THE STATUS OF CORE-COLLAPSE SUPERNOVA SIMULATIONS

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Core-collapse supernovae can be used to place limits on dark matter candidate particles, but the strength of these limits depends on the depth of our theoretical understanding of these astrophysical events. To date, limitations on computing power have prevented inclusion of all the physics that would constitute a realistic simulation. The TeraScale Supernova Initiative (TSI) will overcome these obstacles in the next few years, elucidating the explosion mechanism and other phenomena closely associated with the core collapse of massive stars.

1. What are supernovae?
The term “supernova” dates from the early 1930s, but the concept was around in the 1920s. With the realization that the spiral nebulae are separate galaxies comparable to our Milky Way, it was recognized that the “novae” or “new stars” seen in these nebulae would have to be much more luminous than typical novae occurring in our galaxy. The phrases “giant novae”, novae of “impossibly great absolute magnitudes”, “exceptional novae”, and the German term “Hauptnovae” or “chief novae” were used during the 1920s. In a review article Zwicky explained that it was deduced that “supernovae” were about a thousand times as luminous as “common novae”, and claimed that “Baade and I first introduced the term ’super-
Supernovae are classified by astronomers into two broad classes based on their spectra. These classes are “Type I”, which have no hydrogen features, and “Type II”, which have obvious hydrogen features. These types have further subcategories, depending on the presence or absence of silicon and helium features in Type I, and the presence or absence of narrow hydrogen features in the case of Type II. In particular, supernovae of Type Ia exhibit strong silicon lines, those of Type Ib have helium lines, and those of Type Ic do not have either of these. Astronomers have also identified a number of distinct characteristics in supernova light curves (total luminosity as a function of time).

There are two basic physical mechanisms for supernovae, but these do not line up cleanly with the observational categories of Type I and Type II. Type Ia supernovae are caused by accretion of matter from a companion star onto a white dwarf, which induces a thermonuclear runaway that consumes the entire white dwarf. Supernovae of Type Ib, Ic, and II are produced by a totally different mechanism: the catastrophic collapse of the core of a massive star. The observational distinctions of presence or absence of hydrogen or helium turn out to be unrelated to the mechanism; they depend on whether the outer hydrogen and helium layers of the star, which have nothing to do with the collapsing core, have been lost to winds or accretion onto a companion during stellar evolution. Of the two physical mechanisms, core-collapse supernovae are the focus of the present discussion.

For most of their existence stars burn hydrogen into helium. In massive stars, temperatures and densities become sufficiently high to burn to carbon, oxygen, neon, magnesium, and silicon and iron group elements. The iron group nuclei are the most tightly bound, and here burning in the core ceases. The iron core—supported by electron degeneracy pressure—eventually becomes unstable. Its inner portion undergoes homologous collapse (velocity proportional to radius), and the outer portion collapses supersonically. Electron capture on nuclei is one instability leading to collapse, and this process continues throughout collapse, releasing free-streaming neutrinos until densities and temperatures become so high that even neutrinos are trapped. Collapse is halted when the matter reaches nuclear density; at this point a shock wave forms at the boundary between the homologous and supersonically collapsing regions. The shock begins to move out, and after the shock passes some distance beyond the surface of the newly born neutron star, it stalls as energy is lost to neutrino emission.
and dissociation of infalling heavy nuclei falling through the shock.

The nascent neutron star is a hot thermal bath of dense nuclear matter, electron/positron pairs, photons, and neutrinos, containing most of the gravitational potential energy released during core collapse. Neutrinos, having the weakest interactions, are the most efficient means of cooling; they diffuse outward on a time scale of seconds towards a semi-transparent region near the surface of the neutron star, and eventually escape with about 99% of the released gravitational energy.

In the reigning paradigm—the neutrino-driven explosion mechanism\(^4\)—the supernova explosion is launched as a result of neutrino heating of the material behind the stalled shock, resulting in the revival of the shock and its propulsion through the outer layers of the star. This process may be aided by convection in two regions. First, loss of electron neutrinos from the outer layers of the neutron star causes composition gradients that drive convection, which boosts neutrino luminosities by bringing hotter material to the surface. Second, heating decreases away from the neutron star surface, giving rise to a negative entropy gradient. The resulting convection increases the efficiency of neutrino heating by delivering heated material to the region just behind the shock.

As the neutrinos are transported from inside the neutron star, they go from a nearly isotropic diffusive regime to a strongly forward-peaked free-streaming region. Modeling this process accurately requires tracking both the energy and angle dependence of the neutrino distribution functions.

### 2. Survey of core-collapse simulations

Supernovae have a rich phenomenology—observations of many types that modelers would like to reproduce and explain. Chief among these is the explosion itself, which is not produced robustly and convincingly in simulations. As mentioned previously, 99% of the gravitational potential energy released during collapse escapes as neutrinos; in comparison, the kinetic energy of expelled matter accounts for about 1%, and the optical display is just a fraction of this. Energetically, supernovae are essentially neutrino events; the explosion is just a minor sideshow, the optical display a trivial detail. That the explosion is such a minor part of the system is what makes it so challenging to model convincingly. But the optical data are what we perceive with our unaided inborn detectors—our eyes—and in our anthropic chauvinism, explaining the explosion seems most interesting.

While the explosion is of obvious interest, neutrino signatures are also
of great importance. The handful of neutrinos detected from supernova SN1987A confirmed theoretical predictions of neutrinos releasing the gravitational energy on a time scale of seconds. This was a remarkable success of supernova theory and modeling. The neutrinos are also important because their detection allows limits to be placed on dark matter candidates, such as axions and sterile neutrinos.

There are many other interesting observables, including pulsar spins, kick velocities, and magnetic fields; gravitational waves; element abundances; and all kinds of measurements across the electromagnetic spectrum. Core-collapse simulations—the subject of the present discussion—typically address the explosion mechanism, neutrino signatures, remnant pulsar properties, and gravitational waves. Another class of simulation—not discussed here—assumes a successful explosion and studies the interaction of the shock with the surrounding layers of the star (and beyond) in order to study things like nucleosynthesis and measurements across the electromagnetic spectrum.

From the description of the core-collapse supernova process in the previous section, several key aspects of physics that a simulation must address can be identified:

**Neutrino transport/interactions:** Because neutrinos dominate the system, their treatment is very important, including the number of spatial dimensions treated; dependence on both energy and angle in order to properly model the transition from isotropic diffusion to forward-peaked free streaming; relativistic effects; and comprehensiveness of interactions.

**Hydrodynamics/gravitation:** Convection—both inside and outside the nascent neutron star—can play an important role, so allowance for flows in multiple spatial dimensions is important in the hydrodynamics. The newly born neutron is sufficiently compact that a general relativistic description should ultimately be included.

**Equation of state/composition:** Determination of realistic equations of state of dense nuclear matter at finite temperature involves cutting-edge nuclear physics, as does the determination of neutrino interaction rates with the variety of nuclear species encountered in the supernova environment.

**Diagnostics:** Very important to making convincing explosions is fastidious accounting of total lepton number and energy. Because the explosion energy is only 1% of the basic energy scale in the problem, a determination of the explosion energy accurate to 10% requires that total energy be conserved at a level of about one part in $10^8$ per time step (allowing for systematic error accrual over $\sim 10^8$ time steps).
Simulations of collapse and bounce have been performed by many groups. In briefly describing this work, I list (in alphabetical order) the institutions that represent the “centers of gravity” of many of these groups:

**Livermore National Laboratory:** The neutrino transport in these simulations\(^5,6,7,8\) was energy-dependent, included some relativistic effects, and had a decent set of neutrino interactions; however, the transport was spatially one-dimensional (spherically symmetric). The hydrodynamics and gravitation, while relativistic, were also spherically symmetric. Multidimensional effects were mocked up with a mixing-length approach, and without this explosions were not seen in these models. Inclusion of several nuclear species in a burning network was a high point of these simulations. Explosions were seen in these models, but there was no published accounting of lepton number and energy conservation.

**Los Alamos National Laboratory:** Many groups published spatially two-dimensional simulations in the early 1990s, and a group centered at Los Alamos was one of the first.\(^9\) Descended from those efforts was a recent simulation in three spatial dimensions by Fryer and Warren.\(^10\) The high point of these simulations was their three-dimensional hydrodynamics, and some relativistic effects were included in both the neutrino transport and gravitation. An important liability, however, was the crude treatment of neutrino transport, in which dependence on both energy and angle were integrated out, and some important interactions were left out. Explosions were seen in these models, but there was no published accounting of lepton number and energy conservation.

**Max Planck Institute for Astrophysics:** This group also performed simulations with two-dimensional hydrodynamics in the mid 1990s. Separate simulations were performed for the nascent neutron star\(^11\) and the region above the neutron star.\(^12\) In the latter simulations the neutrino luminosities were parametrized, and explosions were seen if these luminosities were set high enough. While some relativistic effects were included in both the hydrodynamics and neutrino fields, these were parametrized models with no serious neutrino transport. There was no detailed accounting of lepton number and energy conservation.

In more recent work the Max Planck group has published studies in spherical symmetry, but with sophisticated neutrino transport.\(^13,14\) The neutrino transport is dependent on both energy and angle, and includes some relativistic effects. This group has also considered a full range of neutrino interactions.\(^15\) Important limitations of results published to date were the restriction to spherical symmetry and Newtonian hydrodynam-
ics, but initial results on multidimensional models with sophisticated neutrino transport and approximate relativity have recently been reported.\textsuperscript{16,17} While some attention to the accounting of lepton number and energy was reported in connection with test problems, it was not reported in detail in connection with full simulations. No explosions were seen in simulations with the most comprehensive treatments of neutrino transport.

\textit{Oak Ridge National Laboratory:} Like the group at Max Planck Institute for Astrophysics, this group published separate studies of the nascent neutron star\textsuperscript{18} and the neutrino-heated region\textsuperscript{19} with two-dimensional hydrodynamics. The neutrino transport included some relativistic effects, retained the energy dependence of the neutrino distributions, and took some care regarding the conservation of energy and lepton number. However, these neutrino distributions were taken from a spherically symmetric simulation and imposed onto the two-dimensional hydrodynamics. In addition, the hydrodynamics was nonrelativistic. Unlike other multidimensional models published in the 1990s, no explosions were seen in these simulations.

More recently the Oak Ridge group has produced simulations in spherical symmetry but with sophisticated neutrino transport.\textsuperscript{20,21,22} These recent simulations had some notable high points. They included realistic neutrino transport, tracking both the energy and angle dependence of the neutrinos. Unlike other core-collapse simulations, they were fully relativistic in both the transport—including redshifts and trajectory bending—and in the hydrodynamics/gravitation. The price that has been paid for these advances is that the models were spherically symmetric, and therefore unrealistic in that respect. Another high point of these simulations was the careful attention paid to energy and lepton number conservation.\textsuperscript{22} Great effort went into assuring that the finite difference representations of the partial differential equations were consistent with number and energy conservation. This is a standard all simulations eventually must meet in order to be truly credible with respect to conclusions about the explosion mechanism. In this case the simulations provided convincing evidence that explosions simply do not occur in spherical symmetry (at least with standard neutrino physics). This is indicated in Figure 1, which shows the initial outward motion of the shock and its subsequent stagnation and infall.\textsuperscript{21}

\textit{University of Arizona:} This group also performed simulations with multidimensional hydrodynamics in the mid 1990s.\textsuperscript{23} The neutrino transport was integrated over both energy and angles, impairing the realism of the models. They were also nonrelativistic. While these were exploding models, there was no detailed accounting of energy and lepton number conserva-
Figure 1. Failure of spherical model to explode. Thin lines: mass shell trajectories. Thicker lines: shock trajectories in a Newtonian hydrodynamics, $O(v/c)$ neutrino transport model and a fully relativistic model.

3. The TeraScale Supernova Initiative

The overview of core-collapse supernova simulations presented in the last section demonstrates a fundamental trade-off required by the computing power available during the past decade: A sadistic choice between multidimensional hydrodynamics and spatially multidimensional, energy- and angle-dependent neutrino transport, two non-negotiable aspects of realism. As the new millenium begins, computing power has advanced to the point that neither of these crucial pieces of physics need be sacrificed, as initial results$^{16,17}$ from the group at the Max Planck Institute for Astrophysics indicates. Another program designed to take core-collapse supernova modeling to the next level is the TeraScale Supernova Initiative.

The TeraScale Supernova Initiative$^{b}$ (TSI) is a large collaboration funded by the U.S. Department of Energy for several years with the mis-

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$^{a}$Very recently this group reported simulations with Newtonian hydrodynamics and sophisticated neutrino transport in spherical symmetry; no explosions were seen.$^{24}$

$^{b}$http://www.phy.ornl.gov/tsi
sion to explain the supernova phenomena most closely associated with core collapse: the successful launch of the shock (i.e. understand the explosion mechanism); neutrino signatures; pulsar spins, kick velocities, and magnetic fields; gravitational waves; and heavy element ($r-$process) abundances.

This initiative—which grows out of past efforts of the supernova modeling group at Oak Ridge National Laboratory—has a diverse and experienced investigator team, including some 40 investigators from 12 institutions. These investigators include people whose life-long work has been in the areas needed in supernova science, including radiation transport, magneto-hydrodynamics, nuclear and weak interaction physics, and needed aspects of computer science.

TSI also has the support of the U.S. Department of Energy’s computational infrastructure. This includes high priority on the DOE’s terascale machines—which feature several $10^{12}$ bytes of memory and floating point operations per second—and access to the expertise of teams specializing in various aspects of high-performance computing, including advanced solver algorithms, computational meshes, performance on parallel architectures, data management and visualization, and software reusability and interoperability.

Some recent science from TSI involves pure hydrodynamics simulations (no neutrino transport). A standing accretion shock is an analytic solution in spherical symmetry. Its parameters are matched to the density profile in a realistic simulation when the shock stalls, and this is used as an initial condition for two- and three-dimensional simulations. It turns out that the standing accretion shock is unstable in two and three dimensions to the lowest order modes; the average shock radius and turbulent energy increase steadily with time at the expense of thermal and gravitational energy of the gas. The mechanism of instability is nonlinear feedback between aspherical pressure waves rising from small radii and regions characterized by transverse flow velocities—generated by asphericities in the shock—that advect inwards. This must be studied in more detail in simulations involving neutrino transport and realistic equations of state, but this hydrodynamic instability may play an important role in the supernova mechanism and provide an explanation for aspect ratios $\sim 2$ inferred from spectropolarimetry data.

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$^a$Inclusion of collaborators who are not members of TSI brings the total number of people involved to 99, from 28 institutions.

$^d$Movies available at [http://www.phy.ornl.gov/tsi/pages/simulations.html](http://www.phy.ornl.gov/tsi/pages/simulations.html).
4. Summary and Implications for Dark Matter

While many simulations have been performed over the years, it cannot yet be claimed that the supernova explosion mechanism is understood. Models with energy- and angle-dependent neutrino transport have been studied in spherical symmetry, and explosions have not been seen. Many (though not all) models with multidimensional hydrodynamics do exhibit explosions, but these have employed neutrino transport that is too crude to make firm conclusions about the explosion mechanism. Computing power has advanced to the point that models with both sophisticated neutrino transport and multidimensional hydrodynamics are within reach; the TeraScale Supernova Initiative (TSI) is one effort underway to perform such simulations.

Finally, in conclusion, a word on the subject of the conference: dark matter. The nascent neutron star is a hot (temperature of order 50 MeV) and dense (baryon mass density of order $10^{14}$ g cm$^{-3}$) environment. Should hypothetical particles like the axion (a cold dark matter candidate) or a keV-mass sterile neutrino (a warm dark matter candidate) exist, they could be produced in the extreme conditions present in the newly born neutron star. However, copious production and emission of such weakly coupled particles would cause the neutron star to cool more quickly than it would if neutrinos were fastest means of cooling. The handful of neutrinos detected from supernova SN1987A confirms the basic theoretical understanding of stellar core collapse, with associated trapping of neutrinos and their subsequent emission on a time scale of several seconds; this allows limits to be placed on the coupling strength of hypothetical dark matter particles like the axion and sterile neutrino. Presently, these limits are of necessity rather conservative, due to a lack of detailed understanding of the explosion mechanism and subsequent uncertainties about precise conditions in the nascent neutron star. A new generation of simulations—such as those being pursued by TSI—promises to reveal the explosion mechanism and paint a detailed and realistic picture of the physical conditions in the hot and dense neutron star, providing a basis for strengthened limits on the properties of dark matter candidate particles.

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