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# On the Corotation Torque of Embedded Low-mass Eccentric Protoplanets

**S. M. Fendyke** and R. P. Nelson
School of Physics and Astronomy, Queen Mary, University of London, London, United Kingdom, E1 4NS.
(S.M.Fendyke@qmul.ac.uk)

## Abstract

Embedded protoplanets in inviscid, isothermal protoplanetary discs rapidly migrate inward under the action of Lindblad torques (Type I migration). This behaviour can be slowed or even reversed by corotation torques, fuelled by sustained vortensity and entropy gradients across the corotation region. Work by Bitsch and Kley[2] has suggested that this corotation torque attenuates for eccentric planets.

We present results from a series of high-resolution 2D hydrodynamic simulations of low-mass eccentric protoplanets, from which we obtain the corotation torque as a function of eccentricity for disc aspect ratios between $H/r = 0.03$ and $H/r = 0.10$.

We find an attenuation of corotation torque with increasing eccentricity for all disc aspect ratios. This attenuation is closely connected with the narrowing of the corotation region.

## 1 Context

Corotation torques experienced by low-mass planets consist of a linear component[4] and a non-linear component which is physically manifested as the "horseshoe drag"[6]; that is, the torque is generated by the asymmetric exchange of material bound to the planet on horseshoe orbits. One such asymmetry is due to a vortensity gradient across the corotation region, but a similar torque is also generated by an entropy gradient[1]. If these gradients of vortensity and entropy are maintained by the action of viscosity and thermal diffusion respectively, we expect a sustained corotation torque, for which torque formulae exist[5].

## 2 Our simulations

We use a grid-based hydrodynamic code to simulate a protoplanetary disc with an embedded $5\mathrm{M_e}$ planet, and density and temperature gradients of $\sigma = \sigma_0 r^{-0.5}$ and $T = T_0 r^{-2}$ respectively chosen to give a large, positive corotation torque. In place of full radiative diffusion, we relax the entropy profile of the disc towards its unperturbed state on some characteristic timescale.

We run two sets of simulations; one with a negligible viscosity and an adiabatic disc where the corotation torque will saturate, and one with an optimised viscosity and entropy relaxation timescale, in which we expect an optimised corotation torque. Torque time-series are shown in figure 1.

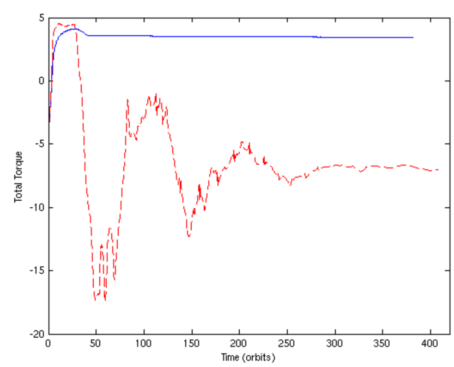


Figure 1: Total torque against time for an embedded $5\mathrm{M_e}$ planet planet on a fixed circular orbit in both an inviscid, adiabatic disc (red, dotted line) and a viscous one with optimised thermal diffusion (blue, solid line). The disc has an aspect ratio of $H/r = 0.05$.

From these, we can measure the corotation torque (i) by directly comparing the two simulations; (ii) by calculating the torque contribution from the corotation region of the disc in the sustained torque case and (iii) by comparing the initial peak of corotation torque, before it has saturated, to the steady state saturated value in the case with negligible viscosity.

# 3 Results

We see an exponential attenuation in corotation torque as eccentricity increases and find that the e-folding eccentricity depends strongly on the aspect ratio of the disc, with thicker discs having a larger e-folding eccentricity. We also find a decrease in the width of the corotation region for more eccentric planets, which is consistent with the $\Gamma \sim x_s^4$ law from the torque formulae of Ward and Paardekooper et al.[5, 6]. This correlation is clearest for thicker discs, where non-linear effects are minimised.

For a disc of aspect ratio $H/r = 0.07$, we show torque measurements in figure 3, and in figure 2, we show time-averaged density fields with the limit of the corotation region superimposed.

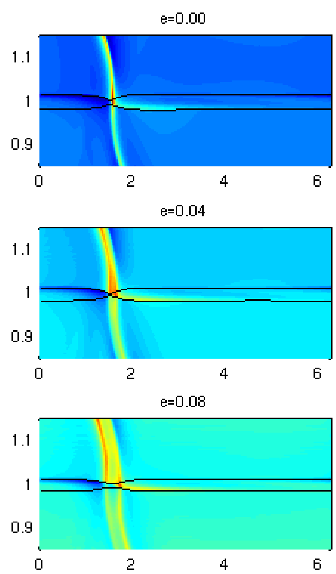


Figure 2: Time-averaged perturbation to the density of a $H/r = 0.07$ disc, plotted as radius against azimuth, for different eccentricities. Colour scales are not the same.

# 4 Conclusion

Previous work has noted that swarms of embedded planetesimals can mutually excite modest eccentricities[3]. We have shown that the corotation torque can reduce drastically for even small eccentricities, impacting its ability to counteract the Lindblad torques and reverse or slow inward migration.

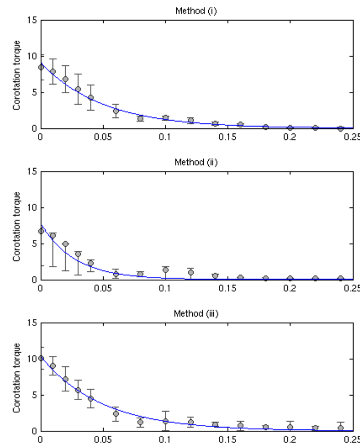


Figure 3: The torque in units of $\Gamma_0/\gamma$ as measured in a $H/r = 0.07$ disc by our three methods.

## Acknowledgements

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