Radiative GRMHD simulations of accretion disks

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We describe some recent results on the evolution of accretion disks around black holes and neutron stars obtained in magnetohydrodynamic (MHD) simulations in general relativity (GR) with the inclusion of radiation (GRRMHD).

Keywords: X-ray sources, neutron stars, black holes, accretion disks, relativity, magnetohydrodynamics

1 INTRODUCTION

It is well known that matter accreting onto a compact object from a binary companion has some angular momentum and forms an accretion disk as it falls towards the compact object. A mathematical solution of a geometrically thin alpha disk structure has been found by Shakura & Sunyaev (1973), here the word alpha stands for a phenomenological prescription of viscous stresses proportional to the pressure in the disk. For a detailed solution of the vertical structure of the alpha disk, including the velocity field, see Kluźniak & Kita (2000). It is now thought that the dissipative stresses in hot accretion disks are a result of the magneto-rotational instability (MRI), which leads to magnetic field amplification on the orbital timescale (Balbus & Hawley, 1992). MRI only operates in those parts of the flow in which angular frequency decreases outwards, a condition certainly satisfied in GR for thin disks around black holes (i.e., in the Kerr metric).

Recent advances allowed radiation to be included in GRMHD codes, and we report some results obtained in our group with two such codes, both treating radiation in the M1 closure scheme: the KORAL code (Sadowski, Narayan, Tchekhovskoy & Zhu, 2013), and the COSMOS++ code (Anninos, Fragile & Salmonson, 2005; Fragile, Olejar & Anninos, 2014).
2 GOVERNING EQUATIONS

The equations of GRRMHD, can be written in their conservative form as

$$\nabla \cdot (\rho u^\mu) = 0, \quad (1)$$

$$\nabla \cdot T^\mu_\nu = G_\nu, \quad (2)$$

$$\nabla \cdot R^\mu_\nu = -G_\nu, \quad (3)$$

$$\nabla \cdot (nu^\mu) = \dot{n}, \quad (4)$$

Here, $\rho$ is the gas density in the comoving fluid frame, $u^\mu$ is the gas four-velocity, $T^\mu_\nu$ is the MHD stress-energy tensor. The radiation stress-energy tensor, $R^\mu_\nu$, completed using the $M_1$ closure scheme which assumes there is a frame in which the radiation is isotropic (that frame being usually quite distinct from the comoving fluid frame), is coupled to the gas stress-energy tensor by the radiation four-force, $G_\nu$. Electron scattering and bremsstrahlung opacities as well as photon conserving Comptonization are included in the codes (Saadowski & Narayan, 2015).

3 STABILITY OF GEOMETRICALLY THIN ACRETION DISKS

For mass accretion rates yielding a luminosity, $L$, exceeding ~ 0.1 of the Eddington luminosity $L_{\text{Edd}}$, the inner parts of the disk have been found to be dominated by radiation pressure (Shakura & Sunyaev, 1973). As found by Shakura & Sunyaev (1976) in a linear perturbation analysis, such disks are unstable to a thermal runaway (see also Ciesielski, Wielgus, Kluźniak, Sadowski, Abramowicz, Lasota & Rebusco, 2012; Lin, Gu & Lu, 2011).

With the COSMOS++ code, we have performed global GRRMHD 3D simulations of thin accretion disks (Mishra et al., 2016) the reader is referred to this reference for all details), and in agreement with previous shearing-box simulations we have found the radiation-pressure dominated disks
to collapse on the thermal timescale. Figure 1 shows the initial and final disk configuration.

Figure 2 shows a perspective view of the end state of the same simulation. Note the ring-like structures, especially the one close to the inner edge of the accretion disk (which is close to the ISCO, the innermost stable circular orbit of test particles). We interpret this as resulting from the viscous instability, discussed in the remarkable paper by Lightman & Eardley (1974), who showed that viscous, radiation-pressure dominated disks suffer an instability, formally corresponding to a negative coefficient in the diffusion equation, leading to the formation of regions of enhanced density. As predicted by Lightman & Eardley (1974), we find the dissipative stresses to be anticorrelated with density. This is the first time in more than four decades that the effect has been reported in numerical simulations, as nobody had ever run simulations of thin accretion disks with the inclusion of radiation prior to the Mishra et al. (2016) work. A gas-pressure dominated disk at lower luminosities (not shown) has been found to be stable throughout the duration of the simulation, confirming that the reported instabilities are not of numerical origin.

4 ULTRALUMINOUS X-RAY SOURCES (ULX)

One particular class of accreting objects which has gained interest in recent years are ultraluminous X-ray sources (ULXs). These are X-ray bright objects with observed luminosities up to $10^{41}$ ergs s$^{-1}$. Currently, the leading explanation for ULXs is beamed emission from accretion in an X-ray binary (King, Davies, Ward, Fabbiano & Elvis, 2001).
implying that near- or super-Eddington accretion is responsible for the large observed luminosities. In particular, a set of three such objects were observed which reveal X-ray pulsations with a period on the order of one second (Bachetti et al., 2019).
indicating the presence of pulsars as the accreting objects. It can now be said with some certainty that a large fraction of ULXs are accreting neutron stars [King, Lasota & Kluźniak, 2017].

We present preliminary results of simulations (Abarca et al., in preparation) of super-Eddington accretion onto a neutron star, which may be relevant to ULXs, using the GRRMHD code KORAL in a 2.5D implementation (Sałdowski, Narayan, Tchekhovskoy, Abarca, Zhu & McKinney, 2015) allowing axisymmetric accretion disk simulations to be run for long durations without depleting the magnetic field due to turbulent dissipation, which normally occurs in axisymmetric simulations of MRI. The effects of a stellar magnetic field have been ignored, and the neutron star calculations are carried out in the Schwarzschild metric. Gas accreting onto the outer layers of a neutron star is expected to slow down and release its kinetic energy (Syunyaev & Shakura, 1986), which can be converted into radiation, as in the study of (Kluźniak & Wilson, 1991), or transferred to outflowing gas.

4.1 Initial conditions and boundary conditions

We initialize our accretion disk in a standard way by starting with an equilibrium torus near the black hole as given in (Penna, Kulkarni & Narayan, 2013). The torus is then threaded with a weak magnetic field of alternating polarity. The total pressure is then distributed between gas and radiation assuming local thermal equilibrium. Once the simulation starts, the MRI quickly develops turbulence and accretion begins.

For the neutron star-like case, we implement a reflective boundary. The reflective boundary is set up so that the reconstructed radial velocity at the inner boundary is zero. We also set the perpendicular velocities $u^\phi$, $u^\theta$ to zero. The inner boundary is then set to only exchange momentum so that we can be sure no mass or energy leaves or enters the domain. For comparison purposes, we also run a black hole-like simulation in the Schwarzschild metric with inflow boundary conditions.

4.2 Preliminary Results

We have run two axisymmetric simulations, one with a reflective inner boundary, and one with a black hole-like inner boundary, both at radius $r = 5GM/c^2$. Snapshots of both are shown in Figs. 3.

In the neutron star simulation gas cannot pass through the inner boundary, so it accumulates into a hot, dense atmosphere. In addition gas is blown off the outer edges of the atmosphere forming a dense outflow. The radiation energy density is very high, but it is not clear how much of this radiation escapes to infinity. The gas with positive Bernoulli number, of which there is a significant amount of, can still absorb or emit the radiation in the funnel region before it reaches infinity.

In Fig. 4 we show the time averaged spatial structure of both disks. The black hole-like simulation is as expected. Super-Eddington accretion leads to a thick disk with strong outflows and an optically thin funnel region reaching all the way down to the inner boundary. The accretion flow is somewhat sub-Keplerian, which manifests as a weak radial
pressure gradient. We see a different picture for the reflective boundary. First, as is also seen in Fig. 3, a large amount of gas is deposited in an atmosphere around the inner boundary. In addition, a large amount of gas is ejected and the entire domain is filled with an optically thick outflow. The photosphere extends practically to the edge of the simulation domain at 100 stellar radii. The last visible contour of optical depth shows an optical depth of about 100 at radius sixty. It is hard to make a statement about the radiative properties as viewed from infinity. However, it is certain that the neutron star surface would be unobservable in this case. A measurement of the radiative flux at the edge of the simulation domain shows a flux which is locally super-Eddington when viewed along the poles.

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