ASTROPHYSICS

Seeing stars

How did the first stars form, and the early Universe develop? A meeting of minds from astronomy, cosmology and nuclear physics achieved some consensus on what we know, and what we don't.

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Last month, more than 60 astronomers, cosmologists and nuclear physicists gathered at the University of Washington's Institute for Nuclear Theory in Seattle for a conference* to discuss progress in understanding the physics of the first stars and the evolution of the early Universe.

In the current picture of structure formation, in the cosmology of a Big Bang with cold dark matter, the first stars form with primordial abundances (hydrogen, helium, lithium and negligible amounts of heavier elements) in the first dark-matter halos to collapse from the initial cosmic-density fluctuations. The development of these primordial perturbations into bound protogalaxies capable of forming stars depends on their ability to form molecular hydrogen from the primordial gas, radiate away their thermal energy with infrared emission from H_2, and cool into dense, self-gravitating clouds. Because the physics that is required to determine the mass scale for primordial star formation is so complex, with critical consequences for later structure, the distribution of stellar masses — which astrophysicists call the initial mass function (IMF) — was a central issue at the meeting.

A specific, testable prediction of the first-stars IMF has been deemed the "holy grail" for theorists interested in unravelling this tangle of early-Universe physics. For the observers of long-lived, chemically primitive stars in the Milky Way, direct empirical constraints on the IMF, derived from the expected unique nucleosynthetic signatures of stellar mass, are the ultimate prize. Significant discussion centred on how to move these two tracks forward and integrate them into a self-consistent picture of star formation at the end of the cosmological Dark Ages.

Two key themes emerged from the reported theoretical results. First, early in the meeting,

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Fireworks — both real and of the intellectual kind — illuminated the conference on *The First Stars and the Evolution of the Early Universe*, held last month at the University of Washington, Seattle.

we heard that *ab initio* simulations of primordial star formation, starting from cosmological initial conditions on kiloparsec scales (10^{21} cm) and resolving down through eight or more decades in spatial dynamic range, have now reached encouraging agreement on the initial physical conditions for primordial star formation, using a variety of numerical techniques. Several speakers argued that the simulations have now converged so robustly on a mass scale of about 100 solar masses for primordial stars, and so strongly disfavour fragmentation to smaller masses, that the discovery of a primordial star in our own Galaxy with a mass lower than that of the Sun would require a complete re-evaluation of the underlying assumptions about structure formation in the early Universe.

There is already some tension with the available chemical abundance data, which indicate that the mass budget of the first generation of stars was primarily formed into stars with masses of around ten solar masses. This discrepancy may be explained by new discoveries in the data, or further refinements to the simulations, but even today's most advanced codes do not yet include

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the radiation-transport physics needed to evolve the protostellar cloud to stellar densities, and particularly to rigorously model the feedback effects of radiation from the young star on its accreting gas. Present calculations stop with an indicated mass range of 100–1,000 solar masses and without a robust prediction of the IMF. Then analytic theory takes over to model the competition between accretion and radiation that determines the final stellar mass, but these calculations suffer from uncertainty in the initial angular momentum of the star, which determines its rotation rate and potentially the major details of its subsequent evolution and explosion.

The hope is that new calculations that address the smaller physical scales of protostellar collapse and evolution — including the formation of an accretion disk and angular momentum transport, as well as effects due to primordial magnetic fields, and possibly decisive feedback effects on the accreting gas — will enable the numerical simulations to achieve detailed predictions of the first-stars IMF.

The uncertainties of complex physics also haunt the other theoretical theme of the meeting — the modelling of stellar evolution and explosions that create and disperse the heavy elements in the modern Universe. Because certain nucleosynthetic processes are uniquely associated with specific ranges of stellar mass (such as magnesium, iron, zinc and europium from stars of more than 8 solar masses, and carbon, yttrium and barium from stars in the mass range 1–8 solar masses), the abundances of various elements in the atmospheres of long-lived stars can reveal the mass distribution and nucleosynthesis of the prior generations that enriched the gas from which they formed. New and impressively detailed chemical abundance analysis of high-resolution spectroscopic data for primitive stars, with iron abundances more than 300,000 times lower than the solar value, were reported at the meeting. Future surveys to greatly expand the samples of stars with similar information were also discussed.

Elemental abundance analyses in galactic stars is the basis of essentially all the empirical information that we currently have about the first stars, but the interpretation of these data typically rely on stellar evolution and explosion calculations that are themselves uncertain in the details of their nuclear physics, rotation and mass loss. Several speakers argued that rotation of primordial stars may be the decisive factor in determining their nucleosynthetic signature, but the mixing and mass loss driven by fast rotation presents serious challenges to the input physics and numerical methods of even state-of-the-art stellar evolution calculations. Rotation may also play a critical role in establishing both the total energy that later goes into driving the supernova explosion and the conditions under which a massive primordial star can, at the end of its life, collapse to a black hole and generate a gamma-ray burst.

By the end of the meeting a loose consensus emerged that perhaps the easiest parts of the physical evolution of the first stars — the phase before the first heavy elements, dust grains, ultraviolet radiation and magnetic fields — had been solved, and that the real challenge lies in better understanding the complexities that govern the transition to the first metal-enriched stellar generation. It now appears reasonable to hope that simulations of primordial star formation and efforts to uncover the unique abundance signatures of diverse supernovae will converge toward mutual constraints and a self-consistent picture in the near future.

For many attendees, the most interesting aspect of the new observations is the sheer amount of quantitative information they contain, and the potential to uncover the rare cases that define new types of nucleosynthetic phenomena or decisively constrain the range of stellar mass. Close interaction between observers and theorists is needed to establish the critical links between data and new theoretical ideas, and the intellectual fireworks at this meeting proved resoundingly that it is indeed an exciting time to be contemplating the first stars.