2011) studied disk formation in magnetized cores including only the classic value of resistivity estimated from Nakano et al.’s (2002) numerical results. The former study found that a relatively small, 10 AU-scale, rotationally supported disk formed within a few years after the formation of the stellar core. Inside the disk, the density is high enough for magnetic decoupling to occur due to Ohmic dissipation. This work was extended to much later times by Machida et al. (2011), who included a central sink region in the simulations. They concluded that the small RSD can grow to large,  $10^2$ -AU size at later times, especially after the most of the envelope material has fallen onto the disk and the central object. A caveat, pointed out by Tomida et al. (2013; see also Dapp & Basu 2010), is that they used a form of induction equation that is, strictly speaking, inappropriate for the non-constant resistivity adopted in their models; it may generate magnetic monopoles that are subsequently cleaned away using the Dedner’s method (Dedner et al. 2002). This deficiency was corrected in Tomida et al. (2013), who carried out radiative MHD simulations of magnetized core collapse to a time shortly ( $\sim 1$  year) after the formation of the second (protostellar) core. They found that the formation of a (small, AU-scale) rotationally supported disk was suppressed by magnetic braking in the ideal MHD limit but was enabled by Ohmic dissipation at this early time; the latter result is in qualitative agreement with Machida

& Matsumoto (2011) and Machida et al. (2011), although it remains to be seen how the small disks in Tomida et al. (2013)’s simulations evolve further in time.

Dapp & Basu (2010) studied the effects of Ohmic dissipation on disk formation semi-analytically, using the “thin-disk” approximation for the mass distribution and an approximate treatment of magnetic braking. The approximations enabled them to follow the formation of both the first and second core. They found that a small, sub-AU, rotationally supported disk was able to form soon after the formation of the second core in the presence of Ohmic dissipation; it was suppressed in the ideal MHD limit, in agreement with the later 3D simulations of Tomida et al. (2013). This work was extended by Dapp et al. (2012) to include a set of self-consistently computed charge densities from a simplified chemical network and ambipolar diffusion. They showed that their earlier conclusion that a small, sub-AU scale, RSD is formed through Ohmic dissipation holds even in the presence of a realistic level of ambipolar diffusion. This conclusion appears reasonably secure in view of the broad agreement between the semi-analytic work and numerical simulations. When and how such disks grow to the much larger,  $10^2$ -AU-scale, size deserve to be explored more fully.

### 3.3. Magnetic Interchange Instabilities

The formation of a large-scale RSD in a magnetized core is made difficult by the accumulation of magnetic flux near the accreting protostar. As discussed earlier, this is especially true in the presence of a realistic level of ambipolar diffusion, which redistributes the magnetic flux that would have been dragged into the central object to the circumstellar region (Ohmic dissipation has a similar effect, see Li et al. 2011 and Dapp et al. 2012). The result of the flux redistribution is the creation of a strongly magnetized region close to the protostar where the infall speed of the accreting flow is slowed down to well below the free-fall value (i.e., it is effectively held up by magnetic tension against the gravity of the central object), at least in 2D (assuming axisymmetry). It has long been suspected that such a magnetically supported structure would become unstable to interchange instabilities in 3D (Li & McKee 1996; Krasnopolsky & Königl 2002). Recent 3D simulations have shown that this is indeed the case.

Magnetic interchange instability in a protostellar accretion flow driven by flux redistribution was first studied in detail by Zhao et al. (2011). They treated the flux redistribution through a sink particle treatment: when the mass in a cell is accreted onto a sink particle, the magnetic field is left behind in the cell (see also Seifried et al. 2011 and Cunningham et al. 2012); it is a crude representation of the matter-field decoupling expected at high densities (of order  $10^{12} \text{ cm}^{-3}$  or higher; Nakano et al. 2002; Kunz & Mouschovias 2010). The decoupled flux piles up near the sink particle, leading to a high magnetic pressure that is released through the escape of field lines along the directions

of least resistance. As a result, the magnetic flux dragged into the decoupling region near the protostar along some azimuthal directions is advected back out along other directions in highly magnetized, low-density, expanding regions. Such regions are termed DEMS (decoupling-enabled magnetic structure) by Zhao et al. (2011); they appear to be present in the formally ideal MHD simulations of Seifried et al. (2011), Cunningham et al. (2012) and Joos et al. (2012) as well.

Krasnopolsky et al. (2012) improved upon the work of Zhao et al. (2011) by including two of the physical processes that can lead to magnetic decoupling: ambipolar diffusion and Ohmic dissipation. They found that the basic conclusion of Zhao et al. (2011) that the inner part of the protostellar accretion flow is driven unstable by magnetic flux redistribution continues to hold in the presence of realistic levels of non-ideal MHD effects (see Fig. 4 for an illustrative example). The magnetic flux accumulated near the center is transported outward not only diffusively by the microscopic non-ideal effects, but also advectively through the bulk motions of the strongly magnetized expanding regions (the DEMS) generated by the instability. The advective flux redistribution in 3D lowers the field strength at small radii compared to the 2D (axisymmetric) case where the instability is suppressed. It makes the magnetic braking less efficient and the formation of a RSD easier in principle. In practice, the magnetic interchange instability does not appear to enable the formation of rotationally supported disks by itself, because the highly magnetized DEMS that it creates remain trapped at relatively small distances from the protostar by the protostellar accretion flow (see Fig. 4); the strong magnetic field inside the DEMS blocks the accretion flow from rotating freely around the center object to form a complete disk.

### 3.4. Magnetic Field-Rotation Misalignment

Misalignment between the magnetic field and rotation axis as a way to form large RSDs has been explored extensively by Hennebelle and collaborators (Hennebelle & Ciardi 2009; Ciardi & Hennebelle 2010; Joos et al. 2012; see also Machida et al. 2006; Price & Bate 2007, and Boss & Keiser 2013). The misalignment is expected if the angular momenta of dense cores are generated through turbulent motions (e.g., Burkert & Bodenheimer 2000; Seifried et al. 2012b; Myers et al. 2013; Joos et al. 2013). Plausible observational evidence for it was recently uncovered by Hull et al. (2013) using CARMA, who found that the distribution of the angle between the magnetic field on the  $10^3$  AU-scale and the bipolar outflow axis (taken as a proxy for the rotation axis) is consistent with being random. If true, it would imply that in half of the sources the two axes are misaligned by an angle greater than  $60^\circ$ . Joos et al. (2012) found that such a large misalignment enables the formation of RSDs in moderately magnetized dense cores with a dimensionless mass-to-flux ratio  $\lambda$  of  $\sim 3$ – $5$ ; RSD formation is suppressed in such cores if the magnetic field and rotation axis

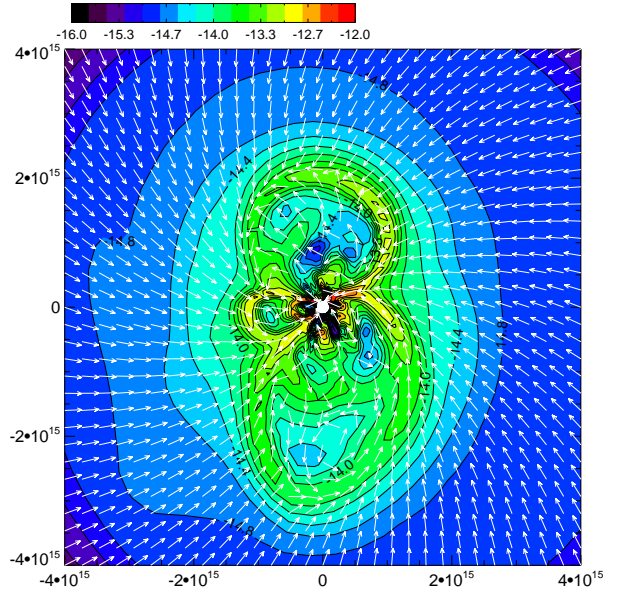


Fig. 4.— An example of the inner protostellar accretion flow driven unstable by magnetic flux redistribution (taken from Krasnopolsky et al. 2012). Plotted are the distribution of logarithm of density (in units of  $\text{g cm}^{-3}$ ) and velocity field on the equatorial plane (the length is in units of cm). The expanding, low-density, regions near the center are the so-called “decoupling-enabled magnetic structure” (DEMS) that are strongly magnetized. They present a formidable barrier to disk formation.

are less misaligned (see Fig. 5). They attributed the disk formation to a reduction in the magnetic braking efficiency induced by large misalignment. In more strongly magnetized cores with  $\lambda \lesssim 2$ , RSD formation is suppressed independent of the misalignment angle, whereas in very weakly magnetized cores RSDs are formed for all misalignment angles.

Based on the work of Hull et al. (2013) and Joos et al. (2012), Krumholz et al. (2013) estimated that the field-rotation misalignment may enable the formation of large RSDs in  $\sim 10$ – $50\%$  of dense cores. If the upper range is correct, the misalignment would go a long way toward solving the problem of excessive magnetic braking in protostellar disk formation.

Li et al. (2013) carried out simulations similar to those of Joos et al. (2012), except for the initial conditions. They confirmed the qualitative result of Joos et al. (2012) that the field-rotation misalignment is conducive to disk formation. In particular, large misalignment weakens the strong outflow in the aligned case and is a key reason behind the formation of RSDs in relatively weakly magnetized cores. For more strongly magnetized cores with  $\lambda \lesssim 4$ , RSD formation is suppressed independent of the degree of misalignment. This threshold value for the mass-to-flux ratio is about a factor of 2 higher than that obtained by Joos et al.

(2012). The difference may come, at least in part, from the different initial conditions adopted: uniform density with a uniform magnetic field for Li et al. (2013) and a centrally condensed density profile with a nonuniform but unidirectional field for Joos et al. (2012); the magnetic braking is expected to be more efficient at a given (high) central density for the former initial configuration, because its field lines would become more pinched, with a longer lever arm for braking. Whether there are other factors that contribute significantly to the above discrepancy remains to be determined.

If the result of Li et al. (2013) is correct, then a dense core must have both a large field-rotation misalignment *and* a rather weak magnetic field in order to form a RSD. This dual requirement would make it difficult for the misalignment alone to enable disk formation in the majority of dense cores, which are typically rather strongly magnetized according to Troland & Crutcher (2008, with a median mass-to-flux ratio of  $\lambda \sim 2$ ). In a more recent study, Crutcher et al. (2010) argued, based on Bayesian analysis, that a fraction of dense cores could be very weakly magnetized, with a dimensionless mass-to-flux ratio  $\lambda$  well above unity (see Bertram et al. 2012 for additional arguments for weak field, including field reversal). However, since the median mass-to-flux ratio remains unchanged for the different distributions of the total field strength assumed in Crutcher’s (2012) Bayesian analysis, it is unlikely for the majority of dense cores to have  $\lambda$  much greater than the median value of 2. For example, Li et al. (2013) estimated the fraction of dense cores with  $\lambda > 4$  at  $\sim 25\%$ . There is also concern that the random distribution of the field-rotation misalignment angle found by Hull et al. (2013) on the  $10^3$  AU scale may not be representative of the distribution on the larger core scale. Indeed, Chapman et al. (2013) found that the field orientation on the core scale (measured using a single dish telescope) is within  $\sim 30^\circ$  of the outflow axis for 3 of the 4 sources in their sample (see also Davidson et al. 2011); the larger angle measured in the remaining source may be due to projection effects because its outflow axis lies close to the line of sight. If the result of Chapman et al. (2013) is robust and if the outflow axis reflects the rotation axis, dense cores with large misalignment between the magnetic and rotation axes would be rare. In such a case, it would be even less likely for the misalignment to be the dominant mechanism for disk formation.

### 3.5. Turbulence

Turbulence is a major ingredient for star formation (see reviews by, e.g., Mac Low & Klessen 2004 and McKee & Ostriker 2007). It can generate local angular momentum by shear flows and form highly asymmetric dense cores (see results from Herschel observations, e.g., Men’shchikov et al. 2010 and Molinari et al. 2010). There is increasing evidence that it also promotes RSD formation. Santos-Lima et al. (2012) contrasted the accretion of turbulent and laminar magnetized gas onto a pre-existing central star, and found

that a nearly Keplerian disk was formed in the turbulent but not laminar case (see Fig. 6). The simulations were carried out at a relatively low resolution (with a rather large cell size of 15.6 AU; this was halved, however, in Santos-Lima et al. 2013, who found similar results), and turbulence was driven to an rms Mach number of  $\sim 4$ , which may be too large for low-mass cores. Nevertheless, the beneficial effect of turbulence on disk formation is clearly demonstrated. They attributed the disk formation to the turbulence-induced outward diffusion of magnetic flux, which reduces the strength of the magnetic field in the inner, disk-forming, part of the accretion flow. Similar results of disk formation in turbulent cloud cores are presented by Seifried et al. (2012b) and Seifried et al. (2013), although these authors attribute their findings to different mechanisms. They argued that the turbulence-induced magnetic flux loss is limited well outside their disks, based on the near constancy of an approximate mass-to-flux ratio computed on a sphere several times the disk size (with a 500 AU radius). They proposed instead that the turbulence-induced tangling of field lines and strong local shear are mainly responsible for the disk formation: the disordered magnetic field weakens the braking and the shear enhances rotation. Similarly, Myers et al. (2013) also observed formation of a nearly Keplerian disk in their radiative MHD simulation of a turbulent massive ( $300 M_\odot$ ) core, although they refrained from discussing the origin of the disk in detail since it was not the focus of their investigation.

Seifried et al. (2013) extended their previous work to include both low-mass and high-mass cores and both subsonic and supersonic turbulence. They found disk formation in all cases. Particularly intriguing is the formation of rotationally dominated disks in the low-mass, subsonically turbulent cores. They argued that, as in the case of massive core with supersonic turbulence of Seifried et al. (2012b), such disks are not the consequence of turbulence-induced magnetic flux loss, although such loss appears quite severe on the disk scale, which may have contributed to the long-term survival of the formed disk. While disks appear to form only at sufficiently high mass-to-flux ratios  $\lambda \geq 10$  in ordered magnetic fields, disks in the turbulent MHD simulations form at much lower and more realistic values of  $\lambda$ . Seifried et al. (2012b) found that  $\lambda$  increases gradually in the vicinity of the forming disk, which may have more to do with the growing accreting mass relative to the magnetic flux than with dissipative effects of the magnetic field by turbulent diffusion or reconnection.

Joos et al. (2013) investigated the effects of turbulence of various strengths on disk formation in a core of intermediate mass ( $5M_\odot$ ). They found that an initially imposed turbulence has two major effects. It produces an effective diffusivity that enables magnetic flux to diffuse outward, broadly consistent with the picture envisioned in Santos-Lima et al. (2012, 2013). It also generates a substantial misalignment between the rotation axis and magnetic field direction (an effect also seen in Seifried et al. 2012b and Myers et al. 2013). Both of these effects tend to weaken magnetic

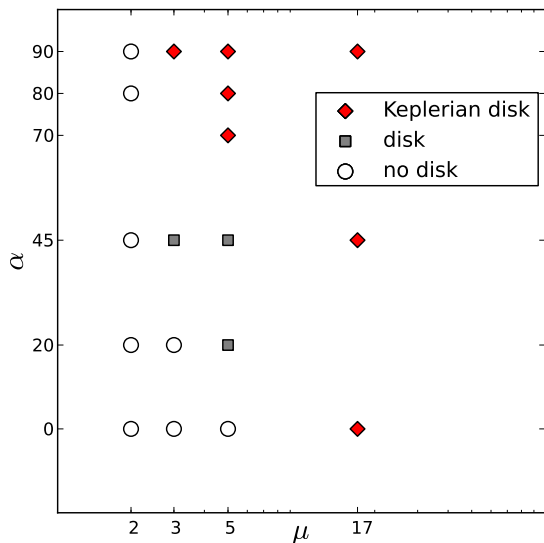


Fig. 5.— Parameter space for disk formation according to Joos et al. (2012). The parameter  $\alpha$  is the angle between the magnetic field and rotation axis, and  $\mu$  is the dimensionless mass-to-flux ratio of the dense core (denoted by  $\lambda$  in the rest of the article). The diamond denotes disks with Keplerian rotation profile, the square those with flat rotation curve, and circle the cases with no significant disk.

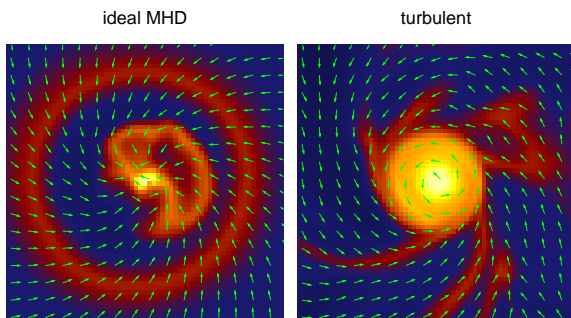


Fig. 6.— Accretion of rotating, magnetized material onto a pre-existing central object with (right panel) and without (left) turbulence (adapted from Santos-Lima et al. 2012). The formation of a nearly Keplerian disk is clearly suppressed in the laminar case (left panel), by excessive magnetic braking, but is enabled by turbulence (right).

braking and make disk formation easier. If the turbulence-induced magnetic diffusion is responsible, at least in part, for the disk formation, then numerical effects would be a concern. In the ideal MHD limit, the diffusion presumably comes from turbulence-enhanced reconnections due to finite grid resolution. Indeed, Joos et al. (2013) reported that their simulations did not appear to be fully converged, with disk masses differing by a factor up to  $\sim 2$  in higher resolution simulations. The situation is further complicated by numerical algorithms for treating magnetic field evolution, especially those relying on divergence cleaning, which could introduce additional artificial magnetic diffusion. To make further progress, it would be useful to determine when and how the reconnections occur and exactly how they lead to the magnetic diffusion that are apparent in the simulations of Joos et al. (2013), Santos-Lima et al. (2012), Li et al. (in preparation) and perhaps Seifried et al. (2012b, 2013).

### 3.6. Other Mechanisms

The magnetic braking catastrophe in disk formation would disappear if the majority of dense cores are non-magnetic or only weakly magnetized ( $\lambda \gtrsim 5$  or even  $\lambda \gtrsim 10$ , see e.g., Hennebelle & Ciardi 2009; Ciardi & Hennebelle 2010; Seifried et al. 2011). However, such weakly magnetized cloud cores are rather unlikely. Although, the recent study by Crutcher et al. (2010) indicates that some cloud cores might be highly supercritical, they are certainly not the majority. Furthermore, consider, for example, a typical core of  $1 M_{\odot}$  in mass and  $10^4 \text{ cm}^{-3}$  in  $H_2$  number density. To have a dimensionless mass-to-flux ratio  $\lambda \gtrsim 5$ , its field strength must be  $B \lesssim 4.4 \mu\text{G}$ , less than the median field strength inferred for the atomic CNM ( $\sim 6 \mu\text{G}$ , Heiles & Troland 2005), which is unlikely. We therefore expect the majority of dense cores to have magnetic fields corresponding to  $\lambda \lesssim 5$  (in agreement with Troland & Crutcher 2008), which are strong enough to make RSD formation difficult.

Another proposed solution is the depletion of the protostellar envelope. The slowly rotating envelope acts as a brake on the more rapidly rotating material closer to the central object that is magnetically connected to it. Its depletion should promote RSD formation. Indeed, Machida et al. (2010) found that envelope depletion is conducive to the formation of large RSDs toward the end of the main accretion phase. This is in line with the expectation of Mellon & Li (2008), who envisioned that most of the envelope depletion is achieved through wind stripping rather than accretion, as would be the case if the star formation efficiency of individual cores is relatively low (say,  $\sim 1/3$ , Alves et al. 2007). Given the ubiquity of fast outflows, their effects on envelope depletion and disk formation should be investigated in more detail.

### 3.7. Summary and Outlook

The formation of rotationally supported disks turns out to be much more complicated than envisioned just a decade

ago. This is because star-forming dense cores are observed to be rather strongly magnetized in general (although the magnetization in a fraction of them can be rather weak, see Crutcher et al. 2010 and discussion above), with a magnetic energy typically much higher than the rotational energy. The field strength is further amplified by core collapse, which tends to concentrate the field lines in the region of disk formation close to the protostar. Both analytic calculations and numerical simulations have shown that the collapse-enhanced (ordered) magnetic field can prevent the RSD formation through catastrophic magnetic braking in the simplest case of ideal MHD limit, aligned magnetic field and rotation axis, and no turbulence. Ambipolar diffusion, the Hall effect, and magnetic interchange instabilities have profound effects on the dynamics of the inner protostellar accretion flow, but they do not appear capable of forming RSDs by themselves under typical conditions. Ohmic dissipation, on the other hand, can enable the formation of at least small, AU-scale disks at early times. How such disks evolve in the presence of the instabilities and other non-ideal MHD effects remains to be quantified. Magnetic field-rotation misalignment is conducive to disk formation, but it is unlikely to enable the formation of RSDs in the majority of dense cores, because of the dual requirement of both a relatively weak magnetic field and a relatively large tilt angle that may be uncommon on the core scale. Turbulence appears to facilitate RSD formation in a number of numerical simulations. It is possible that the turbulence-enhanced numerical reconnection plays a role in the appearance of RSDs in these formally ideal MHD simulations, although turbulence by itself could reduce braking efficiency. The possible role of reconnection needs to be better understood and quantified.

## 4. Early Outflows

### 4.1. Introduction

Generally, low mass young stellar objects are accompanied by highly collimated optical jets (see e.g., Cabrit et al. 1997; Reipurth & Bally 2001) whereas high mass stars are often obscured, hard to observe, and until recently thought to drive much less collimated outflows (e.g., Shepherd & Churchwell 1996a,b; Beuther & Shepherd 2005, and discussion below). Nevertheless, there is strong evidence that the underlying launching process is based on the same physical mechanism, namely the magneto-rotational coupling: magnetic fields anchored to an underlying rotor (e.g., an accretion disk) will carry along gas which will be flung outwards (the same mechanism could also apply to galactic jets, e.g., Pudritz et al. 2007, 2009). For example, Guzmán et al. (2012) concluded that collimated thermal radio jets are associated with high-mass young stellar objects, although for a relatively short time ( $\sim 4 \times 10^4$  yr).

With the seminal theoretical work by Blandford & Payne (1982) and Pudritz & Norman (1983) the idea of magneto-centrifugally driven jets was first established. It was shown that magnetic fields anchored to the disk around a central

object can lift off gas from the disk surface. A magneto-centrifugally driven jet will be launched if the poloidal component of magnetic field is inclined with respect to the rotation axis by more than  $30^\circ$ . Numerical simulations of Keplerian accretion disks threaded by such a magnetic field have shown that these jets are self-collimated and accelerated to high velocities (e.g., Fendt & Camenzind 1996; Ouyed & Pudritz 1997). This driving mechanism, where the launching of the jet is connected to the underlying accretion disk, predicts that jets rotate and carry angular momentum off the disk. The first plausible observational confirmation came from Hubble Space Telescope (HST) detection of rotational signatures in the optical jet of DG Tauri (Bacciotti et al. 2002; see, however, Soker 2005, Cerqueira et al. 2006 and Fendt 2011 for different interpretations of the observation). Further evidence is provided by UV (Coffey et al. 2007) and IR observations (Chrysostomou et al. 2008).

The most viable mechanism to launch jets and wider angle outflows from accretion disks around YSOs is the coupling through magnetic fields where the gas from the disk surface is accelerated by the Lorentz force. Generally, this force can be divided into a magnetic tension and a magnetic pressure term. In an axisymmetric setup, the magnetic tension term is responsible for the magneto-centrifugal acceleration and jet collimation via hoop stress. The magnetic pressure can also accelerate gas off the underlying disk. These magnetic pressure driven winds are sometimes known as *magnetic twist* (Shibata & Uchida 1985), *plasma gun* (Contopoulos 1995), or *magnetic tower* (Lynden-Bell 2003).

Protostellar disks around young stellar objects themselves are the result of gravitational collapse of molecular cloud cores (see Sec. 3). Since the molecular clouds are permeated by magnetic fields of varying strength and morphology (see e.g., Crutcher et al. 1999; Beck 2001; Alves et al. 2008), there should be a profound link between the collapse and magneto-rotationally driven outflows.

There are still many unresolved problems concerning jets and outflows. These include the details of the jet launching, the driving of molecular outflows, the efficiency of outflows around massive protostars, the influence of outflow feedback on star formation, and how efficient they are in clearing off the envelope material around the young stellar object. Shedding light on the last problem will also help determine whether there is a clear physical link between the core mass function (CMF) and IMF (see the chapter by Offner et al. in this volume).

In this section we summarize our knowledge of early jets and outflows and discuss open questions.

### 4.2. Jet Launching and Theoretical Modeling

Self-consistent modeling of jet launching is a challenging task, especially during the earliest phases of star formation, when the core collapse has to be modeled at the same time. The most practical approach to study the self-consistent jet launching during the collapse of self-

gravitating gas is through direct numerical simulation. Even then, the large dynamical range of length scales (from the  $10^4$  AU molecular core to the sub AU protostellar disk) and time scales (from the initial free fall time of  $10^5$  years to the orbital time of one year or less) require expensive adaptive mesh refinement (AMR) or SPH (smoothed particle hydrodynamics) simulations that include magnetic fields. Furthermore, non-ideal MHD effects such as Ohmic dissipation and ambipolar diffusion complicate the calculations (see § 3).

One of the first collapse simulations in which outflows are observed was done more than a decade ago by Tomisaka (1998) with an axisymmetric nested grid technique. These simulations of magnetized, rotating, cylindrical cloud cores showed that a strong toroidal field component builds up, which eventually drives a bipolar outflow. Subsequently, a number of collapse simulations from different groups and different levels of sophistication were performed (among these are work by Tomisaka 2002; Boss 2002; Allen et al. 2003; Matsumoto & Tomisaka 2004; Hosking & Whitworth 2004; Machida et al. 2004, 2005a,b; Ziegler 2005; Machida et al. 2006; Banerjee & Pudritz 2006, 2007; Machida et al. 2007; Price & Bate 2007; Machida et al. 2008; Hennebelle & Fromang 2008; Duffin & Pudritz 2009; Mellon & Li 2009; Commerçon et al. 2010; Bürzle et al. 2011; Seifried et al. 2012). Despite the diversity in numerical approach (e.g. AMR vs. SPH simulations) and initial problem setup, all simulations enforce the same general picture, that magnetically launched outflows are a natural outcome of magnetized core collapse. The details of the outflows generated depend, of course, on the initial parameters such as the degree of core magnetization and the core rotation rate.

#### 4.2.1. Outflow Driving

Traditionally, there is a clear distinction between outflows driven by centrifugal acceleration (Blandford & Payne 1982; Pudritz & Norman 1986; Pelletier & Pudritz 1992) or the magnetic pressure gradient (Lynden-Bell 1996, 2003). A frequently used quantity to make the distinction is the ratio of the toroidal to poloidal magnetic field,  $B_\phi/B_{\text{pol}}$  (e.g. Hennebelle & Fromang 2008). If this ratio is significantly above 1, the outflow is often believed to be driven by the magnetic pressure. However, the consideration of  $B_\phi/B_{\text{pol}}$  alone can be misleading as in centrifugally driven flows this value can be as high as 10 (Blandford & Payne 1982). Close to the disk surface one can check the inclination of the magnetic field lines with respect to the vertical axis. The field lines have to be inclined by more than  $30^\circ$  for centrifugal acceleration to work (Blandford & Payne 1982). Although this criterion is an exact solution of the ideal, stationary and axisymmetric MHD equations for an outflow from a Keplerian disk, its applicability is limited to the surface of the disk. A criterion to determine the driving mechanism above the disk was used by Tomisaka (2002) comparing the centrifugal force  $F_c$  and the magnetic force  $F_{\text{mag}}$ . By projecting both forces on the poloidal magnetic

field lines it can be determined which force dominates the acceleration. For the outflow to be driven centrifugally,  $F_c$  has to be larger than  $F_{\text{mag}}$ . However, for this criterion to be self-consistent the gravitational force and the fact that any toroidal magnetic field would reduce the effect of  $F_c$  have to be taken into account.

In Seifried et al. (2012), a general criterion was derived to identify centrifugally driven regions of the outflows and to differentiate those from magnetic pressure driven outflows. The derivation assumed a stationary axisymmetric flow, which leads to a set of constraint equations based on conservation laws along magnetic field lines (see also Blandford & Payne 1982; Pudritz & Norman 1986; Pelletier & Pudritz 1992). This criterion is applicable throughout the entire outflow.

The general condition for outflow acceleration is (Seifried et al. 2012)

$$\partial_{\text{pol}} \left( \frac{1}{2} v_\phi^2 + \Phi - \frac{v_\phi}{v_{\text{pol}}} \frac{1}{4\pi} \frac{B_\phi B_{\text{pol}}}{\rho} + \frac{1}{4\pi} \frac{B_\phi^2}{\rho} \right) < 0 \quad (1)$$

where  $\partial_{\text{pol}}$  denotes the derivative along the poloidal magnetic field. It describes all regions of gas acceleration including those dominated by the effect of  $B_\phi$ . This general outflow criterion should be compared to the case of centrifugal acceleration where  $B_\phi = 0$ , i.e. in the case with no resulting Lorentz force along the poloidal field line

$$\frac{r}{z} \frac{1}{GM} \left( \frac{v_\phi^2}{r^2} (r^2 + z^2)^{3/2} - GM \right) / \left( \frac{B_z}{B_r} \right) > 1, \quad (2)$$

where  $M$ ,  $r$  and  $z$  are the mass of the central object, the cylindrical radius and distance along  $z$ -axis, respectively. Using both equations, one can distinguish between regions dominated by centrifugal acceleration and those by the toroidal magnetic pressure. Note that Eq. (2) does not assume a Keplerian disk, hence it is also applicable to early-type sub-Keplerian configurations.

An example of those outflow criteria is shown in Fig. 7 where one can see that the centrifugally launched region is narrower and closer to the rotation axis but faster than the outer part of the outflow. Generally, such early type outflows are driven by both mechanisms, i.e. by magnetic pressure and magneto-centrifugal forces, but the centrifugal launching should become more dominant while the underlying disk evolves towards a more stable Keplerian configuration.

Another, indirect, support for the outflow generation mechanism involving magnetic driving comes from a recent numerical study by Peters et al. (2012). Their simulations, which include feedback from ionizing radiation from massive protostars, show pressure driven bipolar outflows reminiscent of those observed around massive stars. But detailed analysis through synthetic CO maps show that the pressure driven outflows are typically too weak to explain the observed ones (e.g., outflows in G5.89 Puga et al. 2006; Su et al. 2012). The failure suggests that a mechanism other

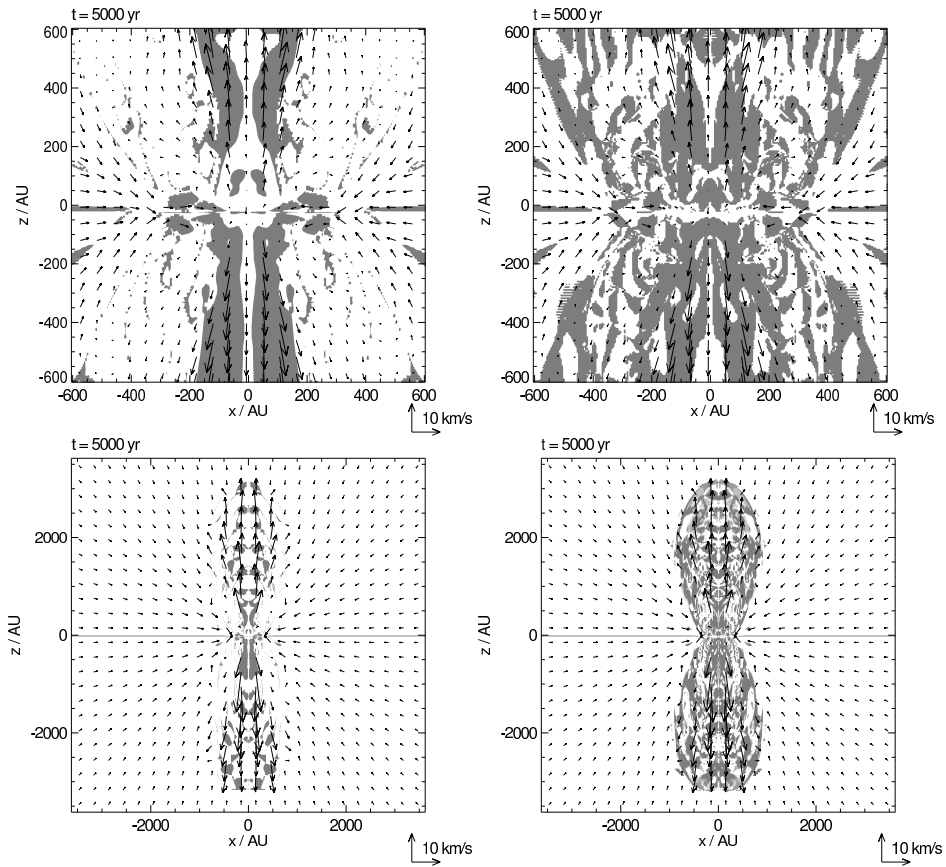


Fig. 7.— Application of the outflow criteria derived in Seifried et al. (2012). The left panels show that centrifugal acceleration works mainly close to the  $z$ -axis up to a height of about 800 AU which agrees very well with the region where the highest velocities are found (see Eq.(2)). The general criterion (see Eq. 1) is more volume filling and traces also regions in the outer parts [from Seifried et al. (2012)].

than ionizing radiation must be found to drive the massive outflows. Since massive star forming regions are observed to be significantly magnetized (e.g., Girart et al. 2009 and Tang et al. 2009), the magnetic field is a natural candidate for outflow driving: the observed massive outflows might be driven magnetically by the massive stars themselves, or by the collection of lower and intermediate-mass stars in the young massive cluster.

#### 4.2.2. Outflow Collimation

A general finding of self-consistent numerical simulations is that the degree of outflow collimation is time dependent and depends on the initial field strength. At very early stages ( $10^3 - 10^4$  yr) outflows in typically magnetized, massive cores (with mass-to-flux ratios of  $\lambda \lesssim 5$ ) are found to be poorly collimated with collimation factors of 1 – 2 instead of 5 – 10, still in agreement with observations of outflows around most young massive protostellar objects (e.g. Ridge & Moore 2001; Torrelles et al. 2003; Wu et al. 2004; Sollins et al. 2004; Surcis et al. 2011). It is suggestive that during the earliest stage, i.e. before the B1–B2-type phase of the scenario described by Beuther & Shepherd (2005), the outflows are rather poorly collimated except in case of an unusually weak magnetic field. In their further evolution, however, the collimation will increase quickly due to the development of a fast, central jet coupled to the build-up of a Keplerian disk. Therefore it might be problematic to directly link the evolutionary stage of the massive young stellar object to the collimation of the observed outflow as suggested by Beuther & Shepherd (2005). Additional difficulties to correlate ages of YSOs and the collimation of outflows arise from the fragmentation of massive disks. For instance, circum-system outflows (from around binaries or higher multiples) from large sub-Keplerian disks at early stages are possible. But those outflows are often uncollimated and might even show spherical morphologies due to fragmentation of the highly unstable accretion disk (e.g., Peters et al. 2011; Seifried et al. 2012). Although, it seems likely that the subsequent outflows from around single massive protostars should be collimated, the evidence from numerical simulations of clustered star formation showing the self-consistent launching of such outflows is still missing due to the lack of resolution.

Direct confirmation of those evolutionary scenarios is difficult as one would need independent information of the age of the YSOs and details of the magnetization of the environment (see also the discussion of Ray 2009). Such observations are hard to obtain and therefore rather rare. However, there is an interesting observation that supports the picture of very early stage, poorly collimated outflows successively collimating over time. Observing two spatially adjacent, massive protostars in the star forming region W75N, Torrelles et al. (2003) and Surcis et al. (2011) find the younger of the two having a spherical outflow whereas the more evolved protostar has a well collimated outflow. Due to their close proximity to each other, they should have

similar environmental conditions. Therefore the difference should rather be a consequence of different evolutionary stages, where the younger, poorly collimated outflow is possibly only a transient.

### 4.3. Feedback by Jets and Outflows

As mentioned earlier, jets and outflows are already present at very early stages of star formation. Hence, their influence on the subsequent evolution within star forming regions may not be neglected. In particular, in cluster forming regions, outflows are believed to influence or even regulate star formation (see also chapters by Krumholz et al. and Frank et al. in this volume) as originally proposed by Norman & Silk (1980). Since then a number of numerical simulations tried to address this issue (e.g., Li & Nakamura 2006; Banerjee et al. 2007; Nakamura & Li 2007; Banerjee et al. 2009; Wang et al. 2010; Li et al. 2010; Hansen et al. 2012), but with different outcomes. Detailed single jet simulations demonstrated that the jet power does not couple efficiently to the ambient medium and is not able to drive volume-filling supersonic turbulence (Banerjee et al. 2007). This is because the bow shock of a highly collimated jet and developed jet instabilities mainly excite sub-sonic velocity fluctuations. Similarly, the simulations by Hansen et al. (2012) showed that protostellar outflows do not significantly affect the overall cloud dynamics, at least in the absence of magnetic fields. Otherwise, the results from simulations of star cluster forming regions (e.g., Li & Nakamura 2006; Nakamura & Li 2007; Wang et al. 2010; Li et al. 2010) clearly show an impact of outflows on the cloud dynamics, the accretion rates and the star formation efficiency. But this seems to be only effective if rather strong magnetic fields and a high amount of initial turbulence are present in those cloud cores. The jet energy and momentum are better coupled to a turbulent ambient medium than a laminar one (Cunningham et al. 2009).

### 4.4. Future Research on Outflows around Protostars

Undoubtedly, jets and outflows from YSOs are strongly linked through the magnetic field to both the disk and surrounding envelope. Deciphering the strength and morphological structure of magnetic fields of jets and outflows will be a key to gain a better understanding of these exciting phenomena. Unfortunately, there are very few direct measurements of magnetic field strengths in YSO jets to date. The situation should improve with the advent of new radio instruments (see also Ray 2009). For example, the *Magnetism Key Science Project* of LOFAR (<http://www.lofar.org>) plans to spatially resolve the polarized structure of protostellar jets to examine their magnetic field structure and to investigate the impact of the field on the launching and evolution of protostellar jets. Prime targets would be the star forming regions of Taurus, Perseus & Cepheus Flare molecular clouds with sub-arc-second resolution. The forthcoming *Square Kilometer Array* (SKA; <http://www.skatelescope.org>) will



also offer unprecedented sensitivity to probe the small scale structure of outflows around protostars (Aharonian et al. 2013).

## 5. Connecting Early Disks to Planet Formation

As we have seen, the first  $10^5$  years in the life of a protostellar disk are witness to the accretion of the bulk of the disk mass, the rapid evolution of its basic dynamics, as well as the most vigorous phase of its outflow activity. This is also the period when the basic foundations of the star’s planetary system are laid down. Giant planet formation starts either by rapid gravitationally driven fragmentation in the more distant regions of massive disks (e.g., Mayer et al. 2002; Rafikov 2009), or by the formation of rocky planetary cores that over longer (Myr) time scales will accrete massive gaseous envelopes (e.g., Pollack et al. 1996, chapter by Helled et al.). Terrestrial planet formation is believed to occur as a consequence of the oligarchic collisional phase that is excited by perturbations caused by the appearance of the giant planets (see chapter by Raymond et al.). There are several important connections between the first phases of planet formation and the properties of early protostellar disks. We first give an overview of some of the essential points, before focusing on two key issues.

At the most fundamental level, the disk mass is central to the character of both star and planet formation. Most of a star’s mass is accreted through its disk, while at the same time, giant planets must compete for gas from the same gas reservoir. Sufficiently massive disks, roughly a tenth of the stellar mass, can in these early stages generate strong spiral waves which drive rapid accretion onto the central star. Such disks are also prone to fragmentation. Early disk masses exceeding  $0.01 M_{\odot}$  provide a sufficient gas supply to quickly form Jovian planets (Weidenschilling 1977). The lifetime of protostellar disks, known to be in the range 3–10 Myr, provides another of the most demanding constraints on massive planet formation. Detailed studies using the Spitzer Space Telescope indicate that 80 % of gas disks around stars of less than  $2 M_{\odot}$  have dissipated by 5 Myr after their formation (Carpenter et al. 2006; Hernández et al. 2008, 2010).

As already discussed, protostellar outflows are one of the earliest manifestations of star formation. Class 0 sources are defined as having vigorous outflows and this implies that magnetized disks are present at the earliest times. Magnetic fields that thread such disks are required for the outflow launching. These fields also have a strong quenching effect on the fragmentation of disks which has consequences for the gravitational instability picture of planet formation. How early does Keplerian behavior set in? Some simulations (e.g., Seifried et al. 2012b) suggest that, even within the first few  $10^4$  years, the disk has already become Keplerian (§ 3) making the launch of centrifugally driven jets all the more efficient. Before this, it is possible that angular momentum transport by spiral waves is significant.

Stars form as members of star clusters and this may have

an effect on disk properties, and therefore, upon aspects of planet formation. Observations show that as much as 90 % of the stars in the galactic disk originated in embedded young clusters (Gutermuth et al. 2009). The disk fraction of young stars in clusters such as  $\lambda$  Orionis (Hernández et al. 2010) and other clusters such as Upper Scorpius (Carpenter et al. 2006) is similar to that of more dispersed groups indicating that the dissipative time scale for disks is not strongly affected by how clustered the star formation process is. We note in passing that the late time dissipation of disks is controlled both by photo-evaporation, which is dominated by the FUV and X-ray radiation fields of the whole cluster and not of the host star, as well as by the clearing of holes in disks by multiple giant planets (see chapter by Espaillat et al.). Calculations show that FUV radiation fields, produced mainly by massive stars, would inhibit giant planet formation in 1/3 to 2/3 of planetary systems, depending on the dust attenuation. However, this photo-evaporation affects mainly the outer regions of disks, leaving radii out to 35 AU relatively unscathed (Holden et al. 2011).

Rocky planetary cores with of order 10 Earth masses are essential for the core accretion picture of giant planets. This process must take place during the early disk phase — the first  $10^5$  years or so (see chapter by Johansen et al.) in order to allow enough time for the accretion of a gas envelope. Therefore the appearance of planetesimals out of which such giant cores are built, must also be quite rapid and is another important part of the first phases of giant planet formation in early protostellar disks. It is important to realize therefore, that the various aspects of non-ideal MHD discussed in the context of disk formation in section 3, being dependent on grain properties, take place in a rapidly evolving situation wherein larger grains settle, agglomerate, and go on to pebble formation.

Finally, a major factor in the development of planetary systems in early disks arises from the rapid migration of the forming planetary cores. As is well known, the efficient exchange of planetary orbital angular momentum with a gaseous disk by means of Lindblad and co-rotation resonances leads to very rapid inward migration of small cores on  $10^5$  year time scales (Ida & Lin 2008; see chapter by Benz et al.). One way of drastically slowing such migration is by means of planet traps — which are regions of zero net torque on the planet that occur at disk (Masset et al. 2006; Matsumura et al. 2009; Hasegawa & Pudritz 2011, 2012). Inhomogeneities in disks, such as dead zones, ice lines, and heat transitions regions (from viscous disk heating to stellar irradiation domination) form special narrow zones where growing planets can be trapped. The early appearance of disk inhomogeneities and such planet traps encodes the basic initial architecture of forming planetary systems. We now turn to a couple of these major issues in more detail.

### 5.1. Fragmentation in Early Massive Disks

Early disks are highly time-dependent, with infall of the core continuously delivering mass and angular momentum

to the forming disk. Moreover, the central star is still forming by rapid accretion of material through the disk. Depending on the infall rate, the disk may or may not be self-gravitating (see below). Disk properties and masses can be measured towards the end of this accretion phase in the Class I sources. A CARMA (Combined Array for Research in Millimeter-wave Astronomy) survey of 10 Class I disks carried out by Eisner (2012) as an example showed that only a few Class I disks exceed  $0.1 M_{\odot}$ , and the range of masses from  $< 0.01$  to  $> 0.1 M_{\odot}$  exceeds that of disks in the Class II phase. This is a tight constraint on the formation of massive planets and already suggests that the process must have been well on its way before even the Class I state has been reached.

Two quantities that control the gravitational stability of a hydrodynamic disk are the ratio of the disk mass to the total mass of the system  $\mu = M_d/(M_d + M_*)$  and the Toomre instability parameter  $Q = c_s \kappa / \pi G \Sigma_d$ , where  $\Sigma_d = M_d / (2\pi R_d^2)$  is the surface mass density of the disk. Heating and cooling of the disk as well as its general evolution alter  $Q$  and infall onto the disk changes  $\mu$  (Kratter et al. 2008). The mass balance in an early disk will depend upon the efficiency of angular momentum transport, which is widely believed to be governed by two mechanisms: gravitational torque as well as the magneto-rotational instability (MRI). Angular momentum transport through the disk by these agents can be treated as “effective” viscosities:  $\alpha_{GI}$  and  $\alpha_{MRI} \simeq 10^{-2}$ . These drive the total disk viscosity  $\alpha = \alpha_{GI}(Q, \mu) + \alpha_{MRI}$ . The data produced by numerical simulations can be used to estimate  $\alpha_{GI}$  in terms of  $Q$  and  $\mu$  (e.g. simulations of Vorobyov & Basu 2005, 2006). The resulting accretion rate onto the central star can be written in dimensionless form as  $\dot{M}_*/M_d\Omega$ , where the epicyclic frequency has been replaced by the angular frequency  $\Omega$  of the disk. The accompanying Fig. 8 shows the accretion rate through the disks in this phase space. The figure shows that the greatest part of this disk  $Q$ - $\mu$  phase space is dominated by MRI transport rather than by gravitational torques from spiral waves. Evolutionary tracks for accreting stars can be computed in this diagram, which can be used to trace the evolution of the disks. Low mass stars will have lower values of  $\mu$ , MRI dominated evolution, masses of order 30 % of the system mass, and have typical outer radii of order 50 AU. High mass stars by comparison are predicted to have high values of  $\mu \simeq 0.35$  and an extended period of local fragmentation as the accretion rates peak, as well as a disk outer edge at 200 AU.

The fragmentation of disks is markedly affected by the presence of significant magnetic fields. One of the main effects of a field is to modify the Toomre criterion. Because part of the action of the threading field in a disk is to contribute a supportive magnetic pressure, the Toomre  $Q$  parameter is modified with the Alfvén velocity  $v_A$  (the typical propagation speed of a transverse wave in a magnetic field);  $Q_M = (c_s^2 + v_A^2)^{1/2} \kappa / \pi G \Sigma_d$ . For typical values of the mass to flux ratio, magnetic energy densities in disk are comparable to thermal or turbulent energy densi-

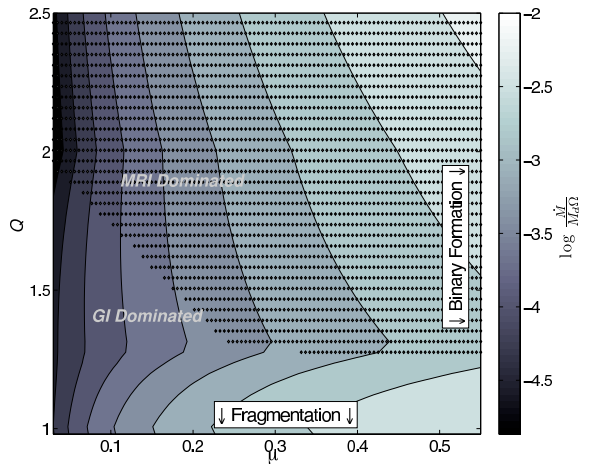


Fig. 8.— Contours of the dimensionless accretion rate  $\dot{M}_*/(M_d\Omega)$  from the disk onto the star from both transport components of the model. The lowest contour level is  $10^{-4.8}$ , and subsequent contours increase by 0.3 dex. The effect of each transport mechanism is apparent in the curvature of the contours. The MRI causes a mild kink in the contours across the  $Q=2$  boundary and is more dominant at higher disk masses due to the assumption of a constant disk turbulence parameter. Adapted from Kratter et al. (2008)

ties. Seifried et al. (2011) find that the magnetic suppression of disk fragmentation occurs in most of their models. Even the presence of ambipolar diffusion of the disk field does not significantly enhance the prospects for fragmentation (Duffin & Pudritz 2009).

Gravitational fragmentation into planets or low mass companions requires that  $Q \sim 1$ , however this is not sufficient. Fragments must also cool sufficiently rapidly as was first derived by Gammie (2001), and generalized by Kratter & Murray-Clay (2011). The condition for sufficiently rapid cooling depends, in turn, upon how the disk is heated. The inner regions of disks are dominated by viscous heating, which changes into dominant radiative heating by irradiation of the disk by the central star, in the outer regions (Chiang & Goldreich 1997). The transition zone between these two regions, which has been called a “heat transition radius” (Hasegawa & Pudritz 2011) is of importance both from the view of gravitation fragmentation (Kratter & Murray-Clay 2011) as well as for the theory of planet traps. This radius occurs where the heating of the surface of the disk by irradiation by the central star balances the heating of the disk at the midplane by viscous heating. Stellar irradiation dominates viscous heating if the temperature  $T$  exceeds a critical value:  $T > [(9/8)(\alpha\Sigma/\sigma)(k/\mu)\tau_R\Omega]^{1/3}$ , where  $\tau_R$  is the Rosseland mean opacity,  $\alpha$  is the viscosity parameter,  $\sigma$  is the Stefan-Boltzmann constant,  $k$  is Boltzmann’s constant, and  $\Omega$  is the orbital angular frequency.

The long term survival of fragments depends upon three different forces including gas pressure, shearing in the disk,

and mutual interaction and collisions (Kratter & Murray-Clay 2011). The role of pressure in turn depends upon how quickly the gas can cool and upon its primary source of energy. Fragmentation in the viscously heated regime — which is where giant planets may typically form — can occur if the ratio of the cooling time to the dynamical time  $\beta$  is sufficiently small for a gas with adiabatic index  $\gamma$ :  $\beta < ([4/9\gamma(\gamma - 1)]\alpha_{sat}^{-1})$ , where the saturated value of the viscous  $\alpha$  parameter refers to the turbulent amplitude that can be driven by gravitational instability. Infall plays an important role in controlling this fragmentation. Generally, a higher infall rate  $\dot{M}$  drives the value of  $Q$  downwards as seen in the Figure. Rapid infall will tend to drive disks closer to instability therefore, and perhaps even on to fragmentation. Irradiated disks, by contrast, have a harder time to fragment. The basic point here is that while gravitationally driven turbulence can be dissipated to maintain  $Q = 1$ , irradiated disks do not have this property. Once an irradiated disk moves into a critical  $Q$  regime, they are more liable to fragment since there is no intrinsic self-regulatory mechanism for maintaining disk temperature near a critical value. The results indicate that irradiated disks can be driven by infall to fragment at lower accretion rates onto the disk.

Spiral arms compress the disk gas and are the most likely sites for fragmentation. A key question is what are the typical masses of surviving fragments. Recent numerical simulations of self-gravitating disks, without infall, have gone much farther into the non-linear regimes to follow the fragmentation into planet scale objects (e.g., Boley et al. 2010; Rogers & Wadsley 2012). Using realistic cooling functions for disks, Rogers & Wadsley (2012) have simulated self-gravitating disks and have found a new criterion for the formation of bound fragments. Consider a patch of a disk that has been compressed into a spiral arm of thickness  $l_1$  (see Figure 9). This arm will form gravitationally bound fragments if  $l_1$  lies within the Hill radius  $H_{Hill} = [G\Sigma_1 l_1^2 / 3\Omega^2]^{1/3}$  of the arm, or:  $(l_1 / 2H_{Hill}) < 1$ .

This criterion also addresses the ability of shear to prevent the fragmentation of the arm. Numerical simulations verify that this criterion describes the survival of gravitationally induced fragments in the spiral arms. The results have been applied to disks around A stars and show that fragments of masses  $15M_{Jup}$  can form and survive at large distances of the order of 95 AU from the central star, in this radiation heating dominated regime. Brown dwarf scale masses seem to be preferred.

Finally we note that clumps formed in the outer parts of disks may collapse very efficiently, perhaps on as little as thousand year time scales. This suggests that clumps leading to the formation of giant planets could collapse quickly and survive transport to the interior regions of the disk (Galvagni et al. 2012). We turn now to planetary transport through disks.

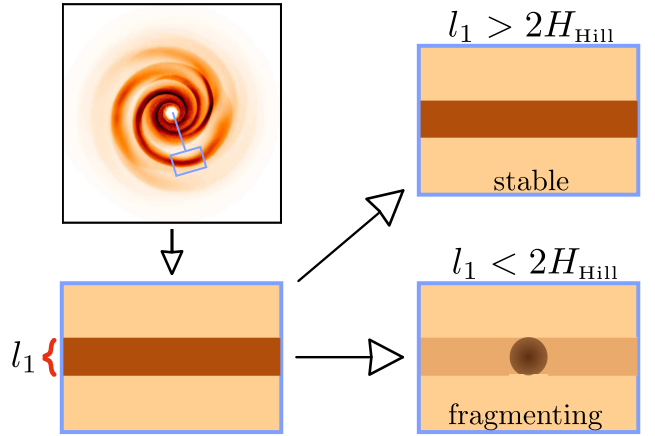


Fig. 9.— The Hill criterion for spiral arm fragmentation: if a piece of the spiral arm of width  $l_1$  lies within its own Hill thickness, then that section of the arm is free to collapse and fragmentation takes place. If such a section of the spiral arm lies outside of its own Hill thickness, then shear stabilizes the arm and fragmentation does not take place. Adapted from Rogers & Wadsley (2012)

## 5.2. Planet Traps and the Growth and Radial Migration of Planets

The survival of planetary cores in early disks faces another classic problem arising from the exchange of orbital angular momentum between the low mass planetary core and its surrounding gaseous disk. In these early phases, protoplanetary cores can raise significant wakes or spiral waves to their interior and exterior radial regions of the disk. These waves in turn exert torques back on the planet resulting in its migration. For homogeneous disks with smooth, decreasing density and temperature profiles, the inner wake (which transfer angular momentum to the protoplanet — driving it outwards) is slightly overcome by the outer wake (which extracts orbital angular momentum from the protoplanet driving it inwards). This results in a net torque which results in the rapid inward (Type I) migration of the planet. As is well known, Monte Carlo population synthesis calculations on protoplanets in evolving accreting disks find that protoplanetary cores migrate into the center of the disk within  $10^5$  years (Ida & Lin 2005, 2008) — the timescale characterizing early disks.

Rapid Type I migration must be slowed down by at least a factor of 10 to make it more compatible with the lifetime of the disk (see chapter by Benz et al.). As noted, this can be achieved in disks at density and temperature inhomogeneities at whose boundaries, migration can be rapidly slowed, or even stopped. We have already encountered two of these in other contexts, namely dead zones and heat transitions wherein there is a change in density and in disk temperature gradient respectively. Heat transitions were shown to be planet traps by (Hasegawa & Pudritz 2011). A third type of trap is the traditional ice line, wherein the temperature transition gives rise to a change in disk opacity with

a concomitant fluctuation in the density (Ida & Lin 2008). Hasegawa & Pudritz (2011, 2012) showed that protoplanetary cores can become trapped at these radii.

Dead zone edges act to stop planetary migration as has been shown in theory (Masset et al. 2006) and numerical simulations (Matsumura et al. 2009). A region that is starved of ionization, which occurs where disk column densities are high enough to screen out ionizing cosmic rays, has large Ohmic dissipation which prevents the operation of the MRI instability. This region is known as a dead zone because it is unable to generate the MHD turbulence necessary to sustain a reasonable viscosity  $\alpha_{MRI}$  (Gammie 1996). A dead zone is most likely to be present in the inner regions of disks in their later stages. During the earliest stages of disk evolution, when the disks are the most massive, these would extend out to 10 AU or so (Matsumura & Pudritz 2006). It is necessary to transport away disk angular momentum to allow an ongoing large accretion flow that is measured for young stars. Older models supposed that a thin surface layer is sufficiently well ionized to support MRI turbulence. Recent simulations show, however, that such MRI active surface layers may not occur (Bai & Stone 2013). The inclusion of all three of the non-ideal effects discussed in § 3 (Ohmic resistivity, Hall effect, and ambipolar diffusion) strongly changes the nature of MHD instability in vertically stratified disks. Going from the dense mid plane to the surface of the disk, the dominant dissipation mechanism changes: from Ohmic resistivity at the mid plane, to Hall effect at mid-scale heights, to ambipolar diffusion in the surface layers. The results show that ambipolar diffusion shuts down the MRI even in the surface layers in the presence of a net (non-zero) magnetic flux through the disk. Instead of the operation of an MRI in the dead zone, a strong MHD disk wind is launched and this carries off the requisite disk angular momentum very efficiently (e.g. review; Pudritz et al. 2007, § 4 of this paper).

Planetary cores accrete most of their mass while moving along with such traps. As the disk accretion rate falls in an evolving disk, the traps move inward at different rates. At early times, with high accretion rates, the traps are widely separated. As the disk accrete rate falls from a high of  $10^{-6}M_{\odot} \text{ yr}^{-1}$  to lower values at later times, the traps slowly converge at small disk radii, which likely initiates planet-planet interactions.

In summary then, this section has shown that the properties of early magnetized disks as characterized by high infall rates and disk masses, as well as powerful outflows, can strongly influence the early phases of planet formation and migration.

## 6. Synthesis

Both observational and theoretical studies of disk formation are poised for rapid development. Observationally, existing dust continuum surveys of deeply embedded “Class 0” objects indicate that a compact emission component apparently distinct from the protostellar envelope

is often present. Whether this component is a rotationally supported disk (RSD) or not is currently unclear in general. With unprecedented sensitivity and resolution, ALMA should settle this question in the near future.

On the theoretical side, recent development has been spurred largely by the finding that magnetic braking is so efficient as to prevent the formation of a RSD in laminar dense cores magnetized to realistic levels in the ideal MHD limit — the so-called “magnetic braking catastrophe.” Although how exactly this catastrophe can be avoided remains unclear, two ingredients emerge as the leading candidates for circumventing the excessive braking — Ohmic dissipation and complex flow pattern (including turbulence, misalignment of magnetic field and rotation axis, and possibly irregular core shapes): the former through the decoupling of magnetic field lines from the bulk neutral matter at high densities and the latter through, at least in part, turbulence/misalignment-induced magnetic reconnection. It is likely that both ingredients play a role, with Ohmic dissipation enabling a dense, small (perhaps AU-scale) RSD to form early in the protostellar accretion phase, and flow complexity facilitating the growth of the disk at later times by weakening the magnetic braking of the lower density protostellar accretion flow.

The above hybrid picture, although probably not unique, has the virtue of being at least qualitatively consistent with the available observational and theoretical results. The small Ohmic dissipation-enabled disk can in principle drive powerful outflows that are a defining characteristic of Class 0 sources from close to the central object where the magnetic field and matter are well coupled due to thermal ionization of alkali metals. During the Class 0 phase, it may have grown sufficiently in mass to account for the compact component often detected in interferometric continuum observations, but not so much in size as to violate the constraint that the majority of the compact components remain unresolved to date. The relatively small size of early disks could result from magnetic braking.

A relatively small early disk could also result from a small specific angular momentum of the core material to begin with. There is a strong need to determine more systematically the magnitude and distribution of angular momentum in prestellar cores through detailed observations. Another need is to determine the structure of the magnetic fields on the  $10^2$ – $10^3$  AU scale that is crucial to disk formation. For example, detection of magnetic field twisting would be direct evidence for magnetic braking. With the polarization capability coming online soon, ALMA is expected to make progress on this observational front.

On the theory front, there is a strong need to carry out simulations that combine non-ideal MHD effects with turbulence and complex initial conditions on the core scale, including magnetic field-rotation misalignment. This will be technically challenging to do, but is required to firm up disk formation scenarios such as the hybrid one outlined above.

All of the evidence and theory shows that the formation of outflows is deeply connected with the birth of magne-

tized disks during gravitational collapse. Early outflows and later higher speed jets may be two aspects of a common underlying physical picture in which acceleration is promoted both by toroidal magnetic field pressure on larger scales as well as centrifugal “fling” from smaller scales. Simulations, theory, and observations are converging on the idea that the collapse and outflow phenomenon is universal covering the full range of stellar mass scales from brown dwarfs to massive stars. Finally, the earliest stages of planet formation take place on the very same time scales as disks are formed and outflows are first launched. While little is yet known about this connection, it is evident that this must be important. Many aspects of planet formation are tied to the properties of early disks.

In summary, firm knowledge of disk formation will provide a solid foundation for understanding the links between early disks, outflows, and planets, opening the way to discovering the deep connections between star and planet formation.

**Acknowledgments.** ZYL is supported in part by NASA NNX10AH30G, NNX14AB38G, and NSF AST1313083, RB by the Deutsche Forschungsgemeinschaft (DFG) via the grant BA 3706/1-1, REP by a Discovery Grant from the National Science and Engineering Research Council (NSERC) of Canada, and JKJ by a Lundbeck Foundation Junior Group Leader Fellowship as well as Centre for Star and Planet Formation, funded by the Danish National Research Foundation and the University of Copenhagen’s programme of excellence.

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