Progress Report: 3D Visualizations of Black Hole Binaries and Disks in Full General Relativity

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Introduction

Accreting black holes are interesting sources of multi-messenger signals and are crucial in explaining a range of high-energy astrophysical phenomena that we observe in our Universe. In order to understand the wealth of observations black holes can produce, it is crucial to compare them to predictions from theoretical modeling. Illinois Relativity Group's research focuses on simulations of relativistic astrophysical processes in order to understand the physics of compact objects and the basis of physics of matter under extreme conditions and the role of general relativity. These simulations provide the necessary waveforms needed for the detection of gravitational waves (GWs) by the LIGO/Virgo scientific collaboration (LVSC), KAGRA, NanoGrav, Pulsar Timing Arrays, LISA, the Einstein telescope, and other current and future detectors. They also provide descriptions of the electromagnetic (EM) signals, such as Gamma Ray Bursts (GRB) and the outgoing EM luminosity, as well as the fraction of the escaping mass that may give rise to kilonovae phenomena that can be detected by current space observatories, including the NICER, CHANDRA, and XMM-Newton X-ray instruments.

Over the summer, we focused on wrapping up two main projects, that we had been working on throughout the academic year, and getting them ready for publication.The two projects are as follows:

Single Black Hole Binaries

Most galaxies are believed to host a central supermassive black hole (SMBH) and as a result of galaxy mergers, SMBH binaries (SMBHBHs) are expected to form (see, e.g., Colpi et al. 2014 [3] for a review). These systems form unique sources for multimessenger signals. SMBHBH evolution is particularly promising as potentially strong sources of gravitational and various forms of electromagnetic (EM) emission. SMBHBHs are understood to be the loudest sources of low frequency GWs, whose detection will be one of the main scientific goals of future spaceborne interferometers such as LISA (Amaro-Seoane et al. 2017 [1]).

Black Hole Disks

Black holes (BHs) immersed in gaseous environments are ubiquitous in the Universe. Black hole-disks (BHDs) appear on a great variety of scales, reflecting their diverse birth chan- nels and sites. From the core collapse of massive stars[22, 14] and the cores of active galactic nuclei[13, 18, 16], to asymmetric supernova explosions in binary systems[5], and the merger of compact binaries where at least one of the companions is not a BH, BHDs may be formed and serve as prime candidates for multimessenger astronomy.

While the grant proposal only mentioned Single Black Hole Binaries, we were also able to complete the Black Hole Disks project during the allocation period.

Methods

Modeling these systems realistically is a central problem in theoretical astrophysics, but has proven extremely challenging, requiring the development of numerical relativity codes that solve Einstein's equations for the space time, coupled to the equations of general relativistic magnetohydrodynamics (GRHMD) for the magnetized fluids. Over the past decade, the Illinois Relativity Group's dynamical space time GRHMD code has proven itself as one of the most robust and reliable tools for theoretical modeling of such astrophysical phenomena[4, 17, 19]. The code evolves the spacetime metric by solving Einstein's field equations in the BSSN formulation (Baumgarte & Shapiro 1999 [2]; Shibata & Nakamura 1995 [20]) coupled to the equations of ideal GRMHD in a conservative scheme via high-resolution shock capturing methods for the evolution of matter and magnetic field. The methods used by the group for solving Einstein's field equations for the gravitational field, and the equations of ideal magnetohydrodynamics in curved spacetime have been described previously in (Khan et al. 2018[7, 8]), which can be refered for more details and further references.

We have also developed a Python-Visit code that allows us to visualize these simulations on large-scale supercomputing clusters. These visualizations are critical in determining if thee is a jet confined by the helical B-field lines emanating from the black-hole poles, if fluid elements in the accretion disk end up into the funnel, the spatial distribution of EM and GW signatures from our systems, etc.

Summary of Findings

Single Black Hole Binaries

We were successfully able to complete stationary stills and movies that will be displayed on our group web page[6] and referenced in our upcoming research article. The project consisted of three simulations, each having a unique spin configuration. The links for these movies are listed below:

- 00 degree Case (Spin arrows are pointed in the plane)[9]
- 45 degree Case (Spin arrows are pointed 45 degree from the plane)[10]

- 90 degree Case (Spin arrows are pointed perpendicular to the plane)[11]

These movies will help researchers understand the formation of X-shaped galaxies. The popular hypothesis is that they are formed due to SBHBH mergers. However, there are also models that show that these galaxies can be formed due to "feeding" of a supermassive black hole[15]. Our research article will test our simulations against predictions of all of these theories.

Black Hole Disks

We were able to complete stationary stills for our upcoming research article[21] that will be published within the next few weeks. In this article we analyze the spin of BHdisks and how they influence the multi messenger signals that we can detect for these systems.

Impact

This grant was crucial in funding my living expenses throughout the grant allocation period. All of the visualizations and publications, that were produced during this period wouldn't have been possible without the grant. This grant advanced the field of astronomy by helping researchers create models that can be used by astronomers to detech BHs.

This also indirectly helped advance society since detecting BHs requires breakthrough technology which in turn has immense practical benefits[12]. The difficult technical challenges in detecting gravitational waves have led to spinoff technologies that have made improvements in lasers, glass technology, semiconductor manufacturing and information processing among other applications. For these detectors to succeed, technology has been developed by LIGO scientists and engineers to measure displacements less than 1/10,000 the diameter of an atomic nucleus. Innovations in areas as diverse as lasers, optics, metrology, vacuum technology, chemical bonding and software algorithm development have resulted directly from this pioneering work.

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