# Final Performance Report for NAG5-10732

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# Final Report on Proposal NAG5-10732: "Planet Forming Protostellar Disks" 2001-2005

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## 1 Introduction

The proposal achieved many of its objectives. The main area of investigation was the interaction of young planets with surrounding protostellar disks. The grant funds were used to support visits by CoIs and visitors: Gordon Ogilvie, Gennaro D'Angelo, and Matthew Bate. Funds were used for travel and partial salary support for Lubow.

We made important progress in two areas described in the original proposal: secular resonances (Section 3) and nonlinear waves in three dimensions (Section 5). In addition, we investigated several new areas: planet migration, orbital distribution of planets, and noncoorbital corotation resonances.

## 2 Planet Migration

Planet-disk interactions cause torques to be exerted on planets, which result in radial planet migration (e.g., Goldreich and Tremaine 1980; Lin, Bodenheimer, and Richardson 1996; Lin et al 2000; Ward 1997; Ward and Hahn 2000). In the case that the planet does not open a substantial gap, the (Type I) migration rate depends on details of resonant disk interactions. If the planet opens a gap, then the (Type II) migration rate is determined by the viscous timescale of the disk.

We determined the migration rates of circular orbit planets for masses from 1 Earth mass to 1 Jupiter mass (Bate et al 2003). A disk, with some standard set of parameters, was simulated by means of the three-dimensional, nonlinear ZEUS hydrodynamics code. The resulting (nongap) Type I migration occurs for planets of mass less than about 0.1 $M_J$ and the migration timescales are plotted in Figure 10 of Bate et al (2003). The timescales are significantly longer than those suggested in previous models (e.g., Ward 1997), although still somewhat shorter than the expected disk lifetimes. For the disk model we applied, the Type I migration timescales are longer than the Type II migration timescales (for planet masses greater than 0.1 $M_J$). Our results for Type I migration are in excellent agreement with the analytic three-dimensional model of Tanaka, Takeuchi, and Ward (2002) (plotted as the dashed line in Figure 10 of Bate et al 2003) and with independent calculations by D'Angelo,

Kley, and Henning (2003). In addition, the dependences of our migration timescales on the disk thickness and surface density gradient are in good agreement with the analytic model, as discussed in Section 3.5 of Bate et al (2003).

It is possible that fast modes of migration might occur for planets that do not open a clean gap. This so-called Type III migration was thought to be caused by gaseous material that lies near the orbit of the planet. Masset and Papaloizou (2003) reported that such fast migration occurs on timescales shorter than 50 orbits of the planet. We (D'Angelo, Bate, and Lubow 2003) investigated this possibility using a very high resolution code. We found that the fast migration is a numerical artifact of the treatment of material within the Roche lobe of the planet.

# 3   Secular Interactions Between Inclined Planets and a Gaseous Disk

In a planetary system, a secular resonance occurs at a location where the precessional frequency of a test particle matches the frequency of one of the precessional modes of the planetary system. At such a resonance, the motion of a test particle can be strongly driven by the planets, resulting in a high orbital inclination or eccentricity. In fact, secular resonances involving Jupiter and Saturn are believed to be responsible for the inner truncation of the asteroid belt (Tisserand 1892).

Secular resonances in the gas disk of a young planetary system are potentially of importance, since much more mass is contained in the gas disk than in the planetesimal disk, as has been emphasized by Ward and others. We investigated the secular interactions for a system of mutually inclined planets with a gaseous protostellar disk that may contain a secular nodal particle resonance (Lubow and Ogilvie 2001). We determined the normal modes of some mutually inclined planet-disk systems. The planets and disk interact gravitationally, and the disk is internally subject to the effects of gas pressure, self-gravity, and turbulent viscosity. The behavior of the disk at a secular resonance is radically different from that of a particle, owing mainly to the effects of gas pressure. The resonance is typically broadened by gas pressure to the extent that global effects, including large-scale warps, dominate. The standard resonant torque formula of Goldreich and Tremaine (1979) is invalid in this regime. For typical disk parameters, we found that a $1 M_J$ planet aligns with its protostellar disk in about $10^5$ yrs. In addition, we demonstrated that the disk itself (in addition to planets) can act as an active source of secular resonances. This result may have important implications for the orbits of small mass bodies and planets such as the Earth, while the solar nebula was present.

# 4    Noncoorbital Corotation Resonances

Resonance theory suggests that the eccentricity of planet that opens a gap will damp on a timescale that is short compared to disk lifetimes (Goldreich and Tremaine 1980). The result is a consequence of a close competition between the eccentricity damping by non-coorbital corotation resonances and the excitation by noncoorbital Lindblad resonances, in which the noncoorbital corotation resonances dominate by only a 5% margin. The result is based on the assumption that the noncoorbital corotation resonances are unsaturated, i.e., operate at maximal efficiency. Eccentricity growth may occur through a process in which the noncoorbital corotation resonances (which cause eccentricity damping) are weakened by a feedback effect, i.e., saturate (Goldreich and Tremaine 1981, Ward 1991). This effect comes about because disturbances generated near corotation are trapped in a small region of radial extent of order the disk thickness $H$ (unlike Lindblad resonances) and can therefore act back on the disk conditions near resonance. The strength of this feedback effect is eccentricity-dependent, and this suggests that eccentricity growth can occur if the planet has some initial eccentricity (Goldreich and Sari 2003). Therefore, eccentricity growth may operate through a finite amplitude instability.

We developed a detailed model for the corotation resonance that includes feedback (Ogilvie and Lubow 2003). We found that an eccentricity of only one percent may be adequate to weaken the corotational torque to the extent that eccentricity growth can occur.

# 5    Waves in Disks

We (Bate et al 2002) investigated the nonlinear propagation of axisymmetric waves excited at Lindblad resonances by means of numerical simulation. We found that the torques were in excellent agreement with analytic models. For thermally stratified disks, the wave energy becomes concentrated near the disk surfaces, in agreement with our wave channeling model.

# 6    Orbital Distribution of Planets

Torques on a young planet by a protoplanetary disk are expected to have caused substantial migration of the planet (Lin, Bodenheimer, and Richardson 1996). By making some simple assumptions, we made predictions of the orbital radii distribution of planets, based on the resulting locations of planets when the disk undergoes dispersal (Armitage et al 2002). The model for disk dispersal combines viscous dispersal with photo-evaporation (Johnstone, Hollenbach, and Bally 1998). By restriction attention to a subsample of planets that should be detectable out to 3 AU, we find good agreement between the model and the observed number distribution of planets with radius. The results show that, once observational selection effects are accounted for, the overall expected frequency of massive planets between 1 and 3 AU is roughly twice that observed. About 15% of stars should possess planets out to

5AU. About 10% of planetary systems could have undergone limited migration of the most massive planets, as apparently occurred in our solar system.

# 7 Dust Disk Around HD 141569A

We developed a model for the observed dust disk in HD 141569A. The model includes the gravitational interaction of the disk with the central star and a fly-by companion, and the radiation pressure from the star. The model treats 3 components: the large solids, dust, and gas. We find that the short blowout time of the dust requires that the fly-by be within a few million years. The gas can help retain the dust but cannot confine it.

# 8 Publications Resulting from Grant

Lubow, S. H. and Ogilvie, G. I. 2001, "Secular Interactions Between Inclined Planets and a Gaseous Disk", ApJ, 560, 997

Ogilvie, G. I. and Lubow, S. H. 2002, "On the wake generated by a planet in a disc", MNRAS, 330, 950

Armitage, P. J., Livio, M., Lubow, S. H., and Pringle, J. E. 2002, "Predictions for the frequency and orbital radii of massive extrasolar planets" MNRAS, 334, 248

Bate, M. R., Ogilvie, G. I., Lubow, S. H., and Pringle, J. E. 2002, "The excitation, propagation and dissipation of waves in accretion discs: the non-linear axisymmetric case", MNRAS, 332, 575

Bate, M.R., Lubow, S.H., Ogilvie, G.I., and Miller, K.A. 2003, "Three-dimensional global calculations of high and low-mass planets embedded in protoplanetary discs", MNRAS, 341, 213.

Ogilvie, G. I. and Lubow, S. H. 2003, "Saturation of the Corotation Resonance in a Gaseous Disk", ApJ, 587, 390.

D'Angelo, G., Bate, M. and Lubow, S. H. 2005, "The dependence of protoplanet migration rates on coorbital torques,'" MNRAS, 358, 316

Ardila, D., Lubow, S. H., et al 2005, "A Dynamical Simulation of the Debris Disk Around HD 141569A," ApJ, in press