Exploring the Formation and Evolution of Planetary Systems
Proceedings IAU Symposium No. 299, 2013
M. Booth, B. C. Matthews & J. R. Graham, eds.

doi:10.1017/S1743921313008260

Inviscid and viscous flow past embedded planets: implications for planet formation

Chris W. Ormel and Ji-Ming Shi

Astronomy Department, University of California, Berkeley
Berkeley CA 94720
email: `[ormel,jmshi]@astro.berkeley.edu`

Abstract. We have investigated the flow pattern that arises past (proto)planets embedded in the nebula disk during its formation. We consider the regime where the planet mass is large enough to gravitationally perturb the gas ($\gtrsim$0.01 Earth masses), but not too large to open a gap or accrete unlimited amounts of gas from the disk. We consider both inviscid and viscid flows and aim to understand the flow pattern on the scales of the Bondi radius. Having described the flow pattern of the gas, we integrate trajectories of small, solid particles. In agreement with previous findings, we show that the ensuing accretion rates can be high—although, due to radial drift motions, pebble accretion is not necessarily an efficient mechanism.

Keywords. hydrodynamics – methods: analytical – planets and satellites: formation – protoplanetary discs

1. Introduction

Quite generally, planets can be characterized into three groups: rocky planets, gas giants, and the intermediate-mass planets. The latter are dominated by a rock/icy core, yet contain appreciable quantities of gas—gas that has been acquired during the nebula phase. Planets like Neptune and the ubiquitously discovered super-Earths (mini Neptunes) fall in this intermediate category.

We aim to describe the interaction between such planets and the nebular gas. In particular, we aim to solve for the flow pattern (gas density and velocity) of the gas on the scales of the Bondi radius of the planet—the radius where the thermal motions of the gas become similar to the escape velocity from the planet, $R_{\rm bondi} = GM_{\rm planet}/c_s^2$ (where G is Newton's constant, $M_{\rm planet}$ the planet mass, and c_s the thermal velocity of the gas). We consider a configuration in which the flow is steady in a frame corotating with the planet, which is assumed to move in a circular orbit.

2. Inviscid and viscid flows

Figure 1 shows the flow pattern that arises in the vicinity of the planet. The flow is barotropic, subsonic, 2D, but compressible. In that case a stream function (Ψ) formulation is feasible (Korycansky & Papaloizou 1996; Ormel 2013). We solve for Ψ numerically and have also derived analytical approximations that closely match the numerical ones.

In Fig. 1 one clearly identifies the horseshoe region where the flow makes a characteristic 'U-turn'. Furthermore, one notes circulating flow in the counterclockwise (prograde) direction near the center on scales of the Bondi radius. This region is the atmosphere of the planet. These two regions are separated by a critical streamline: the separatix (the thick curve that makes an 'X'). Material within the atmosphere is bound to the planet.

We have also conducted hydro simulations with Athena (Stone *et al.* 2008). These simulations have a similar setup as the inviscid simulations, but we do account for a

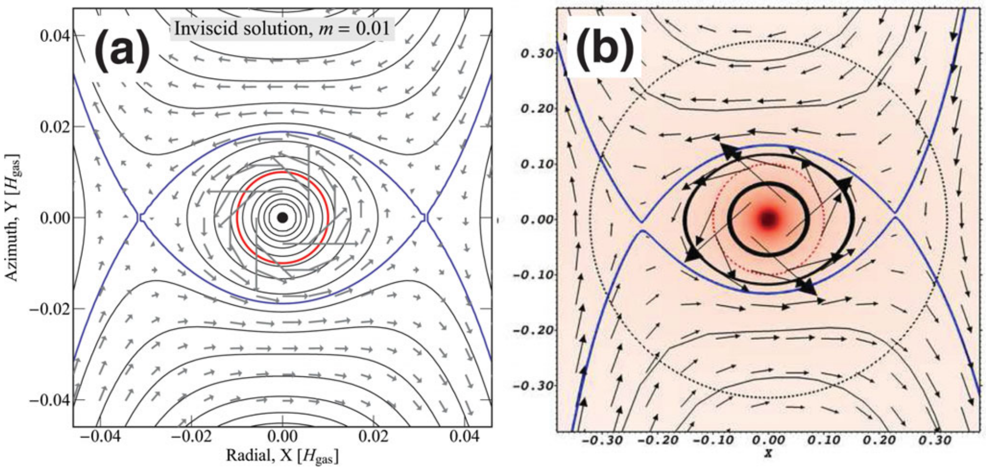

Figure 1. Inviscid (*left*) and viscous (*right*) flow pattern around a planet. The flow pattern is described by velocity vectors (arrows) and streamlines (solid lines). The thick streamline denotes the separatix. Length units are the scaleheights of the disk ($H_{\rm gas}$). The planet mass is nondimensionalized as $m = R_{\rm bondi}/H_{\rm gas}$. The masses in the two panels is not the same: $m = 0.01$ (left) and $m = 0.1$ (right). The flow in both configurations is steady.

viscosity. By choosing a gravitational smoothing parameter on the order of the grid spacing, we can, for the first time, resolve the flow close to the planet, that is, within the Bondi radius (Fig. 1b). We adopt a dimensionless mass parameter $m = R_{\rm Bondi}/H_{\rm gas} = 0.1$, where $H_{\rm gas}$ is the scaleheight of the gas and a kinematic viscosity $\nu = 10^{-3} c_s H_{\rm gas}$.

As the critical streamline provides the interface between the disk and planet atmosphere, we can in this way solve for the size of the planet.

3. Efficient accretion of small particles?

A new model for the formation of planets is by accretion of small particles (Ormel & Klahr 2010; Lambrechts & Johansen 2012). Using the flow solutions of the gas we can integrate trajectories of these particles, for which gas drag is a critical agent determining their fate: accretion on the planet or drift past the planet. With the new flow solution we find that very small particles (dust) couple too strongly with the gas and thereby tend to avoid accretion. For larger particles (those that couple more loosely) the accretion cross section is enhanced. However these particles also tend to drift to the star very quickly (Weidenschilling 1977). Altogether, the accretion efficiency of particles depends sensitively on the local properties of the gas (turbulent strength, gas density, and pressure gradients).

References

Lambrechts M. & Johansen A. 2012, *A&A*, 544, A32
Korycansky, D.G & Papaloizou, E. 1996, *ApJS*, 105, 181
Ormel, C. W. 2013, *MNRAS*, 428, 3526
Ormel C. W. & Klahr H. H. 2010, *A&A*, 520, A43
Stone, J. M., Gardiner, T. A., Teuben, P., Hawley, J. F., Simon J. B., 2008, *ApJS*, 178, 137
Weidenschilling, S. J. 1977, *MNRAS*, 180, 57