I. Project Title

Unbreakable Black Holes Show the Solidity of Spacetime

II. Abstract

As a physics undergraduate, I have been fortunate enough to be awarded two Bill Frost summer research grants to conduct hands on research in the field of physics. My chosen topic of research is interdisciplinary in nature, spanning the topics of general relativity and fluid dynamics with possible future applications to black hole astrophysics. I study a system called a black string, which is essentially a stack (or string) of black holes that extend beyond our observed universe. This topic is not only elegant and exciting, but also extremely important, being related to cosmic censorship, which is one of the most important unsolved conjectures in general relativity. I began by investigating the beautiful and mesmerizing shape and iterative pattern formed by black strings and found that, contrary to recent publications, a disturbed black string will not break, and is in fact strong and stable, behaving like a viscoelastic fluid. A non-breaking string implies that the singularity inside it will not be exposed, which upholds the long held hypothesis of cosmic censorship. I presented this breakthrough discovery at the 2017 CSU Student Research Competition where it won a 2nd place prize. It is now time to bring this discovery to the premier physics publication journal, Physical Review Letters (PRL) and extend my findings to more general systems with the hopes of a second publication. The continuation of my research investigates more subtle features of the black string system where I use Newtonian calculations to conserve energy and gravitational tension.

III. Introduction

A black hole is a region of space with gravity so strong that nothing that falls inside can escape, not even light. The black hole surface (the event horizon) is the edge of no return. This horizon is what shields us from a mystery residing at its center: a singularity of infinite space-time curvature. For decades, specialists in general relativity have hypothesized that nowhere in our universe will such a singularity be exposed. This long-held conjecture has been named cosmic censorship: it is the idea that the event horizon prevents the singularity from ever being exposed, and that the horizon will continue to keep us protected from the physical singularity for all time.

Determining if cosmic censorship can ever be violated is one of the most important unsolved problems in general relativity. To investigate this, gravitational theorists are intensely interested in black strings. A black string is a cylindrical stack of black holes that extends in an extra spatial dimension. When long and thin enough, black strings have a known instability\(^1\) under which they evolve into exotic shapes. A recent breakthrough study\(^2\) numerically evolved a black string's shape and proposed that the string would shrink to zero radius, thus disproving cosmic censorship. By applying the fluid-like behavior of black strings, I uncovered strong evidence that the black string in the recent study\(^2\) may not break, and cosmic censorship is in fact upheld, rather than disproved.
This award-winning insight came through modeling the complex black string system as a simple viscoelastic fluid and applying a fluid’s iterative shape pattern to the black string. It is often useful to model a complex object, such as a black hole or a black string, by studying a simpler counterpart. Luckily, a deep and interesting connection is known between black holes and fluids: both objects exhibit surface tension in their energy conservation laws and thus behave in similar ways\(^1\). Introducing this connection spans multiple disciplines of physics, thereby making it even more intriguing to specialists of all kinds. Although from two completely different disciplines, Figures 1 and 2 show the strikingly similar shape evolution of both the fluid (1) and black string (2) systems.

![Figure 1. Laboratory evolution of a viscoelastic fluid cylinder.](image)

![Figure 2. Numerical evolution of a black string.](image)

Time increases to the right.

There are many current examples of cutting-edge general relativity papers\(^4,5\) citing the results from the numerical evolution of Figure 2. In fact, with this seeming cascade of papers claiming a still disputed result, it is of paramount importance to share our results with the physics community. Since all the papers in this field are being published in Physical Review Letters (PRL), we need to step into the arena already being used to display this type of work.

I used my second Bill Frost summer research grant to deepen and continue my work above. I started to refine a conservation model that I had developed, for energy and gravitational tension, to predict the shapes of the unique "beads-on-strings" structure formed by black strings. The goal is an analytical understanding of the known numerical data\(^2\), to determine if black strings of any initial size will stabilize and preserve cosmic censorship, and to submit this as a second PRL publication.

IV. **Objective(s)**

2. Continue my new and promising spin-off research, which investigates conservation of energy and gravitational tension in the black string system. I hope to have a second manuscript ready for publication by May 2018.

V. **Methodology**

I previously found that the simplest conservation model worked well in one direction (numerical values input into an analytical formula) while in the other direction, it was extremely sensitive to the black string’s shape parameters. So I will augment the setup by calculating the gravitational interactions among the thin "string" segments and the black hole "beads". This adds to the black holes’ known Newtonian interactions. We can use Newtonian approximations for the black holes and the black string threads, because they are small compared to their separations.
The next step is to incorporate our results for these interaction energies into the black string's energy conservation, to see if this resolves the sensitivity that I uncovered within the conservation of energy and gravitational tension as the black string evolves. The interactions we calculate potentially open a new frontier in black hole physics, because they describe how an extended "lumpy" black horizon physically interacts with itself, which has never explicitly been done before.

VI. Timeline
I will be finalizing my first manuscript for publication in early December 2017 and I hope to have it submitted for publication near the end of 2017. December will also be spent performing a literature search for any recent developments in related work.

In January 2018, I will continue my research of self-interacting black strings. Because this method is entirely new, these calculations may be extremely sensitive and may take approximately three to four months to complete. January and February will be spent refining the conservation of energy model for the first generation in the black string evolution. Optimistically, if we can complete conservation of energy, we hope to then develop including conservation of gravitational tension throughout March 2018. During April 2018, we will attempt to push our conservation model to the second and third generations of evolution while beginning our second manuscript for publication. By the beginning of May 2018, we hope to be ready for our second PRL publication submission.

VII. Final Products and Dissemination
The proposed final products are a PRL publication containing the exciting result of non-breaking black strings, which saved the cosmic censorship hypothesis in the first case tested. In addition, a secondary publication in PRL on the Newtonian interaction of black holes and black string segments is desired. This ongoing research project has been the single most important contribution to my growth and success as an evolving physics student, and will undoubtedly help me step into the role of a physics graduate student, and eventually a respected member of the physics community.

VIII. Budget Justification
As explained in the Introduction, it is of utmost importance to submit our work to the premier journal of physics, PRL, which charges $765 per publication, and we anticipate two of them. With so many new gravitational papers being published in PRL, we need our work to have the strong voice it deserves by being published side by side with other profound and cutting-edge ideas. In order to influence the way the community is thinking, we must be part of the leading journal.

Appendix: Bibliography

## PROPOSAL BUDGET

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