

## ON THE PLANET AND THE DISK OF CoKu TAURI/4

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### ABSTRACT

*Spitzer* observations of the young star CoKu Tau/4 reveal a disk with a 10 AU hole that is most likely caused by a newly formed planet. Assuming that the planet opened a gap in the viscous disk, we estimate that the planet mass is greater than 0.1 Jupiter masses. This estimate depends on a lower limit to the disk viscosity derived from the timescale needed to accrete the inner disk, creating the now detectable hole. The planet migration timescale must at least modestly exceed the time for the spectrally inferred hole to clear. The proximity of the planet to the disk edge implied by our limits suggests that the latter is perturbed by the nearby planet and may exhibit a spiral pattern rotating with the planet. This pattern might be resolved with current ground-based mid-infrared cameras and optical cameras on the *Hubble Space Telescope*. The required submegayear planet formation may challenge core accretion formation models. However, we find that only if the planet mass is larger than about 10 Jupiter masses, allowing for a high enough surface density without inducing migration, would formation by direct gravitational instability be possible.

*Subject headings:* planetary systems — planetary systems: formation —  
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### 1. INTRODUCTION

There remains considerable debate about the nature and time-scales associated with planet formation in the disks surrounding young stars (Boss 2002; Mayer et al. 2002; Pollack et al. 1996). The recent discovery of a young star CoKu Tau/4 (age  $\tau_{\text{age}} \approx 10^6$  yr) with a disk containing a 10 AU hole (Forrest et al. 2004; P. D’Alessio et al. 2004, in preparation) suggests that planet formation can take place quite early in the evolution of protostellar systems. The critical theoretical link between the inner hole in the disk and the presence of a planet is the planet’s ability to open a gap that impedes mass flow to smaller radii. Disks with edges and corresponding inner cleared regions have been seen in older objects on large scales such as HR 4796A, with a disk edge at  $\sim 65$  AU (Schneider et al. 1999) and GM Aur with a disk edge at  $\sim 300$  AU (Rice et al. 2003). However, the recent *Spitzer* observations for a smaller scale hole in the younger CoKu Tau/4 systems provide new insights in the process that form planets and the evolution of planet-disk systems. CoKu Tau/4’s age and the presence of the inner disk hole place limits on timescales for the disk-planet interaction and constrain the properties of the disk and planet. As we show, the resulting estimates support the plausibility of the planet-disk scenario for CoKu Tau/4.

Because the outer disk is still present and has a spectral energy distribution similar to other T Tauri stars lacking inner holes, we suspect that the outer disk is still accreting. Massive planet formation is unlikely to occur at extremely small radii from the star, so following the formation of a planet, accretion of the inner disk would leave a hole. Without the planet holding the accretion disk back, the disk edge would not be as sharp as implied by the spectral energy distribution (P. D’Alessio et al. 2004, in preparation). For there to be an observable hole, the viscous timescale,  $\tau_v$ , at the outer edge of the hole must be less than the age of the system. That the planet has not yet migrated to smaller radii and the presence of an inner hole allow us to constrain the properties of the planet and disk and estimate the probability of finding such systems.

### 2. CLEARING THE INNER DISK AND CONSTRAINTS ON DISK VISCOSITY

We parameterize the disk viscosity,  $\nu$ , with a Reynolds number,  $\text{Re} \equiv r^2\Omega/\nu$ , where  $\Omega$  is the angular rotation rate of a particle in a circular orbit around the star and  $r$  is the radius. Using a viscosity  $\nu = \alpha c_s h$ , where  $\alpha$  is the viscosity parameter,  $c_s$  is the sound speed, and  $h$  is the vertical disk scale height, we have

$$\text{Re} = \alpha^{-1} \left( \frac{v_c}{c_s} \right)^2 = \alpha^{-1} \left( \frac{r}{h} \right)^2, \quad (1)$$

where  $v_c = r\Omega$  is the velocity of a particle in a circular orbit. The timescale for the disk to accrete inward is  $\tau_v \sim \text{Re} \tau_{\text{orb}}/2\pi$ , where  $\tau_{\text{orb}}$  is the orbital period. To estimate  $\tau_v$ , we require the disk aspect ratio  $h/r$ . From hydrostatic equilibrium, we have  $h/r \sim c_s/v_c$ . The sound speed is given by  $c_s^2 \sim k_B T/m_p$ , where  $k_B$  is Boltzmann’s constant and  $m_p$  is the proton mass. The temperature  $T$ , if set by radiative balance with the star, is  $T \sim (L_\odot/16\pi r^2 \sigma)^{1/4}$ , where  $\sigma$  is the Stefan-Boltzmann constant. Heat released in the disk by accretion could lead to a higher temperature than that estimated above. Alternatively, the disk could be self-shielding, cooling the midplane below the temperature estimated above (e.g., Chiang & Goldreich 1997). Keeping these complications in mind, we use this temperature as a starting point.

CoKu Tau/4 is an M1.5 star at a distance of 140 pc with an estimated mass of  $0.5 M_\odot$ ,  $\tau_{\text{age}} = 10^6$  yr, and luminosity of  $0.6 L_\odot$  (P. D’Alessio et al. 2004, in preparation; Kenyon & Hartmann 1995). Assuming an inner edge of 10 AU and the luminosity and mass given above, at the disk edge we find  $T \sim 80$  K,  $c_s \sim 0.8$  km s $^{-1}$ , and  $v_c \sim 7$  km s $^{-1}$ . The orbital period at 10 AU is  $\sim 40$  yr. Using this sound speed and hydrostatic equilibrium,  $h/r \sim 0.1$ . However, if the disk is optically thick,  $h/r$  could be lower. We use  $h/r = 0.05$  below, although this particular choice is not significant.

If a planet exists in CoKu Tau/4’s disk at  $r = 10$  AU, then the hole formed because disk material is prevented from ac-

creting across the planet's orbital radius by the transfer of orbital angular momentum from the planet to the disk. The presence of the hole therefore implies that the material in the inner disk ( $r < 10$  AU) has had time to accrete onto the star. This requires  $\tau_v < \tau_{\text{age}} \approx 1$  Myr, which in turn implies

$$\tau_v = \text{Re } \tau_{\text{orb}}/2\pi = \alpha^{-1} \left(\frac{r}{h}\right)^2 \tau_{\text{orb}}/2\pi < 1 \text{ Myr.} \quad (2)$$

Using  $\tau_{\text{orb}} = 40$  yr, the above inequality implies that  $\text{Re} \leq 1.6 \times 10^5$ . Using  $h/r = 0.1$ , we also require that  $\alpha \geq 6 \times 10^{-4}$ . These values are within theoretical expectations. A viscosity parameter  $\alpha \sim 0.01$  typically emerges from protostellar disk model fitting (Hartmann et al. 1998). Note that if  $\alpha$  or  $h$  were orders of magnitude lower, the inner disk would not have had time to accrete onto the star. In principle, the viscosity of the inner disk either could differ from that of the outer disk or could have dropped in the past million years, but here we are just assuming the simplest steady case. The result highlights that the hypothesis that the inner disk has accreted onto the central star is consistent with age constraints and reasonable disk properties. If instead we use  $\alpha \approx 0.01$  and  $h/r = 0.05$  we find  $\text{Re} \sim 4 \times 10^4$  and  $\tau_v \approx 2 \times 10^5$  yr, also less than  $\tau_{\text{age}}$  and thus in principle consistent with the observations. However, the planet formation time must be less than the viscous time at the radius where the planet forms. A viscous time significantly less than 1 Myr challenges core accretion models if the planet formed at the corresponding radius.

Instead of accreting onto the central star, the inner disk could have been depleted by multiple planet formation or agglomeration into large dust grains and planetesimals within 10 AU. Here, however, we focus on the simplest paradigm of a single planet and viscous accretion.

### 3. GAP OPENING AND CONSTRAINTS ON PLANET MASS

The inner disk will begin accreting onto the star once a newly formed planet opens up a gap. The condition for opening a gap provides a limit on the planet's mass. Without a gap, the disk would accrete unimpeded through the orbital radius of the planet. A gap decouples the inner and outer disk, except through their interaction with the planet. Because the planet acts as a time-dependent gravitational potential perturbation, it can resonantly drive waves at Lindblad resonances into the gaseous outer planetesimal disk (Goldreich & Tremaine 1978; Lin & Papaloizou 1979; Ward 1997). These waves carry angular momentum and therefore govern both how a planet opens gaps (e.g., Bryden et al. 1999; Artymowicz & Lubow 1994) as well as the radial migration (e.g., Nelson et al. 2000; Ward 1997).

To open a gap, a planet must be sufficiently massive that spiral density waves dissipated in the disk overcome the inward flow due to viscosity (Lin & Papaloizou 1979; Bryden et al. 1999; Ward 1997). This leads to the condition (Nelson et al. 2000)

$$q \geq 40 \text{ Re}^{-1}, \quad (3)$$

where  $q \equiv M_p/M_*$ , the mass of the planet divided by that of the star. For  $\text{Re} \leq 1.6 \times 10^5$  estimated above for CoKu Tau/4, the gap opening condition implies that  $q \geq 2.5 \times 10^{-4}$  or  $M_p \geq 0.1M_J$ , where  $M_J$  is the mass of Jupiter.

### 4. MIGRATION, MASS LOSS, AND SURFACE DENSITY

Once formed, a planet's interaction with a surrounding disk may lead to the transfer of angular momentum and the migration of the planet closer to the star (Ward 1997). For more massive planets, migration can occur after a gap is opened (denoted type II migration). The condition for opening a gap and the nature of type II migration are linked. A gap is maintained when the torque density from spiral waves driven at different resonances balances the inward torque due to viscous accretion. If the planet mass is less than or comparable to the disk mass with which it interacts, then the planet will migrate on a viscous timescale; it behaves as "just another particle" in the disk and  $\tau_{\text{mig}} \sim \tau_v$  (e.g., Nelson et al. 2000). However, this result is subject to the surface density profile; outward migration rather than inward migration may occur (Masset & Papaloizou 2003).

If the planet mass is large compared with the disk mass with which it interacts, then the inertia of the planet slows migration and  $\tau_{\text{mig}} > \tau_v$ . That CoKu Tau/4's planet still resides a large distance from the star implies that significant migration has yet to occur. The lack of significant migration along with the presence of a hole implies  $\tau_{\text{clear}} < \tau_{\text{mig}}$ , where  $\tau_{\text{clear}}$  is the timescale for the gas within the planet's semimajor axis to accrete onto the star. If we use  $\tau_{\text{clear}} \sim \tau_v$ , then we require  $\tau_{\text{mig}} \geq \tau_v$  for type II migration.

After a gap is opened, the inner disk accretes onto the star while the outer disk experiences a pileup of material at the edge of the disk exterior to the planet. Once  $M_{\text{edge}} \sim M_p$ , migration would take place on a viscous timescale. Here  $M_{\text{edge}} = \pi r^2 \Sigma_e$ , where  $\Sigma_e$  is the surface density just outside the disk edge. The accretion rate of the outer disk may be crudely estimated to be

$$\dot{M}_a \sim \frac{M_{\text{edge}}}{\tau_v} \sim \frac{M_p}{\tau_v} \sim 10^{-9} M_\odot \text{ yr}^{-1} \frac{M_p}{1M_J} \frac{10^6 \text{ yr}}{\tau_v}. \quad (4)$$

Significantly larger accretion rates would have led to larger accumulations of mass in the disk edge and an earlier onset of migration. We note that accretion rates in the range of value of  $\dot{M}_a = 10^{-7}$ – $10^{-10} M_\odot \text{ yr}^{-1}$  are consistent with observations of accretion rates in million-year-old evolved T Tauri systems (Calvet et al. 2000). Larger values of  $\dot{M}_a$  could be accommodated in our calculations by taking a larger planet mass planet and/or a larger required mass in the disk edge to initiate migration. If we assume that the buildup of  $M_{\text{edge}} > M_p$  would have led to inward migration, its absence constrains the disk surface density through  $M_p \geq \pi r_p^2 \Sigma_e$ , where  $r_p$  is the semimajor axis of the planet. Using our limit  $M_p > 0.1M_J$  estimated above, we find  $\Sigma_e \leq 4 \text{ g cm}^{-2}$  in the disk edge, a plausible value for disks around young stars. The discovery of a planet at  $\sim 10$  AU from CoKu Tau/4 is therefore consistent with the hypothesis that inward disk migration has not proceeded to completion because sufficient mass has not accumulated in the disk edge.

### 5. PREDICTED DISK MORPHOLOGY

Having established that a young sub-Jovian mass planet orbiting at 10 AU in the CoKu Tau/4 disk is plausible, we now consider the gravitational and hydrodynamic interaction between the planet and disk. Using the hydrodynamics code developed by Masset (2000, 2002), we have performed a two-dimensional hydrodynamic simulation using the parameters estimated in the previous sections. Figure 1 shows the mor-

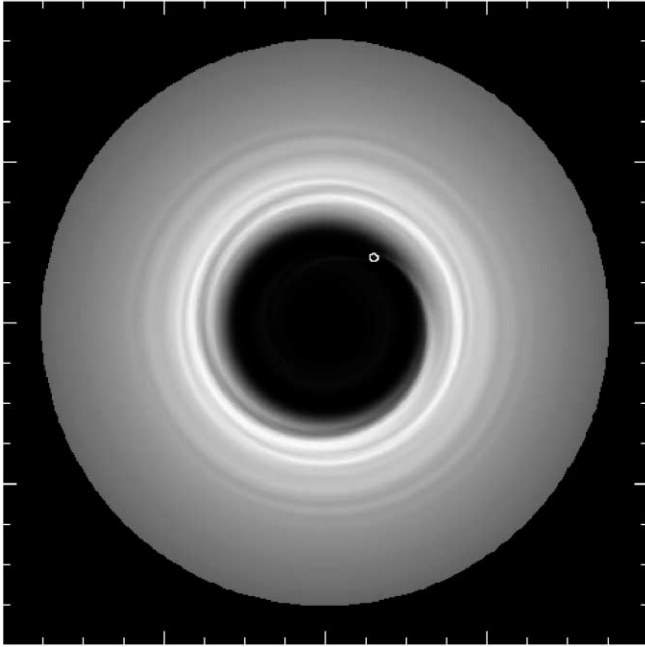


FIG. 1.—Morphology of a planet disk system with planet mass of  $0.1M_J$  for the CoKu Tau/4 system. The disk aspect ratio is  $h/r = 0.05$  and Reynolds number  $Re = 10^5$ . Because of the proximity of the planet and disk, high-order spiral density waves are driven by the planet at Lindblad resonances. If these waves constructively interfere, the result is a spiral pattern that rotates with the planet. The planet in this simulation is accreting gas.

phology from a simulation with planet mass ratio  $q = 3 \times 10^{-4}$ , Reynolds number  $Re = 10^5$ , and disk aspect ratio  $h/r = 0.05$ . In the simulation, the planet was initially set into a circular orbit, with the disk edge located at 1.1 times the semimajor axis of the planet's orbit. The initial surface density was taken to be  $\Sigma = \Sigma_0(1.1r_p/r)^{-1}$ , where  $\Sigma_0 = 10^{-4}M_*/r_p^2$  is the surface density at the disk edge and  $r_p$  is the planet's semimajor axis. For  $r < 1.1r_p$  we set the disk density to be 100 times lower than that at the disk edge to approximate an initial inner hole. The planet is free to migrate via gravitationally induced angular momentum exchange with the disk and can accrete gas within its Roche lobe. Note that the simulated disk is not massive enough for self-gravity to play a role. Figure 1 shows the gas density at time  $t = 100\tau_{\text{orb}}$  after the beginning of the simulation.

The principle conclusion from our simulations relates to spiral density waves driven into the disk from interactions with the planet. Because of the proximity of the planet to the disk edge, the disk contains more than one Lindblad resonance. Multiple spiral density waves can be driven in the disk edge by the planet at these resonances. The range in radius where the waves are launched is of the order of the scale height,  $h$  (Artymowicz 1993). Consequently, we expect the winding of the spiral pattern to depend on the scale height and hence on the disk temperature; i.e., the spiral wave would be more tightly wound if the disk were cooler and the scale height smaller. The two-armed pattern rotates with the planet and is probably caused by the combined effect of more than one density wave, as explained by Ogilvie & Lubow (2002). The spiral pattern could be observable by high angular resolution imaging. At a distance of 140 pc,  $0''.1 \sim 14$  AU. The features exhibited in the simulation are then close to the resolution limit of the ground-based 10 m class telescope at  $10 \mu\text{m}$  or by the *Hubble Space Telescope* (*HST*) at optical wavelengths. Thus it is possible that the spiral pattern might also be detected in optical scattered

light images. In addition, the asymmetry of the disk hole caused by the arm that extends toward the planet may be detectable through imaging.

When the Reynolds number or the planet mass is higher, the disk edge would be farther away from the planet. Then the lower  $m$  Lindblad resonances are the dominant sites of density wave driving. Consequently, two or three density peaks, corresponding to the constructive interference of two and three armed waves, might be detected in images of the disk edge. If the disk aspect ratio is higher than considered here, a one-armed pattern rotating with the planet dominates over the two-armed one seen in Figure 1.

Hydrodynamic simulations have shown differences between two-dimensional and three-dimensional models (Makita et al. 2000), particularly in the opening angle of the spiral density waves. In a three-dimensional disk, the waves may not constructively interfere as they do in our two-dimensional simulation, because of differences in the dispersion relation (Ogilvie & Lubow 2002). Further three-dimensional simulations are required to better determine structures in the disk formed via planet-disk interactions.

In the simulation shown, we allow the planet to accrete 80% of the material found within its Roche lobe. The remaining 20% can flow past the planet into the inner disk (as seen previously by Lubow et al. 1999), accounting for the nonzero gas density within the planet's semimajor axis. If the disk has the high viscosity considered here, then it is likely that the planet is still accreting significantly. A planet that is still accreting may be surrounded by a hot observable circumplanetary disk (e.g., Lubow et al. 1999).

The *Spitzer* observations imply that there is very little dust within the disk edge (P. D'Alessio et al. 2004, in preparation), although the presence of larger bodies is less constrained. Better hydrodynamic modeling will help to understand the flow past the planet into the inner hole and consequently on the disk, planet mass, and planetary accretion.

## 6. DISCUSSION AND CONCLUSIONS

The recent discovery by Forrest et al. (2004) of a young system with a 10 AU hole (P. D'Alessio et al. 2004, in preparation) allows us to explore new constraints on the evolution of young planets and circumstellar disks. On the basis of the assumption that the inner disk has accreted onto the star CoKu Tau/4 within a time equivalent to the age of the star, we estimated that  $Re \lesssim 1.5 \times 10^5$ . Using this, we evaluated the condition for a planet to open a gap in the disk and found that the planet within the disk edge of CoKu Tau/4 is greater than  $0.1M_J$ . The apparent lack of inward migration of the planet leads to estimates of the disk accretion rate and surface density that are consistent with observations of evolved T Tauri systems. Given the inferred planet mass, we expect the disk edge to be very near the planet. This implies that the planet could be accreting material and would interact strongly with the disk by driving waves into the disk from resonances. Idealized simulations suggest that this may produce a two-armed spiral pattern, rotating with the planet and extending a few disk scale heights away from the radius of the planet. Structure in the disk could be detectable with  $0''.1$  high-resolution imaging in scattered optical light with *HST* or by ground-based 10 m class telescopes in the mid-infrared.

The contemporaneous presence of both a sharp edge and an inner hole (suggestive of viscous inner disk clearing) implies that the hole-clearing timescale is less than the planet migration

timescale,  $\tau_{\text{clear}} < \tau_{\text{mig}}$ ; otherwise, the planet would have disappeared along with the hole and the hole refilled. The probability to see both an edge from the planet-induced gap and a disk hole for  $r < (10 \text{ AU} - \delta r_{\text{gap}}/2)$  is then

$$P = [\tau_{\text{mig}}(10 \text{ AU}) - \tau_{\nu}(10 \text{ AU} - \delta r_{\text{gap}}/2)]/\tau_{\text{age}}, \quad (5)$$

where  $\delta r_{\text{gap}}$  is the gap width opened initially by the planet and the timescales are meant to be taken at the radius in parentheses. For  $\delta r_{\text{gap}} \ll 10 \text{ AU}$ ,  $P \sim [\tau_{\text{mig}}(10 \text{ AU}) - \tau_{\text{vis}}(10 \text{ AU})]/\tau_{\text{age}}$ . Once the planet appears at 10 AU, it takes at least one viscous timescale for material to pile at the disk edge and presumably one more for migration to take place, so then  $P \sim \tau_{\nu}/\tau_{\text{age}}$ . For  $\alpha = 0.01$  the estimate for  $\tau_{\nu}$  of § 2 would then give  $P \sim 10\%$ . This argument presumes that planet appearance at 10 AU occurs before a viscous time at 10 AU. (This is more restrictive than the minimal condition that a planet must form faster than a viscous timescale at its formation radius because the planet could have formed at  $r > 10 \text{ AU}$ .)

More robust processes to explain why the inward migration timescale  $\tau_{\text{mig}} < \tau_{\text{clear}}$  are possible and may be necessary. Masset & Papaloizou (2003) find that surface density profiles shallower than  $r^{-1/2}$  can induce an outward planet migration rather than inward, which could certainly explain the presence of the wall and disk. Alternatively, if the inner accretion disk had a radially dependent viscosity coefficient or incurred a change of accretion mode (e.g., nonviscous transport), the surface density profile might evolve so as to produce a hole within the planet radius even if the planet migrated on a local viscous time. More work on these possibilities for CoKu Tau/4 will be needed.

Finally, we note that the planet-disk scenario for CoKu Tau/4 implies that planets of greater than two Neptune masses can form

in  $\leq 10^6$  yr. This may push the envelope of core accretion models (Pollack et al. 1996), and this may appear to favor planet formation by direct gravitational instability (Boss 2002, 2003; Mayer et al. 2002). Our results constrain the properties of the disk from which the planet formed: The Toomre instability parameter for a thermally supported disk at the planet orbit radius  $r_p$  is  $Q = 200 (M_*/0.5 M_{\odot}) (\Sigma/4 \text{ g cm}^{-2})^{-1} (r_p/10 \text{ AU})^{-2} [(h/r_p)/0.05]$ , where we have scaled to the values based on our lower mass limit for the planet in CoKu Tau/4. Planet formation by direct gravitational instability is only possible for  $Q \lesssim 1.5$ . For this condition to be satisfied, the disk would have had to be remarkably thin and/or have a very high  $\Sigma$  in the not-too-distant past. Our upper limit on  $\Sigma$  is proportional to  $M_p$ , so that only if  $M_p = 10 M_J$  would the upper limit of  $\Sigma \leq 400 \text{ g cm}^{-2}$  allow  $Q$  to be low enough for planet formation by direct gravitational instability. Observational constraints on the surface density are needed.

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