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How is protoplanetary migration changed in weakly magnetised discs?

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Abstract

The gravitational interaction between planets and their parent protoplanetary disc plays a prominent role in shaping planetary systems from the early stages of their formation and evolution. The tidal torque exerted by the disc on a planet drives the planet's orbital migration, a change in the planets semi-major axis during the disc lifetime. One of these torque components, the corotation torque, has recently received detailed attention as it may reverse the direction of migration for protoplanets (typically of several Earth masses, also called type I migration). Here we report on new results on the corotation torque in discs threaded by a weak toroidal magnetic field, in which the effects of turbulence are modelled by a viscosity and a resistivity. By means of MHD simulations of planet-disc interactions, we show the existence of an additional corotation torque of magnetic origin. Its sign depends solely on the density and temperature gradients across the planet's horseshoe region, while its magnitude is set by the magnetic field's amplitude and diffusivity within the horseshoe region. Even in discs with magnetic to thermal pressure ratios less than one percent, the magnitude of this new magnetic-related corotation torque can exceed that of the tidal torque in non-magnetised disc models. It could therefore lead to a reversal of type I migration even in radiatively efficient regions of protoplanetary discs.

1. Context

The tidal torque acting on type I-migrating planets has two components. One is the differential Lindblad torque, which arises from the spiral density waves generated by the planet, and which leads to rapid inward migration. The other torque component is the corotation torque, which is exerted by the disc material inside the planet's horseshoe region (a narrow annulus around the planet's orbital radius). The corotation torque has been subject to intense investigation after it was recently discovered that its amplitude may be comparable to, or even greater than the differential Lindblad torque in radiatively inefficient regions of planet formation. The sign and the magnitude of the corotation torque depend on the disc properties inside the planet's horseshoe region (density and temperature profiles, turbulent diffusivity). The radial width of the horseshoe region being a fraction of the disc's pressure scaleheight, and thus of the typical size of turbulent eddies, it is unclear to what extent the corotation torque in turbulent discs should behave similarly as in viscous disc models. Using 3D MHD simulations in which the magneto-rotational instability operates throughout the whole disc, [1] showed the existence of an unsaturated corotation torque in discs with a weak mean toroidal magnetic field, with an additional component of moderate amplitude compared to non-magnetised disc models. This communication aims at introducing the properties of this new corotation torque in weakly magnetised viscous disc models, which will be described in [2].

2. Methods

Two-dimensional MHD simulations have been carried out, adopting a locally isothermal disc model in which the effects of turbulence are modelled by a viscosity ($\alpha = 5 \times 10^{-3}$) and a resistivity (the magnetic Prandtl number is set to unity). The disc's background density, temperature, and toroidal magnetic field are set as power-law functions of radius (with indices taken as free parameters). The disc is perturbed by a planet with planet-to-primary mass ratio $q = 2 \times 10^{-5}$ (corresponding to a 7 Earth-mass planet if the central object is a Sun-like star). At the planet's orbital radius, the disc's aspect ratio is $H/R = 0.05$, and the thermal-to-magnetic pressure ratio is $\beta = 100$.

3. Results

In the presence of a weak toroidal magnetic field, the gas horseshoe U-turns near the planet lead to an accumulation of magnetic flux at the downstream separatri-

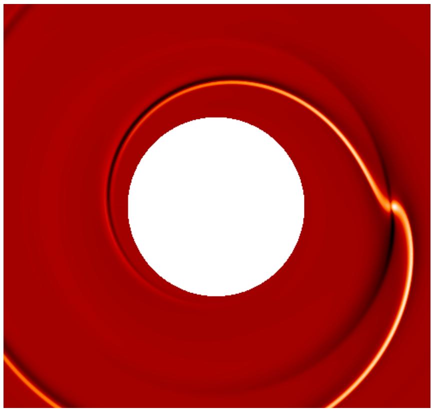

Figure 1: *Surface density perturbation of a disc threaded by a weak toroidal magnetic field, and perturbed by a few Earth-mass planet. In addition to the spiral density waves, the planet triggers the formation of underdense lobes inside its horseshoe region.*

ces of the planet's horseshoe region. This accumulation results in an enhanced magnetic pressure downstream of the horseshoe region, where the gas surface density is reduced to maintain approximate total pressure balance. Underdense lobes are then formed downstream of the horseshoe region (see Figure 1). Their density distribution is asymmetric with respect to the planet's location, which gives rise to a net corotation torque on the planet. Figure 2 compares the time evolution of the tidal torque obtained with and without a magnetic field for two disc models that differ by the choice of background density and temperature profiles (see caption). In these models, the difference between the MHD and hydrodynamical torques, which corresponds to the magnetic-related corotation torque, has the same amplitude but opposite sign. In model 1, the magnetic-related corotation torque is positive enough to make the tidal torque a positive quantity (thereby leading to outward migration).

4. Summary

The presence of a weak toroidal magnetic field gives rise to an additional corotation torque on low-mass planets. Its amplitude is essentially independent of the gradients of magnetic field, density and temperature across the horseshoe region. It depends sensitively on the magnetic field strength and resistivity inside the planet's horseshoe region. Its sign is solely set by the disc's density and temperature gradients. This new magnetic-related corotation torque can be strong enough to cause outward type I migration even in radiatively efficient discs.

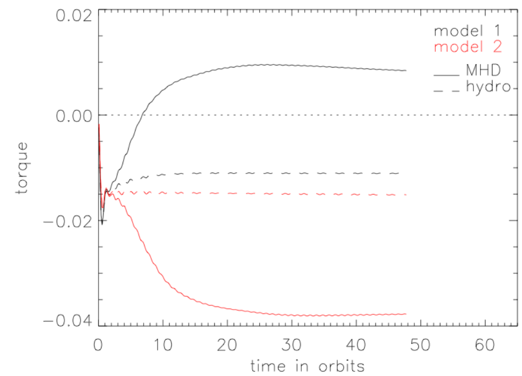

Figure 2: *Time evolution of the torque exerted by the disc on the planet for two disc models with different background density and temperature profiles (model 1: $\Sigma \propto r^{-1/2}$ and $T \propto r^{-1}$, model 2: $\Sigma \propto r^{-3/2}$ and uniform temperature).*

References

[1] Baruteau, C., Fromang, S., Nelson, R. P. and Masset, F. 2011, A&A, 533, A84

[2] Guilet, J., Baruteau, C. and Papaloizou, J., submitted