# Nuclear Astrophysics: Astronomical Constraints

*Potentials, Status and Perspectives of the Fields of Astronomy*

*A Working Group Report*

## General Comments

The endeavor of nuclear astrophysics involves different communities of scientists. There are the observers - builders and users of astronomical instruments - on the one hand, and the theoreticians - inventors and constructors of physical models for astrophysical processes - on the other hand. Because these communities often represent different interests and expertise this can sometimes lead to conflicting priorities. Nevertheless, the multi-disciplinary nature of the field at present makes it important to minimize any such conflicts in order to most optimally make progress the field. This argues for effective communication amongst all the relevant communities engaged in nuclear astrophysics.

Globally, our aim is to understand astrophysical objects and processes that are driven by nuclear physics. This occurs primarily (but not exclusively) in stars and explosions. Such explosions may occur on compact stars leading to flashes, bursts or novae--but leaving the object intact--or can be catastrophic, leading to destruction of the compact star itself. Moreover, understanding the broad field of chemical abundances and their evolution is an important goal of nuclear astrophysics. Main astrophysical issues for stars and explosions are the details of nuclear burning and its coupling to the dynamics and evolution of the object. For chemical evolution the major issue concerning nuclear astrophysics, in addition to the object's properties, are the nucleosynthesis yields for the variety of isotopes of each source.

### Specific Nuclear Astrophysics

For stars some important issues are the convective-shell burning products, mixing, and the metallicity dependencies of structure and yields. For supernovae, explosive nucleosynthesis is a primary question, specifically the explosion dynamics and morphology, and how trace isotopes, such as $^{44}$Ti and $^{56}$Ni, reflect these. Beyond charged particle reactions, neutron capture and Gamma-process environments appear dynamically during both stellar evolution and supernova explosions. Finding and adding their contributions to isotopic yields of the source remains an ongoing challenge.

Ignition/explosion scenarios in white dwarfs and in accreting binaries are key issues in the context of supernovae Ia. For novae, the total ejected mass is still debated, and synthesis of intermediate-mass nuclei such as Na, Mg, Al, S are of concern. The equation of state (EOS) of ultra-dense matter is an important topic for core-collapse supernovae, interacting binaries and compact star astrophysics. Important is the nuclear ignition in binary mergers (of white dwarfs and neutron stars), and near BHs. With respect to interstellar gas we identify spallation physics and cosmic ray propagation as key issues. For chemical evolution of galaxies, understanding abundance distributions and trends with evolutionary tracers such as [Fe/H], [C/Fe], [O/H], and [alpha-elements/Fe] are main issues.

Separating different galactic components such as disk (thin or thick), halo (inner and outer), bulge, and the globular clusters would help significantly in understanding and discriminating underlying processes. For the general cosmic chemical evolution, additional issues are the respective Big Bang Nucleosynthesis reactions (BBN), and any metallicity dependencies of stellar and SN yields.

### WG Plan

The Working Group attempted to survey, per field of astronomy, the status of the instrumental capabilities, some of the key nuclear astrophysics results obtained to date, and briefly summarized the future perspectives in instrumental capabilities. This led to a statement on the contribution of each particular field of astronomy to nuclear astrophysics, both up to now, and looking forward. It is hoped that this effort can be an aid in the prioritization of astronomical equipment needs (accounting for feasibility), and also to identify how existing facilities could best be used for nuclear astrophysics studies through optimized observing proposal strategies.

"Astronomy" in our view includes the following wavebands and "messengers," where for each entry we have also listed some of the primary science goals, measurements and sources relevant to each.

- Electromagnetic Radiation: Specific Elemental Abundances; others
    - Radio: Molecular Isotopes in ISM; Pulsar masses
    - Sub-mm: Cold-gas Cooling Lines (CI etc.)
    - Infrared: PAH and Dust Emission; Atomic Lines (eg. Ag)
    - Optical: Metal Elemental Abundances; timing for pulsation studies
    - Ultraviolet: Element Abundances (eg. Ag); Transient LCs
    - X-rays: Hot-Plasma Abundances; X-ray bursts; transients; compact star structure (EOS)
    - MeV Gamma-Rays: Radioactive Isotopes
    - GeV Gamma-Rays: Cosmic Rays Interactions (spallation)
    - TeV Gamma-Rays: Cosmic Ray Accelerators
- Meteorites and Presolar Grains: Specific Isotopic Abundances & Ratios
- Asteroseismology, Stellar Interiors (Core Size; convection, rotation)
- Cosmic Rays: Specific Isotopes; ISM Spallation
- Neutrinos: ccSNe; solar Nucleosynthesis
- Gravitational Waves: Binary Source and ccSN Dynamics

## WG Summary

Nuclear astrophysics is reflected in (and often dominating) a broad range of astronomical windows and messengers. This ranges from the Cosmic Microwave Background (BBN) and radio pulsars through elemental (Li…Ag) stellar abundances through Type-I X-ray burst light curves through $^{44}$Ti decay gamma-rays through solar neutrinos through cosmic-ray spallation (Li-Be-B) to pre-solar grains. Comparing nucleosynthesis source model predictions to such data is a major challenge, often beyond the capabilities of single scientists or groups. Progress therefore depends on interactions and discussions among observers across different fields and modelers/theoreticians of different sources/processes (including chemical evolution modelers). A dedicated effort to further stimulate such cross-field interaction appears to be a most-promising first step to advance nuclear astrophysics in general. We need to learn which questions can be pursued, and how. We also need to learn how to best exploit the vast observational diversity.

A lack or loss of observational facilities may incur significant setbacks in the above prospects. The nuclear-astrophysics community should speak up as appropriate in critical cases. Primary concerns at present appear to be the potential Green Bank Telescope shutdown, which could adversely impact future NS (pulsar) mass measurements using radio pulsar timing, as well as a potential reduction in Kitt Peak National Observatory availability for optical astronomy. Also, major telescope survey programs are often driven by the “big question” science issues of dark energy, dark matter, and cosmology. This incurs the risk that the also-interesting and unsolved issues of nuclear astrophysics are not addressed adequately. In particular, in the case of expensive space programs, opportunities may be thinned-out below a minimum threshold that keeps expertise for nuclear-astrophysics observations sustained.

## Through the Astronomy Fields

### Radio Astronomy

Current instrumentation includes the eVLA, Arecibo, GBT, and LOFAR on the ground, and the Planck space mission. Capabilities in this field include, spectroscopy resolving isotopes in molecular lines, and an imaging resolution ~milli-arcsec.

The relevance for nuclear astrophysics lies in determinations of abundances of molecules and isotopic ratios ($^{12}C/^{13}C$, $^{16}O/^{17}O$, etc.) in the ISM. Furthermore, radio pulsar observations can provide precise NS masses, and pulsar timing glitches can provide constraints on NS interior physics. Also, measurements of global supernova explosion energy and nova ejected masses can be made. Additionally, radio transients may be powered by nuclear processes.

The future instrumental perspectives are the SKA, MeerKAT, ASKAP, and ATA . Recent pulsar mass measurements have found “heavy,” 2 solar mass neutron stars. Such high mass measurements are quite constraining on EOS models, and given the complimentary focus of nuclear laboratory measurements to constrain the EOS and symmetry energy, it would be a set-back to lose such a capability. Moreover, continued measurements of the double pulsar system (PSR J0737-3039) over the next 5-10 years could provide a direct measurement of the moment of inertia of pulsar A in this system.

### Sub-mm Astronomy

Current Instruments are JCMT, CSO, SCUBA, IRAM, APEX, Mopra, and the space instruments on Herschel (single-dish instruments), and the BIMA, SMA, IRAM, CARMA, ATCA, and ALMA (Interferometers).

Relevant capabilities are in the mapping of dust emission (tracing star formation), and the spectroscopy of molecular lines , with imaging resolution ~ few arcsec.

Their relevance for nuclear astrophysics is through the provision of star formation tracers, and isotopic ratios in different molecular species also related to star formation sites. Rotation-band lines of molecules probe abundances and the gas kinematics. Moreover, mass loss around evolved objects, and the chemistry around new stars can be studied.

The future instrumental perspectives are the LMT, SCUBA-2, and ALMA

## Infrared Astronomy

Current missions and telescopes include; Spitzer, Herschel, Sofia, IRAS, and instrumentation at the VLT. Capabilities include spectroscopy adequate for resolving PAH lines. Studies relevant to dust emission, and ~arcsec imaging.

The relevance for nuclear astrophysics includes abundances of PAHs, ISM chemistry. Moreover for Galactic stars photospheric abundances can be acquired in detail (due to low absorption in the IR).

The future instrumental perspectives are the space missions Euclid and NASA's JWST.

## Optical Astronomy

Current missions and instruments are HST, and on the ground the variety of large-aperture telescopes such as the VLT, Keck, Subaru, Gemini (N and S), and the Magellan telescopes. Capabilities include spectroscopy with resolution adequate for resolving lines of elemental species, and imaging resolution of ~arcsec.

The relevance for nuclear astrophysics is in abundance measurements and isotopic ratios in stellar atmospheres in the Galaxy, the halo system, and nearby galaxies. Current observations are beginning to probe the abundance patterns, and in some cases, the isotopic patterns, that are thought to be produced by the very first generations of stars. Large spectroscopic surveys (SDSS/APOGEE, AEGIS, LAMOST) will be further exploited in the near future. Astrometry (and limited photometry and spectroscopy) with the Gaia mission will enable radial velocity measurements, proper motions and geometric distances for 1 billion stars, and precise luminosities for all classes of stars. Massive ground-based spectroscopic follow-up efforts to obtain radial velocities (and stellar parameters) for stars that are too faint for Gaia need to be supported vigorously. Future instrumental perspectives include the LSST, ELT, and E-ELT.

## UV Astronomy

Past missions were IUE, and FUSE. Currently, HST provides limited UV capabilities, and the GALEX mission provides 4-5 arcsec imaging and spectral resolving power of 200 and 90 in far- and near-UV bands, respectively.

The relevance for nuclear astrophysics includes measurements of abundances of light elements, and low-abundance heavy elements (for example, Ag), as well as the measurement of nova ejecta abundances. Moreover, photometry for studying the time domain behavior of transients is important.

A concern here is limited future instrumental perspectives. The group did not identify a future space capability beyond HST, for example.

### X-ray Astronomy

Current missions include Chandra, XMM-Newton, Swift, Suzaku, MAXI and the recently launched NuStar.

Capabilities include spectroscopy with a range of resolving powers; as high as 1000 with the Chandra and XMM gratings, resolving power < 100 with X-ray CCDs, adequate for identifying some ion species and constraining abundances. Imaging resolution ranges from < 1 arcsec with Chandra to ~arcmin with Suzaku and MAXI. The recently launched NuStar mission adds $^{44}$Ti low-energy line imaging. Sensitive X-ray timing and broad-band spectroscopy provides essential constraints to understand the explosive phenomena such as Type-I X-ray bursts and superbursts. These capabilities also provide direct probes of the neutron star, its environs and the nuclear physics driving the explosions, as for example, by observing the thermal surface emission during X-ray bursts. Long term monitoring (as for example, with MAXI) can provide burst recurrence times as well as capture rare events such as superbursts.

The relevance for nuclear astrophysics includes abundance measurements in hot astrophysical plasmas, SNR, and WHIM abundances. In addition, X-ray light curves and spectra provide detailed probes of the NS surface and nuclear physics processes relevant to thermonuclear X-ray bursts. Such measurements can, in principle, also be used to estimate global NS structure parameters such as the mass and radius, both crucial for EOS constraints.

Future instrumental perspectives include high spectral resolution with micro-calorimeters on Astro-H (2014); wide field surveys with eRosita (2014+); very large collecting area and fast timing (excellent for X-ray burst studies) with ESA's Large Observatory For X-ray Timing (LOFT, 2020+); fast timing and wide field monitoring with India's Astrosat (2013+); precision soft X-ray timing and medium resolution spectroscopy with NASA's Neutron Star Interior Composition EexploreR (NICER) International Space Station (ISS) payload, and possibly high throughput and high resolution spectroscopy with IXO/Athena (2024+).

There is presently a substantial effort to probe the nuclear symmetry energy with laboratory nuclear experiments. These efforts are strongly complemented by astrophysical observations of neutron stars, which probe fundamental physics to higher densities. Recent measurements of ~2 $M_{\mathrm{sun}}$ neutron stars, and the opportunity that could be provided by missions presently in development, such as LOFT and NICER, which can enable direct NS radius measurements (that directly probe the symmetry energy), suggests a strong potential for important breakthroughs in this area within the next decade.

### MeV Gamma-ray Astronomy

Current Missions are INTEGRAL with SPI, Fermi-GBM, and RHESSI. The Fermi-GBM provides low energy and imaging resolution but is an efficient all-sky monitor for 0.1-40 MeV. The other instruments provide high energy resolution of ~3 keV, adequate for resolving isotopes, with modest imaging resolution of ~3 degrees, and with sensitivities ~few $10^{-6}$ photon $cm^{-2}$ $s^{-1}$, they can reach Galactic sources, and SNe to ~5 Mpc.

The relevance for nuclear astrophysics lies in direct measurements of radioactive isotopes from cosmic sources of nucleosynthesis. Surveys can find/measure new sources before their appearance otherwise (511 keV; $^{7}$Be, $^{22}$Na), or when they are embedded in dense clouds (supernovae, $^{44}$Ti), $^{56}$Ni decay is a diagnostic of supernova interiors both in SNIa and ccSNe. $^{26}$Al from stellar groups constrains stellar-group yields (stellar and supernova), and allows the study of ISM dynamics around those. $^{60}$Fe probably originates from the same stellar groups that produce $^{26}$Al, and their isotopic ratio is an important diagnostic of multi-shell-burning structures in late evolutionary stages of massive stars. Positron annihilation relates nuclear astrophysics to the properties of cosmic rays and their propagation near sources of nucleosynthesis as well as pulsars and binaries. Much can be learned from observations of solar flares on nuclear processes in the Sun's outer layers.

In terms of instrumental perspectives there are none presently identified in the major space agencies for the time after INTEGRAL (>2016), although Compton Telescope missions have been proposed, and technology & balloon projects are underway.

## GeV Gamma-ray Astronomy

Past and current space missions include CGRO/EGRET, Agile, and Fermi.

Capabilities include spectroscopy with a resolution of ~0.1 GeV, adequate for resolving nucleonic lines, and imaging with resolution of ~a degree.

The relevance for nuclear astrophysics is less direct than in most other fields, yet is given through the tracing of Cosmic-Rays in the Galaxy, and how this relates to nucleosynthesis sources.

Instrumental perspectives include Fermi (expected to continue for at least several years), but none identified after that in the major space agencies

## TeV Gamma-ray Astronomy

This is ground-based gamma-ray astronomy. Current experiments are H.E.S.S., MAGIC, and Veritas. Instrumental capabilities relevant for nuclear astrophysics lie in its imaging resolution of ~10 arcsec. The relevance is less direct than in most other fields, but is given through constraints on CR accelerators in supernova remnants, and pulsar wind nebulae. Future Instrumental perspectives are focused in the CTA project (2014+)

## Meteorites and Presolar Grain Studies

The Stardust mission provided samples of interplanetary particles, caught from the current medium within the solar system. Then, a rich body of meteoritic samples is available, where condensation occurred a long time ago under poorlyknown conditions, but mineralogical studies help to identify origins. Of particular value are pre-solar grains identified herein, where identification is chemically through extreme resistance to acidic solvents, and observationally through extremely deviant isotopic ratios from solar-system material.

Laboratory instruments are Nano-SIMS, RIMS, Ion Microprobe. They provide capabilities of mass spectroscopy, adequate for resolving ion species., and imaging at few nm scales, i.e. down to resolving individual pre-solar grains.

The relevance for nuclear astrophysics includes measurement of abundances of specific ions in dust-producing nucleosynthesis sources; mixing in stellar atmospheres (esp. in AGB stars); solar system formation history.

Instrumental perspectives include future Nano-scale probe analysis (single grain study of isotope ratios).

### Asteroseismology

Past and current missions and instruments include Kepler, Corot, MOST, and the Whole Earth Telescope. The primary relevant capability is to measure stellar oscillation modes with high precision. The relevance for nuclear astrophysics is in direct constraints on stellar interiors. Study of oscillations can determine the size of convection zones, explore mixing and measure differential rotation within stars. Oscillation frequencies can also depend on the nuclear reaction rates themselves.

No new missions are in advanced planning at present, but exo-planet search missions will likely provide such useful data. The Kepler mission is providing a wealth of new oscillation data on stars in its field of view. These observations have the capability to provide direct constraints on the stellar properties relevant to nucleosynthesis calculations. A deeper exploitation of these observations for nuclear astrophysics, however, will require further development of diagnostics to relate oscillation frequencies to nuclear reaction rates. This is worthy of future efforts and support.

### Cosmic-Ray Astronomy

Direct Cosmic Ray collectors and experiments are ACE, Pamela, ATIC, AMS-II, and indirectly AUGER. Capabilities include measurement of near-earth Cosmic Ray abundances, and Cosmic-Ray composition at VHE/UHE.

Relevance for nuclear astrophysics is in measuring abundances in CRs at different energies. Future instrumental perspectives include AUGER (ground-based), Jem-EUSO (space).

### Neutrino Astronomy

Current Experiments include IceCube, Amanda for GeV neutrinos, Borexino for MeV neutrinos, and SK-IV. Neutrino detections (time tagged) can provide direct diagnostics of core collapse Supernovae (SN) as well a probe of the solar nuclear energy generation process. Excitingly, future detection of SN neutrinos could provide a resolution of the neutrino mass hierarchy. A further goal for future studies is to directly detect the p-p chain solar neutrinos and directly measure the solar luminosity in neutrinos. This can also provide constraints on the solar core metalicity.

Future instrumental perspectives include KM3Net; Laguna, SNO+, CLEAN.

## Gravitational-Wave Astronomy

Current experiments include Virgo, LIGO, Geo600. The goal of these ground-based experiments is the detection of gravitational radiation in the frequency band from about 50 – 2000 Hz. Current detectors have not yet achieved source detections, and several facilities (LIGO, VIRGO) are in the process of upgrading their sensitivities. Primary source types include SNe in the Galaxy, and compact object mergers (NS – NS, NS – BH) in galaxies out to ~300 Mpc. Other potential sources include periodic, rotating neutron stars (pulsars), and perhaps accreting neutron stars with significant r-mode amplitudes. Space-based observatories (such as the LISA concept) are sensitive in a lower frequency band and not as directly relevant to nuclear astrophysics questions.

The relevance for nuclear astrophysics includes the potential for direct study of binary mergers. For neutron stars the waveforms encode information about the EOS. Predictions are uncertain but ~10 events per year may be seen with the upgraded detectors. Theoretical modeling of mergers has advanced substantially in recent years, and there is some indication from these simulations that such mergers may be an important site for explosive nucleosynthesis (perhaps an r-process site). Another important open question is whether or not such mergers lead to short GRBs?

For nearby (< 50 Mpc) events it may be possible to catch the tidal distortion phase of mergers, and this could provide constraints on the NS radius and EOS. Detections in many cases depend on accurate simulated waveforms so a rigorous theoretical program is important to facilitate and optimize the scientific return.

Future ground-based high frequency detector perspectives include Advanced LIGO 2015+; KAGRA Japan 2015/16+; Advanced Virgo 2015/16+; LIGO India 2020+. A global network of such 2nd generation detectors should enable localization of merger (and other) events and trigger multi-wavelength follow-up observations.