Stream Crossing near Pericenter in TDEs

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Abstract

In tidal disruption events the stellar disrupted by massive black hole results in an elongated stream of gas that partly falls back to pericenter. If the black hole rotates around an axis misaligned with the initial stellar orbit, the first stream crossing may occur at periapse if the returing stream fail to collide itself near apocenter due to Lense-Thirring effect. In our work we study the stream crossing near pericenter by performing local hydrodynamical simulations using Athena++ code. From simulations, when the streams collide a strong radiation-pressure dominated shock forms and converts the stream's kinetic energy into thermal energy. We find that the amount of energy dissipation (converting to thermal energy) measured from simulation well agrees with analytical results. At the same time, the strong downstream gas pressure accelerates the gas and causes it to expand. We show the increase of width of downstream gas with distance to BH, which likely leads to collisions in subsequent orbits and accelerating formation of an accretion disc.

Introduction

Many analytical and observational studies have shown that in TDEs observable signal in UV/optical bands may come from the accretion disk (e.g. Dai et al. 2018). To form the disk the stream debris has to dissipated its orbit energy. In this work we investigate a rarely studied pathway to energy dissipation, i.e., the stream crossing near pericenter (Batra et al. 2021). This process occurs when the first crossing fail to occur near pericenter (Dai et al. 2013; Guillochon et al. 2015; Bonnerot et al. 2021). Combining the analytical calculation, we preform the local hydrodynamical simulation (Jiang et al. 2016) to measure the amount of energy dissipation and the effect of gas expand on the subsequent circularization. We set the staller are solar-like, black hole spin $a = 0.9$ and inclination angle between spin axis and orbital angular momentum vector, $i = \pi/3$.

Theoretical calculation

We approximate the adjacent orbits as two ellipses with the BH located at a joint focal point. By theoretical calculation we show that energy dissipation by crossing near pericenter is comparable to apocenter.

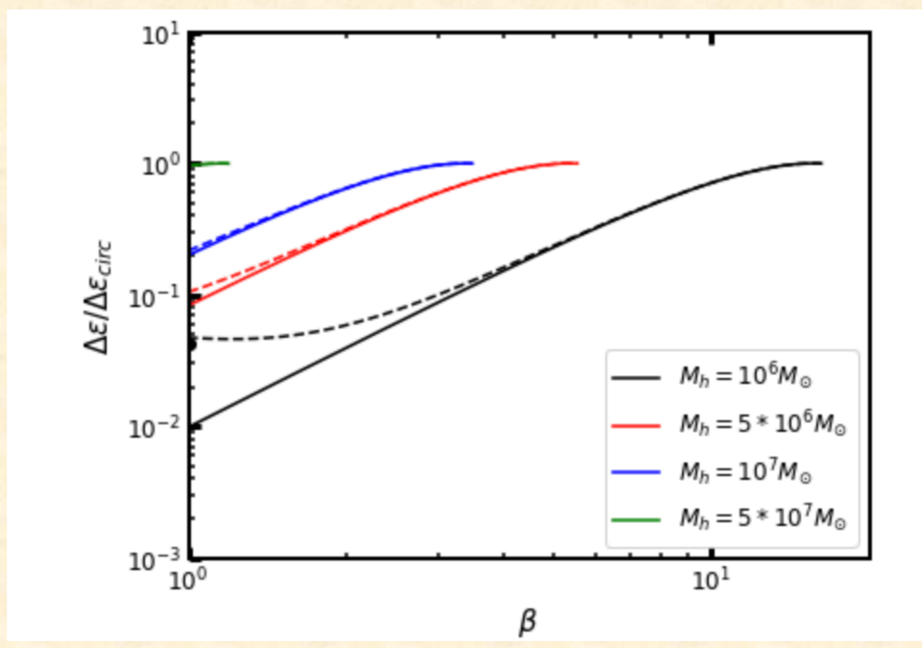

Fig. 1. The ratio of $\Delta\epsilon$ (energy dissipated by single collision) over $\Delta\epsilon_{circ}$ (energy dissipated to complete circularization), as a function of penetration factor β, for several BH mass M_h . *Solid line*: $\Delta\epsilon/\Delta\epsilon_{circ}$ for crossing near pericenter. *Dashed line*: $\Delta\epsilon/\Delta\epsilon_{circ}$ for crossing near apocenter.

Local hydrodynamical simulation

We perform three-dimensional local hydrodynamical simulation for stream crossing near pericenter using the Athena++ code (Stone et al. 2020), and the initial condition is derived by analytical calculation. By injecting two streams to simulation box with certain angles, we simulate the corresponding stream crossing for black hole mass M_h and penetration factor β (seen in Fig.3). We can measure the kinetic energy dissipated by crossing shock and the downstream gas distribution generated by the shock.

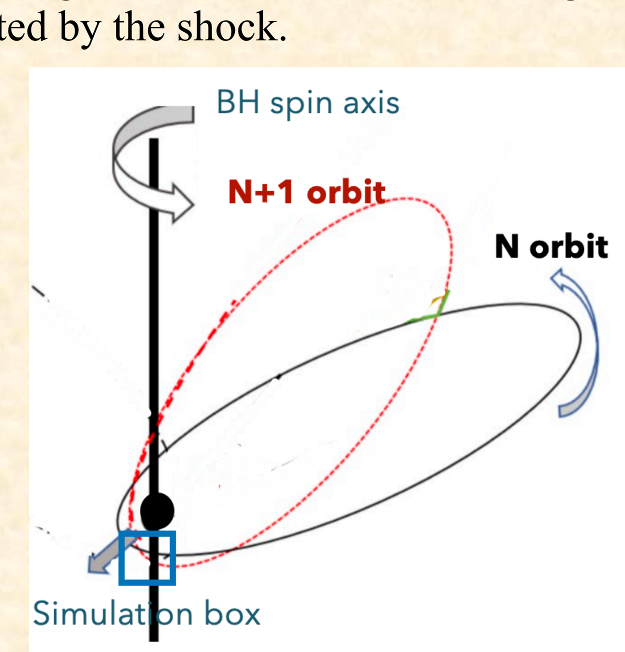

Fig. 2. The schematic diagram of simulation box (blue box)

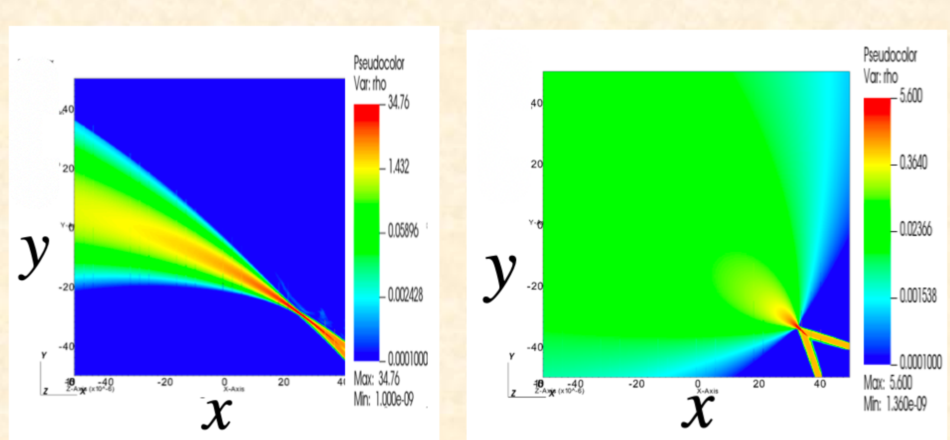

Fig. 3. Snapshot of density distribution on x-y plane (the plane injecting two colliding streams) for two group of TDE parameters. *Left*: Simulation for black hole mass $M_h = 10^6 M_\odot$ and penetration factor $\beta = 1$. *Right*: Simulation for $M_h = 10^6 M_\odot$ and $\beta = 1$. Other parameters are the same.

Results1-the energy dissipation

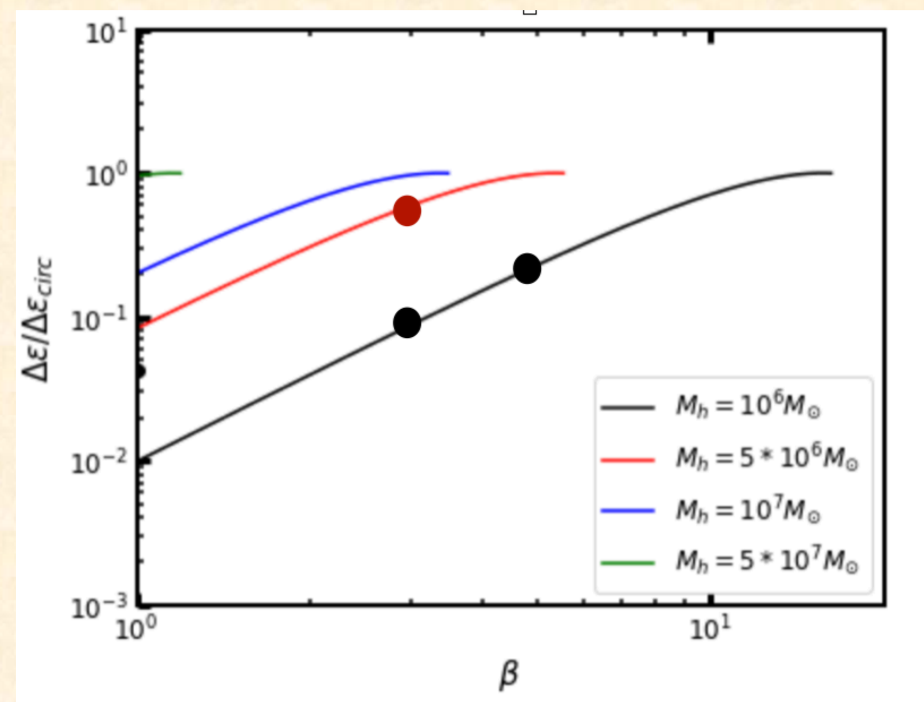

Fig. 1. The ratio of $\Delta\epsilon$ (energy dissipated by single collision near pericenter) over $\Delta\epsilon_{circ}$ (energy dissipated to complete circularization), as a function of β, for several M_h . *Solid line*: $\Delta\epsilon/\Delta\epsilon_{circ}$ calculated by analytical caculation. *dot:* $\Delta\epsilon/\Delta\epsilon_{circ}$ measured by numerical simulation. From comparation, both are in good agreement.

Result2-the variation of stream width

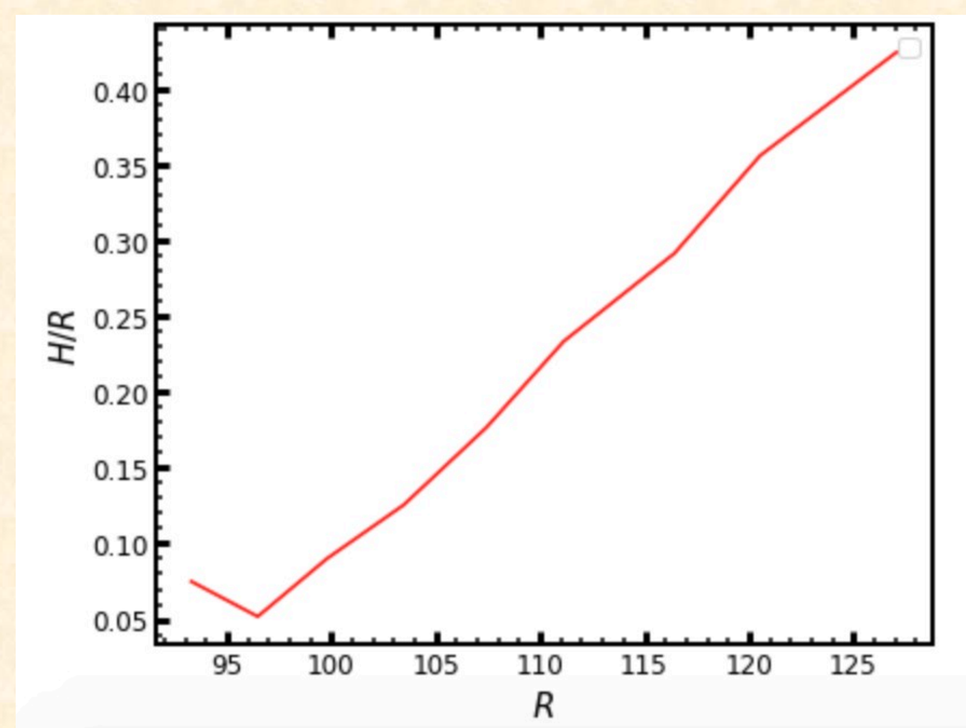

Fig. 3. The ratio of width of downstream gas over distance to BH, H/R , as a function of distance to BH, R, for $M_h = 10^6 M_\odot$ and $\beta = 1$. The width of downstream gas increases with distance to BH, R.

Summary

- 1.There is a good agreement between analytical calculation and numerical simulation for the amount of energy dissipation through the first crossing near pericenter.
- 2. The width of downstream gas width increases with distance to BH (leading to collisions in subsequent orbits and the formation of an accretion disc).

Outlook

Other aspects which may relate to the observable properties of the crossing near pericenter:

- 1. The outflow properties
- 2. The possible radiation

References

L. Dai, J. C. McKinney, N. Roth, E. Ramirez-Ruiz and M. C. Miller, Astrophys. J. Lett. 859, no.2, L20 (2018)
G. Batra, W. Lu, C. Bonnerot and E. S. Phinney, [arXiv:2112.03918].
L. Dai, A. Escala and P. Coppi, Astrophys. J. Lett. **775**, L9 (2013)
J. Guillochon and E. Ramirez-Ruiz, Astrophys. J. **809**, no.2, 166 (2015)
C. Bonnerot and N. Stone, Space Sci. Rev. **217**, no.1, 16 (2021)
J. M. Stone, K. Tomida, , C. J. White and K. G. Felker, ApJS, 249, 4 (2020)
Y. F. Jiang, J. Guillochon and A. Loeb, Astrophys. J. **830,** no.2, 125 (2016)

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