Gamma-ray Bursts in Inhomogeneous Interstellar Media

Note: Much of the work for this project has already been completed as part of the senior thesis requirement for the Department of Physics and Astronomy.

Objective

I intend to use computational relativistic hydrodynamics to study variations in the luminosity of a gamma-ray burst when the relativistic blast wave expands into a non-homogeneous environment.

Introduction and Background

As they age and burn their fuel, extremely massive stars enter a supergiant phase where a combination of low surface gravity and high thermal pressure blows off the outer layers of their atmospheres. By the time a star finally goes supernova, this matter has collected into a shell of a few solar masses that can sit anywhere from 10^{-5} to 100 pc away from the star.[1]

Most current models suggest that these kinds of massive stars are the most likely progenitors for the long gamma-ray bursts (GRB) observed by astronomers. As the star dies, it collapses into a black hole, and the remaining matter collects into an accretion disk that powers relativistic jets emitted along the poles of the black hole. These jets release massive amounts of electromagnetic (EM) radiation, particularly gamma rays.[2] Despite the conceptual elegance of this model and some strong observational evidence to support it, however, the emission profiles of long GRBs are highly variable, and no single model for GRB emission mechanisms can fully explain the source of this variation.[3]

A natural question is what happens when the relativistic jet collides with the matter expelled by the star. If fluctuations in the EM signature during the collision are observed, this may explain some of the measured variation in GRB profiles. Additionally, these collisions may also serve as a measurement tool to determine the location of the star's hydrogen envelope and launch "reverse shocks," or shock waves that propagate backward toward the source of emission, which may help further explain some of the astronomical variations of GRBs.

Methodology

We have developed a code for solving the relativistic hydrodynamics equations based on work previously performed by my advisor, Dr. Neilsen, and his collaborators.[4] Using the Blandford-McKee similarity solution,[5] we will simulate the relativistic jet that produces a GRB with an isotropic spherical blast wave, similar to the one-dimensional setup used by De Colle et al.[6] The hydrogen envelope generated at the end of the life of our model star will be represented by a circumstellar shell of five solar masses at a fixed distance, varied over thickness and density.

Data from the simulations will be processed using a utility I have written to find the moment where the collision occurs, select several evenly spaced frames before and after, and determine the energy and speed of the blast wave. We are also able to calculate the total energy deposited in the shell. By using the coupling time between electrons and ions, we will determine how much of that energy is emitted as thermal radiation (which arises from collisions between electrons and ions) and nonthermal radiation (due to electrons being accelerated). Finally, we can predict the observed image by measuring how much could be detected far away from the star using a prescription similar to that described by De Colle et al.[6]

Preliminary Work

Since I began working on this project in January 2018, I have completed a substantial amount of work on our group's hydrodynamics code, including a solver for a new equation of state, a new set of initial conditions, a great deal of debugging, and extensive testing to confirm the code's stability and the validity of its results. I have also spent a large amount of time writing utilities to process and format the data for the final analysis, which will be performed by our collaborators at Los Alamos National Laboratory.

Investigator Qualifications

I have completed all the coursework necessary for a physics major and a math minor, I expect to finish a minor in computer science in December, and I have taken graduate-level coursework on numerical methods for linear algebra and partial differential equations. Additionally, I have been working as a research assistant for Dr. Neilsen for more than a year and a half. During this time, I have gained a great deal of experience in computational fluid dynamics and learned much about relativistic astrophysics. I have presented on my work at the APS Four Corners Section Meeting, the Pacific Coast Gravity Meeting, and the CPMS Student Research Conference.

Committee Qualifications:

My thesis committee will consist of Dr. David Neilsen as the faculty advisor, Dr. Eric Hirschmann as the faculty reader, and Dr. John Colton as the interim Honors Coordinator for the physics department. Both Dr. Neilsen and Dr. Hirschmann are highly experienced theoretical physicists in the field of relativistic astrophysics. Over the course of their careers, they have developed numerous codes for simulating relativistic fluids (such as GRBs and neutron stars) and solving the Einstein equations of general relativity. The core of the fluid solver used by this project was written largely by them.

Schedule

September 2019

- Debug simulation and initial conditions
- Validate simulation against analytical models (where applicable)

September – October 2019

- Perform production runs for simulation

October – November 2019

- Perform data analysis
- Present preliminary results at APS Four Corners Section Meeting

November – December 2019

- Write preliminary draft of paper

January – March 2019

- Write and polish honors thesis
- Present results at CPMS Student Research Conference

Culminating Experience

As expressed in the timeline for this project, I will present on this work at two conferences, the APS Four Corners Section Meeting in October and the CPMS Student Research

Conference in March. I also expect that our research group will publish our results in a peer-reviewed journal, likely either *The Astrophysical Journal* or *Monthly Notices of the Royal Astronomical Society*. The manuscript of this paper will serve as the foundation of my honors thesis.

Funding

All necessary funding for this project has already been obtained. No additional funding from the Honors Program or other sources will be required.

References

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[3]B.E. Stern and J. Poutanen, Mon. Not. R. Astron. Soc. **352**, 3, L35 (2004)

[4]J. DeBuhr, B. Zhang, M. Anderson, D. Neilsen, E. Hirschmann, T. Grenga, and S. Paolucci, Astrophys. J. **867**, 112 (2018), <https://doi.org/10.3847/1538-4357/aae5f9>

[5]R.D. Blandford and C. F. McKee, Phys. Fluids, **19**, 1130 (1976), <https://doi.org/10.1063/1.861619>

[6]F. De Colle, J. Granot, D. López-Cámara, and E. Ramirez-Ruiz, Astrophys. J. **746**, 122 (2012), <https://doi.org/10.1088/0004-637X/746/2/122>