Report of the Core-Collapse Supernova, NS Merger, and GRBs Working Group

W. R. Hix and C. D. Ott
for the working group participants

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Questions to answer:

1. What are the major recent accomplishments?
2. What are the specific compelling open questions? (Unexplained observations, problems in theoretical modeling, etc)
3. How can one address these open questions? What are the high impact nuclear experiments, observations, theoretical studies that need to be done?
4. What kinds of experiments, theoretical work, and observations are needed?
5. In which direction should this area evolve in light of expected new observational, theoretical, and experimental capabilities?
6. How does this subfield intersect with other subfields? (For example, is there work needed in other subfields to move this subfield forward)

Core-Collapse Supernova and Long GRB modeling

There has been much recent progress in the modeling of massive star collapse. The community agrees that spherically-symmetric (1D) models of core-collapse supernovae (CCSNe) do not lead to explosions and that multi-dimensional effects, in particular convection and the standing accretion shock instability (SASI), are crucial for driving an explosion. Two-dimensional (2D; axisymmetric) simulations with spectral (i.e., energy-dependent) neutrino transport are now available and have demonstrated that the explosion mechanism based on neutrino heating can work for 2D CCSNe, if all relevant multi-physics components are included, in particular, Boltzmann neutrino transport, general relativity, a detailed treatment of electron capture and a neutrino interaction treatment with coupling of energy bins. Much progress has also been made in predicting the neutrino signal seen by neutrino detectors and the gravitational-wave signal seen by Advanced LIGO and its partner observatories from the next galactic CCSN. Understanding these signals is crucial for observationally probing the dynamics and thermodynamics in the core, but most predictions still come from 1D (for neutrinos) and 2D (for neutrinos and gravitational-waves) simulations.

Taking detailed first-principles neutrino radiation-hydrodynamics simulations to three dimensions (3D) is a major challenge, but will be necessary to robustly model the turbulence behind the shock and fully assess the roles of convection, SASI, magnetic fields, and rotation. While first 3D simulations with gray (i.e. energy-averaged) transport have been carried out, spectral transport simulations will be crucial to ascertain the explosion mechanism, its multi-messenger signatures, and nucleosynthetic impact. Developing, running, and validating these simulations will require a broader workforce with interdisciplinary training, access to the necessary computational resources (a single spectral-transport simulation requires $\sim$200 million CPU hours), and code comparisons between groups.

A major deficiency of current CCSN models is the reliance on spherically-symmetric presupernova structure as initial condition for collapse simulations. Progress in the 3D modeling of convective burning suggests that presupernova stellar structure may be significantly different from what current purely 1D models predict. Robust 3D CCSN models will thus crucially depend on advances in multi-D stellar evolution. Connected to this is the challenge to predict the ultimate outcome of stellar collapse (and its various observational signatures, including nucleosynthetic yields) as a function of zero-age-main-sequence mass, metallicity, and rotation.

The connection of long GRBs and extreme CCSNe is now well established observationally, but how and under which conditions a GRB central engine forms in a dying massive star is uncertain. Modeling such extreme events and understanding their nucleosynthetic consequences is tremendously difficult. It will require bringing together CCSN simulation techniques with the methods of numerical relativity to address the general-relativistic dynamics associated with black hole formation, rapid rotation, and ultra-strong magnetic fields important in GRB central engines.

Binary Mergers, Short GRBs, and Gravitational Wave Observations

The past decade has seen a breakthrough in numerical relativity, enabling for the first time long-term simulations of merging binaries of black holes and neutron stars in full general relativity. At the same time, the first generation of laser interferometer gravitational-wave (GW) observatories reached design sensitivity. While no detection was made, interesting upper limits were obtained. It has also become clearer what nuclear astrophysics may be learned from GW observations. Advanced LIGO is expected to turn on in 2015. When it reaches its design sensitivity within a few years, it will have horizons of $\sim$200 Mpc and $\sim$600 Mpc for neutron-star – neutron-star (NSNS) and neutron-star – black-hole

(NSBH) binaries, respectively. Depending on population synthesis models, these ranges correspond to conservative estimates of *tens of observations per year*. Observations at low signal-to-noise ratio will yield constraints on the total system mass and possibly the mass ratio of the components. Rarer closer events will yield detailed information on the individual masses of NSNS and NSBH binaries and the spin of the BH in BHNS binaries. In the last hundreds of orbits before merger, the tidal interaction (which depends on the nuclear equation of state [EOS]) of the components has an influence on the GW signal. In BHNS systems, the NS may be disrupted and the GW frequency at which this occurs can be connected to NS structure. In NSNS systems, a hypermassive NS (HMNS) is formed whose long-term survival and the GW signal emitted in the postmerger phase depend on the system mass, on the nuclear EOS, and neutrino cooling.

While the inspiral phase of these compact binaries is well understood, most uncertainties and challenges are associated with the evolution after the two objects merge. How long does the HMNS survive and does its neutrino-driven wind delay or prevent a GRB due to baryon loading? How massive is the accretion disk that is formed when the HMNS collapses and how massive is it in BHNS systems? Can, and if so, how does the postmerger state evolve to a short GRB? How much matter is ejected and becomes unbound and what is its nucleosynthetic composition? What is the photon signature of the early merger afterglow? Advanced LIGO and its partners, in combination with follow-up photon observations, may help to answer these questions.

Merger simulations using Newtonian gravity or various approximations to general relativity already include realistic nuclear EOS, but use treatments of neutrino interactions and transport too crude for reliable predictions of nucleosynthetic yields. More importantly, they lead to unreliable predictions of the survival time of the HMNS and ejecta masses. Full numerical relativity simulations, on the other hand, capture the general-relativistic aspects of the problem, but generally employ polytropic NS models, which are not useful to study the postmerger evolution. Since Advanced LIGO will be taking data within a few years, relativistic merger simulations must urgently be improved to theoretically underpin Advanced LIGO observations and the follow-up observations in the electromagnetic spectrum. Collaborations between numerical relativists and CCSN modelers will be necessary to incorporate nuclear EOS, spectral and angle-dependent neutrino transport, and neutrino and nuclear interactions into relativistic merger models. Methods need to be developed to accurately follow the long-term evolution of the merger remnant and robustly predict its nucleosynthetic yields and determine the viability of mergers as short GRB central engines and r-process sites. To predict the lightcurve and spectrum of the early merger afterglow in photons, non-LTE radiative transfer simulations will be needed. These, in turn, will require reliable photon opacities for the range of possible exotic and neutron rich nucleosynthesis products of the merger.

Photon Observations

The advent of wide-field optical surveys, with spectroscopic follow-up, has greatly increased the observational catalog of supernovae (thermonuclear SNe and CCSNe), revealing peculiar events and rare features. This includes timely observations of shock breakout, which provides powerful constraints on the progenitor star's structure. Comparisons with archival data from Hubble and other sources has revealed several progenitors in their presupernova state, allowing correlations between CCSN observables and progenitor features, thereby furnishing extremely valuable constraints on stellar evolution and CCSN modeling. Optical spectropolarimetric observations of supernovae and X-ray compositional maps of supernova remnants have revealed wide-spread, but moderately strong, asymmetry in the ejecta, providing insight into the morphology of the central engine. Studies of the afterglows of γ-ray bursts have confirmed the association of long duration bursts with CCSNe while establishing that short duration bursts do not share this association. Our ability to simulate the photon radiative transfer that produces the visual display of all of these events has also improved, with 3D time-dependent light curve and spectrum calculations now possible, including the far-from-equilibrium conditions that occur during shock breakout.

Beyond the constraints they provide on our understanding of CCSNe, this myriad of new observations serves to wet our appetite for yet better observations. Improving our supernova census will require high cadence surveys with near full sky coverage and through follow-up across all wavelengths. Rapid follow-up at X-ray and UV wavelengths are particularly important to maximize the information we can glean from shock breakouts and γ-ray bursts (in particular in combination with gravitational-wave observations). Expanding the catalog of presupernova progenitor observations will require highly-resolved, deep multi-band imaging of a multitude of galaxies. To bridge the gap between these new observations and modeling of the central engines and nucleosynthesis, further improvements in light curve and spectral modeling are needed, requiring support for the person-power and computational capabilities to accomplish this task.

Nucleosynthesis

Our current understanding of CCSN nucleosynthesis and its role in galactic chemical evolution is based on 1D explosions induced by a parameterized piston or parameterized thermal energy deposition. Work in the past decade has highlighted the shortcomings of this approach. 3D simulations that extend to the stellar surface lead naturally to the development of high velocity nickel ”bullets” and other observed features that one dimensional simulations fail to match. Simulations of neutrino-powered explosions, using spectral neutrino transport, result in nucleosynthesis products qualitatively different in composition from either the parameterized bomb/piston nucleosynthesis models or older models using gray neutrino transport. These models have shown that the treatment of neutrino captures on the ejecta, which decrease the neutronization, remedies some defects in the predictions made by previous models of nucleosynthesis, all of which neglected this important piece of physics. These effects remove the over-production of neutron-rich iron and nickel isotopes that have plagued parameterized bomb and piston models. These simulations also show enhanced production of Sc, Cu, and Zn; elements which observations of metal-poor stars suggest are $3-10$ times more abundant than previous models predicted. Moreover, this work suggests that a significant neutrino-driven flow to proton-rich nuclei above A=64, termed the νp-process, could make the innermost ejecta of CCSNe the production site of the light p-process nuclei.

Given the importance of these findings, it is essential that we extend our developing understanding to the whole of supernova nucleosynthesis. First, we must follow 3D, first-principles CCSN models which employ spectral neutrino transport and other essential supernova physics through not just the explosion phase, but until the supernova shock breaks out from the surface of the star, and further until the supernova remnant forms. Only from such extended models can we fully understand the impact of the CCSN engine on the isotopic composition and velocity distribution of the ejecta. Second, we must use these first-principles models, which will be limited in number because of their computational cost, to calibrate simpler, parameterized models as a replacement for the bomb/piston models. These new parameterized models must be computationally frugal, to enable explorations in a wide parameter space of stellar masses, metallicity and progenitor physics, yet capture the essential impact that the neutrinoheated, convectively active central engine has on the nucleosynthesis. Third, we need to ensure the physical fidelity of our nucleosynthesis simulations by securing, by experiment and nuclear theory, the best available reaction rates for the nucleosynthesis processes that occur in CCSN and related events, especially those of interest to the νp-process, which occurs further from nuclear stability than most CCSN nucleosynthesis processes.

r-process

The last decade has seen a tremendous growth in the list of old low-mass stars whose spectra reveal heavy element abundance less than 1/1000th of the Sun yet also exhibit the presence of r-process species. The ages of these stars indicates that the formation of r-process elements began very early in Galactic Chemical Evolution (GCE), suggesting that the r-process occurs during the death throes of short-lived, massive stars. Many sites for the r-process have been suggested, but, at present, the most physically complete models for all of the sites associated with the collapse of stellar iron cores or oxygen-neon cores fail to produce the required combination of neutron-richness and entropy. Models of neutron star mergers are more successful at meeting this requirement, but are challenged to contribute as early in Galactic History as observations of metal-poor stars require. Despite our continued ignorance of the r-process mechanism, considerable progress has been made in the past decade to gather the nuclear data needed to understand the r-process. Theoretical studies have added selected (n, γ) reactions to the existing data necessities of nuclear masses and β-decay rates and measurements of (d, p) surrogate reactions are shedding light on these (n, γ) rates. A wide range of mass measurements for increasingly unstable nuclei have been made in recent years using time-of-flight and Penning trap techniques. β-decay measurements now reach beyond the N=50 shell in Ga-Ge region and similar measurements at RIKEN are now verging on the r-process waiting points in the Rb-Zr region. β-delayed neutron measurements were recently undertaken at HRIBF and ATLAS, enabled by a new generation of neutron detectors.

To address our ignorance of the r-process site, we must increase the physical fidelity of our models of the underlying astrophysical events. This is especially true in the cases of neutron star mergers and collapsars, where the physical fidelity of current models trails that of the iron core and oxygen-neon core collapse models, in part because of the geometric disadvantage of these events being far removed from spherical symmetry. These computationally expensive models should be supplemented by improved studies using the details of the r-process abundances to constrain the conditions under which the r-process occurs. Because the thermodynamic conditions do not uniquely determine the site, these studies will do little to reveal the site, but will provide valuable information about the true r-process path. These improved computational studies will both illuminate the details of the nuclear data that is needed and depend on this data to achieve physical fidelity. FRIB will be essential to this data gathering, as it greatly extends our experimental reach for measuring nuclear masses, β-decay rates, and β-delayed neutron emission, but only if provided with a suitable complement of detectors. Making maximal use of this data, and extending the data to experimentally inaccessible regions will require continued theoretical efforts, both in nuclear structure and nuclear reaction theory. Improved reaction theory is of particular importance if we wish to use (d, p) surrogate reactions to measure (n, γ) reaction rates. In order for astrophysical simulations to take advantage of these nuclear physics efforts, reaction rate databases must be frequently updated, including both with measured rates but also improved theoretical rates that leverage the latest measurements of nuclear masses and other properties.