1 Big Bang Nucleosynthesis

1.1 Significant recent progress

Since the 1999 White Paper, cosmology and particle physics have seen major progress and revealed profound surprises. Big-bang nucleosynthesis (BBN) has played a central role in these developments. BBN has been cast in a new light in the era of precision cosmology: BBN has become a much sharper probe of physics beyond the Standard Model of particle physics and of cosmology. For example, measurements of the cosmic microwave background (CMB) will soon open the way to powerful and clean tests of neutrino physics using BBN. Moreover, the primordial 'lithium problem' increasingly seems to point to new physics at play in the early universe.

The simplest, 'standard' version of BBN (Standard Model of particle physics and the standard cosmology) has only one free parameter: the cosmic baryon density $\Omega_b h^2$, or equivalently the baryon-to-photon ratio $\eta = n_b/n_\gamma$. BBN produces only the lightest nuclides, and consequently requires a far smaller and thus simpler nuclear reaction network than typically found in stellar nucleosynthesis calculations; indeed, the light-element abundances are sensitive to only 11 reactions as well as the neutron lifetime. Moreover, the cross sections for these reactions are all measured in the laboratory at the relevant energies. Consequently, BBN makes tight predictions for light element abundances, and it is feasible to do rigorous error analysis of the predictions and to express the results in terms of likelihood distribution function.

BBN has a strong interplay with the precision determination of cosmological parameters via measurement of CMB anisotropies. Since the first WMAP data release in 2003, the CMB has provided the best cosmic "baryometer," independently of BBN. The BBN and CMB determinations of the cosmic baryon density are in broad agreement; this rough concordance represents a great success of the basic hot big-bang model and a triumph for nuclear astrophysics. Furthermore, the CMB holds the promise (through measures of anisotropies at high multipoles) of also determining the cosmic helium abundance and the number of relativistic degrees of freedom (e.g., neutrinos). Indeed, the South Pole Telescope has presented determinations of these parameters, but with large uncertainties; with the upcoming *Planck* data release, these measurements will become competitive.

Using the precise CMB-determined cosmic baryon density, standard BBN becomes a zero-parameter theory, and makes tight predictions for the light-element abundances. How do these compare with observations? High-redshift deuterium observations agree quite well, and low-redshift helium observations are also consistent. But the predicted abundance of ^{7}Li is *higher* than that observed in Galactic halo stars by a factor 3–4, or $4 - 5\sigma$. This discrepancy marks the primordial 'lithium problem.' Yet this 'problem' is in fact a success story for nuclear astrophysics: we have only become aware of this discrepancy due to the close interplay among theory, observation, and experiment.

1.2 Compelling open questions

- **Does the lithium problem point to new physics?** Taken at face value, the lithium problem suggests new physics at play in the early universe, making a large perturbation to the lithium abundance but not to the abundances of deuterium or helium. Such perturbations can arise due to dark matter decays and/or annihilations; minimal Supersymmetry models can provide such perturbations. Changes in the fundamental constants can also solve the lithium problem.

In fact, BBN provides a strong constraint on any Beyond the Standard Model scenarios that allow dark matter decays and/or annihilations during or after light-element production. In general, the result of these perturbations is to *worsen* agreement between light elements and observations. Such light-element constraints on Supersymmetry are powerful and are complementary to accelerator probes, and extend to parameter regimes inaccessible to the LHC.

- **Will the CMB+BBN reveal new neutrino physics?** *Planck* data will reveal the cosmic baryon density, primordial helium abundance, and number of relativistic degrees of freedom (expressed, e.g., as the effective number $N_{\nu,\rm eff}$ of light neutrino species), based solely on the clean determination of CMB anisotropies. BBN predicts light-element abundances as a function of the baryon density and–going beyond the standard model–of $N_{\nu,\rm eff}$. Thus the *CMB data alone* will provide a zero-parameter test of the consistency of the BBN prediction, and will thus probe new neutrino physics and/or new physics of any other "dark radiation."

1.3 What work is necessary to advance the field?

- **Nuclear experiment.** BBN predictions–both within and beyond the standard picture–are only as reliable as the nuclear inputs used in the calculations. While these are quite well-studied, a few important reactions remain outstanding and merit experimental study. (1) The neutron lifetime remains an important component of the error budget for all light elements. (2) Some otherwise subdominant reactions could become important if their rates were enhanced due to resonances: $^7\mathrm{Be} + d \to {}^9\mathrm{B}^*$, $^7\mathrm{Be} + t \to {}^{10}\mathrm{B}^*$, and $^7\mathrm{Be} + {}^3\mathrm{He} \to {}^{10}\mathrm{C}^*$. (3) Calculations for nonstandard BBN due require accurate determinations of spallation and photodisintegration reaction cross sections and their uncertainties, spanning energies up to 1 GeV.

- **BBN theory.** (1) As extragalactic and CMB determinations of the cosmic helium abundance improve, there is a need for improved precise calculations of the primordial ^{4}He abundance and its uncertainties; this involves numerous subtle effects that are challenging to compute accurately and completely. (2) The effects of neutrino oscillations and their interplay with effects of nonstandard neutrino properties (e.g., CP violation, nonzero chemical potential) must similarly be characterized accurately and completely. (3) A systematic comparison of BBN codes and their uncertainties would be a great service to the field.

- **Astronomical observations.** The possibility remains that the lithium problem could reflect systematic errors in the inference of the primordial lithium abundances from observations of Milky Way metal-poor stars. Indeed, the "Spite plateau" in lithium abundances recently has been shown to "melt down" at very low metallicity ([Fe/H] $<$

−3), indicating that destruction of lithium occurs in at least some of these stars. On the other hand, no lithium abundances are found above the plateau. An understanding of these trends is critical. Fortunately, an independent method has very recently been found to testing lithium observational systematics. Lithium has been detected in the interstellar medium of the Small Magellanic Cloud. The SMC measurement marks the first extragalactic lithium measurement and gives an abundance comparable to that of Milky Way stars with similar metallicity, suggesting that large depletion and/or systematic errors are not plaguing the stellar observations. Future observations of interstellar lithium in low-metallicity galaxies hold great promise of independently determining the primordial ^{7}Li abundance, and possibly separately determining the lithium isotopes and thus providing unique and robust new information on the ^{6}Li abundances.

Deuterium observations in high-redshift quasar absorption line system provide a strong probe of the cosmic baryon density and test of BBN. Unfortunately, suitable systems are rare: after nearly two decades of effort, ~ 10 systems give solid D/H abundances. Clearly there is a need for more. Furthermore, the dispersion among the observations suggests either that unknown systematics are present, or that there are real and unexpected sources of astration. Indeed, there is similarly anomalous dispersion in D/H abundances measured in the local ISM.

Helium-4 observations in extragalactic HII regions are also dominated by systematic uncertainty. Fortunately, *Planck* CMB measurements should give a competitive new measurement of primordial helium.

1.4 Interaction with other subfields

- **Neutrino and particle physics.** BBN remains our earliest reliable probe of the universe, and is sensitive to all four fundamental interactions. Consequently BBN has long been a testbed for probing new physics; BBN will become a stronger probe as theory, nuclear experiment, and observations improve. In addition to the longstanding use of BBN as a laboratory for neutrinos physics, BBN places interesting constraints on much physics beyond the Standard Model, including Supersymmetry.

- **Nuclear Theory.** Standard BBN reactions all involve only nuclides with reactants and compound states hving $A \leq 11$. For these light species, direct calculation of nuclear structure is possible using quantum monte carlo techniques, which can give important guidance in the reaction rates and possible resonant behaviors.

- **Stellar evolution and astrophysics.** The lithium problem currently hinges on the evolution of lithium in halo stars, and its spectral signature. Better theoretical and observational signatures of lithium depletion and diffusion are critical.

- **Chemical Evolution.** BBN provides the initial conditions for chemical evolution. Moreover, BBN is the only source of deuterium, which makes D/H measurements in non-primordial settings a particularly powerful probe of stellar processing.

- Dark Matter. Dark matter decays and/or annihilations during or after BBN can alter light element abundances. BBN thus has an important interplay with dark matter experiments, both indirect techniques (e.g., searches for γ-ray signals from annihilations) and for direct searches.

2 Galactic Chemical Evolution

2.1 Significant recent progress

There have been several important observational advances. Perhaps most profoundly, the Sloan Digital Sky Survey, its follow-on programs, and high-resolution spectroscopic surveys have enabled incredible observational advances with regards to Galactic stellar populations. SDSS has enabled the discovery of two kinematically and chemically distinct components of the Milky Way stellar halo, a population of ultra-faint dwarf galaxies that have extremely low-metallicity stellar populations whose formation was truncated very early in the age of the Universe, and clear signatures of galaxies merging into the Milky Way (including stellar streams and "ringing" of the Galactic disk). Furthermore, these surveys have produced tremendous insights with regards to the early evolution of the Milky Way's progenitors: several interesting low-metallicity populations have been discovered, including carbon-enhanced metal poor stars, and other chemically peculiar stellar populations that have distinct neutron-capture signatures. Nebular spectroscopy has enabled the study of the nucleosynthesis of neutron-capture elements in both galactic and extragalactic planetary nebulae and HII regions. And, finally, low-metallicity, high-redshift Damped Lyman-Alpha systems that are metal-poor, but contain both enhanced carbon and r-process elements have been discovered. All of these observations provide crucial clues to galactic chemical evolution.

Theoretically, ever-growing computational capabilities have resulted in tremendous insights. This includes high-resolution simulations of Population III star formation demonstrating that Population III stars can form in binary or higher-multiple systems. A critical step forward has been made by using semi-analytical models that couple N-body simulations stellar evolution models, as well as full chemodynamic simulations that include both the hydrodynamical and stellar history of a galaxy and its progenitors. These models incorporate chemical evolution models with detailed yields, and enable the comparison of both kinematic and chemical behavior of stellar populations.

2.2 Compelling open questions

A range of important open questions have been identified, which we have sorted into categories:

- **IMF:** Is the stellar initial mass function invariant over time, with metallicity, and/or galaxy type?

- **ISM mixing:** How effective is the mixing of the interstellar medium? in other words, how much of the observed variation in nucleosynthesis at low metallicity is due to distinct progenitor populations vs. inhomogeneous mixing? Similarly, at later times, what is the role of radial mixing in the Milky Way disk?

- **Pop III stars:** What is the initial mass function of Population III stars, and does it evolve over time? What is the typical multiplicity and distribution of rotation rates for primordial stars? Is there a truly unique nucleosynthetic signature of Population III stars, and can we infer Pop III stellar properties from low-metallicity stellar abundances?

- **Galaxy formation:** To what extent can the Milky Way be regarded as a template for galaxies of its type? How did the components of the Milky Way stellar halo form? What are the signatures of galaxies merging into the MIlky Way, and what do they tell us? Is there a fundamental explanation for the differences in enrichment of the Milky Way vs., e.g., the Magellanic clouds? Can hydrodynamic GCE models reproduce the mean trends and the range of variability seen in the solar neighborhood and in star clusters?

- **Stellar populations:** What are the progenitors of the carbon-enhanced metal poor (CEMP) stars, particularly those at the lowest metallicities, and why are there more CEMP stars as one goes to lower [Fe/H]? What are Type Ia supernovae, and how do their populations evolve? How varied can supernova explosions be in their nucleosynthetic outputs? What is the site or sites of the r-process? What are the limits of chemical variability for stars hosting exoplanets?

- **Nucleosynthesis calculations:** What are the key ingredients for modeling the evolution of Population III stars, and for the most massive stars? What is the contribution of intermediate-mass (1-8 Msun) stars to the galactic/extragalactic neutron-capture elements? What are the effects of binary stars and cosmic rays on nucleosynthesis? What is responsible for the behavior of neutron-capture elements at low metallicities?

2.3 What work is necessary to advance the field?

Observationally, photometric and medium-resolution spectroscopic surveys of large numbers of stars are well underway. The most crucial need is for high resolution spectroscopic follow-ups of metal-poor field stars, dwarf galaxies (particularly ultra-faint dwarf galaxies), open clusters, and globular clusters. This will help to establish in detail the star formation history of these objects, as well as the frequencies of various nucleosynthetic phenomena (e.g., carbon-enhanced metal poor stars, r-process enhanced stars, etc.), and their orbital and binary properties. A critical (and related) theoretical advance that is required is for more careful modeling of stellar model atmospheres, particularly in 3D, to study the effect that this has on hard-to-measure elemental and isotopic abundances.

The most critical theoretical advance needed is for libraries of stellar models for GCE evolution using consistent (and possibly open-source) modeling tools and nuclear reactions, densely covering mass and metallicity space. In particular, the field needs improved nucleosynthetic yields for metal-poor and metal-free stars and for intermediate-mass (i.e., asymptotic giant branch) stars. Related to this, there is a critical need for a better understanding of mixing physics in stars and of stellar mass loss, and for an r-process nucleosynthetic models that can explain both the actinide boost phenomenon and the r-process observations in metal-poor stars. On a larger scale, there is a clear need for detailed models of the formation and star formation history of the fundamental building blocks of the Milky Way, including dwarf-like galaxies, and particularly the ultra-faint dwarf population. A related need is for the development of chemodynamical predictions for large spiral galaxies such as the Milky Way and M31, and for techniques to make detailed comparisons between such models and upcoming large astronomical surveys such as LSST, GAIA, HERMES, etc.

Experimental advances that are required include the need for better measurements of helium-burning reactions (the triple alpha and $^{12}C(\alpha, \gamma$ rates in particular), which lead to large uncertainties in massive star yields. In addition, there is a need for better reaction rates for neutron-rich elements near the r-process path.

2.4 Interaction with other subfields

The study of galactic chemical evolution interacts with other subfields of nuclear astrophysics in several ways.

- **Supernova modeling:** Understanding the explosion mechanisms (i.e., explosion energies and predicted nucleosynthetic yields) of core collapse supernovae, which likely requires 3D modeling. Similarly, the progenitors and explosion mechanism for Type Ia supernovae. Also quite useful would be some estimate of the uncertainties from not understanding supernova explosion mechanisms and nuclear reaction rates.
- **Nucleosynthesis:** A better understanding of the site of the r-process, s-process yields from asymptotic giant branch stars, and the abundances of isotopes as well as elements alone.
- **Nuclear and atomic physics:** Measurements relating to the high-density equation of state, as applied to Type II supernovae. Models of ionization states for neutron-capture elements in nebulae, as well as atomic data pertaining to these elements.
- **Cyber-infrastructure:** Techniques for generating, aggregating, analyzing, and curating massive amounts of data from observations, experiment, and simulations. (The planned introduction of 100Gb internet nationwide will be critical to collaboration and to making progress in the era of Big Data.)