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Annual Progress Report for NASA Astrophysics Theory Program Grant NAG 5-3099:

A Systematic Study of Explosions in Core Collapse Supernovae

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1 Summary

This report covers the research conducted from September 1996 to August 1997 (eighteen months into the three year grant). We have obtained a number of significant findings based on the on the work that we have conducted under this grant during the past year. As we stated in our original proposal the work has focused on multi-dimensional models of the convective epoch in core collapse supernovae. During the past year we have developed a large number of models of the convective epoch in 2-D under two levels of neutrino transport approximation and we are currently working on 3-D models. In the following pages will endeavor to give brief descriptions of our results.

2 Gray Supernova Models

Using the SNZEUS code described during our last progress report and in the original proposal we have carried out a number of models of the convective epoch of a core collapse supernova using the gray approximation to radiation transport. This approximation has been almost exclusively used in 2-D models of the convective epoch. The models assume a spectral distribution of neutrinos that is in thermal and chemical equilibrium in the interior and that is decoupled in the exterior regions of the supernova. As part of our original proposal we have employed this approximation in an effort to understand how it's use affects the outcome of the numerical models. One of the aspects of the use of this approximation in the supernova problem is that one needs to choose some ad hoc point at which the neutrinos decouple from the matter. This choice has typically been taken to be at either a fixed optical depth or when the mean free path of the neutrinos exceeds some criterion. In either case the choice is a free parameter in the models. What we were able to find is that the outcome of the models is critically sensitive to the choice of this parameter. Not only were the neutrino luminosities altered by over an order of magnitude when the decoupling point was varied over a "reasonable" range, but the dynamics of the model were too. An example of this is provided in the attached figures where we exhibit the entropy (figs. 1a-1c) and the electron fractions (figs. 2a-2c) at the same time from a series of three models. The decoupling depth was varied slightly among the three models. Looking at the figures one can see that the overall evolution of the models shows a strong response to these variations. Unfortunately, this implies that the models have little predictive power. While one can arbitrarily force the neutrino spectral distribution in the exterior regions to have a particular value that results in the model's explosion, we would like to have a theory that does not require tuning. This work has been submitted to the Astrophysical Journal for publication.

3 Possible Low Entropy r-process Mechanism

An intriguing result that we have found from our gray models of the convective epoch is that at no point does the entropy exceed 15 (in units of Boltzmann's constant). This agrees with other researchers in this area (Burrows et al., Janka et al., and Mezzacappa et al.) who have found similar results in 2-D models. This result can be contrasted with the often cited results of Wilson et al. who claim to see entropies of several hundred. Much work has been carried out by a number of researchers who claim that such entropies are necessary in order for the r-process to occur in supernovae. The fact that the 2-D models have not achieved such high entropies has been a puzzle for several years now and researchers have resorted to more and more complicated attempts to produce such entropies theoretically. However, the need for high entropies in order to cause the r-process is based on the assumption that the electron fraction of the material is near 1/2. As startling result that we have seen recently in several of our models is that very low electron fraction material from near the surface of the proto-neutron star can be advected up in a rapid manner and driven out by the explosion. The rise of the neutron rich material is rapid enough that the combined electron neutrino and electron anti-neutrino fluxes are unable to establish kinetic equilibrium in the material and the material escapes with electron fractions of $Y_e \sim 0.2 - 0.3$. This material might be able to achieve the appropriate conditions for the r-process to occur as it is driven out and the density drops. Similar mechanisms have been proposed for material ejected out of neutron stars. We are now carrying out multigroup simulations in order to ascertain if this phenomena will remain present as the transport algorithm is improved. This work will be submitted to the Astrophysical Journal in the near future.

4 Multigroup Supernova Models

As we originally proposed we have been increasing the quality of the neutrino transport algorithm in an effort to uncover the effects of various approximations on the models. The next logical step after the gray approximation is to explicitly models the properties of the spectrum by the use of multigroup transport. In such models a monochromatic transport equation is solved for a series of discrete energy "groups", hence the assumption of a particular spectral distribution is avoided. We have developed a 2-D multigroup radiation hydrodynamics code which we call V2D. Using V2D we have been carrying out 2-D models of the convective epoch and comparing them to the gray approximation models discussed a few paragraphs earlier. We have found large differences in the way the spectrum develops throughout the collapsed core that have major effects on the neutrino heating rate. We are also examining models to uncover whether the r-process mechanism discussed earlier can occur. This work on multigroup models is not yet complete and will continue over the next year to include a study of EOS effects and a study of how the progenitor masses affect the explosion. When complete it will be submitted to the Astrophysical Journal

5 Numerical Eulerian Instabilities

In both the gray and multigroup supernova models we have carried out over the past year we have uncovered an numerical instability that exists when one employs Eulerian radiation hydrodynamic codes to study the evolution of the proto-neutron star as well as the convection region. A simple explanation of this instability is as follows: Deep within the core the electron-capture rate is extremely large mainly due to the high Fermi energies of the electron and neutrinos. As advection of material from one Eulerian cell to another occurs over the course of a hydrodynamic timestep the material is driven far out of weak equilibrium. As a result when the radiation transport step of the calculation is begun the rate is so far out of equilibrium that the evolution becomes unstable. This instability grows and eventually crashes the calculation. In theory, the timestep for this reactive flow should be determined by the reaction rate. However this is so miniscule that a supernova simulation could never be completed. We have been able to determine an acceptable resolution to this problem by artificially scaling the electron capture rate to become more comparable to the hydrodynamic timescales. Since the function of electron capture in the core is to maintain beta-equilibrium over the neutrino diffusion timescales of several seconds this method works well. This work is being prepared for submission to the ApJ.

6 Dynamic Diffusion and the Relativistic Moment Equations

We have recently been working on the correct formulation of the mixed frame radiation moment equations. In the classical $\bigcirc(v/c)$ mixed frame radiation–energy equation a dynamic diffusion term appears that describes the advection of radiation by matter. In the optically thick or dynamic diffusion limit this term correctly models the behavior of neutrinos being advected along with matter. However, we have found that this term gives incorrect results when applied to the transport of neutrinos in the optically thin regions of the supernova. The breakdown emerges because the approximation of $v/c \ll 1$ is bad in the outer region where the matter is infalling. In this region the dynamic diffusion term causes the infalling matter (which is optically transparent to the neutrinos) to exert a inward dragging effect on the neutrinos slowing their passage through the star. In the gray and multigroup models described above we avoid this problem by manually turning off the term in the optically thin regions. We are currently working on the correct special relativistic formulation of the mixed-frame moment equations in spherical coordinates which will correct this affect as well as accurately describe the doppler shift effects in this situation.

7 Radiation Transport Algorithms

Together with applied mathematicians P. Saylor and D. Smolarksi we have found a method of efficiently solving the multigroup radiation energy equation that allows us to implement radiation transport on parallel computers. This will not only have a profound affect on the work we are doing but on other radiation transport problems in astrophysics as well. For us, this opens the door to 3-D simulations including radiation transport. The method relies on the construction of approximate inverses to the matrices arising from the finite differences of the radiation moment equations. Different aspects of the work are being written up for submission to ApJ and JCP.

8 Publications & Papers Presented

1. "On the Use of the Gray Approximation in 2-D Supernova Models" *submitted to The Astrophysical Journal*

2. "2-D Radiation–Hydrodynamic Models of Convection in Core Collapse Supernovae: Sensitivity to the Gray Approximation for Neutrino Transport" *presented at the Texas Symposium on Relativistic Astrophysics*

3. "Multi-dimensional Gray & Multigroup Radiation–Hydrodynamic Models of Convection in Core Collapse Supernovae" *presented at the Winston-Salem AAS Meeting*

4. "Multigroup Radiation-Hydrodynamic 2–D simulations of Convection in Supernovae" *In preparation for the Astrophysical Journal*

5. "Numerical Instabilities in Dense Matter Radiation Hydrodynamic Calculations" *In preparation for the Astrophysical Journal*

6. "A Parallel Radiation Transport Method" *In preparation for the Astrophysical Journal*

7. "Approximate Inverse Preconditioners for the Radiation Moment Equations" *In preparation for the Journal of Computational Physics*

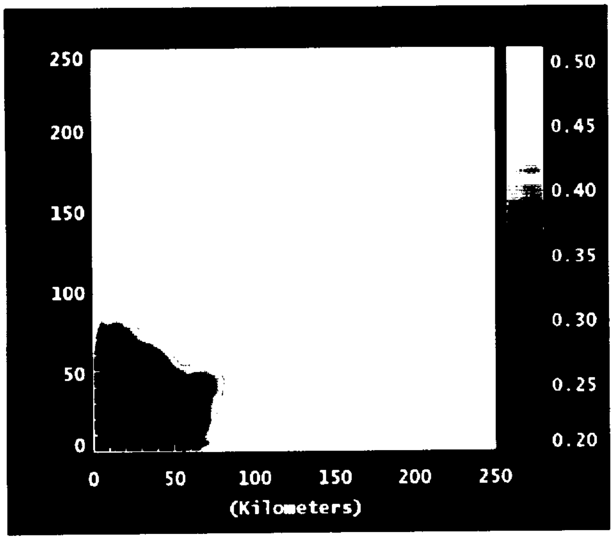


Figure 1a

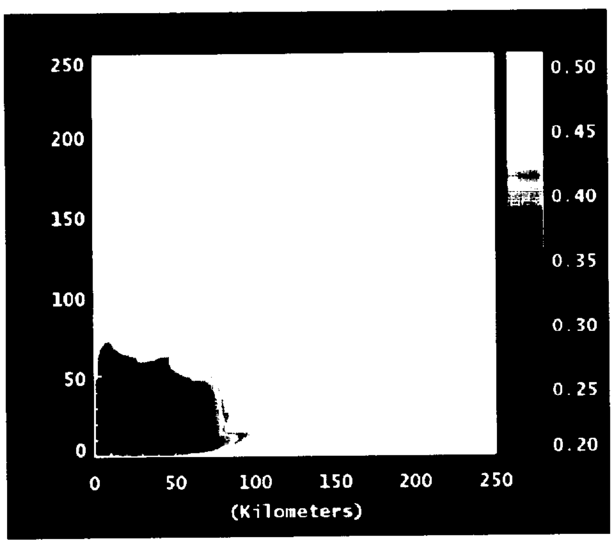


Figure 1b

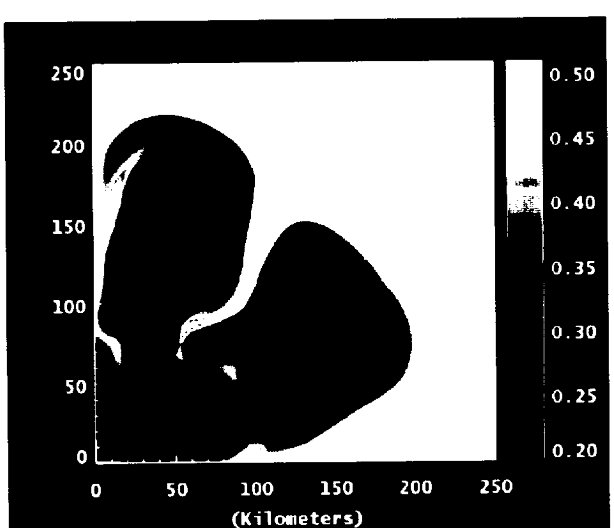


Figure 1c

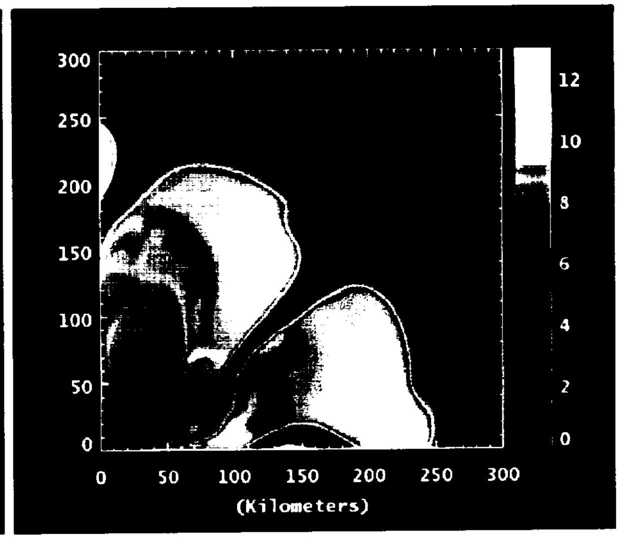
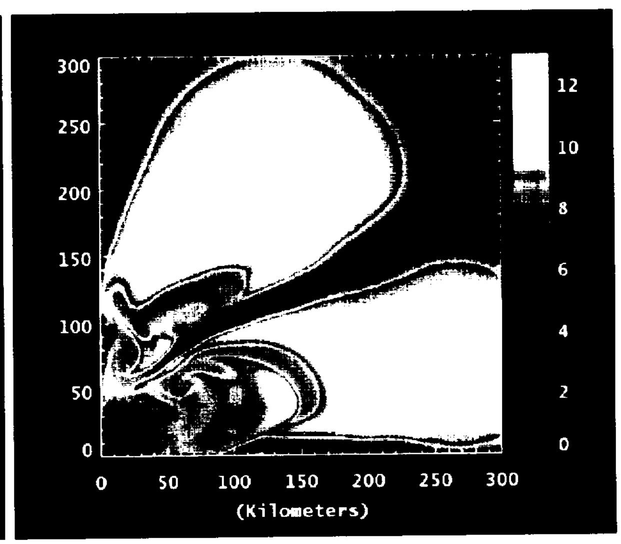


Figure 2a



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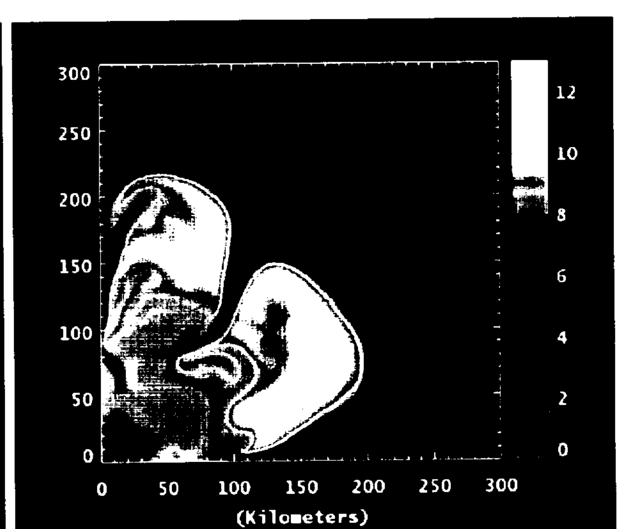

Figure 2c