STELLAR COLLAPSE

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This book is dedicated to the memory of Hirlo Hicks who taught me the conviction to pursue my dreams.

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Preface

This book is designed to provide an incoming graduate student in astrophysics much of the background information on stellar collapse. By including the latest results, this book provides the current status of the field.

This is a fast moving field both in theory where computational resources are allowing increasingly sophisticated models and in observations, where new transient objects are being discovered that are opening wide the implications from stellar collapse. Because rapid rate of new discovers, no book on the subject will remain up-to-date for long nor, if we include more than one author, will all of the authors agree on every subject. However, any future work on stellar collapse will build upon the ideas and techniques presented here, and this book provides an ideal starting point to enter into this field.

The first part of this book is devoted to traditional studies of stellar collapse: the search for the mechanism behind core-collapse supernovae, from progenitor stars (Ch. 1) to observed supernovae (Ch. 2), the physics of the neutrino-driven supernova engine (Chs. 3-5) and the theoretical predictions for the nucleosynthetic yields and gamma-rays produced in core-collapse supernovae (Chs. 6-7). Part I poses several problems with the basic spherically symmetric picture of stellar collapse and core-collapse supernovae.

Part II of this book covers the role asymmetries have played in changing our understanding of stellar collapse. Some scientists argue that a new stellar collapse engine is required to explain all supernovae (Chs. 8,9), but most scientists have instead isolated new set of supernova-like outbursts from hypernovae (Ch. 10) to Gamma-ray bursts (Ch. 11-12) which are a small, but very important due to their extreme asymmetries, subset of outcomes from stellar collapse. These asymmetries are caused by asymmetries deep within the core of the collapsing star and can be tested by observations of the gravitational waves emitted in collapse (Ch. 13).

CHRIS L. FRYER

Foreword

This volume is a major compendium of the current research in supernova theory and simulation, ten major articles by ten major groups that explore the depths of current research. It is truely extraordinary that research in supernova remains so deep and esoteric as the research of these groups testifies. On the other hand it is equally extraordinary that an agreed mechanism has not emerged from $\sim$55 years of research, starting with Zwicky, Hoyle, Fowler and the Burbidges. We all know the conundrum as to why it has taken so long: how can positive kinetic energy, free energy, emerge from a system that is gravitationally bound? Why does it not just collapse and emit its binding energy as neutrinos, or to a black hole with no emission? The fact that a stellar collapse leads to an explosion of the star is a demanding physics challenge, especially to "red blooded males" who love explosions — and even to others. Just as "Nature" abhors a vaccumm, physicists, all those contributing to this volume, abhor not understanding something so "simple" as an explosion. Consequently, I could never, leave it alone.

A Touch of History

The touch of history starts for me with the testing of the US's largest thrmonuclear weapon, 15 megatons at the Bikini Atoll in the Pacific in 1954. To design an experiment to measure the gamma rays and neutrons from such an explosion demanded an intensive education, tutored by Montgomery Johnson, LLNL, Marshal Rosenbluth, and Conrad Longmire, LANL, in hydrodynamics, nuclear physics, radiation energy and pressure, and the competition between diffusion and advection. When one has designed and then analized results from a successful experiment, the confirmation of the physics is awesome. All of these physical processes on which the explosion depends take on a physical reality that is hard to deny. Consequently with the emergence of the space age and this success and understanding, I was asked by Teller and York to consider the effects of such an explosion in space. It soon became apparent to Montgomery and I that the radiation conditions from the surface of a megaton of energy in a cubic meter, $T \sim 5$ kev, would lead to the acceleration of a high opacity surface layer to 100's of MeV per nucleon kinetic energy. (These conditions presaged the concept of the high entropy atmosphere that builds up on a deleptonized neutron star.) Only the magnetic field of the earth or heliosphere would contain such a particle flux. Subsequently the starfish event confirmed just such confinement processes (provided one includes the grad B drift that shifts the conjugate point in latitude.). Wouldn't a supernova do the same thing and produce the cosmic rays of the universe? And so Montgomery and I proceeded to attempt to answer this question and you all know the first attempt to explain a supernova as a "bounce shock", formed when the neutron star elastically rebounds, has failed calculational tests.

Now, as we all recognize, the failure of the bounce shock has led to models depending upon seconds of time, large scale convection driven by the high entopy atmosphere, and thus a much weaker shock. But the story leading up to the first calculations of the bounce shock is more convolved. Again Teller, with Bethe's necessary concurrence, asked me to be the technical representative (knowledge of nuclear weapons) attached to the State Department in Geneva for the negotiations for the test ban treaty in space. The official US, desparately unspoken, position was: what a great idea to get satelites into space to "spy" on the Soviets and Soviets, in turn, thought what a bad idea it would be to allow it to happen. As you know, they did and we did and together we discovered gamma ray bursts rather than each others nuclear explosions. Along the way, we had to justify our sophisticated "spy" satelites rather than an unsophisticated giger counter. So guess who was asked to innocently give a talk on falsly triggering a "giger counter satelite". Well the obvious ploy was to invoke a supernova to do it. After all, those MeV gamma rays would look just like a clandestine nuclear test in space. With such a detection, we would all distrust each other even more, as if that were possible. Well the Soviets, many senior scientists, huddled with their exceedingly capable ambassador, "Scratchy" Serapkin, and after considerable cogitation pronounced with great authority "who knows what supernovae will do." Well they had the authority, because they had far greater knowledge and far greater seniority than myself. Of course a recess was called and I went to the CERN Library for two weeks to soothe my embarrassed feelings and possibly consider what in hell supernovae might do and how. The more I fruitlessly cogitated, the more determined I became not to be, nor the Lab to be, in such an embarrassing postion again. Fortunately Dr. Teller, then the lab director, felt the same way and supernova calculations with Dick White were initiated at the lab with bomb codes.

The first problem was to attempt to calculate the bounce shock starting from the iron-helium thermal decomposition threshold instability. The hardest part was developing numerical hydrodynamics to the point where the properties (speed up) of a strong shock in a density gradient were accurately reproduced. Fortunately, Burgers of South Africa had long before developed an analytical example and very many others contributed the equations of state from relativistic gas to neutron star matter. No matter how we teased the calculations the bounce shock was swallowed by the in-falling matter. Willy Fowler was convinced that thermonuclear burning of the carbon layers would save the day. Not so! Even with half the star's mass, $5M_{odot}$, of detonated carbon! What to do? Fortunately Willy Fowler had insisted that I become somewhat less ignorant about astrophysics. The deal was that I "chat" with his students about explosions while they grill me into learning astrophysics.

We all knew that the normal stellar imploding matter had to transform to neutron star matter by emitting neutrinos, but these would be instantly lost, of would they? Thinking of neutrino fluxes as radiation pressure leading to a ponderamotive force - that was weird. Fortunately Bob Christy could substantiate my early weird thoughts and we were off and running with neutrino driven supernova explosions. Neutrino radiation pressure? That was just another way to make a better explosion. These were not the neutrinos from the deleptonization or neutronization neutrinos, but those from the heat of delayed matter accreting onto the "hard", small (10^6 cm deep), negative gravitational potential $(-c^2/5)$, deleptonized neutron star. The deposition approximation depended upon the high temperature of this shocked atmosphere, $\sim 10to15$ Mev and the higher energy neutrino thermal-tail neutrinos, ~ 50 Mev. These neutrinos had high enough energy so that their cross section for deposition was large enough to heat the imploding matter, but small enough to transport the heat to matter to a less deep, higher gravitational potential layer of the star and consequently reverse the accretion. As we all know, after this work was published, some 5 years after its completion but before publication, neutrino neutral current scattering had been discovered leading to trapping of the neutrinos during collapse and consequently a proto-neutron star that had $\times 10$ the radius of the compact neutron star, and therefore a smaller, less negative and less deep gravitational potential. In addition with the smaller mass fluxes the accretion shock was too low in temperature to give rise to the neutrino deposition explosion.

1. The light Problem

One last bit of history: A stellar explosion without emitting light is not a supernova. The problem is that the heat energy of the explosion is nearly all converted to kinetic energy and work against gravity by adiabatic expansion before it can diffuse out of the expanding star and be observed as light. First reaching the understanding of the origin of the supernova light, with Chester McKee, the NI Co Fe tripply forbidden decay, was the most difficult problem and euphoric understanding of my life, some ten years after the start of our supernova calculations, (These were started in 1959, with neutrino driven exposions in 1961, submitted to Reviews of Modern Physics in $\sim$1962, and published 1966 because Chandra took charge, and the ^{56}Ni came in 1969.) I, we , delayed the publication of these supernova calculations by almost two years searching for a solution to the light emission. One can find in Colgate and White, almost in desperation, the only derivation (according to Bethe) of the ensemble fission product decay curve, $dn/dt \propto t^{-1.2}$, but this too (along with Californium from Fowler) did not work. Alone, in a taxi to the Denver airport, the idea emerged. When waiting in line for the plane to Albuquerque, Hubert Reeves was in the adjoining line going to Paris. I yelled across to him as he boarded "Its ^{56}Ni!". There was the briefest pause, and then "Mon Dieu, d'accord", and we are still working on a better understanding of collapse supernova.

2. How I view the Present Problem

It is a weird and unlikely circumstance that a collapse supernova (Type II) should explode. The peculiar mechanism that facilitates this explosion is the formation and preservation of large scale structures in a high entropy atmosphere residing on the surface of a nearly formed neutron star. The high entropy atmosphere is maintained by two sources: the gravitational energy of initial formation of the neutron star, released by diffusion and transport of neutrinos and secondly and possibly dominantly by the gravitational energy released at the suface by additional low entropy matter falling through to the neutron star surface. The preservation of this entropy contrast between up and down flows requires thermal isolation between the low entropy down flows and the high entropy up flows. This entropy contrast allows an efficient Carnot cycle to operate and thus allows the efficient conversion of thermal energy to mechanical, which in turn drives the explosion. The P-V diagram of various up and down going mass elements in the calculations demonstrates the existence of the cycle and its efficiency. Greater thermal isolation should occur in 3-D as opposed to 2-D calculations because of the difference in relative thickness or surface to mass ratio for the same mass flow in 2 and 3-D. This may explain the observed stronger explosion in 3-D calculations.

3. Justification of this View

The spherically symmetric diffusion of heat from a thermonuclearly explosive fuel is extraordinarily stable as the existence of all the various stars attests. In stars the free energy of thermonuclear burn is many orders of magnitude greater than the gravitational binding energy and so even a very small runaway thermonuclear reaction should lead to explosion, but it usually does not happen, novas and SN Ia's being the exception. The lepton degenerate core of a forming neutron star on the other hand, is strongly bound and so there is no explosive free energy available, yet the supernova explodes and ejects nearly the whole star. However, although the free energy of this interior lepton degenerate gas is small compared to the binding energy at the surface of the degenerate gas, it is large compared to the binding energy of the stellar matter at larger radii of the star. The question is how can this free energy be transported to a much larger radius sufficiently rapidly so that the heat of this free energy can not diffuse away more rapidly than the hydrodynamic equilibration time i.e., the explosion time? How also can this free energy be transported without doing excessive work against gravity, i.e., leave "its" mass behind?

The structure of any star is inherently stable because, with the heat generated in the interior, the diffusion of heat from the center is always slow compared to diffusion from the surface because of the very large density gradient. In the case of a collapsed star, after the formation of the neutron star core, the neutrino flux from the continuing deleptonization and the neutrino flux from the subsequent accretion flows lead to a high entropy, neutrino-dominated atmosphere on the surface as opposed to the interior of the neutron star. High entropy in this case means matter whose internal energy is so high that it is not gavitationally bound. (It is confined by the external pressure of accretion.) We think that the properties of convection, truncated at the large scale by diffusion, uniquely solves this problem. The large scale of the Rayleigh - Taylor instability occurs because neutrino diffusion at the neutrino sphere prevents the growth, i.e., truncates the growth of all smaller scale wave lengths than the local scale height. Convection allows the transport of heat without doing work against gravity. A large scale convective element, a plume in a high entropy, relativistic gas of specific heat ratio, $\gamma = 4/3$, allows a plume or large scale mass element to rise and survive without entrainment or mixing for many scale heights of displacement, because the expansion is homologous and faster than Helmholtz mixing. Thus, the plume or mass element can reach a height where a significant change in gravitational potential occurs. In turn, provided the displacement of the mass element remains adiabatic, the Carnot efficiency for converting the high entropy or heat of the plume to useful work remains high. It is this work, we believe, that causes the supernova ejection or explosion. A fraction of the high entropy atmosphere formed adjacent to the neutron star, is transported, adiabatically, by large scale convection to a larger radius without significant loss of heat and thus to a much lower gravitational potential. In a lower gravitational potential it requires less work from the adiabatic expansion to eject the matter. It requires almost a conspiracy of all three pieces of physics, in our view, to cause a collapse supernova to explode.

The beginning physics in this scenario is the formation of a high entropy atmosphere lying on top of a nascent neutron star. This unlikely sounding circumstance is the inevitable result of continuing deleptonization of the contracting neutron star core and as well low entropy and higher density matter falling onto a tightly bound neutron star. Furthermore, the rate of release of this free energy must be great enough to establish a neutrino fire-ball above the neutrinosphere where the energy flux is so high that the radiation energy density in neutrinos becomes opaque to the neutrinos themselves. We will discuss the origin of this atmosphere first while attempting to evaluate the dynamic range of physical processes that might limit its formation. However, a universal understanding of the Carnot cycle in large scale convection in our view is the key to the understanding of the convective transport process. Viewing this process as a wind negates the possibility of counter current flows and therefore of an energy conversion cycle.

The second law of thermodynamics establishes the limiting efficiency for accessing the free energy of two, different temperature reservoirs. The Carnot cycle describes the sequence of deformations necessary to accomplish this efficiency. A necessary part of this cycle to access this free energy is the thermal isolation of the two parts of the cycle of compression from expansion. Similarly the necessary heat flow isolation between the up and down flows of large scale convection determines the efficiency for transporting heat and free energy from the deep gravitational potential. In our view, this isolation is absolutely necessary in order to maintain an efficient Carnot cycle and is therefore the basis for the somewhat greater energy release of the 3-D calculations (Fryer & Warren, 2002) over those performed in 2-D. In 3-D a given low entropy mass flow is cylindrical in shape and therefore thicker against neutrino heat flow transport than the corresponding entropy mass flow in the form of a sheet in 2-D, namely the surface to mass ratio is more favorable in 3-D.

There is still a long way to go in understanding this convective view of collapse supernova explosions from Colgate, Herant, & Benz, 1993, in Herant, Benz, Hix, Fryer, & Colgate 1994, and in Colgate & Fryer, 1994, and now recently the many calculations in this volume. We need to understand in a more lucid fashion the scale of the buoyant elements as determined by the heat diffusion at the neutrinosphere and secondly the expected homologous, shape preserving expansion of the buoyant elements in the $\gamma = 4/3$ high entropy atmosphere. The continuing dedication of all those contributing to this volume, their students, and students' students will achieve it. It has been and still is a great adventure for all of us.

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The initial set of authors and idea for this book grew out of a special session on stellar collapse at the 200th American Astronomy Society Meeting in Albuquerque. With the basic idea of a graduate level seminar text from the publishers at Kluwer (B. Burton and H. Blom), the authors have designed chapters to give both a review of the field with a taste of the current ideas and problems facing the field. This work was funded under the auspices of the U.S. Dept. of Energy, and supported by its contract W-7405-ENG-36 to Los Alamos National Laboratory, the University of Arizona, and by a DOE SciDAC grant number DE-FC02-01ER41176.