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Is the gap-opening criterion that was derived for laminar discs applicable to gravitationally unstable discs?

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Abstract

We investigate the criterion for gap-opening by giant planets in self-gravitating protoplanetary discs. Firstly, we examine whether this criterion, which was previously determined for laminar discs [1], is applicable to gravitationally unstable discs by simulating different set-ups of embedded planets with a 2-D grid based hydrodynamics code and comparing our results with the predictions made by the criterion. Secondly, we probe the limitations of the criterion by investigating which assumptions on the basis of laminar discs do not capture the physical mechanisms in self-gravitating discs.

1. Introduction

In protoplanetary discs planets exchange angular momentum with their surrounding disc material, which might lead to a change in their orbital separation from the central star. In this way either an inward or outward migration of the planet can be triggered. Due to an asymmetry in the interaction between the planet and the disc the migration is found to be predominantly inwards. For low mass planets the migration (Type I) tends to happen on the orbital timescale, i.e. $t_{\mathrm{M,I}} \sim t_{\mathrm{orb}}$, whereas planets with a sufficiently large mass can open up a gap in the disc, which slows down the evolution of the orbital separation to the viscous diffusion timescale, i.e. $t_{\mathrm{M,II}} \sim t_\nu \sim \frac{R^2}{\nu} \gg t_{\mathrm{M,I}}$ (Type II migration). The conditions under which such a gap-opening occurs in laminar discs have been included in a semi-analytical criterion [1]. Until now it has been unclear as to what extent this approach is valid for self-gravitating discs.

2. Simulation Set-up

For our simulations we use the FARGO hydrodynamics code, which has an implemented energy equation and includes the self-gravity of the disc. Our disc parameters are based on the disc configuration of previous similar simulations [2], but feature updated softening lengths for both the self-gravity of the disc and the planet's gravitational potential [3].

3. Criterion

The original semi-analytical result for the gap-opening criterion is based on the following physical idea [1]. The equilibrium radial surface density profile around an embedded planet is determined by a balance between gravity, viscous and pressure torques. Intuitively it means that the gravity of the planet, which scales with the planet's mass, affects a gap-opening positively by clearing the nearby orbital regions of the disc material, whereas the viscosity and the pressure, resulting from the density gradient at the gap edge, work against it. Having determined the density profile in this way, a minimal depth in the profile at the planet's orbital separation sets the condition for a gap. This physical reasoning is implemented in the following fit to the semi-analytical criterion:

$$\frac{3}{4}\frac{H_p}{R_H} + \frac{50}{q\mathscr{R}} \lesssim 1. \qquad (1)$$

The fit involves the disc scale height H_p, the planet to star mass ratio $q \equiv M_p/M_\star$ and the Reynolds number $\mathscr{R}$ given by $R_p^2\Omega_p/\nu_p$, with the planet's orbital separation R_p, the angular orbital velocity Ω_p and the viscosity ν_p. Furthermore $R_H \approx R_p(q/3)^{1/3}$ is the Hill radius of the planet and the index "p" means that the value is evaluated at the planet's position. A gap opens if the inequality in eq. 1 is satisfied. Therefore it is apparent that low viscosities and high mass planets are more likely to open up a gap. For low values of the viscosity and the planet mass the fit corresponds well to the original semi-analytical result. However the goodness of the fit decreases with increasing viscosity and planet mass, both of which are higher in gravitationally unstable discs. We reproduce the original approach and examine whether or not the fit to the semi-analytical result still holds for these extended parameter ranges.

References

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