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Quantifying the evolution of planetesimals embedded in magnetized protoplanetary discs with dead zones

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Abstract

Sufficiently ionized sections of protoplanetary discs are thought to be in a turbulent state powered by the magnetorotational instability (MRI). Previous work [1, 2] has shown that a swarm of planetesimals embedded in a fully turbulent disc is subject to strong excitation of its velocity dispersion, along with significant radial diffusion of semi-major axes. Implications include the collisional destruction of small bodies, and levels of large-scale spread of populations incompatible with the observed distribution within the asteroid belt. The picture remains unchanged when vertical stratification is included [3], and we suggest that planetesimal growth via mutual collisions cannot occur in a fully MRI-active disc. By contrast, a magnetically dead zone may provide a safe haven in which km-sized planetesimals can avoid mutual destruction [3]. First preliminary results from new simulations indicate that this finding also holds for increased disc masses, i.e., for more extended dead zones.

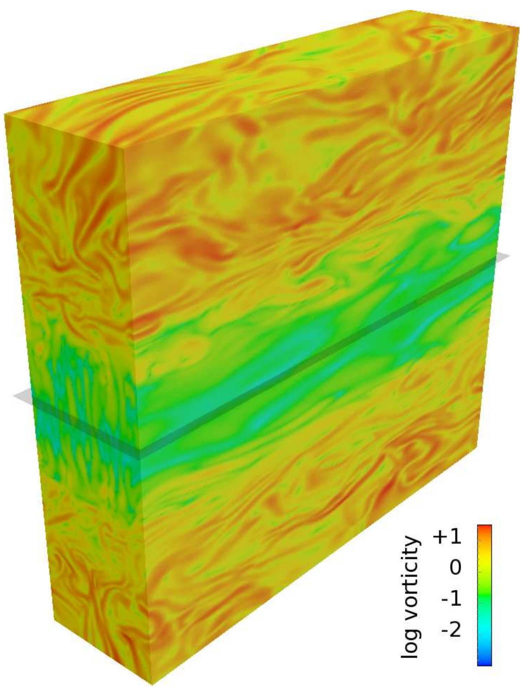

Figure 1: Simulation snapshot visualizing the flow vorticity. Active regions above and below the mid plane are dominated by turbulent eddies, whereas the flow in the dead zone is characterized by sheared density waves (figure taken from [3]).

1. Introduction

In a series of papers, we have examined the dynamics of planetesimals embedded in unstratified, and vertically stratified turbulent discs with and without dead zones, and adopting both local and global disc models. Our main aim in these studies was to quantify the amount of stirring, and examine the turbulent excitation of mutual velocities, as well as the radial diffusion of planetesimals. As these simulations are extremely demanding in terms of computational resources, the ultimate goal will be to provide robust scaling relations with the most important input parameters. This will then allow the modeling of the related processes [4] in a more general context, e.g., for the purpose of population synthesis calculations [5].

For the work presented here, we employ 3D MHD simulations (see Fig. 1) using the shearing box approximation. The magnetically dead zone is derived self-consistently from an equilibrium chemistry model [6] based on external ionization, which is assumed to arise from stellar X-rays, galactic cosmic rays and short-lived radio-nuclei [7].

2. Results

In agreement with our previous study [2], we find that planetesimals in fully turbulent discs develop large random velocities (cf. model A1 in Fig. 2) that, over time, will likely lead to collisional destruction and erosion for bodies with radii below $100\,\mathrm{km}$. Planetesimals of this size will moreover undergo radial diffusion on a scale $\sim 2.5\,\mathrm{au}$ over a $5\,\mathrm{Myr}$ disc life time.

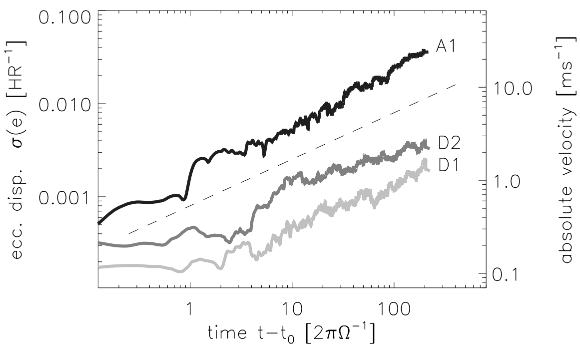

Figure 2: Stochastic growth of the particles' eccentricity as a function of time. Model 'A1' is fully active, 'D1' represents a nominal dead zone (taken from [3]).

By contrast, planetesimals in a dead zone experience a much reduced excitation of their random velocities (see models D1/D2 in Fig. 2), and equilibrium velocity dispersions lie between the disruption thresholds for weak and strong aggregates [8] for sizes smaller than $100\,\mathrm{km}$. We also find that radial diffusion occurs over a much reduced length scale $\sim 0.25\,\mathrm{au}$ over the disc life time, this being consistent with solar system constraints.

While our fiducial model D1 essentially comprises a minimum-mass scenario, preliminary results from new simulations (heavier by a factor of two and four, respectively) indicate that the observed value does only weakly depend on the assumed disc mass (and hence the dead zone thickness). We conjecture that this is due to the cancellation of two counteracting trends: while a heavier disc would in principle allow for stronger gravitational forcing, density fluctuations are equally harder to excite.

3. Summary and Conclusions

In fully turbulent discs without dead zones (model A1), we find that the velocity dispersion of embedded planetesimals grows rapidly, and quickly exceeds the threshold for disruption. We conclude that planetesimal formation via collisional accretion of smaller bodies cannot occur in globally turbulent discs.

Comparing the results obtained for dead zones with different vertical heights (models D1 & D2), we find that the larger dead zone model clearly favours the collisional formation of planetesimals because of weaker stochastic forcing of random motions. The radial diffusion of planetesimals is much reduced in these models, relative to fully active discs. Our simulation D1 suggests radial diffusion over a distance of a quarter astronomical unit, being consistent with solar system constraints. On the other hand, the low diffusion levels for planetesimal semimajor axes in dead zones clearly imply that stochastic torques in such an environment cannot prevent the large scale inward drift of low mass planets via type I migration.

While the models presented in [3] are limited to a minimum-mass nebula, a first preliminary analysis of new models indicates that the finding remains robust for a wider range of disc masses along with more extended dead zone regions. We conjecture that the excited density waves merely act as a mediator, and the stirring amplitude is ultimately determined by the extent of the active regions (also cf. [9]). In a future study, we therefore plan to investigate more closely the link between the MRI active regions and amplitude of the density perturbance near the mid plane. In particular, we are interested in the dependence on the net vertical magnetic flux, which is known to have a profound impact on the saturation level of the MRI.

In conclusion, we suggest that dead zones provide safe havens for km-sized planetesimals against destructive collisions, and are probably a required ingredient for the formation of planetary systems.

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