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Amplification of magnetic fields in accretion discs by GRMHD dynamo

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Abstract. The accretion of magnetized plasma from an accreting torus onto a supermassive black hole has recently received considerable attention thanks to the recent imaging of the *shadow* of the black hole in M87 by the Event Horizon Telescope (EHT) collaboration. In the regime of general relativistic magnetohydrodynamics (GRMHD) typically adopted, an initial magnetic field, small but certainly not negligible, is amplified by the magnetorotational instability (MRI) that develops in the disk, in turn triggering accretion. Here we show the first results about the amplification of an initial tiny magnetic field in the accretion disk by means of GRMHD *mean-field dynamo*, in the fully non-linear regime. This process is able to produce an exponential growth of the field up to the values required to explain the observations.

1. Introduction

The recent imaging of the relativistically hot plasma surrounding the supermassive black hole at the very center of the M87 galaxy (Coll. 2019) has led the numerical GRMHD community to search for the best setup for the modeling of the thick accretion disks around black holes. A *Code Comparison Project* (Porth 2019) was developed in parallel with the EHT observations: the aim was to compare numerical techniques and results produced by the participating codes, including the ECHO code (Del Zanna 2007) developed by our group. The traditional setup requires the magnetic field to be initialized by assuming the ratio between gas pressure to magnetic pressure set to $\beta = p/p_{mag} = 100$. This initial magnetic field is then amplified by the magnetorotational instability (MRI; Balbus (1998)) triggered by pressure perturbations. Our work (Tomei 2020) aims at studying a mechanism to amplify magnetic fields starting from negligible values (say $\beta \sim 10^9$) in global simulations, where the amplification induced by a turbulent 3D dynamo would be impossible to be resolved as done in local *shearing-box* treatments (Bhat 2017). To overcome this difficulty, the unresolved turbulence is supposed to behave in a way to provide an extra α-*dynamo* electromotive term to the comoving electric field

$$< \delta\mathbf{v} \times \delta\mathbf{b} >= \alpha_{\rm dyn}\mathbf{B} - \beta_{\rm dyn}\mathbf{J},$$

due to averaged small-scale velocity and magnetic field fluctuations, proportional to the mean magnetic field $\boldsymbol{B}$ itself. When combined to the differential rotation of the disk, the resulting $\alpha - \Omega$ dynamo is able to operate iteratively and leads to the exponential amplification of any initial magnetic field, even in axisymmetric configurations (e.g. Brandenburg 2005).

The first rigorous treatment of the dynamo effect within resistive GRMHD, as needed to treat the accretion process onto black holes, was presented by Bucciantini (2013), see also Del Zanna (2018), who proposed a covariant form for the generalized Ohm equation. This approach was first applied to the physics of accretion disks by Bugli (2014), where the evolution of magnetic fields was studied by in axisymmetry and in the kinematic regime, that is by solving Maxwell equations alone not considering the feedback on the plasma of the disk. The magnetic field threading the disk is indeed amplified exponentially, not related to the period of rotation, but rather on the microphysics of turbulence. In Tomei (2020), we generalized this work to the fully self-consistent and nonlinear dynamical regime during the accretion phase.

2. Results

We present axisymmetric simulations (resolution 512 × 256) performed with the ECHO code, employing the horizon-penetrating Kerr-Schild coordinates. The disk is initialized with an exact hydrodynamical equilibrium with a superimposed poloidal magnetic loop with negligible intensity. Figure 1 shows the time evolution of the average poloidal and toroidal components of the magnetic field. We can see that a toroidal field immediately arises due to the Ω effect and, after a transient, the mean-field $\alpha-$dynamo starts as well and supports the exponential amplification of the two components up to $\sim$ 4.5 t/P_c, where P_c is the central period of the disk. This phase coincides with the kinematic regime studied by Bugli (2014), as there is there is no noticeable feedback on the disk and the field grows following the normal modes of the dynamo, propagating towards the outer edge of the disk. During this linear phase the toroidal fields remain always stronger than the poloidal component. The new interesting aspect is represented by the situation around $t \simeq 4.5P_c$, where the linear dynamo action saturates.

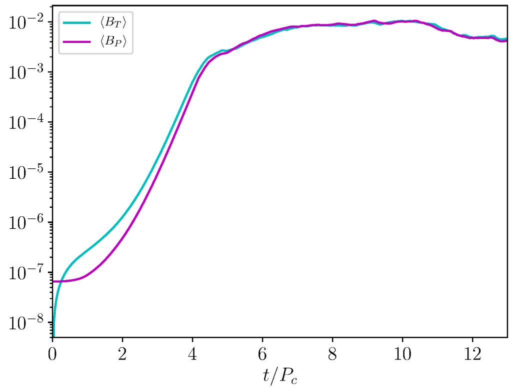

Fig. 1. The time evolution of the average values of the toroidal and poloidal components of the magnetic field. From Tomei (2020).

The three phases are more clearly apparent in Figure 2, where spatial maps of the (poloidal) magnetic field are presented at three different times. In the top left panel we are clearly still in the kinematic, linear phase of the dynamo. The magnetic field does not affect the disk shape, magnetic islands corresponding to the linear dynamo modes migrate towards the outer edge of the disk while growing in amplitude. In the top right panel the disk starts to be affected by the presence of the growing field and dynamo waves are dragged towards the black hole by the accretion. The accretion process is most probably triggered by MRI, that also drives turbulent motions. In this dynamic regime, magnetic structures tend to form low-pressure vortices that drag matter away (third panel), that for high values of the magnetic field can even evacuate the plasma locally. The dynamo modes are barely visible during the phase of the secondary growth (bottom left panel), and they seem to be localized only at the external boundary of the disk, where density and the dynamo term ξ are lower. In order to limit the dynamo action and to obtain a more regular growth we have added an explicit *quenching* term in the dynamo term, activated when the field becomes comparable to the equipartition value: the formation of vortices evacuating the plasma is inhibited and the dynamo structures evolve more smoothly, even in a turbulent environment.

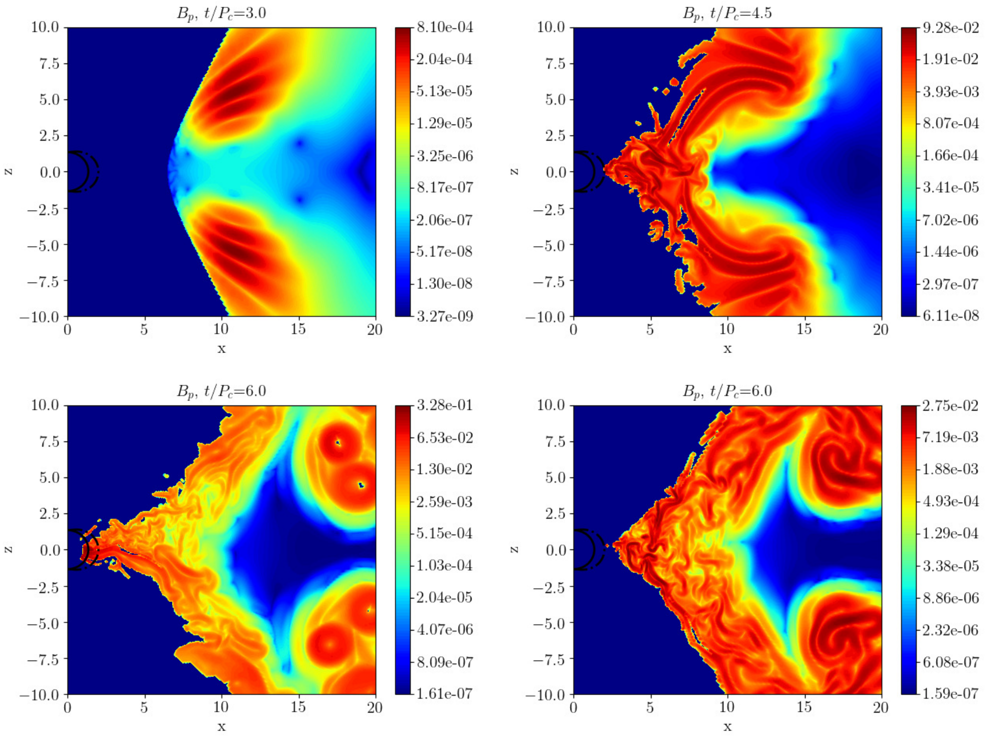

Fig. 2. Color maps of the poloidal magnetic field B_P in logarithmic scale, for three different times t/P_c Black lines near the origin are the contours of the black hole's ergosphere (dashed line) and horizon r_h (solid line). Quenching has been adopted in the last panel. From Tomei (2020).

Finally we tested the dynamo model with an application. By assuming the approximation of an optically thin plasma, as expected for Sgr A*, the accreting supermassive black hole of our Galaxy, we have computed the expected emission, at millimetre wavelengths, for such source. The values obtained in the saturation phase are consistent with previous works (Mościbrodzka 2014). This confirms that the dynamo action, believed to occur in these systems due to small-scale turbulence, is capable of amplifying the magnetic fields, in a self-consistent way, up to the values required to reproduce the observations.

To conclude, we believe that non-ideal resistive-dynamo models of accreting discs around black holes represent a necessary upgrade to the existing ones, which are based on the ideal MHD assumption and on the presence of initial rather strong fields in the disk, whose origin is not investigated and certainly not taken in consideration within a self-consistent model. However, for a detailed comparison against the revolutionary images by the EHT collaboration, an extension of our work to fully 3D simulations and the adoption of ray-tracing techniques for the emission in a curved space-time will be certainly required.

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