Astrophysics Theory Summary

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1 Grand Challenges

Astrophysics theory includes many different topics that were covered by individual working groups. Here we summarize challenges that can be address in the next 10 years.

1. Going beyond one-dimensional modeling in X-ray bursts and classical novae.

2. Stellar evolution models based on 3D hydrodynamical simulations will help to understand and better parametrize convection, as well as provide improved initial models for core-collapse simulations.

3. Mass loss in massive stars is also essential and needs more efforts. New observations?

4. Fast rotating stars may occur often at low metallicities. These stars have more mixing which leads to an efficient s-process even at low metallicities ($[Fe/H] \approx -3$). These stars can explain the primary ^{22}Ne and the abundance ratio of Sr/Ba. However, the outcome is very sensitive to still uncertain reaction rates: ^{17}O(α, n) and (α, γ). Multidimensional models of fast rotating stars from different groups are needed.

5. Core-collapse supernovae simulations are rapidly improving. Explosions in 1D for low mass progenitor (8 $M_{\odot}$) are obtained now with good agreement among different groups. In 2D there are still some discrepancies in the supernova community, explosion energies are in general lower than observed. Key ingredients have been identified and are being investigated: instabilities, neutrino-matter interactions, neutrino oscillations and transport, general relativity effects, progenitor, nuclear equation of state, magnetic fields,...

6. First 3D hydrodynamical simulations of core-collapse supernovae with a simple neutrino transport are becoming available. One of the big challenges of next decade is to improve the microphysics in such simulations which will provide new insights about supernova explosions.

7. In order to study explosive nucleosynthesis in core-collapse supernovae, one needs to run many models changing initial conditions. This allows to enough statistics to calculate the contribution of supernovae to the chemical history of the universe. However, multidimensional simulations of several seconds after the explosion changing initial conditions (progenitor, metallicity, rotation, ...) are too expensive if all microphysics is included. Therefore, simplified models (approximated neutrino treatment, approximate GR, inner boundary) are still a key tool that needs further development and investigation.

8. Neutron star mergers are perfect laboratories for nuclear physics. Next generation of gravitational wave detectors will help to constrain the high density equation of state. The ejecta of this events is very neutron rich and thus suitable for a robust r-process. First simulations including microscopic equation of state and neutrino emission have been recently performed. It is becoming possible to perform full GR simulations with improved microphysics and further work is required in this direction.

9. Multi-messenger studies imply observing supernovae and neutron star mergers not only with photons at different wave lengths but also with gravitational waves and neutrinos. The combination of these observations/communities is key to make advance in understanding these complicated and fascinating environments.

10. Weak rates play a crucial role during stellar evolution, core-collapse supernova collapse and explosion, neutron star mergers, ... Therefore, further theoretical and experimental work is necessary to develop a standard framework. Ideally it would be to have one theory describing weak reactions of nuclei (beta decays, neutrino interactions) and neutrino-matter interactions at densities of the outer layers of the proto neutron star.

11. Nucleosynthesis beyond iron: the origin of half of the elements heavier than iron is still an open question but great progress is ongoing.

2 Nucleosynthesis beyond iron

2.1 s-process

See stars working group

2.2 p-nuclei

From the Basel report (T. Rauscher):

Status: the long-time favored process is the gamma-process (photodisintegration) in ccSN; problems reproducing solar distribution (perhaps also absolute level, see GCE); two regions: light p-isotopes ($A < 100$, not produced in current ccSN), heavy p-isotopes (region around $150 < A < 165$ underproduced but contributions of neutrino-process and s-process are reevaluated); nuclear physics uncertainties in photodisintegration may account for deficiencies in heavy region, not sufficient to explain lack of light p; separate treatment of these regions necessary? separate processes?

Therefore, need to either change p-production in massive stars (ccSN) or to find a different site. Key questions:

- seeds: crucial for photodisintegration mechanism; may affect light p only or all p-nuclei, depending on seed distribution; SNIa models assume strongly enhanced (by factors of several 100s to 1000s) s-process seeds; models still under construction but in principle not ruled out by observation; seeds in ccSN may be changed, e.g., by different weak s-process due to changed neutron producing reactions or stellar physics; impact of rotation (fast rotating massive stars at low metallicity make more s); 12C+12C also strongly affects s-processing. what seeds (amount, distribution) are reasonable?? (within any site; also from GCE point of view)

- influence of neutrino-winds (νp-process?) in ccSN: have to be added to explosive nucleosynthesis in outer layers; would allow a "primary" production of p-nuclei.

- T-evolution (freeze-out): important to determine certain isotopic ratios, e.g., ^{144}Sm/^{142}Nd measured in meteorites.

- nuclear physics: affects production of s-process seeds in massive stars as well as photodisintegration; gamma-process is not an equilibrium process, many 100s of reactions and reaction sequences have to be considered; heavy p: possible problems found in sub-Coulomb (α,γ)

rates on heavy nuclei in comparisons to experiment, implications on (γ,α) not yet clear, may be a laboratory effect; for isotope ratios also ratios (γ,α)/(γ,n) important; light p (+ all?): all reactions affecting s-processing, e.g., neutron sources and neutron poisons, $^{12}C+^{12}C$, etc.

- GCE: Not well constrained because of lack of observations; no stellar isotopic abundances for most elements (except Eu, Ba in a few(?) stars); meteoritic data (both early SS or presolar grains) available but interpretation difficult; could there be any further (current, future) observations which are feasible and may help? Mo at low metallicity (if primary and not stemming from photodisintegrations)? stellar isotopic abundances from young stars (metal-rich) to compare to solar?

2.3 r-processes

How many r-processes exist in the universe? Where do they occur and how often? What are the key nuclei and reactions involved? Although there are not clear answers yet for these questions the latest advances in theory, experiments, observations and chemical evolution are showing us new facets of the origin of heavy elements. These intermediate steps are bringing us closer to answer the big and interdisciplinary question: What is the origin of heavy elements like gold and uranium?

Observations of very old stars point to different sites producing elements below and above $Z \approx 50$. While heavy r-process elements ($56 < Z < 82$) present a robust pattern for ultra metal-poor stars and for solar system abundances, lighter heavy element abundances ($38 < Z < 47$) show significant scatter.

Lighter heavy elements from Sr to Ag may be also produced in several different sites or components. We are now in unique moment to understand the origin of these elements: 1) Observations of ultra metal-poor stars are improving and increasing. 2) The conditions necessary to produce these elements are less extreme than for producing heavy r-process. Therefore, nucleosynthesis studies based on current simulations and models show that lighter heavy elements can be synthesized in neutrino-driven winds and in fast rotating stars. 3) In both cases the nuclear reactions and nuclei involved are not very far from stability, most of them will be constrained/studied in the next years by experiments and theoretical models. It is thus crucial to identify the key nuclei and reactions that need to be measured. 4) Chemical evolution models will show the relative contribution of the astrophysical sites.

For neutrino-driven winds further work is required to understand neutrino-matter interaction in the outer layer of the neutron star. This can be done in the next 10 years (at least this is what Reddy says). Such neutrino reactions are key to determine the neutrino-richness of the wind. In neutron-rich winds the lighter heavy elements are produced by a combination of neutron and alpha captures with beta decays (known as alpha-process, charged particle reactions or weak r-process). If the wind is proton-rich elements like Sr, Y, and Zr can be produced by the νp-process. This is an exciting problem because enough information is available (observations, astrophysical simulations, nuclear experiments and theory) in order to learn more about the astrophysical environments and their extreme nuclear physics conditions.

The origin of heavy r-process elements remains a challenging and exciting problem. The neutrino-driven wind was thought to be the appropriate site, however current simulations show that it is not possible to reach the extreme conditions that the r-process requires. Exciting possibilities are neutron star mergers, jet-like supernova explosions, He shell when radiated by neutrinos of the explosion, and accretion disks. The next 10 years are critical to develop better models of these astrophysical environments and (with help of chemical evolution) to constrain the contribution of different r-process sites. The possibility of having different r-process sites rises the question: Why is the r-process robust? This may be related to the astrophysical conditions, but also to nuclear physics. Therefore, during the next 10 year we have to prepare for the new experimental frontier (FRIB, FAIR, RIBF). Theoretical nucleosynthesis studies based on simulations but also on parametric model are key to identify key nuclei and regions of nuclei that need to be measure to maximize the groundbreaking discoveries at new facilities. This can be only be done by means of theoretical nuclear models for nuclear masses, cross sections, beta decay and fission. Once experiments provide new information, the astrophysical simulations and the nucleosynthesis models (including new theoretical data) need to be ready to test the impact of new measurements on the astrophysical conditions and on the production of new elements.

3 What astrophysics theory needs

In general, the working group felt that there is needed to be improved communication between the astrophysics and nuclear theory communities. Some specific recommendations to improve this are as follows.

1. Recommend that the community facilitate multi-disciplinary (theory, modeling/phenomenology, experiment) collaborations.
2. Recommend that nuclear astrophysics workshops make an effort to have both theoretical groups represented to seed connections.
3. Recommend that the community find mechanisms to facilitate moving students between nuclear and astrophysical theory groups. An example of this is the CompSTAR program.

The overall context is giving by the report of the National Research Council: Connecting Quarks with the Cosmos. In order to address questions such as: How were elements from Iron to Uranium made?, it is necessary to connect astrophysics with nuclear physics. The astrophysics component of nuclear astrophysics has to become stronger and get a driving role. Suggestions to get this goal:

- More funding for current and new stellar evolution and supernova modeling groups, with strong support for young researcher. New experiments, observations (optical, neutrino, gravitational waves), and theory are providing a huge amount of information. Therefore, more woman/manpower in astrophysics modeling is mandatory to maximize these groundbreaking discoveries. Most of the money for astrophysics is going into cosmology, it is necessary to invest more in stars.
- Additional position at the interface of nuclear and astrophysics. For example: PhD and Postdoc positions working in two groups: astrophysics/astronomy and nuclear theory/experiment.
- Support for small interdisciplinary collaborations, topical workshops and exchanges/visits.
- Consider nuclear astrophysics as a combination of interrelated parts/efforts (modeling, equation of state, neutrino interactions and oscillations, ...), not separate them in small parts.

- Nuclear astrophysics experimental programs needs a strong counter part in theoretical astrophysics. This will guide and lead the field towards new findings, not only data production.

4 What astrophysics can provide

A hinderance to progress in nuclear astrophysics is that the connection between an experimental measurement or theoretical calculation and an astronomical observable often requires the use of a numerical model. To facilitate this linkage, the working group encourages the dissemination of open-source "sandbox" codes for use by nuclear theorists and experimentalists. For example, a nuclear theorist might wish to explore how a newly calculated reaction rate might affect stellar evolution or classical novae. An experimentalist might wish to see how a different nuclear compressibility will affect the neutron star mass-radius relation. One example of such a tool is the `MESA` stellar evolution code.

5 Anticipated Observational and Experiment Developments

1. Advanced LIGO should reach sensitivity needed to detect neutron star-neutron star mergers

2. Surveys, such as *SkyMapper*, *PanSTARRS*, *Palomar Transient Factory*, are finding increasing numbers of rare optical transients, which are likely powered by thermonuclear explosions.

3. The ESA *GAIA* mission will measure distances to a high precision of a very large number of stars. The vast amount of high-quality data should lead to commensurate improvements in stellar modeling, and in understanding abundances and chemical evolution.