ABSTRACT

Isolated low-mass stars are formed, in the standard picture, from the collapse of dense cores condensed out of strongly magnetized molecular clouds. The dynamically collapsing inflow traps nearly half of the critical magnetic flux needed for the core support and deposits it in a small region surrounding the protostar. It has been argued previously that the deposited flux can slow down the inflow, allowing matter to pile up and settle along field lines into a magnetically supported, circumstellar disk. Here we show that the disk typically contains ~10% of the stellar mass and that it could become self-gravitating under plausible conditions during the rapidly accreting, “Class 0” phase of star formation. Subsequent fragmentation of the self-gravitating, magnetically subcritical disk, driven by magnetic diffusion, could produce fragments of substellar masses, which collapse to form brown dwarfs and possibly massive planets. This scenario predicts substellar object formation at distances of order 100 AU from the central star, although orbital evolution is possible after formation. It may provide an explanation for the small, but growing, number of brown dwarf companions found around nearby stars by direct imaging. The relatively large formation distances make the substellar companions vulnerable to dynamic ejection, particularly in multiple systems and dense clusters. Those ejected may account for, at least in part, the isolated brown dwarfs and perhaps free-floating planetary mass objects.

Subject headings: accretion, accretion disks — ISM: clouds — MHD — stars: formation — stars: low-mass, brown dwarfs

1. INTRODUCTION

The past several years have witnessed remarkable progress in the study of brown dwarfs (Basri 2000). To date, more than 200 of such objects have been discovered. Most are found in isolation; only a small fraction orbit around stars, typically at separations of tens of AU and beyond. Despite the impressive pace of discovery, investigation into their origins has only just begun. The isolated brown dwarfs could be formed in small multiple systems through cloud fragmentation like stars but ejected through interaction with other (heavier) members before gaining enough mass for hydrogen burning (Reipurth & Clarke 2001). The brown dwarf companions could in principle be produced in (rotationally supported) circumstellar disks through gravitational fragmentation, although it is unclear whether the conditions for fragmentation can arise naturally during star formation (Durisen 2001). In this Letter, we advance a new scenario for forming substellar companions, through the gravitational fragmentation of magnetically, rather than rotationally, supported disks. Such disks are expected to develop around protostars formed out of strongly magnetized clouds (Li & McKee 1996, hereafter LM96), as envisioned in the standard picture of isolated low-mass star formation (Shu, Adams, & Lizano 1987).

Conceptually, the formation of magnetically supported disks parallels that of the more familiar rotationally supported disks. Once gravity has initiated the dynamic collapse of a rotating magnetized dense core of a molecular cloud, both the magnetic flux and the angular momentum associated with rotation are trapped by the collapsing flow and carried to the vicinity of the protostar. However, both must eventually be stripped almost completely from the matter before it enters the star; otherwise, the stellar magnetic field strength and rotation rate would be many orders of magnitude higher than actually observed. These are, respectively, the magnetic flux and angular momentum problem of star formation. The stripping of angular momentum is thought to take place primarily in a rotationally supported disk by friction between adjacent annuli of matter moving at different speeds. The mechanism for magnetic flux stripping is less clear. LM96 proposed that it occurs as the field lines decoupled from the stellar matter expand against the collapsing inflow, reversing the inward motion of charged particles and the magnetic field tied to them. The bulk neutral material can still slip through, but only at a much reduced speed because of frequent collisions with the already stopped charged particles. The slowdown causes the infalling matter to pile up and settle along field lines into a flattened structure—a magnetically supported circumstellar disk (see also Ciolek & Königl 1998 and Contopoulos, Ciolek, & Königl 1998).

We show in this Letter that the magnetically supported disk could become self-gravitating under plausible conditions during the earliest, “Class 0” phase of star formation, when the accretion rate is highest (§ 2). The self-gravitating disk is magnetically subcritical, and fragmentation driven by magnetic diffusion could lead to substellar object formation (§ 3). We discuss the expected characteristics of the substellar companions and their observational implications in § 4.

2. SELF-GRAVITATING MAGNETICALLY SUPPORTED DISKS

We consider the simplest case of an axisymmetric non–self-gravitating disk and derive a condition for the disk to become self-gravitating around a single, isolated star $M_\ast$; possible non-axisymmetric effects will be commented on toward the end of the section. We estimate the disk properties in a way similar to LM96 but include the magnetic compression, which controls the disk density, and the magnetic tension force, which dom-
inates the magnetic pressure gradient in the radial force balance:

$$\frac{GM_*}{r^2} \approx \frac{B_S^2}{2\pi\Sigma}.$$  (1)

We show below that the disk column density $\Sigma$ is roughly independent of the cylindrical radius $r$. To counter the larger stellar gravity at a smaller radius, the field strength must increase inward, roughly as $r^{-1}$. For such a distribution, the radial and vertical field components are comparable on the disk (assuming a potential field outside as usual). They are

$$B_r \approx B_z \approx (2\pi G \Sigma M_\star)^{1/2} r.$$  (2)

The magnetic flux enclosed within a disk of radius $R$ is

$$\Phi_d = \int_0^R 2\pi B_r r \, dr \approx 2\pi R (2\pi G \Sigma M_\star)^{1/2}.$$  (3)

Since this flux is mostly that stripped from the stellar mass $M_\star$ (LM96), we have $\Phi_d \approx \Phi_* = (2\pi G \Sigma M_\star)^{1/2}$, where $\epsilon(\approx 1)$ is the flux-to-mass ratio of the dynamically collapsing envelope that feeds the star-disk system in units of the critical value $2\pi G \Sigma M_\star$. Eliminating $\Phi_*$ from equation (3), we obtain the following estimate of the disk mass:

$$M_d \approx \pi R^2 \Sigma \approx 0.5 \epsilon^2 M_\star,$$  (4)

which is simply the mass needed to "weave down" the magnetic flux released from the star and prevent it from escaping. Even though the star-disk system remains magnetically supercritical, the disk (which contains a small fraction of the mass of the system but most of its flux) is subcritical, by a factor of $\approx 2/\epsilon$. Calculations of the evolution of strongly magnetized clouds driven by ambipolar diffusion suggest that $\epsilon$ is close to $\frac{1}{2}$ (e.g., Nakamura & Li 2002). This value would yield a disk mass of $\approx 10\%$ of the stellar mass, or some $10^2$ Jupiter masses for solar mass stars. Therefore, there appears to be enough matter in the disk to form one brown dwarf near the hydrogen-burning limit, a few less massive brown dwarfs, or several massive planets.

The mass density $\rho$ of the disk is determined by balancing the outward thermal pressure gradient in the vertical direction against the squeezing of the stellar tidal force, disk self-gravity, and the radial component of the magnetic field. It is easy to show that the magnetic contribution dominates and that

$$\rho \approx \frac{B^2}{8\pi a^2} \approx \frac{GM_* \Sigma}{4a^2 r^2},$$  (5)

where $a = 0.188T_{10}^{1/2}$ km s$^{-1}$ is the isothermal sound speed and $T_{10} \equiv T/10$ K. Equation (2) was used to derive the second relation. The column density $\Sigma$ at any radius $r$ is related to the local mass accretion rate $\dot{M}$ and infall speed $V$ through $\Sigma = M_l/(2\pi r V)$. Approximately, $V$ is the speed with which the bulk neutral matter slips across the field lines, which remain more or less fixed in space (LM96). The slippage speed can be written as a product of the magnetic force per unit mass ($\approx GM_\star / r^2$) and the magnetic coupling time $t_c$. The latter is related to the local free-fall time $t_{ff} = (3\pi/32G\rho)^{1/2}$ through $t_c = t_{ff}/t_{ff}$, where the characteristic flux loss time $t_{ff}$ from a magnetically supported cloud has been discussed extensively by Nakano and collaborators. According to Nakano, Nishi, & Umebayashi (2002, see their Fig. 3), $t_{ff}$ is a factor of $\sim 10^{-10}$ larger than $t_{ff}$ up to a density of $\sim 10^{-10}$ cm$^{-3}$ for a cosmic-ray ionization rate of $\sim 10^{-15}$ to $10^{-16}$ s$^{-1}$ and the grain size distribution of Mathis, Rumpl, & Nordsiek (1977). It drops below $t_{ff}$ beyond $\sim 10^{15}$ cm$^{-3}$, as both ions and charged grains become decoupled from the field lines. The decoupling density depends somewhat on the grain size distribution. It could be increased significantly owing to rapid grain growth and/or sedimentation toward the disk midplane (Sano et al. 2000). We will concentrate on the part of the disk that is well coupled to the magnetic field (which makes mass pileup possible), and adopt $t_{ff} = 20t_{ff}$ for a rough estimate. In this case, $t_{ff} = t_{ff}/20$ and the column density is given by

$$\Sigma \approx \frac{9M_\star^2}{a^2 \dot{M}_\star} = 5\dot{m}^2 m_\star^{-1} T_{10}^{-1} \text{ g cm}^{-2},$$  (6)

where $\dot{m}$ is the accretion rate normalized by $10^{-5} M_\odot$ yr$^{-1}$ and $m_\star$ the stellar mass in units of solar masses. As already mentioned, the column density is roughly independent of radius $r$ as long as the accretion rate does not vary much over the disk and the disk is more or less isothermal. For a canonical dust opacity of 0.01 cm$^2$ g$^{-1}$, the disk is typically optically thin, making the isothermal approximation justifiable.

In the absence of a strong magnetic field, a circumstellar disk becomes gravitationally unstable when the radius of a Jeans mass clump is smaller than the Roche value. This condition roughly corresponds to the Toomre's criterion (e.g., Shlosman & Begelman 1989),

$$Q = \frac{a \Omega}{\pi G \Sigma} \lesssim 1,$$  (7)

where $\Omega = (GM_\star / r^3)^{1/2}$ is the Keplerian frequency, even though the disk is not rotationally supported. The presence of a strong magnetic field does not suppress the Jeans instability in the lightly ionized disk; it merely lengthens the growth timescale (Langer 1978; see § 3 for further discussion). Near the outer edge of the disk,

$$R \approx (M_d / \Sigma)^{1/2} \approx 2.6 \times C_{Q_{1/2}}^{-1/2} \rho_{1/2}^3 T_{10}^{1/2} \text{ AU},$$  (8)

where most of the disk mass is located, the Toomre $Q$-parameter has the approximate value

$$Q_{1/2} \approx 0.8 C_{Q_{1/2}}^{-1/2} \rho_{1/2}^3 T_{10}^{1/4},$$  (9)

where $C_{Q_{1/2}}$ is the flux-to-mass ratio $\epsilon$ normalized by the typical value of $\frac{1}{2}$. The most uncertain quantity in the above expression is the accretion rate $\dot{m}$. If it is large enough ($\dot{m} \approx 1$), the disk could become self-gravitating (i.e., $Q_s < 1$).

Low-mass protostars are thought to grow most rapidly during the so-called Class 0 phase (André, Ward-Thompson, & Barsony 2000), which lasts for only a few times $10^4$ yr. To accrete the bulk of the mass of Sun-like stars over such a short period of time, the accretion rate must be of order $10^{-3} M_\odot$ yr$^{-1}$ or higher. Such high accretion rates are inferred from the observations of molecular outflows from Class 0 sources (Bontemps et al. 1996) and found in core-collapse calculations (e.g., Tomisaka 1996; Li 1998). We conclude that during the Class 0 phase of star formation, the magnetically supported disk could become self-gravitating and thus prone to fragmentation into
small pieces. Before discussing fragmentation, we comment on a possible complication.

The disk has a flux-to-mass ratio $B/\Sigma$ increasing toward the center and should be unstable to (nonaxisymmetric) interchange instability (LM96; Ciolek & Königl 1998) according to the criterion of Spruit & Taam (1990), derived in the limit of a frozen-in magnetic field and no self-gravity. Nonlinear developments of the instability could potentially drain the disk material faster than estimated above and thus prevent the disk from becoming self-gravitating. However, in our case the magnetic field is not frozen in the matter and the disks relevant to companion formation are self-gravitating. Moreover, a realistic disk would have a significant amount of differential rotation and be magnetically linked to the surrounding medium, both of which tend to stabilize the instability (Spruit, Stehle, & Papaloizou 1995), as does the (likely differential) twisting of the disk field lines associated with magnetic braking (Sakurai 1989). Nonaxisymmetric calculations are needed to ascertain whether the combination of magnetic diffusion, self-gravity, rotation, and field line linkage and twisting can suppress the instability altogether and, if not, to what extent nonlinear developments of the instability modify the disk structure.

3. MAGNETIC DIFFUSION–DRIVEN DISK FRAGMENTATION

The disk is magnetically subcritical. If frozen in matter, the magnetic field would prevent fragmentation completely (Nakano 1988). However, in a lightly ionized medium, the presence of a strong magnetic field does not change the criterion for fragmentation; rather, the fragmentation occurs on the (longer) timescale for the magnetic field to diffuse out of a fragment of Jeans radius $R_\text{p}$ (obtained from eqs. [5], [6], and [8]), we find

$$M_\text{f} = \frac{1.17 a^4}{G^2 \Sigma} \approx 3 \times 10^{-3} m_2^2 m_3 T_{10}^3 M_\odot.$$  

It corresponds to $\sim 3$ times the Jupiter mass ($M_\text{Jup}$) for typical parameters, which is in the planetary mass range. This typical Jeans mass is smaller than the oft-quoted opacity-limited minimum value ($\sim M_\text{Jup}$). Low & Lynden-Bell 1976; Silk 1977), although in a disk geometry where radiation can escape more easily this minimum could be lower.

Without a magnetic field, a self-gravitating fragment of one Jeans mass will contract in a shorter time onto itself than toward the central star. This remains true even in the presence of a strong magnetic field, since both timescales are lengthened by the same factor, set by magnetic diffusion. The timescale for the magnetic field to diffuse out of a fragment of Jeans radius $R_\text{f} = (M_\text{f}/\Sigma)^{1/2}$ is set roughly by $\tau \approx R_\text{f}/V$, where $V \approx \epsilon_{\text{f}}(GM_*/R_\text{f}^2)$ is the slippage speed of neutral matter across field lines driven by self-gravity. Adopting the same approximation for the magnetic coupling time $t_\text{ff} \approx t_\text{ff}/20$ as before, and computing the free-fall time $t_\text{ff}$ near the disk outer edge where

$$\rho_\text{ff} \approx 3 \times 10^{-14} \epsilon_{\text{f}}^2 m_2^4 m_3^2 T_{10}^{-3} \text{ g cm}^{-3}$$  

(derived from eqs. [5], [6], and [8]), we find

$$\tau \approx 3 \times 10^4 \epsilon_{\text{f}}^2 m_2^{-2} m_3 T_{10}^{12} \text{ yr},$$

which for typical parameters is comparable to the lifetime of the Class 0 phase. Once the fragment has become magnetically supercritical, it collapses dynamically from inside out to form one or more substellar objects, as in the standard scenario for forming isolated low-mass stars through ambipolar diffusion (Shu et al. 1987). The main difference lies in the density of the background, magnetically subcritical material, which is of order $\sim 10^{-20}$ g cm$^{-3}$ in the stellar case but $\sim 10^{-14}$ g cm$^{-3}$ in the substellar case. The density, of course, sets the mass scale (for an $\sim 10$ K gas). In the substellar case, the density is high enough that magnetic decoupling could be a potential problem; its complete treatment is hindered by uncertainties in the grain properties of the disk.

We therefore arrive at the following plausible scenario for the production of substellar companions, based on the standard picture of isolated low-mass star formation. To avoid the famous “magnetic flux problem,” most of the magnetic flux originally trapped by the collapsing core material that enters the star must be stripped and deposited in a magnetically supported disk containing $\sim 10\%$ of the stellar mass. If the disk material is not drained at too large a speed by interchange instability and/or magnetic decoupling, it could achieve a high enough surface density during the Class 0 phase to become self-gravitating. Subsequent contraction of self-gravitating pockets of substellar masses across field lines, over a magnetic diffusion timescale comparable to the Class 0 lifetime, could produce magnetically supercritical fragments, which collapse to form substellar companions. This scenario does not involve rotation directly and should not be affected by density waves, which tend to suppress gravitational fragmentation of rotationally supported disks (Durisen 2001).

4. IMPLICATIONS FOR BROWN DWARF COMPANIONS

If the substellar companions are formed from the fragmentation of magnetically supported disks, they should have initial masses between the opacity-limited Jeans mass, which is in the (upper) planetary mass range, and the disk mass, typically comparable to that of a massive brown dwarf. Further mass increase by accretion from the residual envelope is possible but probably not by much because of the rapid decline of the overall accretion rate after the Class 0 phase, as a result of, e.g., the powerful protostellar wind unbinding much of the envelope. If substantial mass accretion does occur, the substellar objects may be turned into (very) low mass stellar companions.

A prediction of our scenario is that the substellar companions should form at distances of a few hundred AU from the central star, set by the typical size of the self-gravitating disk (see eq. [8]). Interestingly, more than half of the brown dwarf companions detected so far have separations in the range of 50–300 AU (see Reid et al. 2001 for a compilation). The orbits could shrink after formation for several reasons: First, the disk material out of which the objects form was mainly magnetically supported and thus sub-Keplerian. Indeed, the slowdown of radial infall in the disk, coupled with the presence of a strong magnetic field, allows magnetic braking to operate more efficiently, which could remove a large fraction of the disk angular momentum, similar to the case of magnetically subcritical clouds (Basu & Mouschovias 1994). Second, the substellar objects could transport some of their orbital angular momentum to the residual envelope by raising tides in it. In addition, since the disk contains more than one Jeans mass, more than one object could form from its fragmentation, with the ejection of all but one as a likely outcome of gravitational interactions. The final orbit of the remaining object could tighten by a large factor and tend to be highly eccentric (Papaloizou & Terquem 2001). Under extreme
conditions, these interactions could in principle explain the smaller separations of Gliese 86B (~19 AU; Els et al. 2001) and HR 7672B (~14 AU; Liu et al. 2002). To send a brown dwarf even closer in, say, to the ~3 AU distance of HD 168443c (Marcy et al. 2001), would be even more difficult, consistent with the well-known dearth of brown dwarf companions within ~4 AU of solar-type FGK stars—the so-called brown dwarf desert. For the same reason, our scenario may produce (massive) extrasolar giant planets on relatively wide orbits of tens to hundreds of AU but unlikely those within a few AU of their host stars detected through radial velocity surveys. These close-in planets are presumably formed in rotationally supported disks, possibly through the conventional core-nucleation mechanism. Their orbital evolution may be affected, however, by the presence of substellar companions at larger distances.

The substellar companions can also increase their orbital separations after formation, through gravitational interaction with the Keplerian disks they enclose. If formed in binary (or multiple) systems or dense clusters, they would likely be ejected through dynamic interactions, given their relatively large formation distances from the central star (Reipurth & Clarke 2001), although some may remain bound on wider orbits. Such interactions could in principle explain the few thousand AU separations of the brown dwarf companions found in the Two Micron All Sky Survey and follow-up observations, including Gl 570D, Gl 417B, Gl 584C, Gl 337C, and possibly HD 89744B and Gl 618.1B (Kirkpatrick et al. 2001; Wilson et al. 2001). Those ejected could account for, at least in part, the isolated brown dwarfs and possibly the free-floating planetary mass objects that may have been uncovered in σ Orionis ( Zapatero Osorio et al. 2000) and elsewhere.

An aesthetically appealing feature of our scenario is that the brown dwarf companions are produced in essentially the same manner as the isolated low-mass stars envisioned in the standard picture, through the magnetic diffusion–driven fragmentation of a strongly magnetized, self-gravitating medium. Two common products of the fragmentation in the stellar case are circumstellar disks and binaries. By analogy, we expect disks and binaries to result from the fragmentation in the substellar case as well. A surrounding disk could explain the infrared excess observed in the young brown dwarf in the GG Tau quadruple system (White et al. 1999), and brown dwarf pairs have been detected (Basri 2000). Dynamical ejection from the 10^2 AU scale distance from a Sun-like low-mass star should leave intact the inner part of the disk (within a few AU of the brown dwarf) or tightly bound pairs. The former is consistent with the inference of disks around young isolated brown dwarfs (Muench et al. 2001) and the latter with the dearth of isolated brown dwarf binaries with separations greater than ~10 AU (Reid et al. 2001).

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