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Formation of Giant Planets
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Under the support of NASA Origins grant NAG5 4277, we studied the formation of gaps in protoplanetary disks due the tidal interaction between a fully grown protoplanet and protostellar disk. The result of this study is published in the Astrophysical Journal, (vol 514, 344-367, 1999) and in several conference proceedings.

The main focus of this work is to analyze planet-disk interaction during the final stages of protoplanetary formation. When they have grown to a sufficiently large mass, giant protoplanets can exert an effective tidal perturbation on, and induce strong trailing shocks in, their protostellar disks (Lin & Papaloizou 1979, Goldreich & Tremaine 1980, Papaloizou & Lin 1984, Korycansky & Papaloizou 1996). Such shocks are always associated with angular momentum transport (Spruit 1987) that results in material moving away from the companion. When a protoplanet's Roche radius (R_R) exceeds the disk semi–thickness (H), the formation of a gap in the disk near its orbital radius (r_o) becomes possible (Lin & Papaloizou 1986a, 1993). Gaps can be maintained in viscous disks provided the effective viscosity (ν) in the disk near the planet is too small to provide adequate angular momentum transport to counteract the effects of the tidal torques. When a gap forms, accretion of the disk material by the protoplanet is expected to be significantly reduced, possibly even stopping altogether. Important issues arising from the process of gap formation are whether a protoplanet can acquire a mass (M_p) comparable to that of Jupiter (M_J) prior to gap formation anywhere in the disk, and whether gap formation induces enough local gas depletion that the protoplanet effectively terminates its own growth (Lin & Papaloizou 1993).

Based on a series of simulations of *thin* disks with *polytropic* equations of state, using various types of numerical schemes, Lin and Papaloizou (1979, 1986a, 1993) suggested that a protoplanet with a circular orbit and a sufficiently large M_p can clear a gap to the extent that the rate of accretion onto the protoplanet is markedly reduced. If the disk has similar properties and lifetime to those prescribed in a minimum-mass solar nebula model (Hayashi, Nakazawa, & Nakagawa 1985; Strom, Edwards, & Skrutskie 1993), this process would limit the asymptotic mass of a protoplanet to be in the range 1 to $\sim 10M_J$. However, based on the results of a series of numerical simulations employing smoothed particle hydrodynamics, Artymowicz and Lubow (1996) suggested that protoplanets may continue to grow in mass through accretion of disk matter to attain masses characteristic of stars. This is because they conclude that the formation of a gap through the action of tidal torques may not significantly reduce the flow of disk gas below that arising in the absence of such torques.

A renewed motivation to study these issues of companion-disk tidal interaction is provided by the recent discoveries of extrasolar planets. Most of these planets have masses $M_p \sim M_J$ (Marcy & Butler 1998). The gap formation scenario provides a natural explanation for the apparent upper limit in M_p as well as constraints on the location of planetary formation. In all the planetary formation models, the disk temperature (T) must not exceed $\sim 10^3$ K so that solid grains may condense to form protoplanetary cores prior to the gas accretion phase. Yet several planets are found to revolve around their host stars with Keplerian speeds > 120 km s^{-1}. A sufficiently cold ($T < 10^3$K) disk at such disk radius ($r < 0.1AU$) would have $H/r < 1/40$. The corresponding critical M_p for gap formation would be $\sim 0.05M_J$ which is considerably smaller than that observed. In principle, gap formation could be prevented and the protoplanetary may continue for $M_p < M_J$

if the disk has a relatively large effective viscosity. However, its required magnitude is somewhat larger than that inferred from the observations of protostellar disks around FU Ori stars (Bell & Lin 1994). For modest values of effective viscosity ($\alpha \sim 10^{-3}$), gap formation in the inner regions of the disk is essentially unavoidable for low-mass companions with $M_p < M_J$. Under these conditions, *in situ* formation of short period planets would require a residual diffusion of disk gas into the gap to enable these planets to acquire most of their observed mass. Alternatively, protoplanets may be formed in the outer regions of the disk where much larger values of H/r are attainable with $T < 10^3$ K. Thus, tidal truncation of the disk by a planet may be avoided until its M_p becomes comparable to M_J. Under the support of our current grant NAG5 4277, we have shown that in the latter case, post-formation orbital migration would be required for the short period planets (Lin, Bodenheimer, & Richardson 1996).

In order to verify the tidal truncation conjecture, we carried out a series of numerical simulations of protoplanet-disk interaction. Important model parameters include the disk scale height, viscosity, and surface density distribution as well as the protoplanet's mass. Gas removal due to protoplanetary accretion is prescribed with a free-flow boundary condition, *i.e.* gas is removed when it enters into a region closer than a specified radius. This removal process promotes the gas clearing near the protoplanet's orbit.

During the final stages of protoplanetary growth, its accretion cross section is determined by its Roche radius (see below). In the limit of slow radial diffusion, the only region where the disk gas may be accreted onto a protoplanet is within a torus-shape feeding zone. This feeding zone is centered on the protoplanet's orbit with a width of 2-3 Roche radii. The surface density in this region would gradually diminish and a gap would form if the mass accretion rate onto the protoplanet exceeds the diffusion rate of gas into this region. For a protoplanet of one Jupiter mass this clearing process may take many (> 100) orbital periods, as indicated by our numerical simulations. During this clearing stage, the embedded protoplanet continues to accrete some residual gas. Residual gas in the gap also diffuses away from the corotation radius.

When gap formation is completed, the azimuthally averaged surface density, Σ_s, may decrease to less than one thousandth of the background level. The precise level is difficult to determine because of limitations of the numerical techniques. All schemes indicate a large reduction in the accretion rate from the sink hole level once a gap has formed. Very roughly, the accretion rate onto the protoplanet is proportional to Σ_s, so that the mass doubling timescale becomes longer than the evolutionary timescale τ_v of the disk. Our numerical results clearly show that when the tidal truncation condition is satisfied, Σ_s is cleared well below that needed to enable the protoplanet to grow significantly within the inferred life span of protostellar disks. These results are in excellent agreement with those obtained through an independent investigation carried out by Kley (1998).

Based on the results obtained here (for circular orbits only), we suggest that the gap formation process indeed leads to the effective termination of protoplanetary growth. A planet's asymptotic mass is a function of the disk thickness and viscosity. In typical protostellar disks, it is unlikely to be much above a few Jovian masses. There is already a suggestive indication that the mass function of planets around nearby stars may have a well defined upper limit (Marcy & Butler 1998). Additional data on the orbital characteristics of nearby planets and the masses of protostellar disks could be used to test our suggestion.