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Virtual Experiments in Astrophysics

P. Chris Fragile*

College of Charleston, Charleston, SC

Astronomy is one of the, if not the, oldest field of science on Earth. Some of the earliest human records document astronomical events thought noteworthy by the people who witnessed them. However, there is at least one glaring difference between astronomy and its sister fields of natural science – the lack of an ability to perform controlled experiments. That is not to say that astronomers do not follow the scientific method; they certainly do. But they are unable to perform experiments in the traditional sense of being able to prescribe and manage the conditions they wish to test and to make repeated measurements as those conditions are varied in a controlled manner. In astronomy, we are at the mercy of what the universe chooses to show us at any given time. The experiment is happening all around us, and we have essentially no control over it.

One important exception to this is in the virtual world of computational astrophysics. Since the universe, and everything in it, is required to follow the same prescribed set of physical laws, one can create a virtual universe (or virtual stars, solar systems, or galaxies) inside a computer, constrained to follow the same set of physical laws as their real-world counterparts. In this way, we can conduct experiments where we are able to prescribe and manage the conditions, vary those conditions as we desire, and make any number of measurements. In other words, we can do experiments in the traditional sense, albeit virtually.

This is what my research group at the College of Charleston has been doing for more than 16 years now. We work both to develop the computational tools required to conduct the numerical experiments, while also finding novel applications to which to apply them. In the rest of this review, I will describe a few of the tools we have developed, as well as a few of their applications, and finish with a few words on our next big challenge.

1. Developing the Tools

Most objects in astronomy, basically anything larger than a terrestrial planet, including the universe itself, can be reasonably accurately treated as a fluid. Therefore, the first piece of physics that our virtual laboratory must include is fluid dynamics, often called hydrodynamics, even though the fluid in question is astronomy is rarely pure water. In many cases, this fluid is composed of ionized gases, or plasmas, such that electromagnetic forces can play a critical role. In this case, it is necessary to solve the richer set of equations of magnetohydrodynamics (magnetic fields + fluid dynamics). Since astronomy, as an experimental science, is based almost exclusively on the collection of electromagnetic radiation (light) using telescopes, it is often also important to include this radiation in the simulations themselves, at least at some level. In the most extreme cases then, we are required to solve the equations of radiation (magneto-)hydrodynamics. Finally, gravity plays a dominant role throughout astronomy, helping dictate the structure and motion of nearly all objects. For ordinary objects, traveling at ordinary speeds, Isaac Newton's version of gravity is sufficient for this purpose. But for compact objects, such as white dwarfs, neutron stars, and black holes, and objects traveling close to the speed of light, Newtonian physics is no longer adequate, and we are forced to move into the realm of relativity. Combining all of these, our set of tools now comprises general relativistic radiation agnetohydrodynamics. In the rest of this section, I will briefly mention ways in which my group has improved the treatment of radiation and magnetic fields in numerical simulations.

1.1 Treating Radiation

Probably the most glaring shortcoming of almost all numerical simulations of astrophysics until the 2010's was the unrealistic treatment of radiation, which was most often simply ignored. This was not due to a lack of appreciation of its importance on the part of numericists, but simply a reflection of the fact that there are very few efficient ways to treat radiation computationally in large, multi-dimensional problems.

Starting in 2012, my group began to develop new techniques for evolving radiation fields alongside the magnetohydrodynamics. Two of the most crucial advances we made were: 1) choosing to only treat the lowest-order moments of the radiation fields, mirroring what is done with the fluid fields in hydrodynamics [3]; and 2) developing an implicit scheme to handle the coupling of the radiation and fluid fields [4]. Together, these have allowed us to incorporate radiation directly into our simulations and even capture the feedback of this radiation on the fluid.

1.2 Handling Magnetic Fields

Gauss' law of magnetism provides a constraint condition on the magnetic fields found in nature. Mathematically, the constraint is written as $\nabla \cdot B = 0$, where B is the magnetic field vector. Simply put, this says that a naturally occurring magnetic field should be divergence free. Physically, this is equivalent to saying that there are no magnetic monopoles.

However, most computational implementations of magnetohydrodynamics (MHD) are not guaranteed to abide by the $\nabla \cdot B = 0$, constraint, even if the initial field is divergence free. Thus, the magnetic field is allowed to build up unphysical divergence (monopoles) during the evolution. This can potentially lead to unphysical instabilities or anomalous forces within the magnetic fields themselves.

In 2019, my group presented a scheme to evolve the magnetic vector potential rather than the magnetic field itself [6]. Since the magnetic field can be reconstructed as needed by taking the curl of the vector potential, and since the divergence of a curl is always zero, this procedure is guaranteed to maintain a divergence-free field. The benefit of this approach for our purposes is that, since there are no constraints on the vector potential, unlike the magnetic field, it can be updated in the same way as other fields in our code without introducing divergence errors.

2. Finding Novel Applications

Since most of my group's code development has focused on general relativistic radiation magnetohydrodynamics, it would make sense that most of the applications to which we apply the code require at least some combination of relativity, radiation, and MHD. In practice, though, this is a backwards way to think about what we do. We do not (normally) choose the problem based on the physics we have implemented, but rather, we implement the physics necessary to address the problems in which we are interested. In this section, I will briefly describe two of those problems and highlight a few results.

2.1 Tidal Disruption Events

On occasion, a star or other celestial object may have the misfortune of passing too close to a neighboring black hole, resulting in the object being ripped apart by the black hole's extreme tidal forces. During such violent "tidal disruption events" (TDEs), the object being disrupted is simultaneously stretched and compressed in opposing directions. If the object happens to be a white dwarf, which is the dead core of a Sun-like star, the compression may be sufficient to briefly reignite nuclear fusion, in a sense bringing the white dwarf back to life, if only for a few seconds.

For this to happen, the white dwarf must pass relatively close (inside the "tidal radius") to an intermediate mass black hole (IMBH), one about

1,000 to 10,000 times the mass of the Sun. This is because the size of a black hole (and its tidal radius) correlates with its mass; larger mass black holes are bigger. If the black hole has too little mass, its tidal radius is smaller than the size of the white dwarf, so the black hole is initially swallowed by the white dwarf. If the black hole has too much mass, it will be so large that the white dwarf will pass inside before the tidal forces become strong enough to disrupt it.

While large numbers of "stellar mass" and "supermassive" black holes have been discovered, there is currently scant evidence for their intermediate mass cousins. It is important, though, to know how many intermediate mass black holes exist, as this will help answer the question of where supermassive black holes come from. Finding intermediate mass black holes through tidal disruption events would be a tremendous advancement.

While some of the material ripped from the disrupted object will ultimately be swallowed ("accreted") by the black hole, a significant fraction will be flung away into surrounding space as unbound debris. This debris can eventually be assimilated into future generations of stars and planets, so its chemical make-up can have important consequences. The nuclear burning that takes place during the tidal disruption of a white dwarf causes significant changes to its chemical composition, converting the mostly helium, carbon, and oxygen of a typical white dwarf into elements higher up on the periodic table.

These tidal disruptions are one example of the types of events my group has explored through our computer simulations. Fig. 1 illustrates the results of one such simulation. Our work has confirmed that nuclear burning is a common outcome in white dwarf TDEs, with up to 60% of the white dwarfs mass undergoing fusion [1, 2]. The efficiency and elements produced in these events both depend sensitively on how close the white dwarf comes to the black hole, with more distant approaches preferentially producing relatively light elements such as calcium and closer approaches producing heavier elements such as iron. The simulated disruptions also generate short bursts of gravitational waves, of a frequency and amplitude that may be detectable with future space-based instruments.

2.2 Type I X-ray Bursts

X-ray bursts are highly energetic releases of radiation from the surfaces of neutron stars, triggered by the explosive burning of accumulated material. It is the same type of burning that happens in the cores of ordinary stars like the Sun, but in this case, happening on the surface. Thus, unlike the Sun, where it takes hundreds of thousands of years for this radiation to escape and in much weaker form, it happens almost instantly in an X-ray burst. This means that anything surrounding the neutron star is going to get blasted with radiation (see Fig. 2).

One thing we know for sure that surrounds many neutron stars is an accretion disk, a swirling collection of plasma caught in the star's gravitational field. X-ray instruments, such as the NICER mission on board the International Space Station, have given astronomers the tools to study these X-ray bursts and their effects on their surrounding accretion disk in detail.

One reason these studies are so important to astrophysicists is that neutron stars represent the densest state of matter in our universe. Understanding their behavior is an important step toward unlocking the mysteries of subatomic physics and extreme gravity. Understanding neutron stars, though, requires understanding the radiation we receive directly from them, but also from the surrounding disk.

That is where my group's research comes into play. We have performed computer simulations studying the interactions of X-ray bursts with accretion disks, in which we have noticed many changes to the inner parts of the accretion disk [5, 7]. Several of these effects appear to match what has been seen in observations over the last 15 years.

3. Future Directions

My group continues to seek out new astrophysical problems to explore. The one we are currently focused on is understanding so-called Ultra-Luminous X-ray sources (ULXs). The first detections of ULXs were made in the 1980's by the Einstein Observatory, although the name ULX was not adopted until much later. The standard definition of a ULX is any X-ray point source with an inferred luminosity greater than 10^{38} erg s^{-1}. The significance of this measure is that it represents the Eddington limit, the supposed maximal accretion luminosity, of a typical neutron star. Since ULXs, by definition, have luminosities above this limit, they must either involve accretion onto more massive objects (since the Eddington limit scales as the mass of the object) or involve objects that are able to exceed their Eddington limit.

We now know that most ULXs fall into the latter category; they are comprised of neutron stars or relatively low mass black holes accreting at such high rates that their luminosities exceed the Eddington limit. Such "super-Eddington" accretion is still not well understood, partly because of the competing roles played by radiation, magnetic fields, and strong gravity. This is precisely the kind of problem for which virtual experiments, like the ones my group carries out at the College of Charleston, are paramount!

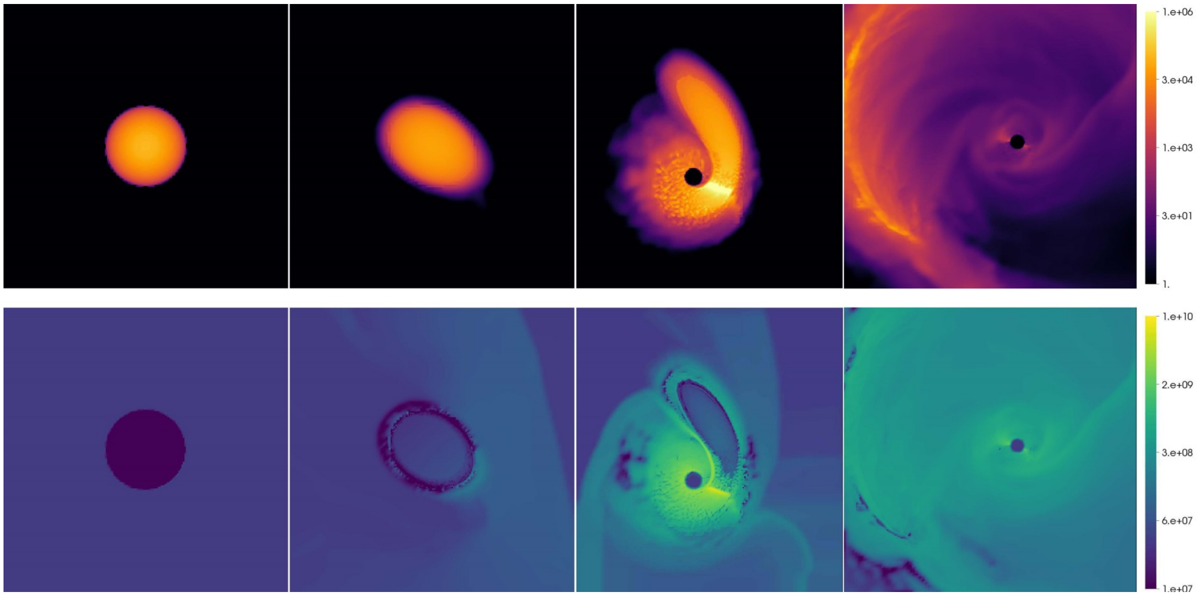

Figure 1: Plot of the mass density (top) and temperature (bottom) at four different times from a computer simulation of a white dwarf being tidally disrupted by a 1,000 solar mass black hole.

Figure 2: Artist's impression of an X-ray burst on the surface of a neutron star that is beginning to impact the surrounding accretion flow. Image Credit: NASA/Dana Berry.

Notes and References

**Corresponding author email: fragilep@cofc.edu*

[1] Anninos, P., Fragile, P. C., Olivier, S. S., Hoffman, R., Mishra, B., & Camarda, K., "Relativistic Tidal Disruption and Nuclear Ignition of White Dwarf Stars by Intermediate-mass Black Holes", ApJ, 865, 3, (September, 2018).

[2] Anninos, P., Hoffman, R. D., Grewal, M., Lavell, M. J., & Fragile, P. C., "Nuclear Ignition of White Dwarf Stars by Relativistic Encounters with Rotating Intermediate Mass Black Holes", ApJ, 885, 136,(November, 2019).

[3] Fragile, P. C., Gillespie, A., Monahan, T., Rodriguez, M., & Anninos, P., "Numerical Simulations of Optically Thick Accretion onto a Black Hole. I. Spherical Case", ApJS, 201, 9, (August, 2012).

[4] Fragile, P. C., Olejar, A., & Anninos, P., "Numerical simulations of optically thick accretion onto a black hole - II. Rotating flow", ApJ, 796, 22, (November, 2014).

[5] Fragile, P. C., Ballantyne, D. R., Maccarone, T. J., & Witry, J. W. L., "Simulating the Collapse of a Thick Accretion Disk due to a Type I X-Ray Burst from a Neutron Star", ApJL, 867, L28, (November, 2018).

[6] Fragile, P. C., Nemergut, D., Shaw, P. L., & Anninos, P., "Divergence-free magnetohydrodynamics on conformally moving, adaptive meshes using a vector potential method", JCPX, 2, 100020, (March, 2019).

[7] Fragile, P. C., Ballantyne, D. R., & Blankenship, A., "Interactions of type I X-ray bursts with thin accretion disks", Nat. Astr., 4, 541-546, (January, 2020).