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Gap opening by planets in discs with magnetised winds

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Abstract. Planets open deep gaps in protoplanetary discs when their mass exceeds a gap opening mass, $M_{\rm gap}$. We use one- and two-dimensional simulations to study planet gap opening in discs with angular momentum transport powered by MHD disc winds. We parameterise the efficiency of the MHD disc wind angular momentum transport through a dimensionless parameter $\alpha_{\rm dw}$, which is an analogue to the turbulent viscosity $\alpha_{\rm v}$. We find that magnetised winds are much less efficient in counteracting planet tidal torques than turbulence is. For discs with astrophysically realistic values of $\alpha_{\rm dw}$, $M_{\rm gap}$ is always determined by the residual disc turbulence, and is a factor of a few to ten smaller than usually obtained for viscous discs. We introduce a gap opening criterion applicable for any values of $\alpha_{\rm v}$ and $\alpha_{\rm dw}$ that may be useful for planet formation population synthesis.

Keywords. planetary systems: formation, planetary systems: protoplanetary disks, planets and satellites: formation

1. Introduction

Gap opening by planets embedded in protoplanetary discs has a significant impact on a wide range of phenomena in star and planet formation. The low levels of turbulence observed by ALMA are at odds with the stirred-up vertical distribution of micron sized dust in some discs, and they are also insufficient to account for the significant mass accretion rates onto the stars (cf. the review and references in Miotello et al. 2022). A number of authors have recently argued that a weak net flux of vertical magnetic field present in molecular cloud cores may enhance MHD-driven disc winds that remove angular momentum of gas at a faster rate than disc turbulence (e.g., Lesur 2021). The goal of our paper is to evaluate the gap opening planet mass in discs where mass and angular momentum transfer are dominated by magnetised winds rather than disc turbulence.

2. Analytical estimates

To derive the conditions for a gap opening in a disc with MHD disc winds, we shall assume for simplicity that $\alpha_{\rm v}$ is negligibly small. At $R > a$, where a is the radial distance of the planet, the angular momentum gain by the gas due to the disc-planet interaction results in an outward flow of gas at velocity

$$v_{\rm p} = \frac{2\Lambda_{\rm p}}{v_K}\,, \tag{2.1}$$

where $\Lambda_{\rm p}$ is the specific torque from the planet on the surrounding gas and can be approximated by (Lin & Papaloizou 1986)

$$\Lambda_{\rm p} = f\,\mathrm{sign}\,(R-a)\;\frac{q^2}{2}\frac{a^4}{\Delta R^4}v_K^2\,, \tag{2.2}$$

where $v_{\rm K}$ is the Keplerian velocity at the radial distance of the planet a, q is the planet-to-star mass ratio, $\Delta R = R - a$, and $0.1 \leq f < 1$ is a constant of order unity that depends on the detail of torque deposition and wave energy dissipation in the disc. In this paper we take $f = 0.15$.

This outward flow of gas, away from the planet, results in the creation of the gap. Due to 3D effects in realistic discs, the torque $\Lambda_{\rm p}$ from the planet saturates at distance $|\Delta R| \sim \kappa R_H$ away from the planet, where κ is a constant of order unity.

The MHD disc winds results in an inward flow of gas at the velocity (Tabone et al. 2022)

$$v_{\rm dw} = -\frac{3}{2}\alpha_{\rm dw}\left(\frac{H}{R}\right)^2 v_K\,. \tag{2.3}$$

where $\alpha_{\rm dw}$ is a dimensionless parameter, defined by analogy with the $\alpha_{\rm v}$ parameter. MHD winds will close a gap opened by the planet when $v_{\rm dw} + v_{\rm p} \leq 0$. Solving the equation $v_{\rm dw} + v_{\rm p} = 0$, we get the critical q to open a gap in such a disc:

$$q_{\rm dw} = \left[\frac{\kappa^4}{2f3^{1/3}}\right]^{3/2} \alpha_{\rm dw}^{3/2} h^3\,, \tag{2.4}$$

where $h = H/R$. The result depends strongly on the parameter κ, which is not possible to constrain from first principles. We find that Eq. (2.4) fits well the gap opening mass determined numerically for $\kappa = 1.65$. With this value for κ,

$$q_{\rm dw} \approx 7\times 10^{-5}\, \left[\frac{\alpha_{\rm dw}}{0.01}\right]^{3/2} \left[\frac{h}{0.1}\right]^3 \tag{2.5}$$

We define a modified parameter for gap opening that combines the previously derived (Crida et al. 2006) criteria for gap opening in a turbulent disc with the condition we derived above for a disc with MHD disc wind parameter $\alpha_{\rm dw}$:

$$\mathcal{P}_{\rm dw} = \frac{3H}{4R_{\rm H}} + \frac{50\alpha_{\rm v}}{q}\left(\frac{H}{R}\right)^2 + \frac{70\alpha_{\rm dw}^{3/2}}{q}\left(\frac{H}{R}\right)^3\,. \tag{2.6}$$

3. Conclusions

In this paper, we showed that planets embedded in protoplanetary discs have easier time opening deep gaps in gas and dust if mass and angular momentum transport is dominated by magnetised winds rather than by the standard turbulent viscosity. In brief, this is because transport of material across the gap region of the planet by advection is less efficient in resisting planet tidal torques compared with that by turbulent diffusion of material in the standard discs.

For more details on this study please see Elbakyan et al. (2022).

References

Crida, A., Morbidelli, A., & Masset, F. 2006, Icarus, 181, 587
Elbakyan, V., Wu, Y., Nayakshin, S., & Rosotti, G. 2022, MNRAS, 515, 3113
Lesur, G. R. J. 2021, A&A, 650, A35
Lin, D. N. C. & Papaloizou, J. 1986, ApJ, 309, 846
Miotello, A., Kamp, I., Birnstiel, T., Cleeves, L. I., & Kataoka, A. 2022, arXiv e-prints, arXiv:2203.09818
Tabone, B., Rosotti, G. P., Cridland, A. J., Armitage, P. J., & Lodato, G. 2022, MNRAS, 512, 2290

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