Shedding light on the MRI driven dynamo in a stratified shearing box

Prasun Dhang[1,2],⋆ Abhijit Bendre[3], Kandaswamy Subramanian[2,4]
[1] *JILA, University of Colorado and National Institute of Standards and Technology, 440 UCB, Boulder, CO 80309-0440, USA*
[2] *IUCAA, Post Bag 4, Ganeshkhind, Pune 411007, India*
[3] *Institute of Physics, Laboratory of Astrophysics, École Polytechnique Fédérale de Lausanne (EPFL), 1290 Sauverny, Switzerland*
[4] *Department of Physics, Ashoka University, Rajiv Gandhi Education City, Rai, Sonipat 131029, Haryana, INDIA*

17 August 2023

ABSTRACT

We study the magneto-rotational instability (MRI) dynamo in a geometrically thin disc ($H/R \ll 1$) using stratified zero net flux (ZNF) shearing box simulations. We find that mean fields and EMFs oscillate with a primary frequency $f_{\rm dyn} = 0.017$ (≈ 9 orbital period), but also have higher harmonics at $3f_{\rm dyn}$. Correspondingly, the current helicity, has two frequencies $2f_{\rm dyn}$ and $4f_{\rm dyn}$ respectively, which appear to be the beat frequencies of mean fields and EMFs as expected from the magnetic helicity density evolution equation. Further, we adopt a novel inversion algorithm called the 'Iterative Removal Of Sources' (IROS), to extract the turbulent dynamo coefficients in the mean-field closure using the mean magnetic fields and EMFs obtained from the shearing box simulation. We show that an $\alpha-$effect (α_{yy}) is predominantly responsible for the creation of the poloidal field from the toroidal field, while shear generates back a toroidal field from the poloidal field; indicating that an $\alpha - \Omega$-type dynamo is operative in MRI-driven accretion discs. We also find that both strong outflow ($\bar{v}_z$) and turbulent pumping (γ_z) transport mean fields away from the mid-plane. Instead of turbulent diffusivity, they are the principal sink terms in the mean magnetic energy evolution equation. We find encouraging evidence that a generative helicity flux is responsible for the effective α-effect. Finally, we point out potential limitations of horizontal ($x-y$) averaging in defining the 'mean' on the extraction of dynamo coefficients and their physical interpretations.

Key words: accretion,accretion discs - dynamo - instabilities - magnetic fields - MHD - turbulence - methods: numerical.

1 INTRODUCTION

The problem of angular momentum transport is a key concept in a rotationally supported accretion disc (for a review, see Balbus & Hawley 1998). The current consensus is that a weak magnetic field instability, namely magneto-rotational instability (MRI; Velikhov 1959; Chandrasekhar 1960; Balbus & Hawley 1991; Balbus & Hawley 1992) is responsible for outward angular momentum transport and drives mass accretion in a sufficiently ionized accretion disc. Although linear MRI ensures outward angular momentum transport, it must be studied in the non-linear phase to account for different observable phenomena in accretion discs.

MRI in an accretion disc is either studied in a local set-up (shearing box; Balbus & Hawley 1992; Brandenburg et al. 1995; Hawley et al. 1995; Davis et al. 2010; Shi et al. 2010; Bodo et al. 2014; Bhat et al. 2016) or in a global simulation (Stone et al. 1999; Hawley 2001; Hawley et al. 2013; Beckwith et al. 2011; Parkin & Bicknell 2013; Hogg & Reynolds 2016; Dhang & Sharma 2019; Dhang et al. 2023). While a global approach is more desirable, it is computationally expensive. On the other hand, the shearing box approach offers an alternate path which is computationally less costly and can provide deep insights into the local processes in MRI-driven turbulence.

In the shearing-box approach (Goldreich & Lynden-Bell 1965), we expand fluid equations to the lowest order of H/R, where H is the density scale height and R is the local radius. Therefore, this approach is valid only for geometrically thin discs with $H/R \ll 1$. Depending on whether the vertical component of gravity ($g_z = -\Omega^2 z$) (producing a vertically stratified gas density) is considered in the momentum equation or not, shearing box simulations are of two types: stratified ($g_z \neq 0$) and unstratified ($g_z = 0$). Further, depending on whether the computational domain can contain net magnetic fields, shearing box models can be classified into zero net flux (ZNF) and net flux (NF) models. Therefore, four possible combinations of the shearing-box model are: i) unstratified ZNF, ii) unstratified NF, iii) stratified ZNF and iv) stratified NF. This work considers a stratified ZNF shearing box model to explore the MRI dynamo in saturation.

Shearing box simulations provide a wide range of behaviour (e.g., convergence, turbulence characteristics etc.) depending on the shearing box model used (for details, we refer to readers to see Table 1 in Ryan et al. (2017)). However, it is to be noted that we will restrict our discussion to the isothermal (i.e. sound speed is constant) models where there is no explicit dissipation and the numerical algorithms provide the dissipation through truncation error at the grid scale. In the presence of an NF, unstratified shearing box simulations show a convergence (in terms of accretion stresses) and sustained turbulence (Hawley et al. 1995; Guan et al. 2009; Simon et al. 2009). On the other hand, stratified NF simulations present different accretion stresses depending on the net flux strength and sustained turbulence (Guan & Gammie 2011; Bai & Stone 2013). Unstratified ZNF mod-

⋆ E-mail:prasundhang@gmail.com