



Note

Meridional circulation of gas into gaps opened by giant planets in three-dimensional low-viscosity disks



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ARTICLE INFO

Article history:

Received 14 October 2013

Revised 9 January 2014

Accepted 13 January 2014

Available online 23 January 2014

Keywords:

Planetary formation

Accretion

Jovian planets

Planet-disk interactions

ABSTRACT

We examine the gas circulation near a gap opened by a giant planet in a protoplanetary disk. We show with high resolution 3D simulations that the gas flows into the gap at high altitude over the mid-plane, at a rate dependent on viscosity. We explain this observation with a simple conceptual model. From this model we derive an estimate of the amount of gas flowing into a gap opened by a planet with Hill radius comparable to the scale-height of a layered disk (i.e. a disk with viscous upper layer and inviscid mid-plane). Our estimate agrees with modern MRI simulations (Gressel, O., Nelson, R.P., Turner, N.J., Ziegler, U. [2013]. arXiv:1309.2871). We conclude that gap opening in a layered disk cannot slow down significantly the runaway gas accretion of Saturn to Jupiter-mass planets.

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1. Introduction

Understanding what sets the terminal mass of a giant planet in a runaway gas accretion regime is an open problem in planetary science. Runaway gas accretion is the third stage of the classical core-accretion scenario for the formation of giant planets (Pollack et al., 1996). We remind the reader that in stage I, a solid core of 5–10 Earth masses (M_{\oplus}) is formed by planetesimal accretion (or possibly by pebble-accretion; see Lambrechts and Johansen, 2012; Morbidelli and Nesvorný, 2012). In stage II, the core starts to capture gas from the protoplanetary disk, forming a primitive atmosphere in hydrostatic equilibrium; the continuous accretion of planetesimals heats the planet and prevents the atmosphere from collapsing. In stage III the combined mass of core and atmosphere becomes large enough (the actual mass-threshold depending on opacity and energy input due to planetesimal bombardment) that the latter cannot remain in hydrostatic equilibrium anymore; thus the planet enters in an exponential gas-accretion mode, called runaway.

The accretion timescale in the runaway accretion mode is very fast and, once started, can lead to a Jupiter-mass planet in a few 10^4 y (see for instance the hydro-dynamical simulations in Kley, 1999; D'Angelo et al., 2003; Klahr and Kley, 2006; Ayliffe and Bate, 2009; Tanigawa et al., 2012; Gressel et al., 2013; Szulágyi et al., 2014) in a proto-planetary disk with mass distribution similar to that of the Minimum Mass Solar Nebula model (Weidenschilling,

1977; Hayashi, 1981). This rapid accretion mechanism can explain how giant planets form. On the other hand, there is no obvious reason for this fast accretion to stop. As its timescale is much shorter than the proto-planetary disk life time (a few My Haisch et al., 2001), it is unlikely that the disk disappears just in the middle of this process, raising the question why Jupiter and Saturn and many giant extra-solar planets did not grow beyond Jupiter-mass.

It is well known that giant planets open gaps in the protoplanetary disk around their orbits (Lin and Papaloizou, 1986; Bryden et al., 1999). Thus it is natural to expect that the depletion of gas in the planet's vicinity slows down the accretion process. Still, all of the hydro-dynamical simulations quoted above that feature the gap-opening process show that the mass-doubling time for a Jupiter-like planet is not longer than 10^5 y.

However, these simulations may have been hampered by the assumption of a prescribed viscosity throughout the protoplanetary disk, or by significant numerical viscosity in the simulation scheme. It is expected that planets form in dead zones of the protoplanetary disk (Gammie, 1996), where the viscosity is much smaller than in numerical simulations, so that Jovian-mass planets could presumably open much wider and deeper gaps, with consequent inhibition of further growth (e.g. Thommes et al., 2008; Matsumura et al., 2009; Ida and Lin, 2004).

On this issue, it is worth stressing that there is quite a confusion on the role of viscosity in gap opening. In a 2D disk isothermal model, Crida et al. (2006) showed that the width and the depth of a gap saturates in the limit of vanishing viscosity. This paper has been challenged recently by Duffell and MacFadyen (2013) and Fung et al. (2013), still for 2D disks. For a massive planet, the

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results of Duffell and MacFadyen actually agree with those of Crida et al., because the former group also finds that the gap has a saturated depth and width in the limit of null viscosity and they demonstrate that this result is not due to numerical viscosity. The actual disagreement is on the ability of small planets to open gaps in disks much thicker than their Hill sphere. Fung et al. address this case just by extrapolation of formulæ obtained for massive planets in viscous disks, so it is not very compelling. We believe that gap opening by small planets in Duffell and MacFadyen is due to the use of an adiabatic equation of state $P = E_{\text{int}}(\gamma - 1)$ which, despite adopting a value for the parameter γ very close to unity, is not equivalent to the isothermal case (see Paardekooper and Mellema, 2008). The issue, however, deserves further scrutiny.

This controversy is nevertheless quite academic, because real disks have a 3 dimensional structure. Thus, in this Note we discuss gap opening in 3D disks and we focus on giant planets that are massive enough to undergo runaway gas accretion, i.e. Jupiter-mass bodies. In Section 2 we present the structure of the gaps and the gas circulation in their vicinity, using three-dimensional isothermal simulations. We also interpret the results with a simple intuitive model. From this model, we derive in Section 3 an estimate for the flow of gas into a gap in a layered disk (i.e. a disk that is viscous on the surface and “dead” near the mid-plane), that is in agreement with the numerical results of Gressel et al. (2013). Conclusions and discussion of the implications for terminal mass problem of giant planet are reported in Section 4.

2. Gaps in 3D disks

In the framework of a study on planet accretion (Szulagyi et al., 2014), we conducted 3D simulations of a Jupiter-mass planet embedded in an isothermal disk with scale height of 5% and α -prescription of the viscosity (Shakura and Sunyaev, 1973). We adopted $\alpha = 4 \times 10^{-3}$ (viscous simulation) and $\alpha = 0$ (inviscid simulation). The latter simulation was conducted with two different resolutions, to change the effective numerical viscosity of the simulation code. The technical parameters of the simulations are described in

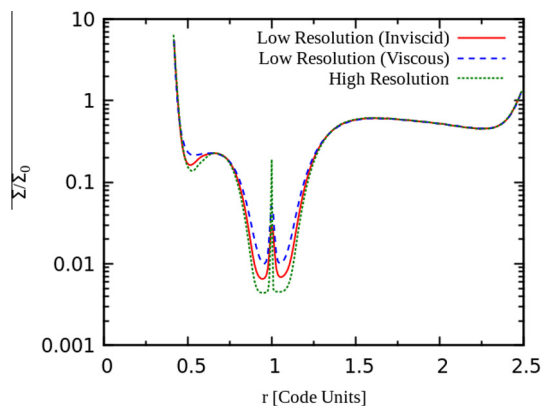


Fig. 1. Gap profiles in the simulations by Szulagyi et al. (2014). The perturbed column density distribution is normalized by the original column density. Here “Viscous” means an α parameter of 0.004 in the Shakura and Sunyaev (1973) viscosity prescription and “inviscid” means $\alpha = 0$; “Low resolution” means $628 \times 208 \times 15$ cells for the directions of azimuth, radius, co-latitude, respectively, but with mesh refinement in the vicinity of the planet (we use 7 levels of mesh refinements, starting from a box centered on the planet with half-sizes $0.27 \times 0.27 \times 0.12$ in code units resolved in $112 \times 112 \times 24$ cells, and doubling the resolution at each level); “High resolution” means twice the number of cells in each direction at each level and still $\alpha = 0$. Notice that the gap becomes deeper with decreasing viscosity and increasing resolution, i.e. decreasing the effective viscosity (prescribed or numeric). The simulation has been performed with the code Jupiter written by F. Masset.

detail in Szulagyi et al. (2014) and the main ones are briefly reported in the caption of Fig. 1.

In Szulagyi et al. (2014) we reported that the flux of material into the gap (and therefore the accretion rate of the planet) decreases by a factor of 2 when the resolution is increased by a factor of 2 (and hence the numerical viscosity is halved). This suggested that the gap properties do not saturate in the limit of small viscosity (prescribed or numeric), or at least not in the range of resolution that we have been able to attain. This observation motivated a deeper investigation, which is the object of the present work.

Fig. 1 gives a clear demonstration of how the gap profile opened by a Jupiter-mass planet in 3D simulations changes with prescribed and numerical viscosity (i.e. with resolution). Each curve shows the radial profile of the surface density, averaged over the azimuth. The surface density has been computed by integrating the volume density over the vertical direction. Clearly, here no convergence is achieved with resolution.

We explain this fact with the following simple model. Consider first the gas in the mid-plane. Its dynamics has to be similar to that in a 2D disk model, and therefore the planet opens a gap with a given profile independent of viscosity in the small viscosity limit. In the vertical direction, the disk has to be in hydrostatic equilibrium. This implies that the volume density ρ scales with z (the distance from the mid-plane) as

$$\rho(z) = \rho(0) \exp\left(-\frac{z^2}{2H^2}\right) \quad (1)$$

where $\rho(0)$ is the mid-plane density and H is the scale-height of the disk. Therefore, at equilibrium the radial density profile of the gap has to be the same at all altitudes. However, the planet cannot sustain the same profile at high altitude as on the mid-plane, because its gravitational potential:

$$\Phi(d, z) = \frac{\mathcal{G}M_p}{\sqrt{d^2 + z^2}} \quad (2)$$

(where \mathcal{G} is the gravitational constant, M_p is the planet’s mass, d is the planet-fluid element distance projected on the mid-plane) weakens with increasing z . Please notice that z plays the role here of the smoothing parameter (usually denoted ϵ) used in 2D simulations, and it is well known that the depth of the gap decreases with increasing smoothing length (see Fig. 2).¹

Away from the mid-plane, the gas tends to refill the gap by viscous diffusion because it is not sufficiently repelled by the planetary torque. As soon as the gas penetrates into the gap, however, it has to fall towards the mid-plane because the relationship (1) is no longer satisfied and has to be restored. Therefore, there is always more gas near the mid-plane in the gap than it would in the ideal case where vertical motion is disabled. This excess of gas is partially accreted by the planet and partially repelled away from the planet orbit into the disk, like in the gap opening process. Outside of the gap, then, the relationship (1) is also not fulfilled, because there is an excess of gas near the mid-plane, coming from within the gap, and a deficit of gas at high altitude, which flowed into the gap. So, the gas has to move towards the surface of the disk to restore the hydrostatic vertical equilibrium profile (1).

In conclusion, there has to be a 4-step meridional circulation in the gas dynamics: (1) the gas flows into the gap at the top layer of the disk; (2) then it falls towards the disk’s mid-plane; (3) the planet keeps the gap open by accreting part of this gas and by pushing back into the disk the gas that flowed outside of the Hill sphere; (4) the gas expelled from the gap near the mid-plane rises back to the

¹ This shows that neglecting the z -dependence of the potential in the numerical simulations, as done in Zhu et al. (2013), changes the dynamics of the gas at a qualitative level and can enable small-mass planets to sustain partial gaps.

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