Erratum: Conclusions and Future Developments

In this thesis, we investigate outflow launching from resistive and dynamo active disks. Resistivity is important for disk evolution and jet launching because it enhances accretion towards the black hole in increase the mass load of the outflows and allows for a physical mechanism for reconnection. We implemented magnetic diffusivity, or resistivity in the GRMHD code `HARM3D`, as well as turbulent dynamo, effectively changing the physics under which the code operates. The implementation follows the mean–field theory of turbulence based resistivity and dynamo. we tested the performance of the code and applied it into simulation of thin disk around black holes. In this chapter, we will summarize the major results presented in the previous section and we will also refer to future further development of the code and further scientific projects that can be investigated.

Summary of Conclusions

In Chapter 3 we briefly illustrated the implementation of magnetic diffusivity and dynamo in the GRMHD code `HARM3D` (Gammie, McKinney, and Tóth, 2003; Noble et al., 2006; Noble, Krolik, and Hawley, 2009). The introduction of diffusivity results in the inclusion of the electric field into the evolution equations along with the dynamo parameter. The final equations are based on the work of Bucciantini and Del Zanna (2013) which have been combined with the already existing equations in the inversion scheme of the original code.

We also changed the numerical grid and extended it into larger radii in order to avoid numerical problems that appeared in the outer boundary mainly due to strong poloidal magnetic field. The new grid places the outer boundary in at radius ~ 10000 which is causally disconnected from the region of the black hole and the accretion disk.

The correct implementation of resistivity in the code has been verified by two different test simulations. Box simulations of weakly magnetized fluid have been executed in which we track the evolution of the magnetic field in the resistive environment. The resistivity in the box causes the diffusion of the field and its evolution follows the diffusion equation which is used as a reference to compare the simulation results. The simulations are repeated for a variety of different magnetic diffusivity parameter values that range from $10^{-10} < \eta < 10^{-1}$. We find excellent agreement between the simulation results and the analytical solution for all the values of $\eta \leq 10^{-2}$, which imposes an upper limit in the diffusivity values under which the code can converge in physically correct solutions. The second test was based on the resistive version of the classical 1D shock tube test shown in Komissarov (2007). In this test, the evolution of the shocks is shown for a similar range of η parameter values as in the diffusive box test. The structure of the shocks appears distorted as we increase the resistivity levels up to $\eta = 0.1$ where ripples appear in the density plots marking the limit of the code which is in agreement with the previous test.

In Chapter 4 we present a reference simulation we run with `rHARM3D` and we use it to investigate the outflows produced from the disk's evolution. First, we study the disk accretion towards the black hole. We separate the simulation into three phases based on the accretion rate. During the first phase of evolution the disk shows low accretion rate which increase with time as more material flows towards the black hole. The second phase is characterized by a interplay between inward and outward motion of fluid in the inner part of the accretion disk. This is also the phase where the strong disk wind develops and the disk looses a large part of its initial mass. In the third phase, the disk has lost most of its mass which explains the low accretion rate and the reduced disk wind.

We identify two different types of disk wind. The first type comes from the inner part of the disk close to the black hole and is dominated by a strong toroidal magnetic field. At this time the inner part of the disk has complete a large number of rotations around the black hole, twisting the poloidal field and inducing a toroidal component. The second type of disk wind is dominated by poloidal magnetic field. Here the outflow is launched almost parallel to the field lines retaining that direction for larger distances.

In Chapter 5 we perform a parameter study around the reference simulation of the previous chapter. We run simulations varying the values of the Kerr parameter and the magnetic diffusivity and we find that the accretion rate towards the black hole is higher for lower values of black hole rotation while the disk wind mass flux is increasing. This results in a mass loss of $\sim 80\%$ for the case of $a = 0.9$ just from the disk wind. The black hole spin also increases the contribution of the B_ϕ-dominated disk wind in the total disk wind mass flux. The Poynting flux also increases with the black hole rotation.

Furthermore, we investigate the effect of diffusivity in the simulations. For lower values of diffusivity the accretion rate is similar to the one from the reference simulation. However, for higher diffusivity the accretion is smoother with a slight increase with time. We also find that the most efficient outflow launching is for values of $\eta \sim 10^{-3}$. For lower diffusivity, the mass loading of the disk wind becomes less efficient, while for higher values magnetic reconnection seems to weaken the outflow.

We make a special reference to the case of the counterrotating system of black hole and accretion disk and the toroidal magnetic field component that is developed. The disk rotation induces extra layers of altering sign in the toroidal field that result in the accretion of the fluid mainly from the disk surface. This behavior, however does not affect the total accretion rate.

We also investigate briefly the direction of the poloidal component of the electric field. Its values and direction are mostly affected by the poloidal velocity because of the relativistic nature of the outflows. As a result, in the disk jet funnel, where the magnetic field lines are almost straight and the velocity of the outflow is parallel to them the poloidal electric field is perpendicular to both the poloidal velocity and the magnetic field. In the disk wind, however, the velocity dominates over the magnetic field resulting in the direction of the electric field to be dictated mainly by the poloidal velocity.

In Chapter 6 we study the generation of (mainly poloidal) magnetic field using a mean–field dynamo in fully dynamical simulations. Both accretion tori and thin accretion disks are investigated. We detect the generation of poloidal magnetic fields with different polarity, depending on the distribution of the dynamo parameter inside the torus. Our focus is on the generation of dipolar poloidal field which can be achieved seemingly only with a constant dynamo distribution. In the case of a non-constant dynamo the generated magnetic field has a quadrupolar structure.

Depending on the distribution of the dynamo number (effectively the ratio between diffusivity and dynamo) the poloidal field the develops will either continue growing in strength or it will diffuse. As the poloidal field grows, its initial structure inside the torus/disk (either dipolar or quadrupolar) will change in a layered structure where its values form layers of opposite sign one next to the other. As a result, the field inside the torus/disk does not have a clear form. This structure also affects the magnetic field in the disk wind and jet even though, long lasting simulations show that a dipolar component can emerge close to the black hole.

We prescribe a dynamo quenching mechanism that compares the magnetization in each cell with a reference equipartition value and quenches the dynamo. We observe visible difference in the lifetime of the simulations which is extended by the quenching mechanisms, however, this is not enough to avoid an early crash of the simulations due to very high magnetization.

Future Plans

The implementation of resistivity and dynamo in the `HARM3D` code opens up possibilities for studying not only jet launching but other astrophysical phenomena. Even though we use the code for simulation in a 3D axisymmetric environment, the code has capabilities for fully 3D simulations. Many of the jet launching studies contacted in the part were using a fully 3-dimensional grid, albeit using ideal MHD. Our resistive and dynamo extension of the code was written including the 3D aspect of the code, but it was unfortunately never properly tested. One the other side, 3D simulations are much more computationally expensive which will delay the quantity of the scientific output especially if the study leans towards highly diffusive disks.

However, before we move into new projects, the discrepancy in the mean–field dynamo closure must be solved. As we mentioned in Chapter 6 what we see in the development of the poloidal field comes in contrast with what has been observed in the literature. As a remainder, a dipolar poloidal magnetic field is expected to be generated by a dynamo distribution that has a negative α (positive ξ) parameter in the upper hemisphere and the opposite sign in the lower hemisphere. In our case, this prescription generates a quadrupolar field.

We spent much time trying to find out a possible difference between the equation and the numerical implementation. We also run many simulations with different sets of parameters in order to make sure that it was a dynamo induced effect. None of the minor errors we found had any effect in this behavior which seems fundamental to the nature of the dynamo itself. Soon afterwards we found out the it was not just the alternate sign in the dynamo between the hemispheres that was causing the issue but also any kind of dependence of the dynamo parameter ξ on the polar angle θ. Looking carefully in the work of Bucciantini and Del Zanna (2013) and Bugli, Del Zanna, and Bucciantini (2014) we noticed that none of the simulations presented show a poloidal field being generated by a dynamo distribution with polar angular dependence. The authors of Bucciantini and Del Zanna (2013) admit that the tests they show are all with a constant dynamo, even though they claim that their scheme takes into account more general cases where both diffusivity and dynamo depend even on other (macroscopic) quantities. Unfortunately, due to time limitations we were not able to solve this discrepancy yet. There might also be a connection between the dynamo discrepancy and the layered structure of the generated magnetic field. It is in our future plans to contact the authors of Bucciantini and Del Zanna (2013) and try to clarify whether this is due to an unidentified error on our side or a limitation of the equations themselves.

Further extension to the code can come from the numerical aspect. As we mention in Chapter 3 we add an extension to the simulation grid in order to avoid certain problems caused by the prescribed poloidal magnetic field in the outer boundary. These problems appear as regions of the grid with low density, low magnetic field and high inwards velocities. They expand to the point that they disrupt the disk its self resulting in the effective termination of the simulation. We are also aware that there is room for improvement in the implementation of a more robust inversion scheme. A fully implicit-explicit scheme, like the one used by Palenzuela et al. (2009), Bucciantini and Del Zanna (2013), and Ripperda et al. (2019) will return better convergence, especially with high diffusivity.

Modifications can be also done in the code to allow for a better dynamo quenching mechanism. Since the simulations run in parallel mode using MPI, we were restricted into using the dynamo quenching mechanism for each core separately. A possible extension of the MPI communication in order to include values related to the plasma-β would allows for an easier detection of the growth of the magnetic field and a more global quenching mechanism that will stop the over-magnetization of the simulation.

The code already includes partitions for simulation of binary black hole systems, which has been used in the works of Bowen et al. (2017), Bowen et al. (2018), and Bowen et al. (2019). It would be very interesting to run similar simulation in either purely resistive MHD or with the inclusion of dynamo.

To our knowledge, there is no GRMHD code that includes both a resistive/dynamo closure and a fully radiative closure in its equations. Such a project would require probably years of theoretical work for the derivation of the necessary equations and then the implementation into a code, however the successful development of such a scheme would allow for a direct comparison of these different physical processes and the effect they have in the disk accretion and jet launching.

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