The cosmic origin and evolution of the elements
White paper for the Canadian Long Range Plan for Astronomy and Astrophysics 2020

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Executive Summary

The origin of many elements of the periodic table remains an unsolved problem. Many nucleosynthetic channels are broadly understood, mostly those involving the quiescent stellar evolution phases that can be reliably modeled in spherical symmetry. However, significant uncertainties remain regarding our understanding of certain groups of elements, such as the intermediate and rapid neutron-capture processes, the p-process, or the origin of odd-Z elements in the most metal-poor stars.

Beyond completing our understanding of the origin of the elements, nuclear astrophysics aims to provide reliable predictions for when, where, and which elements are released from dying stars. Coupled with galactic and extragalactic observations of stellar abundances, this approach, known as galactic archaeology, can provide key insights into how galaxies form and evolve. However, the predictive power and fidelity of our simulations are in many cases insufficient to fully deliver on this vision, partly due to the intrinsically three-dimensional (3D) nature of the stellar processes involved. Only recently can dynamic events in the evolution of massive stars be tracked with high-fidelity, 3D hydrodynamic simulations; these have already led to scenarios that can explain the origin of odd-Z elements. Also, asteroseismology is emerging as a powerful tool to validate these new stellar models which will ultimately create 3D progenitors for 3D supernova explosion simulations that are key to understanding the diverse nature of supernova remnant and stellar abundance observations.

On the observational side, the detection in 2017 of a neutron star merger in gravitational waves started the era of multi-messenger gravitational wave astronomy, with multi-wavelength follow-up of that event resulting in the confirmation of neutron star mergers as sites for the rapid neutron capture process, given the broad agreement with theoretical predictions. Since then, gravitational wave observatories have improved in sensitivity, yielding a higher rate of detections. This trend will continue to increase as future upgrades and new facilities come online. Larger sample sizes will test our understanding of these events, requiring reliable predictions, which are computationally very challenging.

Emerging and future multi-wavelength surveys are delivering large data sets of stellar abundances. These have the potential to provide a new window into galactic formation and evolution processes, if they can be paired with reliable stellar yield models. A key element to fulfill this vision is to address the substantial uncertainties in modeling the stellar atmospheres required to determine abundances reliably. Here, 3D hydrodynamic and non-LTE effects still again provide major challenges.

Unraveling the origin of the elements in the context of galaxy formation and evolution requires, on the Astrophysics side, the interplay between observations of stellar abundances in large surveys, detailed studies of individual objects such as supernova remnants, multi-messenger transient follow-up, new generation of 3D hydrodynamic stellar evolution models, and simulations of explosive events using neutrino radiation-magnetohydrodynamics in numerical relativity with nuclear processes. A key ingredient to interpreting observations and generating theoretical predictions is a wide array of fundamental nuclear data properties, such as nuclear reaction cross sections and the equation of state at high densities. For much of the nuclear data of unstable species required, however, only theoretical predictions are available. Experiments with unstable (rare) isotope beams are now becoming possible in the regime relevant to address this critical nuclear data need. Nuclear astrophysics is therefore an interdisciplinary research frontier that integrates all of these sub-fields of Astrophysics and Experimental Physics.
Sustaining Canadian leadership on the observational side in the next decade will require access to transient and non-transient surveys like LSST, SKA, or MSE, support for target-of-opportunity observing in current and future Canadian telescopes, and participation in next-generation X-ray telescopes such as ATHENA. On the theory side, state-of-the-art predictions for the next decade will require an ambitious succession to the Niagara supercomputer to support large parallel jobs.

The lack of funding for postdoctoral researchers and of funding envelopes for such an interdisciplinary collaboration prevents Canadian scientists from competing on a level-playing field with international groups, as existing funding programs do not meet the needs of the field. We propose a funding instrument for postdoctoral training that reflects the interdisciplinary nature of nuclear astrophysics research. We also propose the creation of a national collaborative funding program that allows for joint projects and workshop organization, increasing ties between these communities.

Canada has a long tradition of leadership in nuclear astrophysics, dating back to the work of Alastair Cameron at Chalk River Laboratory in the 1950s. Work by the Canadian community up to 2010 has been comprehensively summarized in the 2010 white paper Nuclear Astrophysics in Canada. Since then, faculty hires in Astronomy and Physics Departments have further boosted activity in the field, including transient observations (Drout, Gaensler, Haggard, Hložek, Sivakoff) and theory (East, Fernández, Siegel), as well as survey science on galactic nucleosynthesis (Bovy, Venn), and nuclear experiments (Christian).

This white paper provides a brief overview of recent activity in the community, highlighting strengths in each specific sub-field. We then provide recommendations to improve interdisciplinary collaboration. Other white papers that relate to this topic are led by Ruan (E035, transients), Spekkens (E042, SKA), Hložek (E023, LSST), Venn (E015, Machine Learning), Côté (E045, Gemini), and Hoffman (E048, Colibrí).

1 The formation and evolution of the elements in stars and galaxies

1.1 Observational diagnostics

The metallicity of the ISM is a direct tracer of galactic enrichment, measuring the abundances in the material that is being incorporated into the currently-forming stellar population. Typically, these abundances are measured from optical emission line studies of HII regions, but careful analysis of dust-to-gas ratios and/or molecular line emission also provide some insights into enrichments (Wilson & Rood, 1994). The original observations of abundance gradients came from extragalactic HII regions where abundance gradients in galaxies have been known for decades (Searle, 1971). These gradients constrain the models of galaxy growth, with the ISM gradients providing complementary information to stellar metallicity. Specifically, ISM studies show the enrichment of gas that is being incorporated into the current generation of stars. The ISM should also show local enrichment by supernovae, and searches for these signatures are becoming possible thanks to refined methods for determining HII region metallicity as well as the deployment of 2D integral field unit spectroscopy from SITEELLE (Rousseau-Nepton et al., 2019), MANGA (Thorp et al., 2019) and MUSE (Figure 1). These signatures of local enrichment provide observational constraints on abundance yield from stars, outflow rates driven by star formation, and mixing processes within the ISM (e.g., Armillotta et al., 2018).

While ISM studies provide unique insights into the current production and distribution of chemical elements within galaxies, stellar abundances derived from spectroscopy probe the complete production history from the birth of galaxies in the early Universe to the current time (Venn et al., 2004). The most metal-poor stars found in the Galactic halo and in dwarf galaxies can even carry the chemical fingerprints of the first stars that formed in the Universe (Frebel & Norris, 2015). The Canadian efforts on the Pristine Survey (Starkenburg et al., 2018; Venn et al., 2019), the new Gemini Observatory blue-sensitive GHOST spectrograph (Pazder et al., 2016), and the Maunakea Spectroscopic Explorer (MSE Science Team et al., 2019) will put Canadian scientists at the forefront of nuclear astrophysics research on the rise of the elements in the early Universe. The Solar System composition is another powerful diagnostic as it includes all stable elements and isotopes (Asplund et al., 2009). It is the only system...
1.2 Nuclear processes in galaxy evolution

Galaxy formation and evolution plays a central role in studying the evolution of the elements (Mackereth et al. 2019). The mechanical energy and radiation released into the ISM by stars shape the internal structure of galaxies and regulate its star formation (e.g., Hopkins et al. 2018). This energy deposition is triggered by various nuclear processes, and because those processes are responsible for creating the elements and isotopes, the evolution of galaxies and the evolution of the elements are intrinsically linked together. Understanding the origin of matter in the Universe therefore requires state-of-the-art 3D hydrodynamic simulations of galaxies, and high-performance computing facilities such as the Niagara supercomputer cluster at Compute Canada (4).

Canadian researchers are leading international collaborative efforts to combine expertise and create connections between nuclear astrophysics and galaxy simulations (e.g., Coté et al. 2018a). Including our nuclear astrophysics expertise into cosmological simulations of galaxies (e.g., Starkenburg et al. 2017) is necessary to best interpret the chemical abundances of metal-poor stars and to maximize the scientific returns of major Canadian investments such as Pristine, GHOST, and MSE. In addition, this will create an innovative bridge between the physics of the early Universe and Canadian nuclear physics experiments.

The foundation of chemical evolution in galaxies is the life-cycle of stars and the mixing of elements within the galactic gas (e.g., Nomoto et al. 2013). The next frontier is a better quantification of inhomogeneous mixing within the turbulent and multi-phase ISM (e.g., Rennehan et al. 2019), and a better understanding of the physical mechanisms by which chemical elements are transferred from one generation of stars to another. Numerically addressing the fundamental interactions between stars and their environment will complement the unique observa-
1.3 Multi-dimensional stellar models and nucleosynthesis

Canadian researchers are leading with their collaborators the frontier of 3D hydrodynamic simulations of stellar convection in the late phases of low-mass (Herwig et al., 2014) and massive stars (Jones et al., 2017). Such simulations provide key input into comprehensive stellar model and yield calculations (Ritter et al., 2018b) that are input to the galaxy models described in §1.2.

Realistic 3D simulations of convection interacting with nuclear production processes activate unique new nucleosynthesis pathways away from stability, thereby providing the astrophysical environment for the formation of rare isotopes that are now possible to probe experimentally at TRIUMF-ISAC (§3.1). For example, 3D simulations have been instrumental in establishing the new role of the intermediate n-capture process to explain abundance patterns observed in metal-poor stars (Denissenkov et al., 2019). The urgent need of new nuclear physics data has already triggered nuclear physics experiments at TRIUMF (§3.1) and at other major nuclear physics labs (e.g. NSCL/MSU/JINA).

A very exciting new development is the prospect of comparing the 3D simulations outputs directly with space-based asteroseismology observations from TESS, and in the future Plato. In 2018, as part of the early user access to the Compute Canada Niagara super-computer, the UVic group performed the highest-resolution 3D simulation of core convection in a massive star. Subsequent analysis of the frequency spectrum of the internal gravity waves excited in the stable layer above the core convection showed astonishing agreement with recently discovered asteroseismic features observed in massive stars (Figure 2).

Figure 2: Left: A part of a thin central-plane slice of the horizontal velocity component of a 3D simulation of core convection in a massive star. In the upper-right part of the partial image the internal gravity waves in the stable layer can be discerned. Right: The associated spectrum of the internal gravity waves in the simulation are reproducing astonishingly well the asteroseismic, observed low-frequency excess recently discovered in massive stars by Bowman et al. (2019).

|YouTube movies: | [https://bit.ly/2HzTKtw](https://bit.ly/2HzTKtw) |
| R&D Magazine: | [https://bit.ly/2K95Gac](https://bit.ly/2K95Gac) |
Figure 3: Left: optical/IR spectral energy distribution for the kilonova from GW170817 as a function of time, showing the shift from blue optical to near infrared within a few days (from Drout et al. 2017). Right: kilonova light curve predictions for generic BH-NS mergers in various spectral bands (from Fernández et al. 2017). The rapid color evolution of the light curve over a few days is a consequence of the sensitivity of the optical opacity to the presence of heavy $r$-process elements.

2 Explosive transients

2.1 Neutron star mergers: gravitational waves and $r$-process nucleosynthesis

Compact object mergers are the main target for direct detection in gravitational waves by ground based interferometers. Neutron star mergers in particular had long been predicted to be a site for the $r$-process (Lattimer & Schramm, 1974), and in 2017 they were first detected in both gravitational and electromagnetic waves (Abbott et al. 2017; multiple Canadian co-authors). The observations were in broad agreement with state-of-the-art theoretical predictions for the kilonova counterpart, providing evidence for the operation of the $r$-process in these events (Figure 3).

At present, the LIGO and Virgo observatories are carrying out their 3rd observing run, and will soon be joined by the Japanese KAGRA observatory. Future observing runs and upgrades are planned for the next decade, with steady increases in sensitivity (Abbott et al., 2018). Extensive electromagnetic follow-up capabilities are in place worldwide, with public alerts issued within seconds of a gravitational wave detection. The Canadian community played a key role in the follow-up of GW170817 (e.g., Drout et al. 2017, Haggard et al. 2017) as well as in formulating theoretical predictions for and interpretation of electromagnetic counterparts (e.g., Lehner et al. 2016, Siegel & Metzger 2017, Fernández et al. 2017, Côté et al. 2018b). At present, Canadian teams have standing follow-up allocations on Gemini, CFHT, Chandra and the Jansky VLA. For more information, see white paper led by Ruan (E035). Reliable theoretical predictions for the electromagnetic signal and nucleosynthesis yield from neutron star mergers in the next decade will require simulations that combine numerical relativity, neutrino-radiation-magnetohydrodynamics, and nuclear processes. These calculations are carried out at the limit of current capabilities, requiring compute clusters of the scale of Niagara or even larger (§4).
2.2 Type Ia Supernovae: progenitors and remnants

Type Ia supernovae (SNe Ia) are a vital component of nucleosynthesis, in particular being responsible for much of the iron in the Universe (e.g., [Hitomi Collaboration et al. 2017]). They are now firmly understood to be the thermonuclear explosions of carbon-oxygen white dwarfs (WD) (Maoz et al. 2014). However, it remains unknown whether they arise due to one hot and luminous WD growing slowly via accretion and surface nuclear-burning until reaching $\sim M_{\text{Ch}}$ (“single-degenerates”) or via the interaction and merger of two WDs (“double-degenerate”), or some combination thereof. While there has been great progress in modelling binary populations (e.g., Chen et al. 2014) and WD explosions (e.g., Zhu et al. 2015), fundamental uncertainties in binary stellar evolution (e.g., common envelope physics, Ivanova et al. 2013) and explosion simulations have held back our understanding of how often these scenarios occur, and whether they produce explosions which resemble SNe Ia.

A number of recent breakthroughs in modelling WD accretion (e.g., Denissenkov et al. 2017) and the impact accreting WDs have on their environment (e.g., Woods et al. 2017) have begun to disfavour the classic single-degenerate model as the dominant channel. On the other hand, however, near-$M_{\text{Ch}}$ explosions consistent with a single-degenerate origin appear to be essential sites for the production of $^{48}\text{Ca}$ and other neutron-rich isotopes (e.g., Seitenzahl & Townsley 2017); abundance measurements of the Perseus cluster from the X-ray telescope Hitomi favour a mixture of sub-$M_{\text{Ch}}$ and near-$M_{\text{Ch}}$ explosions (Hitomi Collaboration et al. 2017).

Going forward, multi-wavelength observations of supernova remnants (SNRs) can provide a powerful means of assessing the viability of differing progenitor scenarios on a case-by-case basis, while providing a direct probe of the heavy elements synthesized in their explosions. Observations of optical emission lines (both from space, e.g., HST, and the ground, e.g., CFHT, Gemini) in the vicinity of SNRs can provide a powerful constraint on the temperature and luminosity of their progenitors (e.g., Graur & Woods 2019), while simultaneously providing crucial insights into the long-term evolution of the remnant, the physics of the shock, and the nature of the surrounding ISM (e.g., Blair & Raymond 2017). At the same time, X-ray spectroscopy provides an especially powerful probe of the yields of SNe Ia, and comparison with explosion models allows one to determine the mass and structure of the WD at the time of explosion (e.g., Dave et al. 2017). In the next decade, multi-wavelength spectroscopy from the optical to gamma rays, high-resolution imaging, and improved modelling will all be essential to definitively identify the viability and relative contributions of differing progenitor models. In particular, the availability of quantum calorimeter (e.g., XARM, Athena) X-ray observations of SNRs will provide a qualitative improvement of our understanding of element distribution in these explosions (§4).

2.3 Core-collapse supernovae: progenitors, explosion, and remnants

The explosions of massive stars play a key role in the evolution of the Universe, by enriching it with heavy elements. Recent progress in understanding the explosion mechanism has revealed that asphericities originating in pre-supernova stellar convection constitute a major uncertainty in modelling the supernova explosion (e.g., Janka et al. 2016). 3D simulations (§1.3) can now realistically characterize the emergence of such asphericities in dynamic mergers of convective O- and C-burning shells (Andrassy et al. 2018), and the associated dynamic nucleosynthesis can explain for the first time the observed galactic chemical evolution of potassium and other odd-Z elements (Ritter et al. 2018a).

An opportunity emerges in Canada now by connecting the advances in 3D stellar hydro with state-of the art explosion simulations of successful (e.g., Fernández 2015) and failed supernovae (Fernández et al. 2018), exploring the potential of collapsars as key sites for the $\tau$-process (Siegel et al. 2019), and diagnosing the progenitor, SN explosion mechanism and engine with X-ray observations of SNRs (e.g., Braun et al. 2019 – see Fig. 1). High-resolution X-ray spectroscopy is particularly needed to unveil the SN explosion mechanism, as demonstrated in a brief Hitomi observation of the LMC SNR N132D (Hitomi Collaboration et al. 2018). Furthermore, there is significant Canadian expertise (both observational and theoretical) in studying the diversity of compact stellar remnants, their evolution and their connection to their supernovae (e.g., Zhou et al. 2019, Hebbar et al. 2019, Rogers & Safi-Harb 2016). The next leap in probing nucleosynthesis yields in core-collapse supernovae and connecting the SNR to its progenitor requires a combination of multi-wavelength, high-resolution spectroscopy
(particularly in the optical/UV and X-rays which will be provided by JWST, CASTOR, XRISM and ATHENA), combined with improved modelling in 3D (e.g., Moumen et al. 2019).

2.4 Nuclear burning on neutron stars

Thermonuclear reactions on neutron star surfaces, and in their upper crusts, provides a rich regime of intriguing physics. A recent, exciting example is the theoretical discovery that cycles of electron capture and decay (Urca reactions) should occur in neutron star crusts, as well as in the core, leading to rapid cooling (Schatz et al. 2014). This theoretical development contrasts with recent observations which show, paradoxically, that neutron star crusts require some source of variable extra nuclear heating that is not currently understood, based on observations of the cooling of neutron stars after extended periods of accretion (e.g., Deibel et al. 2015). Observational progress requires high-sensitivity, high-spatial-resolution X-ray observations of cooling neutron stars over periods of years to decades (see, e.g., Brown & Cumming 2009).

Faster burning on neutron star surfaces generates X-ray "bursts", which show a variety of unusual behaviours that we do not currently understand. Burst oscillations are variations, near (but often not exactly at) the neutron star spin frequency, observed during parts of bursts. Although we have models interpreting them, e.g. as burning fronts, some burst oscillations strongly disagree with these models (e.g., Mahmoodifar et al. 2019). Some bursts show evidence of nuclear burning products in the best (though quite limited) X-ray spectra, but the identity of the burning products cannot yet be determined (e.g., Strohmayer et al. 2019). To make progress on understanding nuclear burning in bursts, we need X-ray observatories with very large effective areas (to catch many photons in the short bursts), and preferably high spectral resolution (to resolve lines). NICER is making progress now, but we need the higher effective area of ATHENA, eXTP, STROBE-X, and/or Colibrì to solve some of these issues (§ 4).

3 Experimental nuclear astrophysics

3.1 Nuclear data for nucleosynthesis

TRIUMF (www.triumf.ca) is Canada’s particle accelerator centre in Vancouver, BC. Several TRIUMF research scientists (B. Davids, I. Dillmann, R. Kruecken, A. Kwiatkowski, C. Ruiz) and Canadian University professors (e.g. A. Chen, D. Muecker, R. Kanungo and G. Christian) conduct active nuclear astrophysics programs at the TRIUMF-ISAC (radioactive beam) facility, as well as at facilities abroad. The focus of the measurements are astrophysically important reaction rates of stable and radioactive nuclei, as well as the determination of properties of exotic, short-lived nuclei like half-lives, branching ratios, masses, and specific nuclear structure features far off stability.

Almost all experimental setups at the ISAC facilities devote part of their research time to help solving questions around the origin of the elements, with focus on measuring important reaction rates for nova and X-ray burst nucleosynthesis [e.g. $^{19}$Ne($p, \gamma$)$^{20}$Na (Wilkinson et al. 2017), $^{38}$K($p, \gamma$)$^{39}$Ca (Lotay et al. 2016), (Christian et al.) 2018] measured with the DRAGON recoil separator], nuclear properties of short-lived isotopes for the rapid neutron-capture ($\nu$) process [e.g. decay half-lives of neutron-rich $^{128-130}$Cd (Dunlop et al. 2016) measured with the GRIFFIN spectrometer], and in the near future also the indirect determination of neutron-capture cross sections of radioactive nuclei for the intermediate-neutron-capture ($\iota$) process [e.g. upcoming experiments with the EMMA recoil mass spectrometer in 2020/21 to constrain neutron-rich $^{137,139,142}$Cs($n, \gamma$) and $^{139}$Ba($n, \gamma$) reactions]. The latter are crucial inputs in nucleosynthesis calculations from core-collapse and neutron star merger simulations.

The presently constructed new “Advanced Rare IsotopE Laboratory” (ARIEL[3]) will triple the radioactive beam capabilities at ISAC within the next decade. Particularly the nuclear astrophysics program will greatly benefit from the possibility to carry out longer beam times and to produce cleaner radioactive isotope beams.

[3]https://fiveyearplan.triumf.ca/platforms/ariel/
3.2 Neutrino Astrophysics

SNOLAB (www.snolab.ca) is the Canadian underground science laboratory specializing in neutrino and dark matter physics and is located in the Vale Creighton Mine near Sudbury ON (TRIUMF scientists are also involved in the domestic neutrino program at SNOLAB).

Canada has a dedicated neutrino detector for core-collapse supernovae (HALO, Zuber 2015), which is part of the global supernova early warning system (SNEWS). A galactic core-collapse supernova will result in a strong neutrino signal for many detectors, providing information about the supernova engine which is not available through any other means (gravitational waves probe other aspects of the explosion mechanism, and photons can only be observed once the shock reaches the stellar surface).

Neutrinos from a Galactic supernova will also be observable with the new generation SNO+ detector (The SNO+ collaboration 2019b[a]) and the upcoming “next Enriched Xenon Observatory” (nEXO). Canadian scientists are also involved in other world-class international neutrino experiments, such as TK2 and the upcoming Hyper-Kamiokande in Japan. These detectors are also capable of probing Solar neutrinos, which directly diagnose nuclear reactions in the core.

4 Resources needed and recommendations

1. Participation in observational surveys (transient and non-transient). Sustaining Canadian leadership in this field requires participation in international surveys and facilities including LSST, Gemini, SKA, and next-generation X-ray instruments such as ATHENA. See also white papers led by Ruan (E035), Spekkens (E042), Côté (E045) and Hoffman (E048).

2. More Niagara-scale computing power. Taking the next step in solving the theoretical challenges in the field will require more machines of similar or higher caliber for large parallel jobs (see Box 3 below).

3. Collaborative grants. As demonstrated in this WP, nuclear astrophysics requires coordination and interplay between different sub-areas of Astrophysics and also with Experimental Physics. The field would greatly benefit from new funding programs for interdisciplinary work (e.g., funding workshops, see Box 3 below).

4. Postdoctoral funding. The interdisciplinary approach needed to tackle key questions in Nuclear Astrophysics needs to be reflected in the HQP training. The JINA example (Box 3 below) shows that the most successful PDFs have been exposed during their training to multiple aspects of nuclear astrophysics research, and are therefore able to identify the best opportunities and create new science outcomes. We recommend that the collaborative nuclear astrophysics funding instrument proposed above also includes a component for postdoctoral fellows that are specifically dedicated to work in at least two complementary areas outlined in this WP, and under the umbrella of the collaborative research grant. The CITA National Fellowship and the NSERC Postdoctoral Fellowship, while important for attracting elite researchers to Canada, are not sufficient to meet the needs of the field. See also white paper led by Ngo (E028).

1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?

This research program addresses key open questions in our understanding of the origin of the elements. It combines detailed simulations of astrophysical sites in stars and stellar explosions with nuclear physics experiments and theory, in order to make predictions that are tested with large surveys and detailed spectroscopic abundance observations. The research also relates to broader questions in astronomy, such as the formation and evolution of the early universe and of galaxies. Stellar objects are used as laboratories to study physics in extreme regimes such as neutrinos in supernova explosions and/or strong gravity environments where detectable gravitational waves are produced.

https://snews.bnl.gov
2: What are the main scientific risks and how will they be mitigated?

The main risk involves not carrying out this research program and/or falling behind international competition. On the theoretical side, ensuring that more computing power of Niagara scale or larger continues to be provided by Compute Canada or some other national organization is key. On the observational side, Canadian participation in large surveys like LSST or MSE, funding CASTOR, ensuring the availability of target-of-opportunity capabilities in existing and future Canadian telescopes, and having access to next generation X-ray instruments like Athena will ensure that Canadian researchers can carry out the groundbreaking observations needed to lead in the field. Finally, having a separate postdoctoral funding program will allow many small Canadian teams – that rely mostly on students and/or external collaborations – to grow to the next level and compete on a level-playing field with European or US groups.

3: Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?

A substantial number of new hires at Canadian institutions in recent years have led to nuclear astrophysics emerging as a significant Canadian strength. Our expertise comprises most of the research areas needed to attack the most exiting problems in the field. On the Astrophysics side (§1 and §2) this expertise resides in researchers at Universities (including UVic, UManitoba, UToronto, McGill, UAlberta, Perimeter/Waterloo/Guelph) and on the Nuclear and Neutrino Physics side (§3) in scientists at TRIUMF and SNOLAB. Canadian researchers have been involved in the leadership of the US NSF Physics Frontiers Center JINA, and in science collaborations such as NuGrid. Several Canadian scientists based overseas also have significant expertise in this field and often collaborate with domestic researchers.

Canadian activities are presently held back from reaching their full potential due to the lack of dedicated funding instruments that promote and enable the required networking and coordination activities. In the US the NSF Physics Frontier Center Joint Institute for Nuclear Astrophysics (JINA) has (with some Canadian participation) been extremely successful in defining and driving the field. As JINA is engaging into the fourth renewal campaign there is a great opportunity to fund a complementary Canadian Virtual Centre that would be closely connected to and leveraged off JINA.

High performance computational resources are provided through Compute Canada and regional consortia, as well as via international collaborations (such as NERSC-DOE and NSF). The Niagara supercomputer has been transformational for enabling some of the key new results highlighted in this white paper, which would not have been possible with previous-generation facilities. A new community of computational astrophysics has emerged which is addressing theoretical challenges on stellar evolution, gravitational wave Physics, explosive events, and galaxy evolution. It is of paramount importance that there is an appropriate succession path for Niagara, enhancing on the existing capabilities according to technical opportunities. In order to maintain the presently reached status, as an absolute minimum a next generation machine needs to have three times the computing capability by 2023 and the capability must be nine-fold by 2028. As a comparison, the 2019-launched NSF machine Frontera (TACC) has 5.3 times as many nodes as Niagara, and each of them is about 1.7 times more powerful.
4: Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?

The groups and communities represented in this WP are coordinating informally. The community is eager to collaborate more effectively, but, as stated in the previous box, what is missing is a collaborative funding instrument that matches the needs of nuclear astrophysics. This would bring the Canadian collection of efforts at several institutions, including TRIUMF/SNOLAB and Universities, and the associated international collaborators together, and enhance the impact of Canadian participation in international projects, mostly with the US, Europe, and Japan.

5: Will this program position Canadian astronomy for future opportunities and returns in 2020-2030 or beyond 2030?

Given existing expertise in the field, the investments that we propose will position Canada as a leading player worldwide in the next decade: carrying out the state-of-the-art numerical simulations needed to predict nucleosynthetic yields from stellar to galactic scales, following up multi-messenger transients at increasing detection rates, surveying the Galaxy and beyond to reconstruct the chemical enrichment history of the Universe, and exploring the frontier properties of nuclei and particles.

6: In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?

Investment in more supercomputing capabilities of Niagara scale or larger will not only benefit our field, but all other fields of Astrophysics (and other sciences) in which significant parallel computing power (jobs of more than 1000 tasks) is required. Observational facilities and surveys are generally multi-purpose, thus Canadian participation in any of them will provide benefits beyond our subset of the community. A new program for funding postdoctoral researchers will help retain HQP in Canada that took significant investment to train (instead of giving it away to our competitors or international collaborators), and will also help attract international talent, bringing in expertise that would otherwise not be found in Canada.

7: What are the main programmatic risks and how will they be mitigated?

Currently there is a disconnect between the nuclear/particle experiment side and the astronomy side in Canada. We need resources and a platform to stimulate and enable these inter-disciplinary collaborations. New funding opportunities for workshops will help gather these communities and provide a larger pool of HQP to recruit from. Combining these types of events with a new program for postdoctoral funding, we can transfer expertise from one community to the other and maximize the benefits of existing investments by each community.

8: Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, outreach or education?

A key benefit of our recommendations is improvement in interdisciplinary collaboration among the various sub-fields of astronomy involved and with the nuclear / particle experimental community. This will strengthen HQP training in a wide range of skills. In particular, our expertise in high-performance computing, combined with the diversity of our group, can provide a fertile ground for increasing the participation of under-represented groups in computing-intensive areas such as Data Science.
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