THE ASTROPHYSICAL JOURNAL, 508:707–713, 1998 December 1

DO PROTO-JOVIAN PLANETS DRIVE OUTFLOWS?

A. C. QUILLEN[1] AND D. E. TRILLING[2]

Received 1997 December 2; accepted 1998 June 30

ABSTRACT

We discuss the possibility that gaseous giant planets drive strong outflows during early phases of their formation. We consider the range of parameters appropriate for magneto-centrifugally driven stellar and disk outflow models and find that, if the proto-Jovian planet or accretion disk had a magnetic field of $\gtrsim 10$ G and moderate mass-inflow accretion rates through the disk of less than $\sim 10^{-7} M_J$ yr^{-1}, it is possible to drive an outflow. Estimates based both on scaling from empirical laws observed in protostellar outflows and the magneto-centrifugal disk and stellar plus disk wind models suggest that winds with mass-outflow rates of order $10^{-8} M_J$ yr^{-1} and velocities of order ~ 20 km s^{-1} could be driven from proto-Jovian planets. Prospects for detection and some implications for the formation of the solar system are briefly discussed.

Subject headings: ISM: jets and outflows — MHD — planetary systems — stars: mass loss — stars: pre–main-sequence

1. INTRODUCTION

Outflows and jets are ubiquitous in astronomy and are observed in a wide range of astrophysical objects ranging from active galactic nuclei on the largest and most energetic scales, to X-ray binaries and protostars on the smallest scales. One property that these objects have in common is that they are suspected to be undergoing accretion from a gaseous disk. It is possible that outflows play a crucial role in removing angular momentum from an accretion disk (e.g., Shu, Adams, & Lizano 1987) and so are a natural consequence of accretion.

The prograde, low-eccentricity, equatorial, low-inclination orbits of the regular satellites of the giant planets of our solar system suggest that these planets had disks during some phase of their formation. Additionally, the Galilean satellites have densities that decrease with increasing distance from Jupiter (Io, Europa, Ganymede, and Callisto, from innermost to outermost). If the satellites formed from a gaseous disk, then this decrease in density, due to an increase in volatile contents, suggests that the temperature of the circum-Jovian disk varied with radius. The early circum-Jovian environment can be viewed as analogous in many ways to a forming planetary system (Stevenson, Harris, & Lunine 1986). However, we note that formation models for the Galilean satellites are varied and not necessarily straightforward (e.g., Lunine & Stevenson 1982; Anderson et al. 1997; McKinnon 1997; Coradini et al. 1989; Prinn & Fegley 1981; Prinn 1993; Korycansky, Bodenheimer, & Pollack 1991; Korycansky et al. 1990; Pollack, Lunine, & Tittemore 1990). Fluid simulations of gaseous planet formation can also show such an accretion disk. Because Jovian planets have strong magnetic fields and could have had accretion disks, we are prompted to consider the possibility that they, too, produced magnetically accelerated outflows during some early phase of their formation.

[1] Steward Observatory, University of Arizona, Tucson, AZ 85721; aquillen@as.arizona.edu.
[2] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; trilling@lpl.arizona.edu.

In protostellar objects, observations show that the mechanical energy in thrust, carried in molecular outflows, can be large compared with the bolometric luminosity of the central young stellar object (Lada 1985). As a result, the acceleration mechanism cannot rely on radiation pressure alone, and other forces are required to drive the outflow. The notion that rapid rotation coupled with strong magnetic fields could drive outflows was explored in the context of the solar wind by Mestel (1968). Subsequently, Blandford & Payne (1982) introduced an elegant, scale-free hydromagnetic wind model for jet acceleration from a magnetized disk that gives centrifugally driven wind solutions. These solutions also have the possibility of being self-collimated (Heyvaerts & Norman 1989). Similar outflow models were applied directly to protostellar objects (Pudritz & Norman 1983; Königl 1989; Pelletier & Pudritz 1992; Hartmann & MacGregor 1982, and others). One requirement of the disk magneto-centrifugal wind models is that the field lines bend outward from the disk by more than 30° from the normal to the disk. However, it is unclear how the internal disk structure maintains this field geometry (Wardle & Königl 1993; see the review of Shu 1993). This problem provoked a modification of the stellar and disk wind-accelerated model of Shu et al. (1988), commonly referred to as the X-wind model (Shu et al. 1994a, 1994b, 1995), which considers the truncation of the accretion disk from the magnetosphere of the spinning central protostar.

The mechanical luminosity and force or thrust (rate of momentum injection) of bipolar molecular outflows scales with the radiant luminosity of the driving stellar source (Lada 1985; Cabrit & Bertout 1992). The possibility that low-mass (brown dwarf or lower mass) companions in binary systems might drive outflows was suggested by Wolk & Beck (1990), who scaled from properties observed empirically in protostellar outflows and argued that brown dwarfs would be capable of driving outflows.

In this section we discuss why or why not we might expect the accretion physics of Jovian (or giant) planets to be similar to that of low-mass protostars. In § 2 we estimate ranges for the magnetic field, the accretion rate in the disk, and the radius for which magneto-centrifugal outflow models could operate. In § 3, with a similar approach to that of Wolk & Beck (1990), we compare outflow velocities and mass-outflow rates consistent with the empirical scaling laws to those appropriate for the theoretical models.

1.1. *Why Might the Physics of Accretion Be Similar for Protostars and Proto-Jovian Planets?*

We first mention the relevance of the magnetic field under physical conditions appropriate to protostellar and proto-Jovian disks. As is true in the inner radii of protostellar disks (e.g., Gammie 1996; Shu et al. 1994a), within a few planetary radii the proto-Jovian disk is expected to be above 1000 K (Lunine & Stevenson 1982), and so thermal ionization results in a sufficiently high ionization fraction that the gas and magnetic field are well coupled (Takata & Stevenson 1996). Below a temperature of 1000 K, thermal ionization does not dominate. However, ionization caused by cosmic rays, live radioactive nuclides, and X-ray emission from the central star or planet can produce enough ionization to couple the gas and magnetic field (Levy, Ruzmaikin, & Ruzmaikina 1991; Morfill, Spruit, & Levy 1993) but only in the outer layers of a dense gas disk (Gammie 1996; Takata & Stevenson 1996; Glassgold, Najita, & Igea 1997). As proposed by Takata & Stevenson (1996), it is therefore likely that the dynamics of Jovian planets and their gaseous disks were influenced by the magnetic field, as is true in the case of protostars.

The thrust of protostellar bipolar outflows is large enough that the stellar radiative luminosity cannot account for the observed momentum and energy outflow. A magnetic field is therefore expected to drive the acceleration of the outflow, and the bolometric luminosity is not key. Protostellar molecular outflows have been identified surrounding sources with luminosities as low as 0.2 $L_\odot$ and higher than 10^6 $L_\odot$ (Bally & Lane 1991). The lowest luminosity sources are still capable of driving outflows and may represent a new class of sources (Andre, Ward-Thompson, & Barsony 1993). This enormous range of luminosities suggests that the underlying physics of accretion and outflow is not primarily dependent on radiative luminosity.

The early phase of contraction during which the luminosity depends on gravitational energy, and not nuclear burning (nucleosynthesis), should be similar for low-mass stars and Jovian planets. The spectral energy distribution of class I (embedded) sources have been successfully modeled as embryonic stellar cores surrounded by circumstellar disks and massive gas and dust envelopes whose density structure is consistent with rotating infalling molecular cloud cores (Adams, Lada, & Shu 1987). The bipolar outflow phase for protostars is likely to occur during this early stage of collapse (or perhaps even earlier in the class 0 sources). Between 50% and 80% of luminous class I sources show molecular outflows, suggesting that most young stellar objects go through an outflow stage (Morgan & Bally 1991) and that class I sources spend a significant fraction of their lifetime undergoing outflow (Lada 1985). Subsequent studies find that *all* embedded protostellar sources have some degree of outflow activity, suggesting that the outflow phase and the infall/accretion phase coincide (Bontemps et al. 1996).

Although Jupiter is rotating quite quickly, it is currently spinning well below the centrifugal breakup speed. Because it has contracted since formation, its spin must have been even lower in the past. Currently Jupiter's spin down is dominated by the magnetic braking resulting from the interaction of the solar wind and Jupiter's magnetosphere (e.g., Isbell, Dessler, & Waite 1984). This torque is so low as to suggest that Jupiter's angular momentum has not changed significantly since formation. However, since the Sun was probably more active in the past, the spin-down rate from this process could have been more efficient when the solar system was younger. If Jupiter was formed spinning near breakup, a remarkably efficient spin-down process is required to account for its present angular rotation rate. Protostars are also observed to be spinning well below breakup speed. As proposed by Takata & Stevenson (1996), there may have been a connection between the angular momentum of the proto-Jovian disk and the planet, as has been proposed for protostars (Königl 1991). Takata & Stevenson (1996) have proposed that magnetic interactions between the planet and the proto-Jovian disk could provide sufficient torque to de-spin the planet from rotational breakup to its present rotational state. Another possibility is that angular momentum transfer between the core and the outer envelope resulted in the ejection of a high angular momentum disk (possibly forming the proto-Jovian disk) and a relatively slowly spinning planet (Korycansky et al. 1991).

1.2. *Why Might the Physics of Accretion Be Different for Protostars and Proto-Jovian Planets?*

Formation scenarios of Jovian planets fall into two broad categories: (1) as a direct condensation from the protosolar nebula (Boss 1997) and (2) in a two-phase process where a rocky core is formed and a gaseous envelope is subsequently accreted to form the planet's atmosphere (e.g., Bodenheimer & Pollack 1986; Podolak, Hubbard, & Pollack 1993; Podolak et al. 1996; Lissauer 1993). The direct condensation scenario predicts near-solar abundances, whereas in the two-phase scenarios the details of the model determine the core-to-envelope mass fractions (e.g., Pollack et al. 1996; Wuchterl 1993). The two-phase scenario in particular involves processes quite distinct from those involved in stellar formation. Condensation of material is favored where and when protosolar disk temperatures are low enough to permit condensation of volatiles. This material in the protosolar disk nebula can then coalesce into planetesimals, which themselves can accrete into rock and volatile bodies of substantial size (e.g., Goldreich & Ward 1973; Wetherill & Stewart 1993; Weidenschilling & Cuzzi 1993). Once a rocky core of 10–30$M_{\rm E}$ ($M_{\rm E} = 6 \times 10^{27}$ g) has formed, runaway accretion of the planet's gaseous envelope occurs (Lissauer 1993; Bodenheimer & Pollack 1986; Pollack et al. 1996). Recent *Galileo* results on the composition of Jupiter have caused a downward revision in the estimate of Jupiter's core mass from 10–30$M_{\rm E}$ (Hubbard 1984) to the revised lower estimates of 0–12$M_{\rm E}$ (Guillot, Gautier, & Hubbard 1997). Absence of a rocky core would support the direct condensation models, although even in these models, small cores of rock or ice may exist (Boss 1997). A core mass of 12$M_{\rm E}$ would be consistent with either direct condensation or the core formation and runaway accretion growth scenarios.

It is possible that the Galilean satellites formed directly from a proto-Jovian gaseous accretion disk. If we make this assumption, then the densities of these satellites suggest that pressures of about 1 bar (10^6 dynes cm^{-2}), required for formation of methane and ammonia, were present in the proto-Jovian disk (Prinn 1993; Prinn & Fegley 1981). This in turn suggests that the pressure in the protosolar disk was probably far lower than that of the proto-Jovian disk. Finally, protostars form from the collapse of a largely isotropic molecular cloud, whereas planets form in protostellar disks. Disks have thicknesses that may not be much more than a planet's tidal or Hill sphere radius, and therefore planet formation takes place in an environment that is much closer to two-dimensional than it is to isotropic.

1.3. *The Angular Momentum Problem*

Rotations observed in molecular cloud cores present a problem in the collapse of clouds, in that angular momentum must be removed to collapse protostars. The "angular momentum problem" for Jupiter is complicated by the protosolar disk, because formation of the object must involve the transfer of angular momentum to and from the protostellar disk and the proto-Jovian disk/planet system. This makes it difficult to estimate a centrifugal radius for the Jovian protoplanet and disk system. Because of this difficulty, we first consider the range of possible values for the angular momentum of the proto-Jovian disk and planet system. However, if accretion into the Hill sphere occurs through the Lagrange points (of the planet/star system), then it is possible to estimate a centrifugal radius and compare this radius to the radius of the planet. If this radius is large, then it follows that material accreted into the Hill sphere would likely go into an accretion disk before falling onto the planet itself.

The planet core is likely to accrete material that falls within its tidal or Hill sphere radius, $r_{\rm H} = D(M_p/3M_*)^{1/3}$, where D is the semimajor axis of the planet's orbit, M_* is the mass of the Sun (or central star), and M_p is the mass of the planet. This tidal radius therefore represents a maximum radius for the proto-Jovian disk. We can estimate this radius for the current Jupiter mass and semimajor axis:

$$r_{\rm H} = 5.3 \times 10^{12}\ {\rm cm}\left(\frac{D}{5.2\ {\rm AU}}\right)\left(\frac{M_p}{M_{\rm J}}\right)^{1/3}\left(\frac{M_*}{M_\odot}\right)^{-1/3}, \quad (1)$$

where $M_{\rm J}$ and $M_\odot$ are the masses of Jupiter (2×10^{30} g) and the Sun (2×10^{33} g), respectively. We can see that, even for a much smaller proto-Jovian planet mass, the tidal radius is a few hundred times larger than the current radius of Jupiter (7×10^9 cm).

If accretion into the Hill sphere radius occurred through the Lagrange points (at a distance of $r_{\rm H}$ from the planet and at a low velocity in the rotating frame in which both Jupiter and the Sun are stationary), as seen in simulations (Artimowicz & Lubow 1996), then we can estimate the spin angular momentum of the accreting material. The spin angular momentum per unit mass (with respect to Jupiter) would be $\sim r_{\rm H}^2 \Omega_p$ (where $\Omega_p = (GM_*/D^3)^{1/2}$ refers to the orbital angular rotation rate of the planet about the star), resulting in rotation for the planet that is prograde with respect to its orbit about the star (e.g., Kuiper 1951). If we estimate a centrifugal radius r_c based on this spin angular momentum, we find that $r_c \sim r_{\rm H}/3$, still well outside the planet radius even during the early formation stages of the collapsing planet. It is therefore likely that material accreted into the Hill sphere from the protostellar nebula would go into (and through) an accretion disk before falling onto the planet itself. The formation of giant gaseous planets therefore could be similar to that of protostars, in that some mechanism (such as an accretion disk and accompanying outflow) is required to transfer angular momentum outward for accretion onto the central object (planet) to occur.

2. OUTFLOW MODELS

2.1. *Accretion Disk Parameters*

We must first explore the physical conditions appropriate in a proto-Jovian accretion disk. If accretion from the protosolar disk went into a proto-Jovian disk before accreting onto the planet, then the accretion rate $\dot{M}_D$ through the disk should be similar to that estimated from nondisk formation models. Pollack et al. (1996) calculate an accretion rate of $10^{-6} M_{\rm E}\ {\rm yr}^{-1}$ (or $10^{-9} M_{\rm J}\ {\rm yr}^{-1}$; here $M_{\rm J}$ is a Jupiter mass) of planetesimals for the formation of the rocky core, but after the planet reaches a critical core mass, gas accretion occurs much faster, possibly greater than $10^{-3} M_{\rm E}\ {\rm yr}^{-1}$ (or $10^{-6} M_{\rm J}\ {\rm yr}^{-1}$). This accretion rate is similar to the timescale estimated for the dissipation of protostellar disks (e.g., Skrutskie et al. 1990), so we scale our relations from this accretion rate.

We must also estimate the magnetic field in the proto-Jovian disk. There is evidence that there were strong magnetic fields in the protosolar disk from measurements of primitive meteorites (see the review in Morfill et al. 1993). Inferred magnetic fields range from 0.1 to 1 G. Since these fields were the result of fields averaged over a long time period, the meteorite remanence record suggests that the presence of magnetizing fields as intense as a few G existed in the protosolar disk at a distance of several AU from the Sun. If the proto-Jovian disk had a much higher pressure ($\sim$1 bar) than that of the protosolar nebula (Prinn 1993; Prinn & Fegley 1981; Lunine & Stevenson 1982), then the magnetic field therefore could be as high as 5×10^3 G in the proto-Jovian disk and remain within equipartition. For comparison, the current magnetic field of Jupiter is approximately 10 G but is generated from an internal dynamo.

Here we check that the above accretion rates $\dot{M}_D$ could be sustained and would be consistent with the range of pressures and temperatures estimated for a proto-Jovian accretion disk. Accretion through the disk implies that there is dissipation of energy into the disk. For a self-luminous disk the temperature as a function of radius is

$$T(r)^4 = \frac{3GM_p \dot{M}_D}{8\pi\sigma_{\rm SB} r^3}, \quad (2)$$

where $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant. Using the accretion rate mentioned above, we estimate

$$T = 370\ {\rm K}\left(\frac{M_p}{M_{\rm J}}\right)^{1/4}\left(\frac{\dot{M}_D}{10^{-6} M_{\rm J}\ {\rm yr}^{-1}}\right)^{1/4}\left(\frac{r}{10^{11}\ {\rm cm}}\right)^{-3/4}. \quad (3)$$

The sound speed at this radius would be $\sim 2\ {\rm km\ s}^{-1}$, implying a reasonably thin disk $h/r \lesssim 0.2$ (from hydrostatic equilibrium, where h is the vertical scale height). For a surface density $\Sigma = 10^4\ {\rm g\ cm}^{-2}$, the central disk pressure would be $\sim 5 \times 10^3$ dynes cm^{-2} at this radius. This pressure is lower than predicted, based on the chemical composition (Prinn 1993), but still sufficiently high that a 10 G field would still be well within equipartition. For this surface density, an α (accretion or viscosity) parameter of $\alpha \sim 10^{-3}$–10^{-4} would be consistent with the above accretion rate. For a higher density disk (e.g., Lunine & Stevenson 1982), a lower α would be consistent with the above accretion rate.

Under conditions of low ionization fraction for an outflow to be launched the neutral component must be well coupled with the ions (e.g., Wardle & Königl 1993). This coupling is described by η, the ratio of the dynamical time to the mean collision time of a neutral atom in a dilute sea of ions (e.g., Wardle & Königl 1993; or, equivalently, Shu et al. 1994a); $\eta = \gamma_i \rho_i r/v_c$, where v_c is the rotational velocity of a particle in a circular orbit. When $\eta \gg 1$, the neutrals move with the ions and so can be described as well coupled to the magnetic field. Here $\gamma_i \sim 3 \times 10^{13}$ cm^3 g^{-1} s^{-1} is the drag coefficient between ions and neutrals and ρ_i, the density of ions, is the product of the atomic mass of the ions, the ionization fraction, and the total density. We can then estimate

$$\eta \sim 1 \times 10^8 \left(\frac{n_e/n_{\rm H}}{10^{-12}}\right)\left(\frac{\rho}{10^{-6}\ {\rm g\ cm^{-3}}}\right) \times \left(\frac{M}{M_{\rm J}}\right)^{-1/2}\left(\frac{r}{10^{11}\ {\rm cm}}\right)^{3/2} . \quad (4)$$

For the disk with ionization state explored by Takata & Stevenson (1996; with temperatures not largely different than in eq. [3]), the density ranges from $\rho = 10^{-3}$–10^{-12} g cm^{-3} for radii between 1 and 100 planet radii and at scale heights less than $z/h < 4$. The ionization fraction (ranging from $n_e/n_{\rm H} = 10^{-16}$ to 10^{-9}) is roughly inversely correlated with the density (compare Fig. 3 with Fig. 4 of Takata & Stevenson 1996). We conclude that over the whole model disk $\eta \gg 1$, and the neutrals can be said to be well coupled to the ions. However, this does not mean that the particles are necessarily well coupled to the magnetic field.

The magneto-centrifugal wind models can operate where the charged particles are sufficiently coupled to the field lines that they are flung out centrifugally from the outer layers of the disk (for a favorable field geometry). This occurs when the magnetic Reynold's number is high or $\gg 1$. For the disk with ionization state explored by Takata & Stevenson (1996), the magnetic Reynold's number is only large (>1) in the outer layers (greater than a few vertical scale heights where ionization is produced mainly by Galactic cosmic rays) and within a few planetary radii of the planet (due to thermal ionization). The magnetic field should primarily be important in these regions.

2.2. *Magneto-centrifugally Driven Disk Outflow Models*

In the magneto-centrifugal disk wind or outflow models, the angular momentum of the wind is tied to that of the disk, and so the wind flux is directly related to the accretion rate, $\dot{M}_D$, through the disk. A parameter ϵ

$$\epsilon \equiv \frac{\dot{M}_D \sqrt{GM_p}}{3B^2 r^{5/2}} \quad (5)$$

(see Pelletier & Pudritz 1992, that paper's eq. [7.1]) describes $\frac{1}{3}(r/r_{\rm A})^3$, the ratio of the radius r to the Alfvén radius, $r_{\rm A}$, of the field line passing through r. For a wind to be produced, the field lines must be more than 30° from normal to the disk and $\epsilon < 1$. Here B is the magnetic field in the disk at r, and G is the gravitational constant.

For these rough Jupiter-sized parameters, assuming $r \sim 10^{11}$ cm as a typical size for a circumplanetary disk (Stevenson et al. 1986), we have

$$\epsilon \sim 0.02 \left(\frac{\dot{M}_D}{10^{-6} M_{\rm J}\ {\rm yr^{-1}}}\right)\left(\frac{M_p}{M_{\rm J}}\right)^{1/2} \times \left(\frac{B}{10\ {\rm G}}\right)^{-2}\left(\frac{r}{10^{11}\ {\rm cm}}\right)^{-5/2} . \quad (6)$$

Since $\epsilon < 1$, we find that, if the magnetic field in the disk is greater than 10 G and the inflow rate is not high, we would expect a wind or bipolar outflow to be driven from the disk (assuming the field geometry is favorable).

For these models (Pelletier & Pudritz 1992), the mass flux $\dot{M}_w$ in the wind is related to the accretion rate through the disk by

$$\dot{M}_w = f^2 \dot{M}_D , \quad (7)$$

where

$$f \approx \left(\frac{r}{r_{\rm A}}\right) . \quad (8)$$

The terminal speed of the outflow is

$$v_\infty \sim v_c \left(\frac{r_{\rm A}}{r}\right) , \quad (9)$$

where v_c is the velocity of rotation in the disk at the radius from which the wind originates.

If the wind originates from the range of Jupiter's nearby moons at 5×10^{10} cm (the distance of Io from Jupiter) and $r_{\rm A}/r \sim 3$ (typical of solutions in Pelletier & Pudritz 1992), then the outflow velocity could be as large as ~ 20 km s^{-1} and the mass-outflow rate in the wind would be $\sim 10^{-7} M_{\rm J}$ yr^{-1} (for an inflow rate of $10^{-6} M_{\rm J}$ yr^{-1}).

We note that a magneto-centrifugal disk wind would be launched at radii greater than a few planetary radii from the outer ionized layers of the disk. It is unclear that there would be direct coupling between accretion ($\dot{M}_D$) in a dense neutral disk and an outflow launched in the low-density layers at a few scale heights above the disk (where the ionization is sufficient that the MHD approximation is valid). Since equation (4) holds for lower accretion rates, if the outflow is only coupled to the outer layers of the disk, then the mass-outflow rate may be much lower than estimated above.

2.3. *Magneto-centrifugally Driven Stellar Outflow Models—The X-Wind*

A more detailed alternative model is the magneto-centrifugally driven stellar and disk outflow model of Shu et al. (1994a) and subsequent papers. In this model the stellar magnetic field is sufficiently strong that the disk is truncated at a radius R_x, given by

$$R_x = \alpha_x \left(\frac{\mu_p^4}{GM_p \dot{M}_D^2}\right)^{1/7} \quad (10)$$

(Ghosh & Lamb 1978, 1979a, 1979b), where $\mu_p = B_p R_p^3$ is the magnetic moment of the planet, R_p is the planet radius, and B_p is the planet's bipolar magnetic field; α_x is a dimensionless parameter that can be calculated depending upon the details of the model and ranges from 0.5–1.2 (Shu & Shang 1997). Shu et al. (1994a) argue that if the magnetic field is strong enough to truncate the disk ($R_x/R_p > 1$), then it is automatically strong enough to launch a magneto-centrifugally driven wind.

For Jupiter-sized parameters,

$$\frac{R_x}{R_p} = 1.3\alpha_x \left(\frac{B_p}{10\ \mathrm{G}}\right)^{4/7} \left(\frac{R_p}{2 \times 10^{10}\ \mathrm{cm}}\right)^{5/7} \times \left(\frac{M_p}{M_\mathrm{J}}\right)^{-1/7} \left(\frac{\dot{M}_D}{10^{-7} M_\mathrm{J}\ \mathrm{yr}^{-1}}\right)^{-2/7} . \quad (11)$$

Here we have chosen to scale from a lower accretion rate more appropriate for later stages of evolution and a smaller radius more appropriate for activity nearer the planet surface. We see that if the inflow rates are moderate and the planetary magnetic field is larger than 10 G, we find it is likely that the disk was truncated by the magnetosphere of the planet, and so an X-wind could be driven from the planet plus disk system. Since the truncation is likely to occur within a few planetary radii, we expect that the ionization state of the disk (due to thermal ionization) is sufficient to couple the magnetic field to the disk.

For the X-wind model, $f \approx \frac{1}{3}$, but this factor in protostars depends on the mass/radius relation for deuterium burning. For an accreting proto-Jovian planet, the mass radius relation could be substantially different (e.g., Pollack et al. 1996; Guillot et al. 1996; Saumon et al. 1996), and so we do not necessarily expect this factor to be similar.

For the X-wind model, the wind is most energetically driven from the X-point or the radius at which the disk rotates at the same speed as the planet. The speed of the outflow is then related to the velocity of rotation at that radius as in equation (9) above. Given Jupiter's current angular rotation rate (of the magnetic field), this radius is 1.6×10^{10} cm and has a circular velocity of 28 km s^{-1}. The proto-Jupiter would have been larger and rotating more slowly, making the radius of corotation somewhat larger. To estimate the wind speed we would then divide by f, which for moderate factors of $f \sim \frac{1}{3}$ would imply moderate outflow speeds of order $\sim$30 km s^{-1}.

2.4. *Scaling from Young Stellar Objects*

In this subsection we scale from the empirical relations observed in protostellar outflows to estimate wind outflow rates and velocities. This approach was introduced by Wolk & Beck (1990). The mechanical luminosity and force or thrust (rate of momentum injection) of bipolar molecular outflows scales with the radiant luminosity of the driving stellar source (Lada 1985; Cabrit & Bertout 1992). Observational estimates of the bolometric luminosity L_bol of the stellar source, the outflow mechanical luminosity L_CO, and the outflow momentum injection rate F_CO (force or thrust) can be fitted to the following scaling "laws" (Cabrit & Bertout 1992, 1986). The subscript CO here refers to the carbon monoxide line emission in which the protostellar outflows are studied. We note that a proto-Jovian outflow may not be bright in carbon monoxide emission for a variety of reasons (e.g., Jupiter's composition) but consider these laws for conceptual and scaling purposes. The force law is the following:

$$\frac{F_\mathrm{CO}\, c}{L_\mathrm{bol}} \sim 2000 \left(\frac{L_\mathrm{bol}}{L_\odot}\right)^{-0.3} , \quad (12)$$

where c is the speed of light, $F_\mathrm{CO} \sim \dot{M}_w v_w$, v_w is a wind velocity (though there is an added complication that much of the material observed in the outflow could be entrained gas), and $L_\odot$ is the solar luminosity, 3.9×10^{33} ergs s^{-1}. The luminosity law is as follows:

$$\frac{L_\mathrm{CO}}{L_\mathrm{bol}} \sim 0.04 \left(\frac{L_\mathrm{bol}}{L_\odot}\right)^{-0.2} , \quad (13)$$

where $L_\mathrm{CO} = \dot{M}_w v_w^2$.

Jupiter, during its formation at early times, has $L_\mathrm{bol} \sim 10^{-6}\, L_\odot$ at a few times 10^6 yr after formation (Burrows et al. 1997), so if the physical processes for the early accretion phase are similar to those in protostars, then we would predict that

$$F_\mathrm{CO} \sim 2.6 \times 10^{-6} \left(\frac{M_\mathrm{J}}{\mathrm{yr}}\right) \left(\frac{\mathrm{km}}{\mathrm{s}}\right) \left(\frac{L_\mathrm{bol}}{10^{-6}\, L_\odot}\right)^{0.7} \quad (14)$$

and

$$L_\mathrm{CO} \sim 4.0 \times 10^{-6} \left(\frac{M_\mathrm{J}}{\mathrm{yr}}\right) \left(\frac{\mathrm{km}}{\mathrm{s}}\right)^2 \left(\frac{L_\mathrm{bol}}{10^{-6}\, L_\odot}\right)^{0.8} . \quad (15)$$

These scaling laws suggest that outflows of $10^{-7} M_\mathrm{J}$ yr^{-1} could occur for moderate outflow velocities of order 10 km s^{-1}; the same sizes as we estimated could be possible in the theoretical models discussed above.

3. SUMMARY AND DISCUSSION

In this paper we have considered the possibility that the formation of Jovian planets involved an outflow/accretion phase is similar to that observed in protostars. There are a number of similarities in the expected formation of the these objects but also a number of significant differences. We assume here that accretion onto the planet took place through a disk. Since the Hill sphere (tidal) radius of Jupiter is a few hundred times larger than its current radius, it is unlikely that gas and planetesimals captured by the gravitational field of Jupiter had little spin angular momentum. If accretion into the Hill sphere occurs through the Lagrange points, then the accreting material should have spin angular momentum (with respect to the planet) equivalent to a centrifugal radius of $\frac{1}{3}$ of the Hill sphere radius, again much larger than the planet radius. This suggests that formation of Jupiter could have involved accretion of a significant fraction of the planet mass through a disk.

Order of magnitude estimates of magneto-centrifugal disk wind and stellar plus disk (X-wind) models suggest that if the accretion of the planet occurs through a disk, at a rate that is not extremely high (or less than $10^{-6} M_\mathrm{J}$ yr^{-1}), and if the magnetic field in the disk or planet was larger than 10 G, an outflow could be driven from a proto-Jovian planet. Here we have assumed disk accretion rates appropriate for formation of Jupiter on timescales of 10^6–10^7 yr. However, winds could also be driven at lower disk accretion rates with lower magnetic fields from a lower mass disk that might have existed at a later stage of formation or was formed subsequent to formation of the planet (e.g., Korycansky et al. 1991). The feasibility of an outflow depends on the magnetic field geometry and the ionization structure of the disk. While the X-wind models are launched at small radii where the ionization state is sufficiently large to couple the magnetic field to the gas, the disk wind models can only be launched from the outer, diffuse layers of the disk. Future work should therefore explore self-consistent models for such an accretion disk to determine the feasibility of outflows at varying accretion rates.

If Jovian planets indeed form via an accretion disk plus outflow process similar to that in protostars, then there are number of possible interesting consequences, which we list below.

1. The resulting planet size (and possibly percentage of gas mass) could be determined by the efficiency of the outflow rather than by the gas supply or dissipation of the protosolar disk (as suggested for protostars; Shu et al. 1987; Nakano, Hasegawa, & Norman 1995).

2. It is possible that some fraction of mass similar to the final planet mass could have been processed chemically through proto-Jovian disks during the time of planet formation. This gas mass would be rich in molecules such as methane and possibly ammonia, which require pressures higher than typical of the protosolar disk but which could have existed in the proto-Jovian disk (Prinn 1993; Prinn & Fegley 1981). Some of this gas ejected as part of the outflow could become part of the protosolar disk or part of the Oort cloud leaving a chemical signature of planetary processing that might be detected in later evolutionary stages of protostellar disks, or perhaps in the solar neighborhood in terms of abundance variations in meteorites or comets. Gas ejected by an outflow from a Jupiter-sized planet could escape the solar system altogether, whereas outflows from lower mass planets might be more likely to enrich the outer solar system. Chemical variations in the different circumplanet disks could lead to quite a wide variety of molecules dispersed. This dispersion could be compared to the efficiency of various mixing processes in the protosolar disk.

An outflow could also lead to variations in abundances in the forming planet. This might lead to alternative explanations for Jupiter's near solar abundance, water content, high carbon and sulfur content, and depleted oxygen content (Niemann et al. 1996; as opposed to chemical enrichment by infalling planetesimals subsequent to formation).

3. The rotation of Jovian planets could be interpreted naturally as resulting from planet/disk interactions (Takata & Stevenson 1996) rather than from three-body or hydrodynamic affects as gas flowed into the Hill sphere (as in Coradini et al. 1989; Artimowicz & Lubow 1996) or from angular momentum transfer between the core and envelope (Korycansky et al. 1991).

4. Outflows from proto-Jovian planets and their accretion disks could provide a way to detect forming planets. These outflows could involve dispersal of a significant fraction of the final planet mass into the protostellar disk or even out of the stellar gravitational field (or solar system) altogether. This dispersed material might be optically thin (making it easier to detect) and would have a chemical and kinematic signature differing from the protostellar disk. The inner regions of the circumplanet accretion disks would be significantly hotter than the surrounding protostellar nebula, with luminosities similar to the young planet itself, but covering a broader range of wavelengths. Some preliminary prospects for detection are discussed in the Appendix.

We thank the referee for many comments that have improved this paper. We also acknowledge support from NSF grant AST 95-29190 to M. and G. Rieke and NASA projects NAG 5-3359 and NAG 5-4667. D. T. is supported by an NSF Graduate Research Fellowship. This work could not have been carried out without helpful discussions and correspondence with J. Lunine, J. Najita, C. Strom, J. Valenti, F. Melia, A. Nelson, D. DeYoung, H. Chen, W. Hubbard, M. Hanson, L. Golub, S. Saar, A. Dessler, E. Deluca, T. Ruzmaikina, G. Rieke, E. Young, D. Sudarsky, M. Rieke, D. Willner, J. Bechtold, J. Beijing, M. Meyer, A. Sprague, R. Brown, T. Fleming, and M. Sykes.

APPENDIX

SOME PROSPECTS FOR DETECTION OF FORMING JOVIAN PLANETS

The circumplanet accretion disk itself could have a luminosity (reprocessed radiation from the planet and/or from accretion) $L_\nu = \nu F_\nu$ similar to the bolometric luminosity of the planet. However its spectral energy distribution would be such that it would be bright over a larger range of wavelengths than the planet (e.g., Adams et al. 1987), which should be closer to a blackbody. This implies that it may be possible to search for longer wavelength (e.g., mid-IR) emission from the hot regions of circumplanet accretion disks at radii from the central star that are not expected to be bright at these wavelengths. A proto-Jovian accretion disk could have a flux at $\lambda = 10\ \mu$m of

$$F_\nu \sim 1\ \mathrm{mJy}\left(\frac{L_{\mathrm{bol}}}{10^{-6}\ L_\odot}\right)\left(\frac{\lambda}{10\ \mu\mathrm{m}}\right)\left(\frac{D}{10\ \mathrm{pc}}\right)^{-2},$$

which is detectable by the *Infrared Space Observatory* (*ISO*), SIRTF, and other mid-IR cameras. However, high angular resolution would be required to differentiate this emission from the protostellar disk emission.

To explore the possibility of detection of proto-Jovian outflows, we first estimate the column density of material that could have been ejected. If 1% of a Jupiter mass is ejected over a circular region of radius 5 AU, then with a Jupiter abundance of ammonia or methane ($\sim 2 \times 10^{-3}$ number density with respect to H_2; Niemann et al. 1996) we estimate a column depth in methane or ammonia of 1.3×10^{21} cm^{-2} and a column of hydrogen atoms of $N_{\mathrm{H}} \sim 6 \times 10^{23}$ atoms cm^{-2} (which could be in molecular form). The cooling time is short, so much of this gas could be cold, although ambipolar diffusion may result in heating the outflowing gas near the planet (as is predicted for protostellar outflows; Safier 1993a, 1993b). The level of column depth suggests that extinction against the central source or planet could be high for typical Galactic dust to gas ratios.

We now consider some highly sensitive ways for detecting cold gas in emission. Cold (~ 10 K) ammonia can be detected at the mJy level as emission in the inversion transitions (23 GHz) at a column of $N_{\mathrm{NH_3}} \sim 10^{14}$ cm^{-2} (e.g., Gomez et al. 1994), so although we expect our emitting region to be small (and so a factor dependent on the beam size will affect the detection limit), it is possible that ammonia in young stellar systems could be detected in the vicinity of nearby young stars during the time of planet formation. Ammonia is also enhanced in protostellar outflows (e.g., Tafalla & Bachiller 1995).

Carbon monoxide can currently be detected at the 10 mK level in emission in the rotational transitions [e.g., $^{12}C^{16}O$ (1–0) or (2–1)] in the millimeter and submillimeter bands at a column depth of $N_{CO} \sim 10^{16}$ cm^{-2}. Detection limits in carbon monoxide emission for nearby young stars could therefore place limits on the fraction of residual cold gas-phase carbon monoxide in young solar systems (e.g., Koerner & Sargent 1995). However, detection of a Jovian outflow might easily be confused with other phenomena, such as an outflow from the central star or inflow from infalling molecular clumps into the whole stellar and disk system. A combination of high spectral resolution and a variety of molecular tracers (e.g., Bachiller 1997) would be required to differentiate between phenomena.

Ejected outflow material could also be detected in absorption against the central source. Molecules such as water, methane, and carbon dioxide in the form of ices with column depths of 10^{16}–10^{17} cm^{-2} (and also silicates at 10 μm) have been detected in absorption against 100 Jy sources with *ISO* (e.g., Whittet et al. 1996). Absorption against a central star is likely if an extended (out of the ecliptic) and a high column density of these molecules exists. For comparison, a solar-type star at 100 pc is about 100 mJy at 10 μm. This suggests that the next wave of near-IR spectrographs (e.g., SIRTF) could observe young solar-type main-sequence stars out to a few hundred pc and search for absorption of ices and silicates against the central star in the mid-IR (2–30 μm). High spectral resolution observations could also be done of molecular absorption lines at optical wavelengths.

Outflow velocities of order 20 km s^{-1} are large enough to drive shocks that would emit at $\sim$2000 K. This opens up the possibility of detecting shocked molecular hydrogen and other tracers of hot dense gas. Outflowing gas near the planet could also be detected in emission at relatively hot temperatures of 100–1000 K (typical of the forming disk and planet) in the near and mid-IR lines. At these wavelengths dilution caused by the central stellar source is likely to be a problem; however, the lines emitted would not be characteristic of emission from the central star, and the kinematics of the emitting gas would be peculiar: that of an outflow coupled with the orbital motion of the planet.

Possible targets for a search for forming proto-Jovian planets would be $\sim 10^6$ yr old stars lacking evidence for energetic accretion. These stars would be likely sites for currently forming Jovian planets. Candidates would be X-ray bright, T Tauri stars or solar-type stars in relatively (but not extremely) young stellar clusters.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. 1987, ApJ, 312, 788
Anderson, J. D., Lau, E. L., Sjogren, W. L., Schubert, G., & Moore, W. B. 1997, Nature, 387, 264
Andre, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Artimowicz, P., & Lubow, S. H. 1996, ApJ, 467, L77
Bachiller, R. 1997, in IAU Symp. 178, Molecules in Astrophysics: Probes and Processes, ed. E. W. van Dishoeck (Dordrecht: Kluwer), 103
Bally, J., & Lane, A. P. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 471
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Bodenheimer, P., & Pollack, J. B. 1986, Icarus, 67, 391
Bontemps, S., Andre, P., Terebey, S., & Cabrit, S. 1996, A&A, 311, 858
Boss, A. P. 1997, Science, 276, 1836
Burrows, A., et al. 1997, ApJ, 491, 856
Cabrit, S., & Bertout, C. 1992, A&A, 261, 274
———. 1986, ApJ, 307, 313
Coradini, A., Cerroni, P., Magni, G., & Federico, C. 1989, in Origin and Evolution of Planetary and Satellite Atmospheres, ed. S. K. Atreya, J. B. Pollack, & M. S. Matthews (Tucson: University of Arizona Press), 723
Gammie, C. F. 1996, ApJ, 457, 355
Ghosh, P., & Lamb, F. K. 1978, ApJ, 223, L83
———. 1979a, ApJ, 232, 259
———. 1979b, ApJ, 234, 296
Glassgold, A. E., Najita, J., & Igea, J. 1997, ApJ, 480, 344
Goldreich, P., & Ward, W. R. 1973, ApJ, 183, 1051
Gomez, J. F., Curiel, S., Torrelles, J. M., Rodríguez, L. F., Anglada, G., & Girart, J. M. 1994, ApJ, 436, 749
Guillot, T., Burrows, A., Hubbard, W. B., Lunine, J. I., & Saumon, D. 1996, ApJ, 459, L35
Guillot, T., Gautier, D., Hubbard, W. B. 1997, Icarus, 130, 534
Hartmann, L., & MacGregor, K. B. 1982, ApJ, 259, 180
Heyvaerts, J., & Norman, C. 1989, ApJ, 347, 1055
Hubbard, W. B. 1984, Planetary Interiors (New York: Van Nostrand-Reinhold)
Isbell, J., Dessler, A. J., & Waite, J. H., Jr. 1984, J. Geophys. Res., 89, 10716
Königl, A. 1989, ApJ, 342, 208
Königl, A. 1991, ApJ, 370, L39
Koerner, D. W., & Sargent, A. I. 1995, AJ, 109, 2138
Korycansky, D. G., Bodenheimer, P., Cassen, P., & Pollack, J. B. 1990, Icarus, 84, 528
Korycansky, D. G., Bodenheimer, P., & Pollack, J. B. 1991, Icarus, 92, 234
Kuiper, G. P. 1951, in Astrophysics, ed. J. A. Hynek (New York: McGraw-Hill), 357
Lada, C. J. 1985, ARA&A, 23, 267
Levy, E. H., Ruzmaikin, A. A., & Ruzmaikina, T. V. 1991, in The Sun in Time, ed. C. P. Sonnett, M. S. Giampapa, & M. S. Mathews (Tucson: University of Arizona Press), 589
Lissauer, J. J. 1993, ARA&A, 31, 129
Lunine, J. I., & Stevenson, D. J. 1982, Icarus, 52, 14
McKinnon, W. B. 1997, Icarus, 130, 540
Mestel, L. 1968, MNRAS, 138, 359
Morfill, G., Spruit, H., & Levy, E. H. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: University of Arizona Press), 939
Morgan, J. A., & Bally, K. 1991, ApJ, 372, 505
Nakano, T., Hasegawa, T., & Norman, C. 1995, ApJ, 450, 183
Niemann, H. B., et al. 1996, Science, 272, 846
Pelletier, G., & Pudritz, R. E. 1992, ApJ, 394, 117
Podolak, M., Hubbard, W. B., & Pollack, J. B. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: University of Arizona Press), 1109
Pollack, J. B., Hubicky, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzwig, Y. 1996, Icarus, 124, 62
Pollack, J. B., Lunine, J. I., & Tittemore, W. C. 1990, in Uranus, ed. J. T. Bergstrahl, E. D. Miner, & M. S. Matthews (Tucson: University of Arizona Press), 469
Prinn, R. G. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: University of Arizona Press), 1005
Prinn, R. G., & Fegley, B. 1981, ApJ, 249, 308
Pudritz, R. E., & Norman, C. A. 1983, ApJ, 274, 677
Safier, P. N. 1993a, ApJ, 408, 115
———. 1993b, ApJ, 408, 148
Saumon, D., Hubbard, W. B., Burrows, A., Guillot, T., Lunine, J. I., & Chabrier, G. 1996, ApJ, 460, 993
Shu, F. H. 1993, in Molecular Clouds and Star Formation, ed. C. Yuan & J. You (Singapore: World Scientific), 97
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Shu, F. H., Lizano, S., Ruden, S., & Najita, J. 1988, ApJ, 328, L19
Shu, F. H., Najita, J., Ostriker, E., & Shang, H. 1995, ApJ, 455, L155
Shu, F. H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994a, ApJ, 429, 781
Shu, F. H., Najita, J., Ruden, S., & Lizano, S. 1994b, ApJ, 429, 797
Shu, F. H., & Shang, H. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Low-Mass Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 225
Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., Strom, K. M., & Shure, M. A. 1990, AJ, 99, 1187
Stevenson, D. J., Harris, A. W., & Lunine, J. I. 1986, in Satellites, ed. J. A. Burns & M. S. Matthews (Tucson: The University of Arizona Press), 39
Tafalla, M., & Bachiller, R. 1995, ApJ, 443, L37
Takata, T., & Stevenson, D. J. 1996, Icarus, 123, 404
Wardle, M., & Königl, A. 1993, ApJ, 410, 218
Weidenschilling, S. J., & Cuzzi, J. N. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: University of Arizona Press), 1031
Wetherill, G. W., & Stewart, G. R. 1993, Icarus, 106, 190
Whittet, D. C. B., et al. 1996, A&A, 315, L357
Wolk, S. J., & Beck, S. C. 1990, PASP, 102, 745
Wuchterl, G. 1993, Icarus, 106, 323