Visualizing magnetic field structure in 3D blast waves

Introduction

This report explores the formation of a dense shell of gas from a shockwave blast explosion, building off theoretical work by Ferriere et al. 1991. The project focuses on visualization of the gas expansion in 3 dimensions to understand magnetic field evolution. The results of this project can help analyze and better understand stellar explosions and their impact on interstellar gas.

Methods

The equation for the radius of a spherical shock wave,

$$R = S(\gamma)t^{2/5}E^{1/5}\rho_0^{-1/5}$$

(where R is the radius, $S(\gamma)$ is a function of γ, γ is the ratio of the specific heats of air, t is time, E is the energy released, and ρ_0 is the atmospheric density), as presented in Taylor 1950, was first graphed and analyzed (Figures 1 and 2). Existing code containing data of gas velocities and densities from a shockwave blast and its 2D visualization was also analyzed to understand the visualization process (Figures 3 and 4).

Various packages in the matplotlib library were used to create a 3D visualization of the gas density and velocity and magnetic field lines. The voxel function was used to plot the gas density throughout the spherical shockwave. The entire shell was plotted before deciding to plot an octet of the shell, making the transparency gradient corresponding to gas density visible (Figures 5 and 6). Then, the vector field was plotted using the quiver function (Figure 7).

The bulk of this project focused on writing a suitable streamline function to predict the bend of magnetic field lines from the gas velocity vector field. The function was written using interpolation and numerical integration techniques with the initial version relying on Euler's method. The integrator was made more accurate using a second order Runge-Kutta method. The final, optimized version of the integrator used an area conserving 1/3 step size by alternating corrections to each of the x, y, and z directions to compensate for overestimation. The accuracy of each integrator was tested by analyzing its ability to plot a helix from an elliptical vector field with the same step size and number of iterations (Figure 8).

The finalized streamline function was then implemented with an arbitrary set of sampling points.

Results

This section presents the various representations produced of the spherical shock wave blast data.

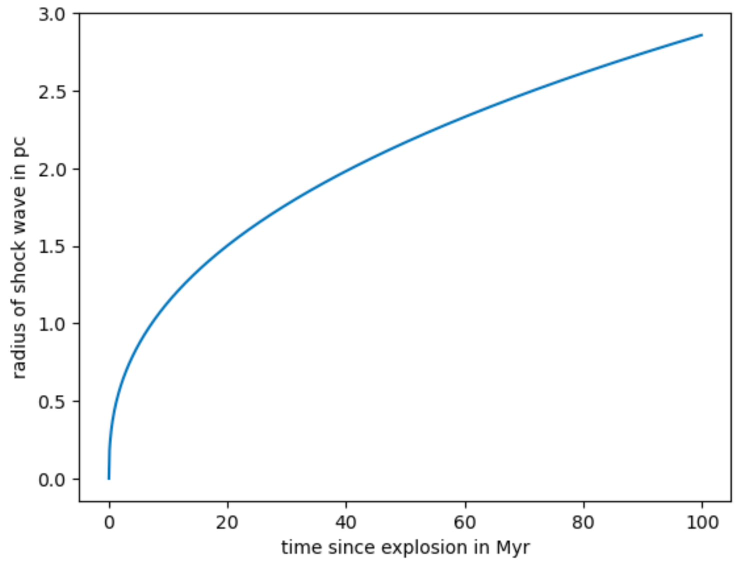

Figure 1. Time versus radius of shock wave.

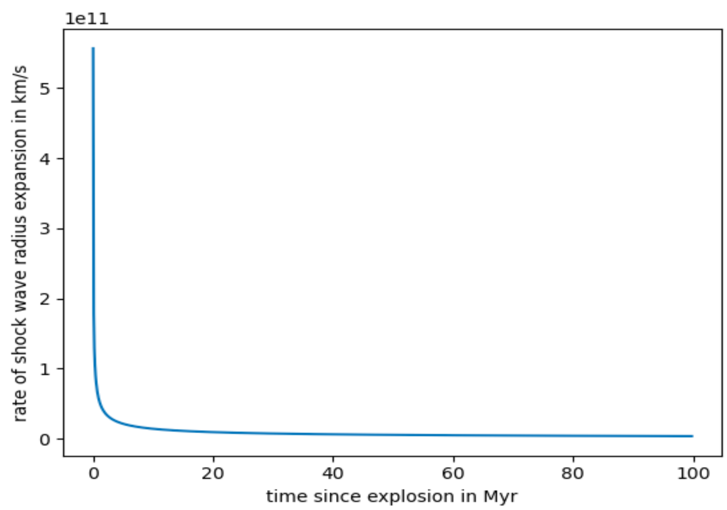

Figure 2. Time versus rate of shock wave radius expansion.

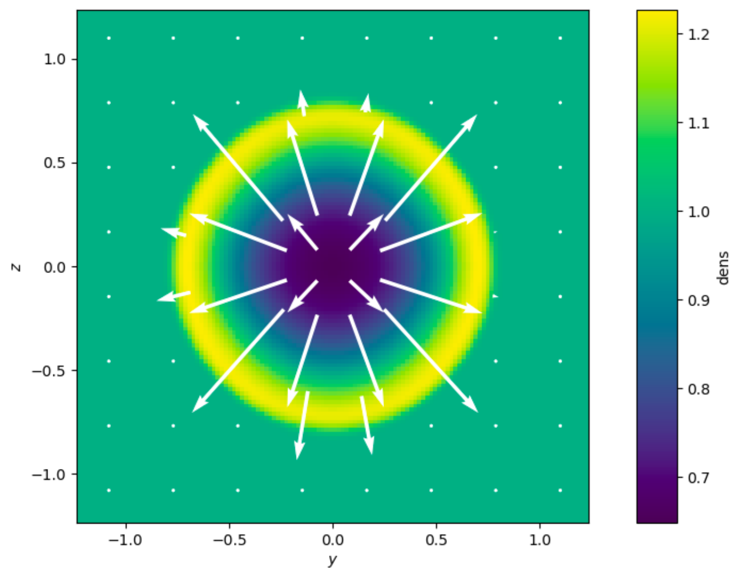

Figure 3. Velocity vectors of gas expansion.

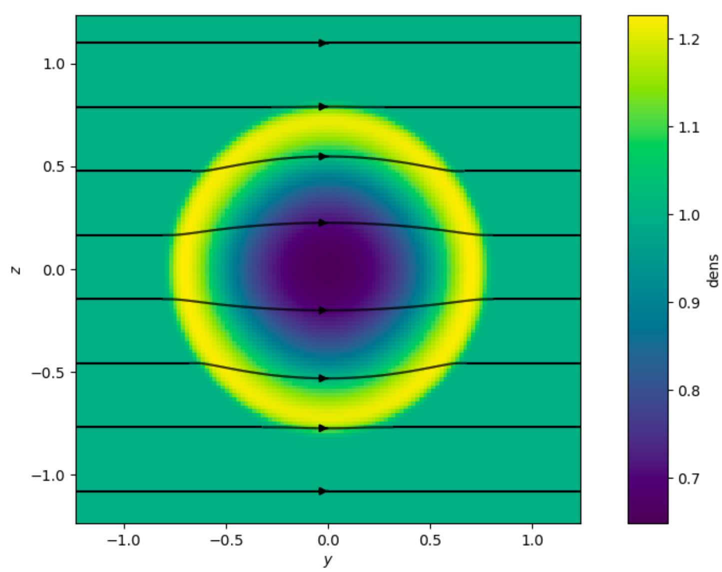

Figure 4. Magnetic field lines bending around spherical shock wave.

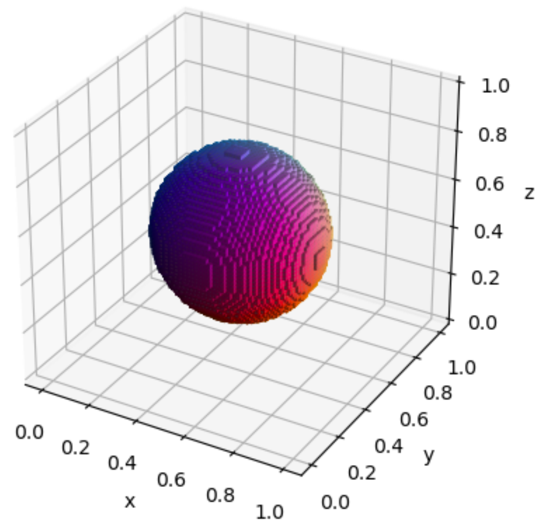

Figure 5. Outer surface of spherical shock wave.

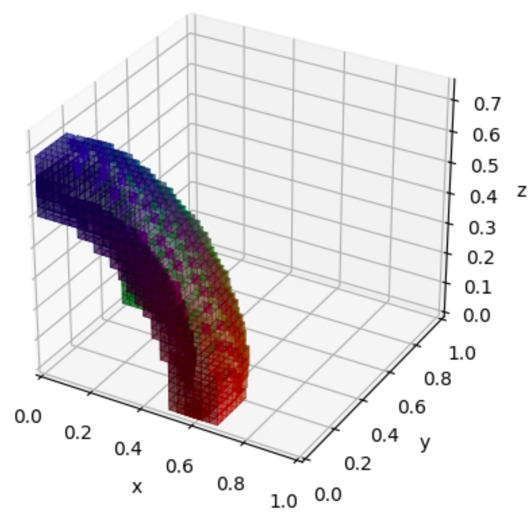

Figure 6. Octet of spherical shock wave with gas density transparency gradient.

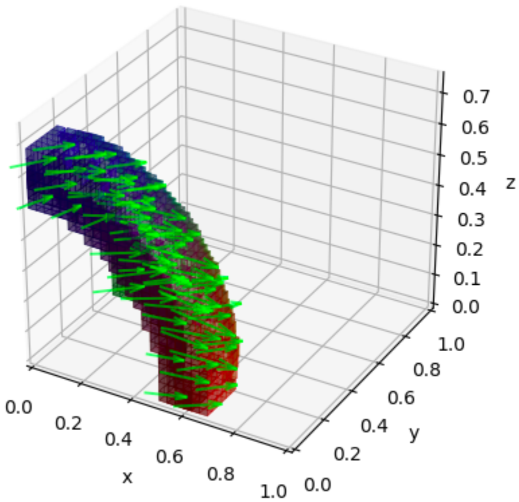

Figure 7. Gas density gradient with gas velocity vectors.

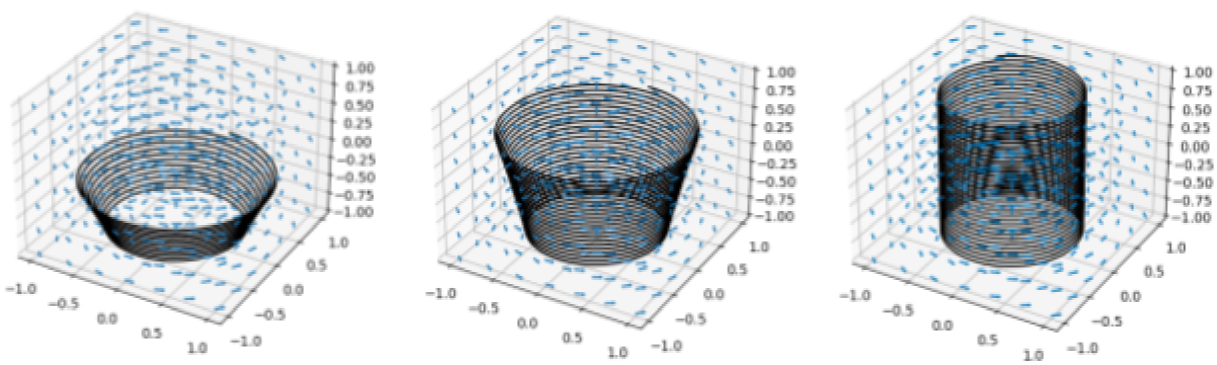

Figure 8. From left to right: Euler's method, R-K method 2nd order, optimized integrator.

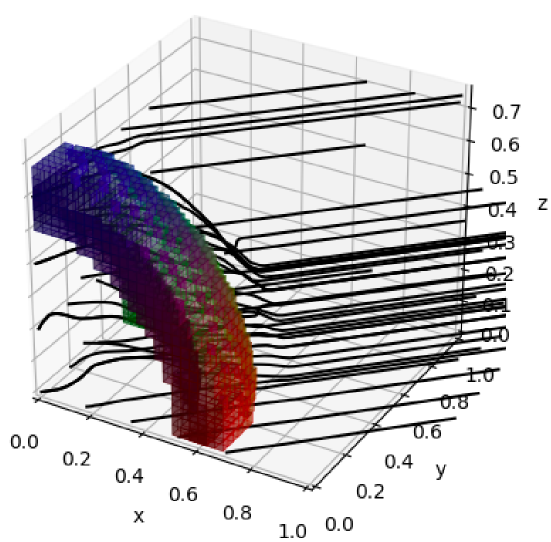

Figure 9. Gas density gradient with magnetic field lines.

Discussion and Conclusion

The results of this project matched the expectations almost entirely, successfully modeling the bending in magnetic field lines due to a spherical shock wave blast in 3 dimensions. However, serious computational limits due to the processor being used were apparent and required the resolution of the plots to be reduced for the program to run. The interactive nature of matplotlib's 3 dimensional graphing also required more computational power. Moving forward, it will be necessary to refine the presentation of the streamlines. Doing so will require determining optimal sampling points, improving the resolution of the graph, and experimenting with the color coding of the streamlines and the transparency gradient of the gas density.

References

Ferriere et al. (1991, ApJ, 375, 239)

Shu (1992, The Physics of Astrophysics II, Chapter 17)

Taylor (1950, Proc Roy. Soc. A, 1065, 159)