

**A new window on microbial activity.** The incorporation of  $^{15}\text{N}$  stable isotope into a mixed population of cells (animal cells and bacteria) is determined by comparing two quantitative mass images ( $^{12}\text{C}^{14}\text{N}^-$  and  $^{12}\text{C}^{15}\text{N}^-$ ) obtained by

multi-isotope imaging mass spectrometry (MIMS). The increase in  $^{15}\text{N}/^{14}\text{N}$  ratios relative to the natural abundance ratio can then be measured to identify the fate of the  $^{15}\text{N}$ .

resolution or, like micro-autoradiography, require that microorganisms be fed radioactive-labeled substrates (9). The uptake of radiolabeled isotopes directly links individual microbial cells to their activity in the environment. However, because this approach requires radioactivity, its use is limited to elements that have a radioisotope with a suitable half-life (>1 day; for example,  $^{14}\text{C}$  and  $^3\text{H}$ ) and excludes the study of other elements such as nitrogen. MIMS, on the other hand, can be used to measure the distribution of any stable isotope as well as any radioisotope with a suitable half-life. Hence, the approach used by Lechene *et al.* holds great promise for studying symbiont-host interactions and microbial activity in the environment.

Combining MIMS with fluorescence in situ hybridization (FISH) is an even more

powerful technique for identifying and characterizing single microbial cells. FISH uses fluorescent-labeled probes that are specific to the organism of interest and that bind to the intracellular 16S ribosomal RNA (2). Replacing fluorescent probes with isotopically labeled (stable or radioactive) or halogenated probes would allow individual cells to be directly identified (by probe hybridization to targets) by MIMS (10). The hybridization procedure is essentially identical to that used for FISH, and the same probes can be applied. By combining this probing technique with isotope labeling of substrate, one can assess the metabolic activity of cells and simultaneously identify their phylogenetic characteristics during a single MIMS scan. This approach links the identity of microbial cells to their in situ activity. MIMS is truly an imaging

breakthrough, whose application is only just beginning to yield information once considered inaccessible.

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## ASTRONOMY

# From Darkness to Light

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What is the nature of the dark matter that is believed to dominate the structure of the universe at large scales? How did the cosmic dark ages end when the first stars lit up the universe again a few hundred million years after the Big Bang? These questions might be intimately related. On page 1527 of this issue, Gao and Theuns (1) present numerical simulations of cosmological structure formation in the early universe. Their simulations demonstrate how sensitively the formation of the first stars depended on the detailed properties of the still mysterious dark matter. The macrophysics of early star formation might thus hold important lessons for the microphysics of exotic elementary particles.

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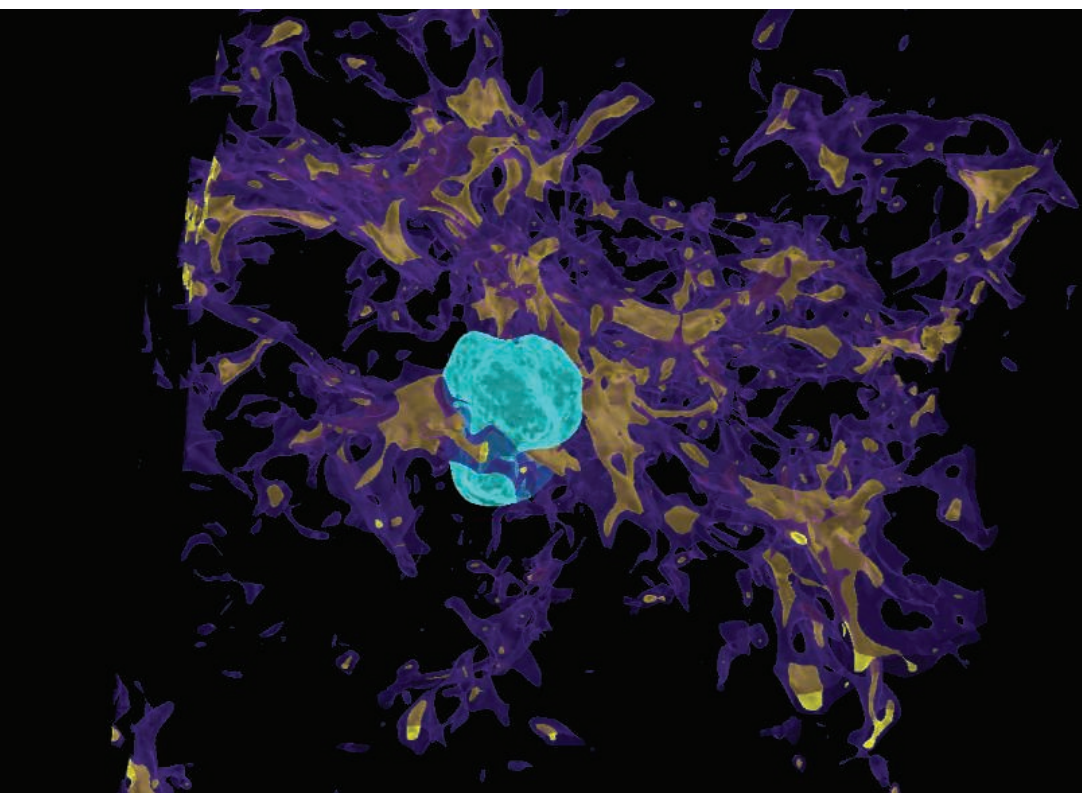
According to the standard model (2), star formation in the early universe was very different from the present. Stars today form in giant clouds of molecular gas and dust embedded in the disks of large galaxies like our Milky Way, whereas the first stars emerged inside "minihalos," agglomerates of primordial gas and dark matter with a total mass of a million times that of the Sun.

Another difference arises from the initial absence of elements other than the hydrogen and helium that were synthesized in the Big Bang. Gas clouds today can efficiently cool via radiation emitted by atoms, molecules, or dust grains that contain heavy elements. Because the primordial gas lacked those coolants, it remained comparatively hot. For gravity to overwhelm the higher thermal pressure, the mass of the first stars must have been larger as well. Numerical simulations have led

A supercomputer simulation shows that matter in the early universe might have formed dense filaments before collapsing into the first stars.

most researchers to believe that the first stars were predominantly very massive, typically a few hundred solar masses.

The emergence of the first stars fundamentally changed the early universe at the end of the cosmic dark ages (3). Owing to their high mass, these stars were copious producers of heavy chemical elements that were rapidly dispersed by supernova explosions. They also produced many ultraviolet photons that were energetic enough to ionize hydrogen, the most abundant element in the universe. Thus began the extended process of what cosmologists call "reionization" (see the figure), which transformed the universe from a completely cold and dark neutral state into the fully ionized medium of today. Observations of the polarization in the cosmic microwave background (CMB), due to the scattering of CMB photons off free electrons, place constraints



**Cosmic renaissance.** This supercomputer simulation shows a primordial star of 100 solar masses, formed inside a dark matter minihalo and surrounded by a bubble of ionizing radiation (light blue). The bubble is embedded in the still-neutral cosmic gas (weblike structure in shades of purple and yellow). This frame depicts the initial step in the process of cosmic reionization.

on the onset of reionization. Measurements made with the Wilkinson Microwave Anisotropy Probe (WMAP) indicate that about 10% of the total signal was likely produced by the first stars (4).

Our picture of how the first stars formed and how they affected the evolution of the cosmos assumes that dark matter is made up of weakly interacting massive particles (WIMPs). Such particles are predicted by several theories but are as yet undetected because they interact with normal matter only via gravity and the weak nuclear interaction. A plausible WIMP candidate is the “neutralino,” the lightest “superpartner” in many supersymmetrical theories (5). Supersymmetry postulates that for every known particle there is a superpartner, thus effectively doubling the zoo of elementary particles. Most of these superparticles that were produced briefly after the Big Bang are unstable and have decayed. The lightest of them, however, could not decay into any other particle and thus would exist today.

The neutralino is expected to be rather massive, having roughly the mass of a hundred protons, and so it would move comparatively slowly (it would be “cold”). Such cold dark matter (CDM) particles preserve any density perturbations from the very early uni-

verse. To see this, consider the opposite case in which the dark matter would be “hot,” corresponding to very light particles. Streaming velocities would then be very large, and such hot dark matter could not be trapped in small density condensations. The first structures to form in the universe would then be large, massive systems, whereas in CDM models, small-scale structures would survive and would be the first to emerge.

CDM models predict that the first stars formed in dark matter minihalos. In turn, the evolution of the primordial gas falling into these minihalos yields stars with roughly a hundred times the mass of the Sun. Gao and Theuns are now challenging this CDM-based standard view. They consider a situation in which the dark matter is slightly less cold, termed “warm dark matter” (WDM). WDM models agree with CDM models on large scales, but they lead to drastically different predictions for the small scales that are relevant for the formation of the first stars. In the WDM scenario investigated by Gao and Theuns, there are no minihalos that could host the formation of the first stars; instead, the primordial gas would collapse first into massive filamentary structures. The completely different history experienced by the star-forming

gas would likely result in stars with a different distribution of masses, possibly skewed toward somewhat less massive stars. The simulations presented here cannot yet resolve the formation of the actual stars, rendering any conclusions about the precise stellar masses tentative.

How do we decide between the CDM and WDM models? One way is to compare the predicted strength of the CMB polarization signal with the WMAP measurement (6). If the suppression of small-scale features in WDM models is too severe to produce enough ionizing photons, such scenarios can be excluded. A complementary strategy to empirically probe the mass and mass distribution of the first stars is to hunt locally for fossils of the dark ages, low-mass stars in our Milky Way that contain only a tiny amount of heavy elements. These would carry the imprint of the first stars that produced those elements with an abundance pattern that sensitively depends on mass (7, 8). Again, the simulations are not yet detailed enough to make predictions with the required degree of precision, but the game is clearly on now.

This new frontier of connections between particle physics and the first stars offers intriguing possibilities. If dark matter particles could decay, or if they were concentrated so that annihilation reactions could occur, then heating of the primordial gas would result, with the potential to greatly modify star formation (9, 10). Cosmology has a huge stake in the search for possible dark matter candidates soon to be carried out at the Large Hadron Collider at CERN.

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