General Relativistic Radiation Magnetohydrodynamic Simulations of Thin Magnetically Arrested Disks

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Received 2013; in original form 2013.

ABSTRACT

The classical, relativistic thin-disk theory of Novikov and Thorne (NT) predicts a maximum accretion efficiency of 40% for an optically thick, radiatively efficient accretion disk around a maximally spinning black hole (BH). However, when a strong magnetic field is introduced to numerical simulations of thin disks, large deviations in efficiency are observed, in part due to mass and energy carried by jets and winds launched by the disk or BH spin. The total efficiency of accretion can be significantly enhanced beyond that predicted by NT but it has remained unclear how the radiative component is affected. In order to study the effect of a dynamically relevant large-scale magnetic field on radiatively efficient accretion, we have performed numerical 3D general relativistic - radiative - magnetohydrodynamic (GRRMHD) simulations of a disk with scale height to radius ratio of $H/R \sim 0.1$ around a moderately spinning BH ($a = 0.5$) using the code HARMRAD. Our simulations are fully global and allow us to measure the jet, wind, and radiative properties of a magnetically arrested disk (MAD) that is kept thin via self-consistent transport of energy by radiation using the M1 closure scheme.

Our fiducial disk is MAD out to a radius of $\sim 16R_g$ and the majority of the total $\sim 13\%$ efficiency of the accretion flow is carried by a magnetically driven wind. We find that the radiative efficiency is slightly suppressed compared to NT, contrary to prior MAD GRMHD simulations with an ad hoc cooling function, but it is unclear how much of the radiation and thermal energy trapped in the outflows could ultimately escape.

Key words: accretion, accretion discs, black hole physics, hydrodynamics, (magnetohydrodynamics) MHD, methods: numerical, gravitation

1 INTRODUCTION

Black hole accretion disks are present in Active Galactic Nuclei (AGNs), X-ray binaries, gamma-ray bursts (GRBs) and tidal disruption events (TDEs) and are able to convert gravitational potential energy and BH spin energy into radiation, jets and winds through the stresses induced via the magnetorotational instability (MRI) (Balbus & Hawley 1991, 1998). Magnetic field threading the disks (Blandford & Payne 1982) and magnetic field threading the black hole (BH) (Blandford & Znajek 1977). Novikov & Thorne (1973) developed a general relativistic model for thin disks which has been successfully applied to interpret observations of many astrophysical systems, however, a few important assumptions are inherent to their model. They assumed all the energy is carried away by the radiation, the presence of jets and winds were excluded, and radiative emission approximately ceases inside the inner-most stable circular orbit (ISCO), where stresses in the NT model disappear and in their model a maximally spinning black hole is then predicted to have an efficiency of 42%. However, Gammie (1999) and Krolik (1999) suggested that additional stress inside the ISCO can increase the gravitational potential energy converted by the disk beyond the NT prediction.

General Relativistic Magnetohydrodynamic (GRMHD) simulations of standard and normal (SANE) disks (untitled and titled) have found at most $\sim 10\%$ deviations in accretion efficiency compared to the predicted value from the NT73 model. Shafee et al. (2008), Noble et al. (2009, 2010), Penna et al. (2010), Morales Teixeira et al. (2014) and this difference is likely associated with the amount of magnetic flux that threads the black hole and disk.

On the other hand, when an accretion disk piles up magnetic flux on the black hole and inner disk until the MRI is quenched and no more large-scale flux can be concentrated inward (magnetic forces pushing out balance gas forces pushing in), the accretion efficiency increases far beyond NT values, largely by maximizing the

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jet power. This is referred to as a magnetically arrested disk (MAD) state. (Narayan et al. 2003; Avara et al. 2016) built upon prior numerical work to study MAD disks in the thin, radiatively efficient Sub-Eddington regime for the first time. They were able to demonstrate the self-consistent inward transport of magnetic flux by a thin disk thereby saturating into the MAD state, and characterized the radiation, wind, and jet efficiencies, disk structure, and jet power in such a system. They found that a Sub-Eddington, moderately thin disk can be as much as twice as radiatively efficient as the NT model would predict. However, Avara et al. (2016) made use of an ad hoc cooling function to maintain a particular disk thickness, and large unknowns in converting the cooling in those simulations to the dissipation of a real system called for more realistic numerical experiments which include self-consistent radiative transport and proper ray-tracing.

GRMHD simulations of thick disks in the MAD state have found a broad range of high accretion efficiencies, 30%, for example, for a black hole with $a/M=0.5$, and 140% for a black hole with $a/M=0.99$ (Tchekhovskoy et al. 2011). Tchekhovskoy & McKinney (2012) studied the differences in the jet power of prograde and retrograde black holes and found accretion efficiencies of up to ~300% for the prograde case and ~80% for the retrograde case, for a black hole with $a/M=0.9375$. These simulations were the first to demonstrate that the amount of magnetic flux threading the horizon and inner disk in the MAD state is determined by the accretion state alone and not the initial magnetic conditions of the simulations, so long as sufficient large-scale flux is available to be accreted.

In this paper we study the accretion efficiency and behavior of a thin disk in the sub-Eddington limit, with half-height ($H$) to radius ($R$) ratio of $H/R \approx 0.1$ around a black hole with dimensionless spin ($a/M$)=0.5, where $a$ is the black hole spin and $M$ the mass of the black hole, and that reaches the MAD state. We perform General Relativistic - Radiation - Magnetohydrodynamics (GRMDH) simulations and compare our values with the results from the simulation MADIHR from Avara et al (2016) that used an ad hoc cooling function to control the scale-height. In our simulations we made use of the code HARMRAD (McKinney et al. 2014) which includes self-consistent radiative transport and solves the GRMHD equations using the M1 closure (Levermore 1986).

The structure of the paper is as follows: the methodology and numerical setup are presented in §2, results are presented in §3, the discussion is presented in §4, and in §5 we present our conclusions and look forward.

2 INITIALIZATION OF OUR SIMULATIONS

In this section we will describe the initialization of our simulations where in Section 2.1 will be described the initial conditions of our accretion disk, in Section 2.2 will described the two grids we have adopted in our simulations and in Section 2.3 will be described the equations used in the diagnostics.

2.1 Thin disk model

We have started our simulations with a Keplerian accretion disk around a black hole with $M_{BH}=1M_\odot$ and spin $a/M=0.5$ where the initial conditions of our disk followed the NT73 solution with an initial density tuned in order to have a quasi steady-state accretion flow which has $M=0.4M_{\text{Edd}}$, where $M_{\text{Edd}}$ is the Eddington accretion rate defined as $M_{\text{Edd}} = (1/\eta_{\text{NT}})L_{\text{Edd}}/c^2$, $\eta_{\text{NT}}$ is the NT73 accretion efficiency and $L_{\text{Edd}}$ is the Eddington luminosity defined as

$$L_{\text{Edd}} = \frac{4\pi G M c}{\kappa_{\text{es}}} \approx 1.3 \times 10^{46} \frac{M_{\text{BH}}}{10^8 M_\odot} \text{ergs s}^{-1}, \quad (1)$$

where for our case we have $\eta_{\text{NT}} \approx 8.6\%$ and $M_{\text{Edd}} \approx 1.68 \times 10^{38} \text{g s}^{-1}$.

The density profile of our disk was given by

$$\rho(r) = \rho_0 e^{-r^2/(2\Sigma r^2)}, \quad (2)$$

with

$$\rho_0 = \Sigma/(2H), \quad (3)$$

where $\Sigma$ is the surface density, $H$ is the height and their expressions are given by NT73 solution for the inner region (equation 5.9.10 in NT73).

The initial radial velocity profile of the disk was given by

$$V_r = \alpha_{\text{visc}} (H/R)^2 r/\Omega, \quad (4)$$

where $\Omega$ is the angular velocity and $\alpha_{\text{visc}}$ was set to 0.5.

Due to the poor resolution in the radial direction at large radii we have truncated the accretion disk at $R_o=120R_\odot$ to avoid material from under resolved regions to reach the black hole using an exponential cutoff for the density given by

$$\rho_i(r) = \rho(r)e^{-r/(r_{\text{Edd}}+1)}, \quad (5)$$

and with the objective to better resolve the MRI we have set $H/R$ inside the innermost stable circular orbit (ISCO) to be constant and equal to 0.03.

The total ideal pressure was given by $P_{\text{gas}} = (\Gamma_{\text{rel}}-1)\mu_{\text{gas}}$ with $\Gamma_{\text{rel}}=4/3$ and $\mu_{\text{gas}}$ is the internal energy density with the pressure randomly perturbed by 10% to seed the MRI. The accretion disk was surrounded by an atmosphere with $p = 10^{-5}\langle r/R_s \rangle^{-1.1}$, gas internal energy density $\epsilon_{\text{gas}} \approx 10^{-6}\langle r/R_s \rangle^{-5/2}$ and the radiation energy density and flux were set by the local thermodynamic equilibrium (LTE) and flux-limited diffusion (McKinney et al. 2014) with a negligible radiation atmosphere. We set the rest mass and internal energy densities to zero near the black hole within the jet and near the axis using numerical ceiling of $B^2/p=300$, $B^2/\epsilon_{\text{gas}}=10^9$ and $\epsilon_{\text{gas}}/p=10^{10}$.

We have chosen a configuration for the magnetic field of the disk to be a large scale and poloidal which has a single loop with a transition to a monopolar field at $R_o=120R_\odot$. For $r < R_o$ the $\phi$ component of the vector potential was given by

$$A_\phi = \text{MAX}((r+5)^{0.1} - 0.02, 0)(\sin \theta)^{1.4}, \quad (6)$$

with $v=1$ and $h=4$ while for $r > R_o$ the vector potential was given by

$$A_\phi = \text{MAX}((R_o+5)^{0.5} - 0.02)(\sin \theta)^{1.8(R_o/2)^{0.5}}. \quad (7)$$

Our field was normalized inside one MRI wavelength per half-height $H$ giving a ratio of gas+radiation pressure to average magnetic pressure of $\beta \approx 10$ ($\beta = (p_{\text{gas}} + p_{\text{rad}})/p_{\text{mag}}$). With the objective to investigate the effects of the field having a transition to a monopolar field we set $R_o=120R_\odot$ for simulations RADHR and RADLR, and $R_o=200R_\odot$ for RAD+HR. The motivation for this change of the field transition radius is to try to reach the MAD state...
out to large radii, accumulating most of the initial large-scale magnetic flux into the inner disk.

For the radiation we have assumed that our initial disk has solar abundance with mass fractions of hydrogen, helium and metals equal to $X=0.7$, $Y=0.28$ and $Y=0.02$ which gives an electron fraction of $Y_e = (1 + X)/2$ and mean molecular weight of $\mu \approx 0.62$. The expressions for the electron scattering, absorption-mean energy, bound-free and free-free opacities were the same used by McKinney, Dai & Avara [2015].

### 2.2 Numerical grid

In this section we will describe the two grids we set in our simulations RADHR, RADLR and RADvHR where for our simulations RADHR and RADLR we have made use of the same grid from McKinney et al. [2012] while for RADvHR we use a similar grid with important modifications that will be described below. In all of our simulations we have adopted the same boundary conditions as in McKinney et al. [2012] while for RADvHR we use a similar grid from McKinney et al. [2012].

In this section we describe the two grids we set in our simulations. The parameters for the polar grid of each of ours simulations are given in Table 1. Before we introduce the equations for the new $\theta$ grid, we must define some variables that are given by

\begin{equation}
T_s(x) = \frac{e^{-1/x}}{e^{-1/x} + e^{-1/(1-x)}},
\end{equation}

and

\begin{equation}
\text{Trans}(X, L, R) = \begin{cases} 
0.0 & \text{if } x \geq L, \\
1.0 & \text{if } x \geq R, \\
T_s\left(\frac{x-L}{R-L}\right) & \text{if } L < x < R.
\end{cases}
\end{equation}

To concentrate most of the cells in the disk, the expressions for $S_0$ and $S_2$ that control the cells at small, middle and large radii were changed. In our case $S_0$ was changed to

\begin{equation}
S_0(r, r_{in}, r_{out}) = \text{Trans}(\log(r), \log(r_{in}), \log(r_{out})),
\end{equation}

where the objective of $S_0$ is to control the cell size at middle and large radii. The expression for $S_2$ has been changed and in our case is given by

\begin{equation}
S_2(r, r_{in}, r_{out}) = 1 - S_0(r, r_{in}, r_{out}),
\end{equation}

where this expression for $S_2$ controls the cell size at small and middle radii. Then the new expression for $h_2$ is given by

\begin{equation}
h_2 = h_1S_2(\rho, 40, 200) + S_0(\rho, 40, 200)(h_1S_2(\rho, 200, 500) + h_2S_0(\rho, 200, 500)),
\end{equation}

where

\begin{equation}
h'_2(r) = h_2 + \left(\frac{r - r_{in}(\rho)}{r_{out}(\rho)}\right)^{\delta_2},
\end{equation}

is the same equation for $h_2$ in McKinney et al. [2012]. The original equation for $\theta_2$ has also been modified and in our case is given by

\begin{equation}
\theta_2' = \theta_2S_0(\rho, 20, 40) + \theta_2'\theta_2S_0(\rho, 20, 40),
\end{equation}

where $\theta_2'$ and $\theta_2''$ are the original expressions for $\theta_2$ and $T_2$ presented in McKinney et al. [2012].

Similarly to the other expressions, the original expression for $h_0$ was modified to

\begin{equation}
h_0(\rho) = h_1S_2(\rho, 40, 200) + S_0(\rho, 40, 200)(h'_{\rho}(\rho)S_2(\rho, 200, 500) + h'_{\rho}(500)S_0(\rho, 40, 200)),
\end{equation}

where the expression for $h'$ is now given by

\begin{equation}
h'_\rho(r) = 2 - Q\rho(\rho/r_1) - \left[Q_{\text{diff}}(\rho/r_0=r_{in}/r_0)\right]^eta.
\end{equation}

The expression for $\theta_1$ in our case is given by

\begin{equation}
\theta_1 = T_0\theta_2(\rho, 20, 200) + \theta'_2\theta_2(\rho, 20, 200),
\end{equation}

where $T_0$ is the original expression from McKinney et al. [2012]. Finally the expression for $\theta$ is

\begin{equation}
\theta = \theta_2'\theta_2S_2(\rho, 1, 10) + S_0(\rho, 1, 10)\theta_1.
\end{equation}

The parameters for the polar grid of each of ours simulations are listed in Table 2.
of time. Our simulation RADHR has $Q_{\Omega, MRI} \sim 110$, $Q_{\Omega, MRI} \sim 13$ and $Q_{\Omega, MRI} \sim 11$, 13 and 4 respectively. The value of $Q_{\Omega, MRI}$ in the $\phi$ direction shows that the turbulence is not well resolved since the previous works mentioned above have shown that it’s required to have at least 6 cells in order to resolve the turbulence but even being under resolved we can still identify some physical effects as we will discuss in the next sections. We have also measured the disk thickness per unit MRI wavelength, $S_\phi$ (where for $S_\phi < 0.5$ the MRI is suppressed). Initially for our simulation RADHR, $S_\phi \sim 0.9$, and the time averaged flow has $S_\phi \sim 0.26$ out to $r \sim 16R_g$. The simulation RADvHR has $Q_{\Omega, MRI} \sim 21$, $Q_{\Omega, MRI} \sim 8$ and $Q_{\Omega, MRI} \sim 12$, 8, 3 and our simulation RADvHR at its end has $Q_{\Omega, MRI} \sim 56$. $Q_{\Omega, MRI} \sim 13$ and $Q_{\Omega, MRI} \sim 15$, 22, 7 and the MAD state built up to $13R_g$. As we can see our simulation RADLR is under resolved and will be used for reference to study resolution effects of the flow at late times and check how the MAD state builds up while the turbulence in our simulation RADvHR was better resolved.

2.3 Diagnostics

In this section we provide the equations used in our analyses to compute the accretion rate, efficiencies, opacities, disk thickness, magnetic flux and stress.

The half-angular thickness ($H$) normalized by radius ($R$) is given by

$$H(R, \phi) = \frac{H_0}{R^2} + \frac{\int r \rho \theta \phi \rho dA_{\phi \theta}}{\left( \int r \rho dA_{\phi \theta} \right)^{1/2}},$$

where we choose $n=2$ and $H_0/R=0$, unless otherwise specified, with $dA_{\phi \theta}$ being the area differential. $\theta_0$ is computed as the result of this expression when one sets $n=1$ and $\theta_0 = H_0/R = \pi/2$ on the right hand side.

The mass accretion rate is given by

$$\dot{M} = \int \rho u' dA_{\phi \theta},$$

where $\rho$ is the fluid mass density, $u'$ is the radial components of the four-velocity and the accretion efficiency is given by

$$\eta = \frac{\int (T' + \rho u' + R') \rho dA_{\phi \theta}}{[M]},$$

where $T'$ is the plasma stress-energy tensor, $R'$ is the radiation tensor and $[M]$ is the time-averaged $\dot{M}$. Different from [Avara et al. 2016] we have used the values of the accretion rate at every radius in order to correct the mass and energy that have been injected during the evolution to keep the simulation stable.

In these equations $\eta$ is composed of free particle (PAKE, where the PAKE term is the sum of kinetic plus gravitational terms), thermal (EN), electromagnetic (EM) and radiation (RAD) components. The jet is defined as PAKE+EN+EM in regions where the magnetic energy is greater than the rest mass energy density, $2P_B/\rho > 1$ where $P_B$ is the magnetic pressure. The wind is defined as PAKE+EN and located outside the jet where $2P_B/\rho < 1$ and the flow is outgoing ($\theta^2 > 0$). It’s also possible that the wind contains unupped EM and RAD components that would be converted at unresolved radii distant from the region in which we reach inflow or outflow equilibrium.

Of central importance to this work is the measurement of magnetic flux threading the disk and horizon. The magnetic flux on the upper half hemisphere of the black hole horizon is given by

$$\psi_H = 0.7 \int_{\theta = \pi/2}^{\theta = \pi} \sqrt{dA_{\phi \theta} B^2} \sqrt{|M|},$$

where this integral is only carried out over $\pi/2 < \theta < \pi$ to only consider the upper half hemisphere. For integration over $\theta = 0$ to $\theta = \pi/2$ the flux is positive when compared with the equation above for radial magnetic field strength $B$ in Heaviside-Lorentz units.

The magnetic flux in the $\theta$ direction at a radius $r$ and angle $\theta$ is given by

$$\psi(r, \theta) = 0.7 \int_{\theta = \pi/2}^{\theta = \pi} \sqrt{-\gamma dx'_{(1)} dA_{(2)} B^2} \sqrt{| M |},$$

where for simplicity this quantity is calculated using internal code coordinates $x' = (x_{(1)}, x_{(2)}, x_{(3)})$. The total poloidal magnetic flux threading the equatorial plane of the disk inside some radius is then given by

$$\psi_{\text{eq}}(r) = \psi_H + \psi_{\text{eq}}(r),$$

where all definitions of $\psi$ are integrated over the entire $\phi$.

Another important characteristic quantity is the absolute magnetic flux ($\Phi$) which is calculated in the same way to $\psi$ but by taking the absolute value of $B'$ or $B''$ in the integrals, integrate over all $\theta$, divide by 2 and does not immediately normalize by the accretion rate.

Gammie [1999] introduced a new normalization for $\Phi$ which has also been used in this work to normalize $\Phi$ and is given by

$$\Phi \approx 0.7 \int \sqrt{|M|},$$

where $\Phi_{\psi_{\text{eq}}}(r, \theta) = (1/2) \int dA_{\phi \theta} B' B'$ and this already accounts for $\Phi_{\psi}$ being in Heaviside-Lorentz units (Penna et al. 2010). According to Tchekhovskoy et al. [2011] the magnetic flux in gaussian units is given by

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**Table 2. Polar grid Parameters**

| Simulation   | $n_0$ | $c_2$ | $n_3$ | $r_s$ | $r_o$ | $h_s$ | $r_{0,3}$ | $r_{1,3}$ | $n_{1,1}$ | $r_{1,1}$ | $r_{0,1}$ | $Q_{\phi}$ | $n_{0,0}$ | $h_0$ | $r_{1,2}$ | $r_{0,2}$ | $r_{\text{break}}$ |
|--------------|-------|-------|-------|-------|-------|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-------|-----------|-----------|---------------|
| RAD(HR,LR)   | 1.0   | 1.0   | 6.0   | 40.0  | 40.0  | 0.1   | 40.0      | 0.0       | 0.5       | 30.0      | 30.0      | 40.0      | 1.8       | 5.0   | 0.1       | 8.0       | 3.0           |
| RADvHR       | 1.0   | 1.0   | 6.0   | 1000.0| 600.0 | 0.1   | 40.0      | 0.0       | 0.7       | 30.0      | 30.0      | 40.0      | 1.7       | 5.0   | 0.1       | 5.0       | 2.0           |
In the thin disk theory an important measurement is the viscous parameter $\alpha$ which according to the GR model it is used to estimate the radial velocity of the flow through the relation

$$v_{r,\text{visc}} = \frac{GM\dot{M}}{\sqrt{Mr^2c}},$$

(27)

where $\dot{\tau} = 0.2\dot{\phi}_H$.

In the thin disk theory an important measurement is the viscous parameter $\alpha$ which according to the GR model it is used to estimate the radial velocity of the flow through the relation

$$v_{r,\text{visc}} = \frac{GM\dot{M}}{\sqrt{Mr^2c}},$$

(28)

as defined in McKinney et al. [2012] which leads to a measurement of the effective $\alpha$-viscosity given by:

$$\alpha_{\text{eff}} = \frac{v_r}{v_{\text{visc}}/a},$$

(29)

where the $\alpha$ value for a disk unstable to MRI is given by

$$\alpha_b = \alpha_{\text{mag}} = -\frac{b^2}{p_b + p_{\text{rad}}},$$

(30)

which the terms from the Reynolds stress haven’t been taken into account since compared the Maxwell stress they are negligible. Our measurements of $\alpha$ only includes material with $b^2/p < 1$ in order to only measure disk material and volume averaged over $\theta$ and $\phi$ with a weight $p$. $\alpha_b$ is responsible to measure the stress in dense regions while $\alpha_{\text{eff}}$ measures the effective $\alpha$ based on the radial velocity of the flow in dense regions.

In order to obtain the depth for each instant in time we compute

$$\tau = \int pk_{\text{visc}}dl,$$

(31)

where $dl = -f_\theta dr$, $f_\theta = u'(1 - (v/c)\cos\theta)$, where for large radii $(v/c) \sim 1 - 1/(u'\gamma^2)$, $\theta = 0$ and the integral is carried out from $r_0=1000R_g$ to $r$ (to consider only transient material that would contribute to the optical depth, a radius where the disk wind has reached) to $r$ in order to obtain $\tau(r)$. In the angular direction $dl = f_\theta r d\theta$, $\theta = \pi/2$ and the integral is carried out from each polar axis towards the equator to obtain $\tau(\theta)$. The radiation photosphere is defined as $\tau_r = 1$, which is an upper limit to the radius of the photosphere for an observer since radiation can escape.

Finally the radiative luminosity is given by

$$L = -\int dA_{\text{visc}}R_g,$$

(32)

where the luminosity is measured at $r = 50R_g$ and only the gas that has $\tau_r(r) < 1$ is included.

3 RESULTS

In this section we will show how our three simulations evolved from highly magnetized NT-type initial conditions into disks that are MAD on the black hole and in the innermost region of the accretion flow. We focus our discussion mainly on the simulation RADHR, our higher-resolution, long-time run, and demonstrate the effect of self-consistent radiative transport on accretion efficiency and general disk behavior as compared to the GRMHD simulations of Avara et al [2016]. We test convergence of the simulations by comparing those run with different grids and resolutions.

Our fiducial simulation RADHR (and its low-resolution analog RADLR) has been run to a final time of $t = 40,000R_g/c$, by which the inner accretion flow has reached a MAD quasi-equilibrium state where magnetic flux continues to accumulate at the outer edge of the MAD region at $\sim 16R_g$, and the disk is slightly sub-MAD beyond this transition radius.

Figure 1 and Figure 2 show the three main regimes of behavior in RADHR, culminating in the long-term evolution of the MAD inner disk illustrated in the disk cross-sections. The first stage of evolution involves the rapid evolution of magnetic flux threading the horizon to balance the inner-most accretion flow and dynamical effects of the plunging region inside the innermost stable circular orbit (ISCO), as the system evolves away from equilibrium NT conditions, subject to the dynamically-relevant large-scale poloidal magnetic flux. The second behavioral stage involves mass accretion rate and magnetic flux growing until $t \sim 17,000R_g/c$. At that point there is a weak point in the inner disk and a large magnetic disruption occurs which redistributes a lot of poloidal flux into the disk, increasing the size of the MAD region. The final stage, covering roughly the second half of the simulation, involves a quasi-steady state MAD accretion flow, order unity oscillations of the horizon threading flux (consistent with prior numerical findings), and a general accretion structure very similar to the MADHR simulation in Avara et al [2016], where only the horizon and inner disk reach the MAD state over the time they were able to run their simulation.

3.1 Time evolution of the accretion flow and the build up of the MAD state

In this section we will describe how the MAD state built up in our simulation RADHR by analyzing the time evolution of density, accretion rate, magnetic flux ($\mathcal{L}_{\text{MAD}}$), and efficiencies.

In a movie of frames like Figure 2 we find that the flow is highly dynamic with magnetic Rayleigh-Taylor (RT) instabilities seeming to dominate the flow behavior with periods of high magnetic flux on the black hole (i.e. high $\mathcal{L}_{\text{MAD}}$), followed by magnetic RT modes resulting in episodes of significant mass accretion and expansion of magnetic flux out into the disk that has been trapped on the horizon by the plunging region of the accretion flow.

In the same movie we find that the unbound material, defined where $2P_{\rho/p} > 1$, has shown a very non-uniform distribution with the north part having a larger opening angle than the south, which is slightly more uniform in angular distribution.

We find that the mass accretion rate is highly variable until $\sim 17,000R_g/c$, after which it reaches a quasi-steady state with an average mass accretion rate, averaged over the time interval $30,000-40,000R_g/c$, of $0.4M_{\text{Edd}}$. The accretion rate has some highly variable behavior, with sharp spikes, which will be investigated in the future. The radiative luminosity follows the same trend and has an average value of $0.2L_{\text{Edd}}$.

The amount of magnetic flux on the horizon of the black hole has a similar behavior compared to the mass accretion rate where it has increased until $\sim 17,000R_g/c$ and after this initial period has lost part of this flux after this initial evolution and at the end it has an averaged value of $\mathcal{L}_{\text{MAD}}=3.5$, where the major part of this magnetic flux was provided by the flux threading the disk and some magnetic flux coming from the wind material that was unable to reach infinity. We have detected in our simulations the presence of a weak jet however according from theoretical expectations, a thin disk in the Standard Accretion Normal Evolution (SANE) state does not pro-
provide a sufficient amount of magnetic flux able to extract rotational energy from the black hole in order to spin it down and drive a powerful jet, argument that was supported by a GRMHD simulation of a thin disk in the SANE state provided by Sadowski et al. (2013).

The disk initial conditions are chosen with enough magnetic flux to ultimate evolve into the MAD state out to large radii, beyond where we could possibly hope to reach inflow equilibrium during the simulation. However, the NT-type initial conditions necessary to study the disk with self-consistent radiative transport, and attainable resolution constraints, lead to a significant portion of the poloidal magnetic flux in the outer disk being lost through initial transients. The lack of radiation in Avara et al. (2016) allowed for conditions with more flux at large radii preventing this flux from escaping and so those disks become MAD to a larger radial extent. Despite this loss of flux in the disk, analyzing the suppression factor ($S_\phi$) of RADfHR reveals that at late times the disk still is able to reach the MAD state out to $r = 16R_g$. As in MADfHR, this radius grows over time as disk and coronal processes transport more magnetic flux inward, piling up on the outer edge of the MAD region.

Analyses of the time evolution of the efficiencies (total, jet, wind and radiation) have shown that during the entire evolution the wind has carried out the major part of the total efficiency greater than 40% in the initial evolution and at the end reached a quasi-steady state with an averaged efficiency of 18% (mostly carried by the particle term (PAKE) has been found. The jet and radiation have carried out similar amounts of the total efficiency. This is likely due to the small resolution in the $\phi$-direction for RADfHR (64 cell for RADfHR and 208 cells for MADfHR), which is known to strongly affect the MRI evolution and building up of the MAD state which strongly affects the transport of magnetic flux.

### 3.2 Radial dependence of the accretion flow

Analyzing the mass accretion rate profile (upper panel of Figure 3) of our simulation RADfHR we found that the simulation has reached a quasi-steady state (regions with very similar mass accretion rate) out to a radius of $r \sim 15R_g$, but it is clear from the radial dependence of $M$ that going further out there are larger deviations where the disk is still evolving from initial conditions. The large-scale magnetic flux in these types of simulations enhances these effects due to large-scale coronal flows, large mass transfer from MRI channel modes, and initial radiative evolution since the disk in this simulation does not start in an equilibrium state due to the radiation. Inside the ISCO there is also a deviation in the radial dependence of $M$ due to mass injection associated with the floors which demands a careful analysis. It is worth noting that in these and in MADfHR the radial dependence of $M$ near the BH flattens when the number of snapshots over the averaging time period increases, though it is unclear if it would improve beyond the average shown here if more snapshots were available from the simulation output. One of the reasons why the radial profile is not flat in simulations with radiative transfer is that in order to keep the code stable against numerical instabilities mass and energy must be injected in the domain which is not trivial to track.

The additional mass added by the floor in the simulation is removed from the calculation of $M$ where cells have rest-mass values of $b^2/\rho > 1$. The profile of MADfHR is much flatter because they time average over a later and longer period, 30,000–70,000$R_g/c$ in MADfHR, an ad hoc cooling function evolves the disk toward equilibrium faster than the self-consistent processes we capture with full radiative transport, which demands more time to reach thermal equilibrium, and because the higher resolution allows large-scale initial transient modes to break up faster thus having a smaller impact on later evolution (e.g. parasitic modes of the MRI at intermediate and large radii).

The plot of the efficiency (second panel of Figure 3) and its different components shows an efficiency of roughly 18% at the horizon with most of it in the matter component followed by the electromagnetic part, with the radiation presenting a negative contribution due to the photon capture by the horizon via streaming and also photon advection. Similar efficiencies have been found in MADfHR where they found a total efficiency greater than ours because in their simulation due to the ad hoc cooling function the
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Figure 2. Snapshot of our simulation RADHR at the time $t=40,000R_g/c$ where the top two panels represent the $X-Z$ at $y=0$ and $X-Y$ at $z=0$ slices of the density with the red line showing where $B^2/\rho = 1$, the yellow line where $\tau = 1$ for electron scattering and the black lines with arrows trace field lines where thicker black lines show where field is lightly mass loaded. The top sub-panel shows the mass accretion rate at the horizon (red line) and the luminosity (green line). The middle sub-panel shows the magnetic flux in the horizon normalized so that order unity is a dynamically substantial amount of magnetic flux. The bottom sub-panel shows the accretion efficiencies in the horizon (red line), jet efficiency (green line) measured at $15R_g$ and radiation (blue line) measure at $50R_g$. The full movie of our simulation RADHR is available on https://www.youtube.com/watch?v=vbbrCdkcORA

radiation does not interact with the material through absorption and scattering.

For our system with a black hole spinning with $a/M = 0.5$, the corresponding value expected for the efficiency according to the NT73 model is 8.2% and for our simulation RADHR we found an efficiency of 18.6% which corresponds to a deviation of 125%. At the black hole horizon, the amount of the total efficiency in matter, electromagnetic and radiation forms are $\eta_{\text{MAK}}=22.5\%$, $\eta_{\text{EM}}=1.5\%$ and the remaining efficiency in radiation form.

We measured the jet, wind and radiation efficiencies at $r=50R_g$ and we found that at this radius the jet is carrying an efficiency of 4.3%, the wind is carrying an efficiency of 7.4% and the radiation an efficiency of 2.9%, where for the jet 4.1% is in the electromagnetic form and 0.2% in the matter while for the wind 4% is being carried by the electromagnetic part and 3.4% by the matter. The summed values of the efficiencies carried by the jet, wind and radiation is less than the total efficiency and this difference is because even at $r=50R_g$ it’s not trivial to guarantee that the wind material will reach infinity and for this reason we have assumed that the wind efficiency is $\eta_{\text{wind}} = \eta_{\text{MA}} = \eta_{\text{jet}} + \eta_{\text{rad}}$ and following this condition we found that the wind has an efficiency of 11.4%.

The plot of the amount of magnetic flux (third panel in Figure 3) in the disk shows that some magnetic flux has been driven outwards since the black hole lost part of its initial flux when compared with the amount of magnetic flux in the beginning of the simulation, compared to MAdiHR, where the amount of magnetic flux increased.

In these simulations with self-consistent radiative transport, we start with a NT disk with a scale height of 0.1, but there is no a priori reason to expect that the MAD disk resulting from these initial conditions should persist at this disk width. There was some tuning of initial conditions using test simulations to try to attain a scale height of 0.1 but this result is entirely self-consistent with the mass accretion rate and radiative transport alone. On the other hand, the disk scale height was fixed directly in MAdiHR. This is one of the central advantages of including self-consistent radiative transport, which would allow an inherently thermally unstable disk to collapse or puff up if that were the true physical behavior.

The radial profile of the disk shown in Figure 3 and also the density profile of the disk shown in Figure 1 show the inner region ‘choked’ by magnetic compression, where the disk scale height is reduced to $\sim 0.04$. In the inner edge of the disk the scale height grows to 0.1 at $r=5R_g$ and then to 0.12 at $r=20R_g$. Beyond that radius we don’t show the values because the disk hasn’t reached thermal equilibrium in these locations. For comparison, the simulation MAdiHR had $H/R \sim 0.05$ near the black hole and 0.1 throughout the rest of the disk. Thus there is significant similarity in disk structure as a function of radius in simulations with radiative transfer.
Time averaged quantities averaged over the period $t = [30,000 - 40,000]R_g/c$ as function of the radius for our simulation RADHR. The first panel shows the mass accretion rate ($\dot{M}$), the second panel the energy efficiencies ($\eta$), the following panels the magnetic flux ($\Psi$), the disk scale-height ($H/R$) and the suppression factor ($S_{d}$). In the plot of $\eta$ the black line corresponds to the total (gas+radiative), the green line corresponds to the electromagnetic, the red line corresponds to the matter and black dashed line corresponds to radiation components respectively. The magenta line in the plots of $\Psi$, $H/R$ and $S_{d}$ corresponds to their initial values. The thick lines correspond to our simulation and the thin lines correspond to the simulation MADiHR.

The solution of Shakura & Sunyaev (1976) for the inner region of the disk is radiation pressure dominated and thermally unstable. Piran (1978) found a stability criteria for thin disks based on the dependence of the cooling and dissipative terms with the surface density since they are expected to have different slopes. Unlike these predictions, and similar to the findings of Mishra et al. (2016) and Sadowski (2016a,b), our simulations exhibit thermally stable disks, likely due to the large amount of magnetic flux in the which can provide a magnetic pressure strong enough to keep the disk stable. Over the 30,000–40,000R_g/c time period for RADHR we found that the disk has reached thermal equilibrium only in the inner parts, not having enough time to reach an equilibrium state further out. We determine that a given radius has reached thermal equilibrium when that part of the disk has reached inflow/outflow quasi-equilibrium and the scale height, in part governed by vertical radiative transport and pressure support evolving under temperature evolution, stabilizes to roughly a fixed value.

Finally the plot of the suppression factor ($S_{d}$) shows that initially our disk is not MAD (MAD region has $S_{d} < 0.5$) and at the end our simulation has reached the MAD poloidal flux limit out to a radius of 16R_g, while the simulation MADiHR was already in the MAD state up to a radius of 30R_g.

### 3.3 Time dependence of the accretion flow

In this section we will describe the time evolution of the accretion flow following the results analyzing how the disk scale-height, magnetic flux and effective viscosity evolved.

The time evolution of the disk scale-height (upper panel of Figure 4) shows that the disk that started from a non-radiative equilibrium configuration has reached thermal equilibrium up to a radius of 20R_g where this plot shows that the values of $H/R$ at the ISCO and 20R_g. Middle: Magnetic $\alpha$ measured at 10R_g given by the solid black line (full, un-smoothed data in gray). Bottom: Amount of magnetic flux on the horizon normalized by the amount of magnetic flux contained in the portion of the disk which reaches one inflow time by the end of the simulation, i.e. the total magnetic flux available for the inner disk and horizon.
Measuring the absolute flux threading the horizon as a function of time, included in Figure 2 and Figure 3 for simulation RADHR, we found that the black hole gains a significant quantity of poloidal magnetic flux across the first half of the simulation, in the initial transitory phase due to large scale MRI channel modes that survive until the $\phi$-symmetry of the field is eaten away by parasitic and other modes. Then, similar to MADIHR, during the early evolution we observe the two modes of flux accumulation as it is transported both through the disk along the disk surfaces through a coronal-type mechanism. Similar to the build-up of flux from sub-MAD to MAD conditions on the horizon seen in MADIHR of Avara et al. (2016) there is a steady build-up of flux on the horizon in RADHR until at $\sim 17,000R_g/c$ where there is more flux on the horizon than the disk can confine, and a significant portion of the flux on the horizon finds a low pressure weak spot in the previously rather axisymmetric disk and reconnects which pushed out into the disk through that point.

When the net vertical magnetic flux threading any given radius in the disk increases as flux is transported inward (or alternatively decreases if it is diffusing outward), we expect the value of $\alpha_{mag}$ to increase at that radius. Once a section of the disk has reached the MAD state, however, if that flux does not diffuse away the value of $\alpha_{mag}$ (eq. 29) is expected to saturate at a maximum and this can be seen in the evolution of $\alpha_{mag}$ at 10$R_g$ in Figure 4, where it’s possible to see that by the time $t=20,000R_g/c$ the value of effective $\alpha_{mag}$ is roughly 0.1.

### 3.4 Luminosities

In Figure 5 we show the time-$\phi$ averaged structure of the radiative and EM fluxes for our simulation RADHR to demonstrate the angular distribution of this outgoing energy, the primary origins in the accretion inflow/outflow and the distribution of reprocessing.

The profile of the EM flux shows that most of it comes from the wind in the south direction which is less isotropically distributed in $\theta$, while the wind pointing to the north direction shows a more uniform distribution. The electron scattering surface (yellow line) has a narrower opening angle in the south direction, due to the substantial quantity of material blocking the radiation at large distances.

The radiation flux along jets in both directions also exhibits a non-uniform distribution having a more enhanced emission in the north side in a opening angle roughly similar to the EM emission. The disk seems to spontaneously break the north-south symmetry of the emission and then the larger radiation flux to the north may maintain that asymmetry for long periods of time. It is not clear if the asymmetry would persist if the RADHR simulation was run longer, but we see this present to some degree in each of our RADGRMHD simulations and a weaker asymmetry was seen in some simulations of Avara et al. (2016) as well suggesting the magnetic wind may be playing a role in the observed behavior. This kind of asymmetry has also been reported by Narayan et al. (2016) when computing the radiative emission from their simulation of a super-critical accretion flow. In their case the asymmetry was also due to the fact M1 scheme needs improvements to properly handle the radiation field in the funnel region.

A zoom-in in both images shows that the emission comes mainly from the region inside $r=15R_g$ and these two images also show a large deviation from the profile expected from the NT33 model since in our case both fluxes are far from homogeneous distribution in both sides because the NT33 model does not take into account the contribution from both jet and wind.

Figure 5. Time-$\phi$ averaged electromagnetic luminosity per unity angle ($\partial\Phi_{\text{EM}}$)/($\partial M_{\text{out}} c^2$) (top panel) and radiation flux and radiative luminosity (bottom panel) with the blue, yellow and green lines showing $\phi$-averaged values where $p^2/p=1$, $\tau_r=1$ and $\phi=0$ respectively.

### 3.5 Resolution effects

In this section we will demonstrate how the resolution has affected the time evolution of our simulations RADLR and RADvHR when compared with our simulation RADHR. We will start describing the time evolution of RADLR that, like RADHR, has been run up to a time of 40,000$R_g/c$. Then, we will describe RADvHR, which was run until 18,000$R_g/c$, as long as resources allowed.

The time evolution of the mass accretion rate of our simulation RADLR (first plot of Figure 6) has increased in the first quarter of the simulation up to a time 12,000$R_g/c$ with the accretion rate decreasing after this time followed by a minimum during the time interval 20,000-27,000$R_g/c$. During the last quarter of evolution, RADLR has an accretion rate exhibiting weak variability, where it is possible to observe magnetic RT modes. It has a final time-averaged mass accretion rate of 0.2$M_{\text{Edd}}$ and the radiation luminosity is 0.1$L_{\text{Edd}}$. Due to the poor resolution of this simulation, the quasi-steady state seems only to be observed in the last quarter of this simulations, since only large flow dynamics are resolved.

The time evolution of the magnetic flux (second plot in Figure 6) on the black hole ($\Psi_{bh}$), similar to RADHR, shows episodes...
of high magnetic flux indicating that the flow is highly dynamic
with magnetic RT instability dominating the accretion flow behav-
ior. Large RT modes allow episodes of significant accretion and
release of horizon-trapped magnetic flux. At the end of the simula-
tion RADLR, the black hole has $\Psi \approx 3.5$ which is very similar to
the value of RADHR. However, flux levels differ in the disk at $r=10R_g$
where RADLR has $\Psi=1.2$, versus $\Psi=2.1$ for RADHR. This dif-
f erent distribution of flux leads to the MAD state in RADHR only
existing out to a radius of $13R_g$.

During the time evolution of the efficiencies the major part has
also been carried by the wind with the jet efficiency being weaker
compared to RADHR and the radiative efficiency being higher with
the jet having an efficiency of 3.1% and the radiation 4.6%, com-
pared to 4.3% and 2.9% for RADHR respectively. The total ef-
ciency has a deviation of 106% from the value of predicted by
NT73.

The time evolution of the mass accretion rate for our simu-
lation RADvHR (first plot of Figure 7) seems to indicate that the
inner accretion flow reached a quasi-steady state after a time of
$11,000R_g/c$ with an averaged mass accretion rate of $0.5\dot{M}_{\text{Edd}}$
which is very close to the target value and an averaged radiation lumi-
nosity of $0.1\dot{L}_{\text{Edd}}$. Compared to the time evolution of RADHR, we
found that RADvHR has reached the quasi-steady state faster due
the MRI being better resolved allowing more magnetic flux to reach
the black hole.

The time evolution of the magnetic flux (second plot of Figure
7) shows that during the time period 7,000-10,000$R_g/c$ the black
hole lost a significant amount of magnetic flux reaching a quasi-
steady state behavior after this period with an averaged magnetic
flux value of $\Psi \approx 4.9$.

Since the MAD state is more efficient for RADvHR we can ex-
pect a larger efficiency for RADvHR when compared to RADHR
and also we should expect that more rotational energy could be
extracted from the black hole. As expected we found that RADvHR
has a total efficiency of 21.3% (deviation of 160% from NT73
model), the jet has an efficiency of 5.6% (greater than the value
found in RADHR) and the radiation has an efficiency of 2.4%. The
radiative efficiency is small compared to RADHR probably due
to the fact there is less material absorbing the radiation in under-
resolved regions that could be located close to the disk.

As we pointed out a minimum in the mass accretion rate and
magnetic flux has been observed in our simulation RADLR and
RADvHR while we haven’t found it in our simulation RADHR and
further investigation is required in order to better understand its
origin. This minimum has occurred at different time windows as
expected due to different resolutions occurring faster as resolution is
increased.

We have found that resolution has affected the time evolu-
tion of the $r_{\text{in}}=1$ line for electron scattering where for our simu-
lation RADLR we found it has a smaller opening angle in the
south direction, probably due to more material absorbing radiation
in under-resolved regions with RADvHR going in the opposite di-
rection since this simulation has the larger opening angle in the
north side. We should point out that since RADvHR hasn’t been
evolved long enough we cannot guarantee this behavior could be
observed at very late times.
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The total efficiency and its different components (PAKE, EM and RAD) versus radius averaged over the time period 12,000-18,000 \( R_g/c \) show that the simulation MADiHR has larger total and radiative efficiencies compared to these RAD simulations. However, the non-radiative components in MADiHR are similar to radiative simulations, suggesting the large difference in total efficiency is the lack of self-consistent radiative transfer. RADHR, RADLR, and RADvHR have similar efficiencies, with the latter demonstrating the highest efficiency. Figure 8 presents the values averaged over the time period 30,000-40,000 \( R_g/c \) for RADHR, RADLR, and MADiHR, and during the time period 15,000-18,000 \( R_g/c \) for RADvHR where one can see that even at the late times this behavior doesn’t change, with MADiHR still demonstrating the largest efficiency. The EM component shows that RADvHR has the largest efficiency during this time period with RADvHR and RADHR showing similar values inside the plunging region, and this behavior hasn’t changed at late times. The PAKE term shows that RADvHR and MADiHR have a similar efficiency during this time period, and at late times this component increases for MADiHR. However, we cannot guarantee that RADvHR will follow the same trend since this simulation hasn’t been evolved to the same final time. A possible source of these peaks is that when a bunch of magnetic flux via initial transients pushes out into the disk, there are large sections of the disk dominated by magnetic flux and void of high density material.

In all three simulations, RADHR, RADLR, and RADvHR, the time evolution of the disk scale-height, stress and magnetic flux presented in Figure 8 for RADLR and Figure 10 for RADvHR at three different locations shows that, as expected, RADLR has more difficulty reaching a quasi-steady state value where a peak close to \( t \approx 22,000 R_g/c \) in the disk scale-height has been observed and the values seem to be trying to reach a quasi-steady state value at the end of the simulation. RADvHR presents strong variability and large peaks in the disk scale-height in the initial evolution and after 10,000 \( R_g/c \) the values at the three locations seem to be trying to converge to a constant value. RADLR presented a strong variability in the stress since this simulation had more difficulty accumulating flux into the MAD state. Less variable behavior is observed in RADvHR due to the ability of the MAD state to build up faster in this case and more magnetic flux being accumulated in the disk in this case. When compared with RADHR and RADLR. A possible source of these peaks is that when a bunch of magnetic flux via initial transients pushes out into the disk, there are large sections of the disk dominated by magnetic flux and void of high density material.

The electromagnetic and radiation fluxes presented in Figure 11 show that the EM luminosity has a more uniform angular, and more north-south symmetric, distribution, for RADHR, with the jet emission in the north stronger when compared with this direction and our simulation RADHR. Different from RADHR the radiation luminosity of RADvHR is broader and stronger in the
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Figure 8. Plot of the efficiencies where the plots show the total efficiency, the efficiency carried in the matter form, efficiency carried in the electromagnetic form and the efficiency carried by the radiation respectively. The continuous line corresponds to the simulation RADHR, the dashed line is for the simulation RADvHR, the dashed-dotted line is for the simulation RADLR and the dotted line is for the simulation MADiHR. This plot only shows values inside the radius where the accretion flow of our simulation RADHR has reached thermal equilibrium. The data from simulations RADHR, RADLR and MADiHR were averaged over the time period 30,000-40,000 $R_g/c$ while the simulation RADvHR was averaged over the time period 15,000-18,000 $R_g/c$.

south direction, the wind in RADvHR presenting a stronger emission in this case (yellow streams) with the $\tau_{es}=1$ surface showing in this simulation a broader opening angle in both directions indicating that at this time period a significant amount of material is blocking the radiation and similarly to RADHR most of the emission is coming from the region inside 15$R_g$.

4 DISCUSSION

We have presented the first GRRMHD simulations of a thin accretion disk around a spinning black hole in the so called MAD state with the objective to study the accretion efficiencies and compare our results with the recent paper from [Avara et al. (2016)]. Our results have shown that the wind efficiency is greater than the jet efficiency, and the total efficiency reported in this work is similar to that found by [Avara et al. (2016)] when taking into account that in their simulation the total efficiency is slightly higher due to the use of an ad hoc cooling function that does not take into account the effects of scattering and absorption of the radiation. As in [Avara et al. (2016)], we have also seen the presence of a weak jet with a non-uniform distribution in the south direction indicating that a large amount of material in this region is blocking the radiation as seen by the location of $\tau=1$ for electron scattering.

We have found that the radial profile of the mass accretion rate is not flat as seen in [Avara et al. (2016)] due to the use of radiative transfer which requires a long evolution in order to reach thermal equilibrium and also due to the density and energy floors required to keep our simulation stable and the non triviality of removing floor material during analysis. Future simulations will provide more time-snapshots in order to better remove effects of floors. Improvements in the M1-closure scheme are required in order to be able to properly handle multiple light rays.

We quantify the effects of resolution on our results by comparing our fiducial simulations to bother lower and very high resolution simulations to better understand convergence. Our simulation RADvHR demonstrates the highest efficiency from all of our RAD simulations as expected, though MADiHR had an even larger efficiency since radiative transfer wasn’t taken into account. All simulations reported in this study have shown that the wind carries the largest portion of outgoing energy, and the results reported here and in [Avara et al. (2016)] showed that the accretion flow can extract rotational energy from the black hole producing a weak jet.

We have also carried out initial analyses of the stability of our thin disk and in all simulations we have found that our thin disk in the MAD state has been supplied with a large amount of magnetic flux which produced a strong magnetic pressure that was able to support the disk against the collapse due to radiative loses.

In a future study we will evolve our simulation RADvHR much longer in order to study the jet power and check if the absorption in the south direction will increase and also include different

Figure 9. Same as Figure 8, but with values for our simulation RADLR.
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5 CONCLUSIONS

We have shown the results of the first known simulations of radiatively efficient thin disks, with $H/R \sim 0.1$, around a spinning black hole with $a/M=0.5$, that are in the MAD state and include self-consistent radiative transport. Our longer high-resolution simulation RADHR reached the MAD state out to $16R_g$ and most energy extracted by the disk is carried away by the wind consistent with the findings of Avara et al (2016) but with a smaller total efficiency due to a significantly smaller radiation component. This is because our calculations include self-consistent absorption and scattering of the radiation, advection by plunging material, and true ray-tracing. We measured the electromagnetic and radiation luminosities and we found anisotropic emission in both cases. Radiation, on the other hand, prefers emission to the north. A key result of this work that will be explored in the future is the thermal stability of the disk, likely a result of the very strong magnetic fields intrinsic to the MAD state. It remains to be shown if there is a qualitative difference in disk stabilization by a strong magnetic field in a standard disk that is MRI dominated, compared to a disk in the MAD state where the MRI no longer dominates the accretion process.

6 ACKNOWLEDGMENTS

DMT thanks Ramesh Narayan, Olek Sadowski, Roman Gold, Jane Dai and Peter Polko for the several helpful comments. DMT thanks the Brazilian agencies CNPQ (proc 200022/2015-6), CAPES (88887.130860/2016-00) and FAPESP (2013/26258-4) for the financial support that made this project possible. DMT also thanks the Physics and Astronomy departments of University of Maryland for their hospitality where the major part of this work has been carried out. JCM thanks the support by NASA/NSF/TCAN (NNX14AB46G) as well as computing time from NSF/XSEDE/TACC (TG-PHY120005) and NASA/Pleiades (SMD-14-5451).

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