The First Generations of Stars

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The very first stars that formed after the Big Bang, some 13 to 14 billion years ago, are likely to have been quite massive and extremely short-lived; no examples are expected to remain in the universe today. However, they may have left behind their “calling cards” by producing a distinctive distribution of elements recorded in the atmospheres of long-lived stars that formed just after these massive progenitors. Stars that are extremely iron-poor (hyper metal-poor stars) are believed to be very old, and are thus possible candidates for second-generation stars.

On page 451 of this issue, Iwamoto et al. (... describe a model that attempts to account for the elemental abundances in two hyper metal-poor stars. The stars, HE 0107-5240 (2) and HE 1327-2326 (3), contain less than 1/100,000 of the iron observed in the Sun. Furthermore, they are both greatly enhanced, relative to the Sun, in the light elements carbon, nitrogen, and oxygen (for HE 0107-5240; studies of the oxygen abundance in HE 1327-2326 are under way); these are the most important elements for the formation of life, at least of the form with which we are familiar.

Star formation in the Milky Way and throughout the present universe is poorly understood. This is because it takes place in a complex environment, where one has to account for the effects of the elements produced by previous generations of stars, the influence of magnetic fields, and star formation—triggering events such as shocks from nearby supernovae. In the very early universe, the physics of star formation is thought to have been much simpler, because only hydrogen, helium, and a small amount of lithium were present; stars most likely formed via radiative cooling by molecules involving these elements.

Modern computational models of early star formation predict that most stars that formed in the early universe were probably quite massive, on the order of several hundred times the mass of the Sun. Such stars burn their fuel extremely rapidly (within a few million years after their birth) and then explode. Astronomers are uncertain which elements might form in these very massive stars during their explosive death throes, but current calculations indicate that they should eject large amounts of iron and only small amounts of carbon (4, 5).

This prediction is incompatible with the elements observed in the hyper metal-poor stars modeled by Iwamoto et al. (...). However, contemporary observations show that when stars form, they do so with a distribution of masses. The distribution of stellar masses in the early universe may have included first-generation stars with only 25 times the mass of the Sun. Iwamoto et al. suggest that these lower-mass first-generation stars are responsible for the elemental abundance patterns now observed in the second-generation stars HE 0107-5240 and HE 1327-2326.

These two stars—the most iron-poor stars known today—are inferred to have masses that are ~80% that of the Sun. Stars in this mass range have very long lifetimes, because they burn their fuel slowly—so slowly that, if they were born in the early universe, they could still be detected today. According to one popular model, the formation of such low-mass stars was triggered by shocks from the explosions of the massive first-generation stars (see the figure). These second-generation low-mass stars provide our only means to quantify the distribution of elements that were formed by their long-gone progenitors.

The search for stars with extremely low metallicity (astronomers refer to all elements heavier than hydrogen and helium as “metals”) began 50 years ago, when it was recognized that stars with lower metallicity than the Sun exist in the Milky Way. In the past decade, several thousand stars with iron abundances less than 1% of the solar abundance have been identified. Many of the most extreme examples have been studied at high spectral resolution with the world’s largest telescopes. These studies have shown that, of the 12 stars with the lowest iron abundance known to date, five exhibit highly enhanced light elements such as carbon, nitrogen, and, in some cases, oxygen (6). It seems inescapable that early element production favored the light elements. The early production of light elements is a crucial ingredient in models for early star formation, because these species pro-
Magnetic and electronic materials permeate every aspect of modern technology. For example, the vast amount of data generated by consumer electronic products is often stored as regions of opposite magnetic polarization in ferromagnets (materials with a spontaneous magnetic polarization that can be reversed by a magnetic field). The sensors industry relies heavily on a related class of materials known as ferroelectrics (materials with a spontaneous electric polarization that can be switched by an applied electric field). Many ferroelectrics are also ferroelastic—that is, a change in their electric polarization is accompanied by a change in shape. As a result, they are used to convert sound waves into electrical signals in sonar detectors, and to convert electrical impulses into motion in actuators. Such materials, which combine two or more “ferroic” properties (see the first figure) in the same phase, are known as multiferroics (1).

Trends toward device miniaturization have led to increased interest in combining electronic and magnetic properties into multifunctional materials, so that a single device component can perform more than one task. Ferromagnetic ferroelectric multiferroics are particularly appealing not only because they have the properties of both parent compounds, but also because interactions between the magnetic and electric polarizations lead to additional functionalities. For example, the magnetoelectric effect (the induction of a magnetization by an electric field, or of a polarization by a magnetic field) could yield entirely new device paradigms, such as electric field–controlled magnetic data storage. However, attempts to design multiferroics that combine ferromagnetism and ferroelectricity in the same phase have proved unexpectedly difficult.

Recent theoretical breakthroughs in understanding the coexistence of magnetic and electrical ordering, combined with advances in thin film growth techniques and experimental methods for observing magnetic and electric domains, have generated a flurry of research activity on such magnetoelectric multiferroics (2). Theoretical studies have shown that the usual atomic-level mechanisms driving ferromagnetism and ferroelectricity are mutually exclusive, because they require empty and partially filled transition metal orbitals, respectively (3). This recognition has prompted a search for alternative ferroelectric mechanisms that are compatible with the occurrence of magnetic ordering (for example, in HoMnO$_3$ (see the second figure)). As a result, previously unknown multiferroic materials have been discovered.

These new multiferroics are in turn proving to be a rich source for exploring the fundamental science of phase control and magnetoelectric interactions. Huge magnetoelectric effects have been observed in the form of ferroelectric phase transitions induced by magnetic fields in perovskite manganites (4) and ferromagnetism induced by electric fields in hexagonal manganites (5). Magnetoelectric memory effects and magnetic switching of ferroelectric domains (and the converse process) have been demonstrated. An optical technique has been developed that...