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# Merger! In AGN disks: 3D global simulations

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## ABSTRACT

## 1. INTRODUCTION

## 2. METHODS

### 2.1. *Basic Equations*

We numerically solve hydrodynamical Euler equations in 3D:

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}(\rho \boldsymbol{v}) = 0, \tag{1}$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \boldsymbol{\nabla} \cdot [\rho \boldsymbol{v}\boldsymbol{v} + P\boldsymbol{I}] = -\rho \boldsymbol{\nabla}\phi, \tag{2}$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E+P)\,\boldsymbol{v}] = \rho \boldsymbol{v} \cdot \boldsymbol{\nabla}\phi, \tag{3}$$

where $\rho$, $pmbv$, and $P$ are the gas density, velocity, and pressure, respectively. $E$ is the total energy, which is given by

$$E = \frac{P}{\gamma - 1}, \tag{4}$$

where $\gamma$ is the adiabatic index. We take $\gamma = 1.4$. $\phi$ represents the static gravitational potential of the binary, which is given by $\phi = -GM_b/r_b$, where $M_b$ and $r_b$ represent the binary mass and spherical radius, respectively.

We use the grid-based higher-order Godunov hydrodynamic code `Athena++` (Stone et al. 2020), which is the successor of the widely used code `Athena` (Stone et al. 2008), to solve these equations numerically. We adopt the second-order piecewise linear reconstruction method, and the second-order Runge–Kutta scheme to update the equations. We use the Harten-lax-van Leer Contact (HLLC) (Toro et al. 1994) to approximate Riemann solvers for pure hydrodynamic simulations. The equations are solved in nondimensional form.

### 2.2. *Disk model*

Isentropic disk model from Fung et al. (2017). The simulations are performed in spherical coordinates, where $r$, $\phi$, and $\theta$ denote the usual radial, azimuthal, and polar coordinates, respectively.

$$\Phi = -\frac{G(M_* + M_p)}{1+q}\left[\frac{1}{r} + \frac{q}{\sqrt{r^2 + R_p^2 - 2rR_p\cos\phi' + \epsilon^2}} - \frac{qR\cos\phi'}{R_p^2}\right] \tag{5}$$

The location of the BBH's center of mass is (i.e. the semi-major axis of the center of mass) $R_{CM} = 1$, and the semi-major axis of the binary's orbit around the center of mass is $a_{bin} = 0.025R_{CM}$. In eq. 5, $q = M_b/M_*$ is the mass ratio of a black hole binary to a supermasive black hole, $\epsilon$ is the smoothing length of the BBH's potential, and $\phi' = \phi - \phi_p$ denotes the azimuthal separation from the BBH. $GM = 1$, $R_{CM} = 1$.

Keplerian velocity $v_k = \sqrt{\frac{GM}{r}}$ and keplerian frequency $\Omega_k = \sqrt{\frac{GM}{r^3}}$ equal to 1 at the BBH's orbit.

$v_p$ - BBH's orbital speed. $q = 1.5 \times 10^{-5} \approx 5M_\oplus$

The simulation domain spans $0.65R_p$ to $1.35R_p$ in the radial, and the full $2\pi$ in azimuth.

The Hill radius of a BBH is:

$$r_H = R_{CM}\left(\frac{q}{3}\right)^{\frac{1}{3}} \tag{6}$$

$r_s$ is a small fraction of $r_H$, between 3% to 10% of $r_H$.

The isentropic equation of state:

$$p = \frac{c_0^2 \rho_0}{\gamma}\left(\frac{\rho}{\rho_0}\right)^{\gamma} \tag{7}$$

In Eq. 7, $c_0$ is the isothermal sound speed when $\rho = \rho_0 = 1$. The disk's scale height $H = 0.05$ scales the sound speed as $c_0 = H\Omega = 0.05$.

#### 2.2.1. *Initial conditions*

For hydrostatic equilibrium:

$$\rho = \rho_0\left[\left(\frac{R}{R_p}\right)^{(-\beta+\frac{3}{2})\frac{2(\gamma-1)}{\gamma+1}} - \frac{GM(\gamma-1)}{c_0^2}\left(\frac{1}{R} - \frac{1}{r}\right)\right]^{\frac{1}{\gamma-1}} \tag{8}$$

**Table 1.** Normalization Units and Corresponding Values

| Quantity | Unit | Value |
|---|---|---|
| Length | $r_p$ | $7.41 \times 10^{13}$ cm |
| Velocity | $v_{K0}$ | |
| Time | $r_p/v_{K0}$ | $3.7 \times 10^8$ s |
| Density | $\rho_0$ | |
| Pressure | $\rho_0 v_{K0}^2$ | |
| Mass accretion rate | $\rho_0 r_p^2 v_{K0}$ | |

$\beta = \frac{3}{2}$ defines the surface density profile $\Sigma \propto R^{-\beta}$.

The orbital frequency of the disk:

$$\Omega = \sqrt{\Omega_k^2 + \frac{1}{r\rho}\frac{\partial P}{\partial r}} \tag{9}$$

$v_r = v_\theta = 0$

#### 2.2.2. *Resolution*

We apply static mesh refinement (SMR) level od leverl $l = 4$ around the location of the binary.

The resolution for non-refined disk is $[192, 80, 1032]$ cells in $r$-,$\theta$-, and $\phi$-directions.

We increased the resolution in the following regions: $0.97 - 1.03R_{cm}$ in $r$-direction, $89^o - 91^o$ in $\theta$-direction, and $178^o - 182^o$ in $\phi$-direction. The definitions of the normalization units and the corresponding values are listed in Table 2.2.2.

### 2.3. *Athena++ simulations*

### 2.4. *Accretion onto the binary*

We use the sink particle accretion prescription as in Muñoz et al. (2019). They remove a fraction of gas mass in sink cells at every time step and the mass removal fraction is a function of distance in units of sink radius. We use the spline function to calculate the mass removal fraction (the input is distance to each black hole divided by the sink radius). *The caveat:* the prescription doesn't work in the global simulation in the same way as in local simulations done in previous works.

## 3. RESULTS

## 4. DISCUSSION

## 5. OTHER WORKS

## REFERENCES


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