**PLANETS RAPIDLY CREATE HOLES IN YOUNG CIRCUMSTELLAR DISCS.** P. Varnière, E.Blackman, A.Frank & A.C. Quillen, *Department of Physics & Astronomy, University of Rochester, NY 15627-0171, USA (pvarni@pas.rochester.edu)*.

Recent spectral observations by the Spitzer Space Telescope (SST) reveal that some discs around young ($\sim few \times 10^6$ yr old) stars have remarkably sharp transitions to a low density inner region in which much of the material has been cleared away. It has been recognized that the most plausible mechanism for the sharp transition at a specific radius is the gravitational influence of a massive planet. This raises the question of whether the planet can also account for the hole extending all the way to the star. Using high resolution numerical simulations, we show that Jupiter-mass planets drive spiral waves which create holes on time scales $\sim 10$ times shorter than viscous or planet migration times. In addition, although the hole surface densities are low, they are finite, allowing mass accretion toward the star. Our results therefore imply that massive planets can form extended, sharply bounded spectral holes which can still accommodate substantial mass accretion rates. The results also imply that holes are more likely than gaps for Jupiter mass planets around solar mass stars.

**Introduction** The discovery of extrasolar planets some 10 years ago has led to a renaissance in our understanding of the formation and evolution of planetary systems [10]. Planets form accretion disks that surround and feed mass onto young stars, but there is significant gravitational feedback between the planets and their parent disks [8]. This produces a variety of disk architectures that often differ from our own solar system. Understanding planet-disk interactions is essential for understanding planetary positions, observational signatures for exo-planets, and the time scales that planet formation models must accommodate.

Despite significant theoretical progress [8], key questions remain. The time scale for planet formation, $\tau_f$, remains uncertain. Gas giant planets might form rapidly ($\tau_f \sim 1000$ y) through gravitational instability [4], or slowly through core accretion [9] where agglomeration of dust grains creates a rocky core that accretes surrounding gas. Core accretion has been estimated to take $\sim 10$ My, although recent arguments [16, 13] lowering this to $\sim$Myr may be required by SST observations.

SST has provided a rapidly growing database of high resolution IR spectral observations of young disk-star systems. From the deficit of emission at wavelengths characteristic of the disk inner regions, the observations imply that some systems have mass-depleted inner disks: Surrounding the star CoKuTau/4 is a disk with a 9 AU spectral hole bounded by a very sharp outer edge, strongly indicative of the influence of a planet. Within 9 AU, the hole seems to require a density to be $\leq 10^{-4}$ times that which would otherwise be present if the disk inferred at 9AU were extended via standard models all the way to the star (D'Alessio et al. 2005). Such holes extend beyond the scale for which a magnetic field would be important [7] and the sharpness is unlikely to be explained by a radiation pressure or a wind [1]. While the presence of a planet is currently the most plausible explanation for the sharp edge and hole, the young age [1] of the system, $\leq$ 2My presents challenges for planet formation models [15]. SST observations of other systems reveal direct evidence for accretion in systems with and without spectral holes (Muzerolle et al., 2005, N. Calvet & D. Watson, personal communication)

Here we show, via direct numerical simulations, that Jupiter mass planets orbiting a solar mass star clear out inner holes all the way to the star on a time scale faster than the viscous or planet migration time scales. For disks embedded with sufficiently massive planets, holes should therefore be commonly observed.

**Quantitative Results: fast accretion**

We take the case in which $r_p = 1$ AU and $M_p = 0.001\, M_\odot = 1\, M_J$. At $t = 1000$, the surface density in the inner regions

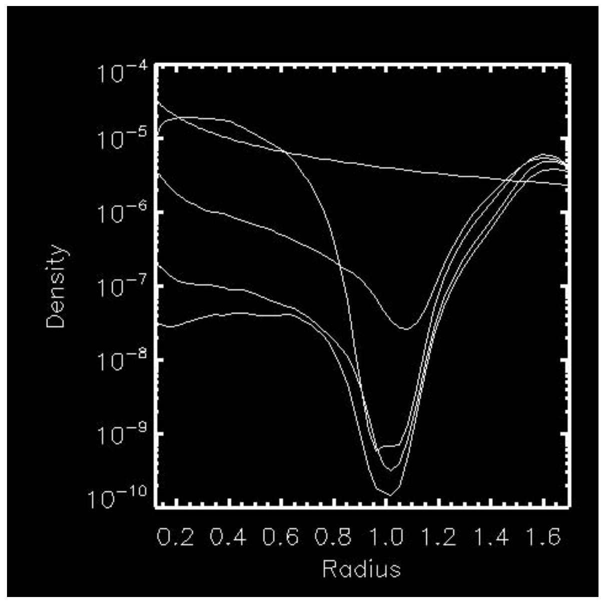


Figure 1: Evolution of the density at function of time ($t = 0, 1000, 2000, 4000, 10000$ years).

first increases as matter is pushed toward the star and the gap opens, but an inner hole forms subsequently as material is lost to the star. The gap near 1AU forms in less than 1000 orbits and a hole cleared all the way to the star (i.e. $\Sigma(r_* \leq r \leq r_p)$ drops by factor $\geq 10$ for all $r_* \leq r \leq r_p$, where $r_*$ is the radius of the star) clears by $\sim 2000$ orbits which is $\sim 1/10$ the viscous time at $r = r_p$, By 6000 orbits, the surface density has droped by a nearly a factor of $10^{-5}$.at 1AU and by $10^{-3}$ at 0.4AU.

Fig. 2 shows the time evolution of disk mass $M_r(t)$ within $r_\star \leq r \leq r_p$. The cases shown have $M_p = 0.001\, M_\odot = 1\, M_J$ and $M_p = 0.002\, M_\odot = 2\, M_J$ and $r_p = 1$ AU. From $900 < t < 2000$ orbits, $M_r(t)$ rapidly depletes by a factor of 25. This is $\sim 0.1$ viscous accretion times at $r = r_p$ and consistent with the rapid gap formation, followed by a slower,

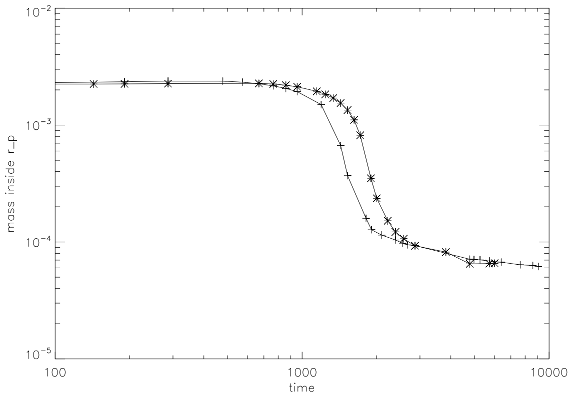


Figure 2: Evolution of the mass interior to the planet as a function of time for a planet at 1AU. the "*" represents a 1 $M_J$ planet and the "+" a 2 $M_J$ planet.

but still faster-than-viscous depletion at smaller $r$.

This simulation thus demonstrate both (1) rapid hole formation and (2) substantial accretion rates even after a hole of with a $10^{-3}$ deficit in surface density has formed. Note also that the absence of significant planet migration on the hole clearing time suggests that spectral holes likely accompany massive planets.

Our key result, that massive planets rapidly form spectral holes in disks, thus implies: (1) For planet formation on a time scale $\tau_f > t_h(r_p)$, all disks with a massive planet will have a sharply bounded hole from outer radius $r_{out} = r_p$ to inner radius $r_{in} = r_*$. (2) For $\tau_f < t_h(r_p)$, a fraction $f$ of disks with a massive planet would show a sharply bounded gap from $r_{out} > r_p$ to $r_{in} > r_*$. (3) However, $f$ is small for massive planets. Therefore, disks which appear to show gaps but not holes [11, 12] are best explained either by planets with low enough mass to make $\tau_h$ as long as the viscous time (in which case only the early gap formation is observed), or by spectral features from dust and inclination effects without a planet.

**Conlcusion**

We find that a massive planet embedded in a protoplanetary accretion disk produces a low surface density hole faster than can be accounted for by purely viscous evolution. In particular, (1) after less than $1000$ orbits a very low surface density gap forms that extends approximately 1/3 the distance to the star. (2) By about $2000$ orbits, a low surface density hole, with a factor of $\geq 10$ density depletion extending all the way from the planet orbital radius to the stellar surface appears on a time scale $\sim 1/10$ of the the viscous evolution time calculated at $r = r_p$.

The gap and hole are both the result of the enhanced angular momentum transport and accretion induced by spiral waves [5, 2, 17]. We find that the gap can be explained by the launching and damping of of $m = r/h \sim 25$ waves and the faster-than-viscous hole formation is consistent with launching and damping of $m = 2$ waves. Our results are consistent with previous studies of gap formation but we have followed the evolution of the disk long much longer than in previous simulations [3, 6, 14, 18] and we are able to see the hole clearing all the way to the star.

Our results imply that spectral holes, rather than spectral gaps, should be commonly observed when a sufficiently massive planet is present inside a disk. We also emphasize that the use of the term "spectral hole" is important because even though the holes have a reduced density for all $r_* < r < r_p$, they need not be fully evacuated and substantial accretion rates can be maintained even after the hole forms.

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