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204

TIDAL DISRUPTION OF A STAR BY A SUPERMASSIVE BLACK HOLE

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ABSTRACT

The analysis of stars in galactic nuclei that are captured and tidally disrupted by a black hole of mass $> 10^6 M_\odot$ requires the inclusion of general relativistic effects. We present the first numerical study of tidal breakup of a $1 M_\odot$ main sequence star by a $10^7 M_\odot$ black hole. We use a smoothed particle code to solve the hydrodynamic equations for a relativistic fluid in a static curved spacetime geometry to analyze, among other things, the fraction of the debris captured by the hole and the velocity of fragments escaping the hole.

INTRODUCTION

Stellar disruption by tidal forces of supermassive black holes is one of the most important unsolved problems in the astrophysics of active galactic nuclei (AGN).¹ Studies in the 1970s suggested that tidal distortion and disruption of stars passing near massive black holes could perhaps be an essential mechanism for fueling AGN.^{2,3} However, it was shown^{2,4} that tidal disruption alone could not achieve the observed luminosity because it requires such a high concentration of stars that collisions among the stars would dominate the process. When stellar disruption occurs, part of the debris is accreted by the black hole, resulting in a burst of activity. The remaining material may well be ejected at speeds much larger than the mean velocity of the stellar system. Stellar disruption could also then have important observational ramifications since its signature may provide direct evidence for the presence of supermassive black holes.⁵

When a star gets close enough to a black hole, it can no longer be treated as a point mass particle. There is a characteristic radius within which the star becomes subject to tidal distortions and disruptions. This *tidal radius* (R_t) is defined as the distance where the surface gravity of the star equals the tidal acceleration.^{2,6} For a $1 M_\odot$ star, the tidal radius is given by $(R_t/R_s) \approx 0.5\eta^2(R_\odot/M_\odot)(M_h/M_\odot)^{-2/3}$ where $R_s = 2M_h$ is the black hole's Schwarzschild radius with M_h its mass, and the parameter η is the strength of the tidal encounter. For $M_h > 10^6 M_\odot$, $R_t < 37 R_s$. Encounters of stars in this regime are close enough to the hole that Newtonian approximations are inadequate. Black holes with $M_h > 10^6 M_\odot$ have $R_t < R_s$. The star gets swallowed before being disrupted. Therefore, there is a window ($10^6 - 10^8 M_\odot$) where the analysis of tidal stellar disruption by black holes requires a general relativistic numerical simulation. Our goal is then to provide enough features of stellar disruptions by supermassive black holes in support of a possible observation. To this end, we are analyzing in detail what happens to the gas after the star has been disrupted, namely, amount of material ejected and accreted, and the duration of the mass-accretion phase.

NUMERICAL METHOD

We have implemented a general relativistic smoothed particle hydrodynamic (SPH) code.⁷ The code uses a discretized Lagrangian version of the hydrodynamic equations for a relativistic fluid in a static curved spacetime geometry (Schwarzschild or Kerr metric) using SPH methods.⁸ We have developed an algorithm that transforms relativistic hydrodynamical contact interactions

Fig. 1: (a) Trajectory of the star's center of mass. (b) The star's initial configuration.

Fig. 2: Projection of the star in the XZ-plane (right column), and on the orbital XY-plane (left column).

in the local comoving frame of the fluid to a global laboratory frame. Our computer program has variable smoothing length, second order time integration, fluid self-gravity and artificial viscosity. A fundamental requirement of any SPH algorithm is that of finding all particles within the smoothing length of the kernel. We have implemented a suitable method for 3-dimensional problems that uses a data structure called an *oct-tree*.⁹ The oct-tree data structure collects particles into cubical regions called *cells*. This algorithm is naturally suitable for massively parallel machines. We have tested our code by simulating (1) shock tubes, and (2) relativistic Bondi collapse of a fluid onto a black hole. To avoid coordinate complications in the spacetime geometry, we calculate the stellar disruption in the rest frame of the black hole.

DISCUSSION

We present preliminary results from a $1M_{\odot}$ star tidally disrupted by a $10^7M_{\odot}$ black hole with tidal strength $\eta = 1$. We use a 7000 particle polytropic model of a star with $\Gamma = 5/3$. The tidal radius R_t for a black hole of this mass is $\sim 8R_s$. The evolution begins with the star $3R_t$ away from the black hole in a parabolic orbit. The distance of closest approach was $0.4R_t$. As the star approaches the black hole, tidal forces compress the star towards the plane of the orbit. On the other hand, since each particle on the star tries to follow an independent Keplerian orbit, the star acquires a pencil-like structure in the plane of the orbit. The star is extended in the directions determined by the tidal forces by a factor of ~ 5 at the moment of closest approach and compressed by a factor of ~ 3 in the direction perpendicular to the plane of the orbit. Figs. 1 show the trajectory followed by the center of mass of the star and its initial configuration. After the first encounter, the star becomes bound to the hole in an elliptic orbit due to the loss of total orbital energy that gets transferred to internal energy of the star. Figs. 2 are snapshots of projections of the star perpendicular to and on the orbital plane. As predicted by Carter and Luminet,¹⁰ we observe an increase on the central density. We also find that a considerable portion of the debris remains bounded to the hole, and the rest is ejected with velocities of $\sim 5000\text{km/s}$. Detailed quantitative results of the amount of accreted material and distribution of velocities of debris ejected will be given elsewhere.⁷ We are currently studying tidal disruption of stars by Kerr (rotating) black holes; we are interesting in analyzing the effects on the stellar orbit relative to the black hole spin axis.

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