Interactions of High- and Low-Mass Planets with Protoplanetary Disks

Stephen H. Lubow

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Matthew R. Bate

School of Physics, University of Exeter, Exeter EX4 4QL, UK

Gordon I. Ogilvie

Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Abstract. We present three-dimensional numerical simulations of the interaction of a circular-orbit planet with a protoplanetary disk. We calculate the flow pattern, the accretion rate, and torques on a planet. We consider planet masses ranging from 1 Earth mass to 1 Jupiter mass.

1. Introduction

Planet formation is believed to involve accretion from the surrounding disk of material. We consider this gas accretion onto a planet. A non-Keplerian flow pattern develops near the planet. Furthermore, the planet is subject to gravitational torques due to its interaction with the gas disk which result in planetary migration. We have extended the 2D simulations by Lubow, Seibert, and Artymowicz (1999) to 3D, in order to analyze these effects more realistically. We expect 3D effects to be important for planet masses below 1M_J, since the Hill sphere radius becomes smaller than the disk thickness.

2. Computational Procedure

The calculations were performed by using the 3D, spherical version of the ZEUS finite-difference code (Stone et al. 1992). The disk model is similar to that of Lubow et al. (1999), except that we include the third dimension. The disk is locally isothermal with T(r) ∝ r^{-1}, and disk thickness ratio H/r = 0.05. The initial surface density is taken to be Σ(r) ∝ r^{-1/2} away from the planet. The total disk mass is assumed to be 0.0075 solar masses in the radial interval from 1.6 to 21 AU. The planet’s orbital radius is taken to be 5.2 AU. Thus, the surface density of the unperturbed disk at the planet’s orbital radius is 75 g cm^{-2}. We apply a constant kinematic viscosity ν = 10^{-5} which, at the planet’s radius, corresponds to viscosity parameter α = 4 × 10^{-3}.
We adopt a grid \((r, \theta, \phi) = (180, 36, 288)\) that is non-uniform in \(r\) and \(\phi\). The highest resolution is achieved close to the planet. Zones near the planet measure 0.002875 in \(r\) and \(\phi\), and twice this value in \(\theta\). We model 4 vertical scale heights above the midplane.

We consider separately planets of masses 1, 0.1, 0.03, 0.01, and 0.003 \(M_J\) which orbit about a 1 \(M_\odot\) star. The latter planet mass corresponds to 1 Earth mass. In all cases, the flow is resolved within the planet’s Hill sphere.

### 3. Surface Density

The planet-disk interaction modifies the disk in the vicinity of the planet (Fig. 1). In Fig. 2, we plot the azimuthally-averaged disk surface density. Only a 1\(M_J\) planet opens a deep gap and a mass of at least 0.1\(M_J\) is required for the surface density to be perturbed significantly. Lower mass planets result in much less severe surface-density perturbations.
4. Migration Rates

In Fig. 3, left panel, we plot the migration rates of the 5 planets. We find that the migration rate increases linearly with planet mass, as expected for Type I migration where the planet does not open a gap in the disk. We also plot the migration rates expected from the linear theories of Ward (1997) and Tanaka et al. (2002). Ward’s calculations approximate the disk as two-dimensional and do not include co-rotation resonances. Tanaka et al. consider three-dimensional disks and both Lindblad and co-rotation resonances. Our results are in excellent agreement with Tanaka et al. for $\leq 0.1$ Jupiter masses (i.e. in the Type I regime).

5. Accretion Rates

In Fig. 3, right panel, we plot the accretion rates onto the planet against planet mass for the 5 planets (filled circles). Also plotted are the rates obtained for higher mass planets from the two-dimensional calculations of Lubow et al (1999).

6. Conclusions

- The migration rate scales linearly with $M_p$ for planets that do not open a gap. The results are in excellent agreement with the linear analysis of Tanaka et al. (2002). Planets with masses $> 0.1$ $M_J$ migrate on the disc’s viscous timescale.
- The mass accretion rate increases linearly with planet mass $M_p$ for low-mass planets and peaks at $\approx 0.1$ $M_J$. At higher masses, the mass accretion rate declines as a gap is opened in this disk.
Lubow et al.

Figure 3. Migration time, $\tau$, and accretion rate, $\dot{M}_p$, versus planet mass. Our results are plotted using solid circles. Open circles give accretion rates for very high-mass planets taken from Lubow et al. (1999). The long and short dashed lines give the linear predictions of migration rates from Ward (1997) and Tanaka et al. (2002), respectively. We find the accretion rates of low-mass planets increase linearly with mass (dotted line) until $\approx 0.1 \, M_J$ and decrease for higher masses.

Acknowledgments. The computations reported here were performed using the UK Astrophysical Fluids Facility (UKAFF). SHL acknowledges support from NASA grants NAG5-4310 and NAG5-10308.

References

Lubow, S.H., Seibert, M., & Artymowicz P. 1999, ApJ, 526, 1001.
Stone, J.M., & Norman, M.L. 1992, ApJS, 80, 753.
Tanaka, H., Takeuchi, T., & Ward, W.R. 2002, ApJ, 565, 1257.
Ward, W.R. 1997, Icarus, 126, 261.
This figure "lubow1a.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/0209364v1
This figure "lubow1b.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/0209364v1
This figure "lubowlc.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/0209364v1
This figure "lubow1d.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/0209364v1