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QUASI-SPHERICAL ACCRETION FLOW FROM THE COLLAPSE OF MASSIVE STARS

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1. INTRODUCTION

The collapse of massive stars is a very interesting topic, since they are the progenitors of massive black holes, such as the ones that LIGO observes. It is often assumed that the final mass of the black hole is set by direct collapse of star, but let's revise that. Once the core of the high-mass star has collapsed into a black hole, in-falling material will increase its mass. If the accretion is spherically symmetric, then all of the mass goes into the black hole, there is no feedback, and the end result is a high-mass black hole. A problem arises when we consider angular momentum. If we consider the Newtonian case, there is a centrifugal barrier, and so the orbits become parabolic, but we are in a black hole, so we need general relativity (GR), where that barrier disappears. Therefore particles with sufficient energy can actually accrete into the black hole.

If the angular momentum is enough, the particles can circularize, and form a disk. In that case, there can be efficient transport of matter into the black hole that results in energetic outflows.The energy of those outflows is comparable to the binding energy of the star, $BE_{*}/BE_{\rm BH} \sim v_{\rm esc}^2/c^2 \sim 10^{-6}$, so the outflows can actually stop the inflating material, not allowing the mass of the black hole to increase. This is shown in Figure 1, taken from (Batta et al. 2017). It shows the angular momentum profile of a $34 M_{\odot}$ star ready to collapse. Where the angular momentum is equal to the critical angular momentum, the infall is stopped, and the resultant black hole is much smaller than it would have been if it was direct collapse. The question is now, what happens when the angular momentum is smaller than the critical, is there still circularization and feedback?

Let's consider a particle of the in-falling material. If the angular momentum is therefore, several cases can be considered depending on the energy and angular momentum. First,

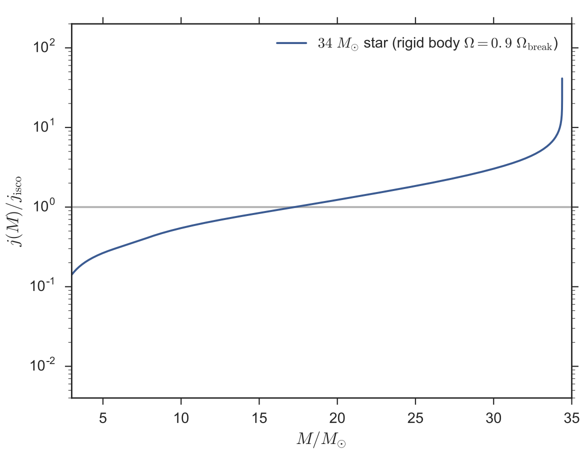

Figure 1. Angular momentum profile of a $34 M_{\odot}$ star ready to collapse. Taken from (Batta et al. 2017)

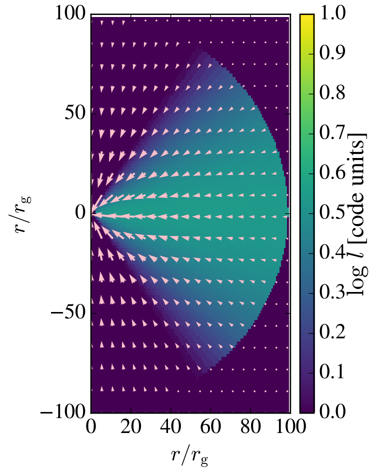

Figure 2. Initial conditions of angular momentum

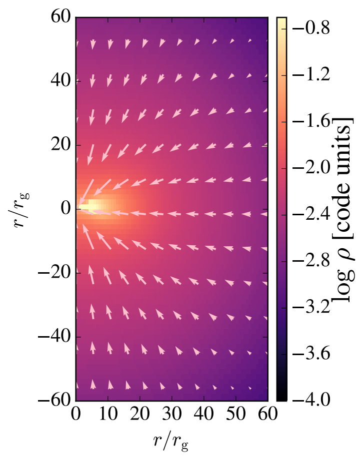

Figure 3. Density profile after $t = 200 r_g/c$ for $C = 0.9$, and a non-spinning BH.

the particle can be directly accreted. Second, the particle can encounter its circularization radius and orbit around the black hole. And third, there are particles that would have been accreted, but they cross the z=0 plane, colliding with a particle coming from the opposite direction, lose vertical momentum and circularize. The last two cases will result in a mini-disk forming around the black hole (Lee & Ramirez-Ruiz 2006). This mini-disks can be efficient and stop the inflating material. Thus, the question that we asked is very important, and it can be rephrased as: at what angular momentum can the feedback stop?

In order to answer it, we need numerical simulations, specifically GRMHD (General Relativity Magnetocoolhydrodynamics!).

2. NUMERICAL METHODS

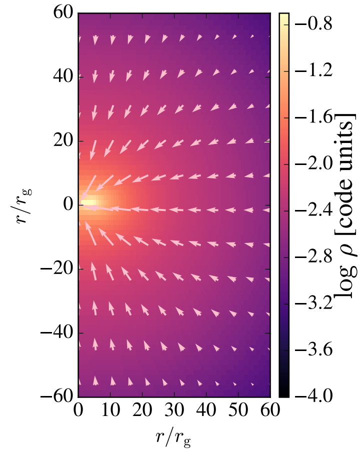

Figure 4. Density profile after $t = 200r_g/c$ for $C = 0.6$, and a non-spinning BH.

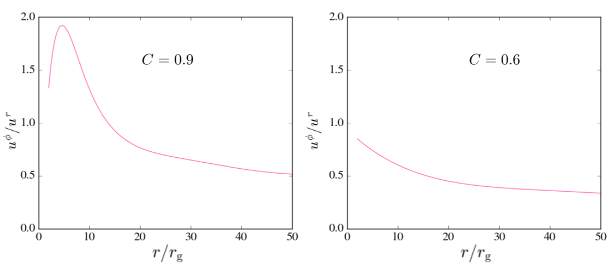

Figure 5. Comparison of number of orbits for different slowdown parameters.

We performed numerical simulations using HARM2D (High Accuracy Relativistic MHD) Gammie et al. (2003). HARM solves the conservation equations in GR:

$$\nabla_\mu(\rho u^\mu) = 0 \nabla_\mu(T^{\mu\nu}) = 0 \quad (1)$$

Where ρ is the density, u the four-velocity, and the stress energy tensor is the sum of the gaseous energy stress tensor and electromagnetic: $T^{\mu\nu} = T^{\mu\nu}_{\text{gas}} + T^{\mu\nu}_{\text{EM}}$. HARM2D considers a polytropic equation of state $P = k\rho^\gamma$ and the energy density $P = (\gamma - 1)u$, where γ is the adiabatic index, here taken to be the relativistic index 4/3, P the pressure, u the energy density, ρ the density, and k a proportionality constant. We use a spherical, uniform grid, and do not consider magnetic fields.

Our initial conditions mimic the vicinity of the black hole formed from the collapse of the core. Our domain is $100r_g$, where $r_g = GM_{\text{BH}}/c^2$ is the gravitational radii. Matter is infalling following a Bondi solution, with the sonic point outside of our domain. Setting the sonic point, we set the equation of state. Using the relativistic version of the Bernoulli term, we estimate the velocity at each point.

$$\left(\frac{\rho + P}{n}\right)^2 \left(1 - \frac{2GM}{r} + v^2\right) = ct \quad (2)$$

Where n is the number density. As for the angular momentum, we choose

$$l = Cl_0 \sin^2(\theta) \quad (3)$$

where C is a slowdown parameter, l_0 is the angular momentum of a circular orbit at the innermost stable circular orbit radius of a non-spinning BH, and θ the usual angle. Fig 2 shows the initial conditions for the angular momentum.

3. RESULTS

Fig 3 and fig 4 show the result of a simulation for different slowdown parameters. It is notable that a mini-disk is created in the case for $C = 0.9$, whereas the accretion is almost spherical for the case $C = 0.6$. Another way to see this is comparing the angular velocity and the radial velocity, meaning how many orbits will the particle spend in the disk. If the number is greater than 1, then we have a mini-disk. This is shown in fig 5. Therefore, the transition between mini-disk and no disk happens somewhere around $C = 0.6$.

The next step would be to calculate the efficiency, in order to estimate if the in falling material is stalled and the black hole has a final lower mass.

REFERENCES

Batta et al. 2017, ApJ

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