PERSPECTIVES: COSMOLOGY

How the Cosmic Dark Age Ended

Martin J. Rees

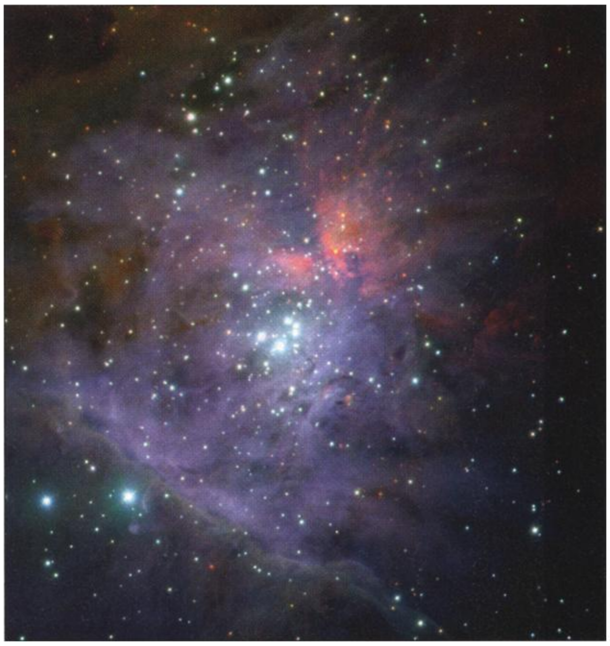
Our universe started off intensely hot, bright, and dense, cooling down as it expanded. After about half a million years, the temperature fell below 3000 K. Thereafter, the primordial black-body radiation shifted into the infrared, and the cosmos became utterly dark.

The dark age was over by the time the universe was a billion years old. By then, the first quasars observed today had lit up (*1*, *2*). These quasars are probably powered by massive black holes in the centers of galaxies. Their presence thus implies that some galaxy-scale structures had formed by then. But cosmic structures seem to develop in a hierarchical way: Small-scale structures form first and then agglomerate into larger systems. So the stars that provided the very first cosmic light could have formed earlier, in units smaller than present-day galaxies. But how much earlier? And what were these first stars like?

Theorists are now deploying elaborate computer codes to address these questions. At first sight, these projects may seem overambitious—after all, present-day star formation is still poorly understood. We can map the dusty giant molecular clouds (GMCs) where stars are now forming in our galaxy, but even with that information we still cannot accurately model the rate at which stars condense nor their distribution of masses.

The first stars formed in a very different environment, to which theory is our only guide. The physical conditions were, however, simpler than today, and the starting conditions are well defined. Matter was initially distributed fairly smoothly, but gravity enhances density contrasts in an expanding universe: Overdense regions are decelerated by an excess gravitational force, so that they expand progressively slower than their surroundings and eventually condense out. According to the standard "hot big bang" model, the primordial gas consisted of 77% by weight of hydrogen and 23% of helium, with traces of deuterium and lithium. The main coolant in this mixture was molecular hydrogen,

The author is in King's College, University of Cambridge, Cambridge CB2 1ST, UK. E-mail: mjr@ast.cam.ac.uk



Nearby star factories. The Orion Nebula, shown here as a representative-color composite of 81 near-infrared images, is a region populated by young stars, hot gas, and dark dust. Star formation in this region is likely to differ substantially from that described by Abel *et al.* (*3*).

which is inefficient below 200 K; the gas therefore could not get as cool as 10 K, the prevailing temperature in GMCs. Also, magnetic fields, thought to be important in present-day star formation, were probably absent.

So the question "When and how did the first star form?" is well posed. On page 93 of this issue, Abel *et al.* (*3*) provide an answer. Building on earlier contributions by others (*4*, *5*), they report three-dimensional calculations—incorporating the relevant gas dynamics, chemistry, and radiative transfer—of star formation in the core of a collapsing primordial cloud.

The simulations show that by the time the universe was 100 million years old, the dark matter had developed an intricate filamentary structure. At the density peaks where filaments intersect, gravitationally bound concentrations of dark matter condense out. The gas "feels" the gravitational pull of these irregular clumps of dark matter. Gas pressure tends to smooth its small-scale distribution, but clumps with masses exceeding a few times 10^5 solar masses provide a deep enough potential well to overwhelm the pressure of the gas and pull it inward. Moreover, the infalling gas gets hot enough (a few hundred K) for collisional excitation of H_2, followed by photon emission, to carry energy away, thereby allowing further contraction and compression. This sets the stage for the formation of the first stars.

The challenge of modeling these phenomena stems from the vast dynamic range involved: A solar-type star is 10^{25} times as dense as the primordial gas when the infall starts. Abel *et al.* use an "adaptive mesh refinement" technique that follows the three-dimensional dynamics and homes in, with ever-finer resolution, on the densest part of a collapsing cloud.

In an earlier paper (*6*), the authors kept track of the gas flow, the free electron density, and the reactions that form and destroy H_2 until a gravitationally bound opaque gaseous body of a few hundred solar masses had nucleated near the center. They have now carried the story much further. Their final mesh size [finer than in (*6*) by five orders of magnitude] reveals, within the opaque cloud, a dense core of less than 1 solar mass, with density of 10^{14} atoms per cm^3. The rest of the gas settles onto this core. The initial infall rate is so high that a buildup to 70 solar masses occurs within 10,000 years; during the next 2 million years, the star may accrete well over 100 solar masses before it blows up as a supernova.

The final mass of this star is qualitatively important. Stars between 140 and 260 solar masses end their lives in an explosion that disrupts them completely, owing to an instability when the center gets hot enough to generate electron-positron pairs (*7*). Outside this mass range, dying stars leave remnant black holes, which could have important consequences today (*8*). There is little prospect of detecting one of these supernovae: They are so far away that their light has been traveling toward us for 99% of the age of the universe. However, some of them may give rise to gamma-ray bursts. These bursts and their afterglows are far brighter than supernovae and could be readily detected, offering a direct probe of the end of the dark age.

During its short (2 million years) but energetic lifetime and its explosive death, a first-generation star would expel all the remaining gas (more than 10^5 solar masses) from the entire gravitationally bound clump of dark matter, thereby preventing the formation of other stars. Hence, only one atom in a thousand got incorporated into first-generation stars. More efficient star formation had to await the subsequent buildup of larger and less fragile systems with deeper potential wells that could retain gas (in effect, the first small galaxies).

The environmental impact of these very early massive stars was crucial. They emitted mainly in the ultraviolet and initiated the reionization of the intergalactic medium, a process that was not completed until the universe was 1 billion years old (*1, 2*) but must have started much earlier. They produced (and, when they died, dispersed) the first carbon, oxygen, and iron. Gas that contains even small amounts of these elements cools more efficiently. It is also more opaque, rendering radiation pressure more effective in stemming infall onto young stars. Consequently, all later stars may be of lower mass, perhaps more akin to those forming in the Orion Nebula today (see the figure).

Today, the stars modeled by Abel *et al.* are vastly outnumbered by the stars that formed later in galaxies. It will be an even greater challenge to compute the complicated internal gas dynamics and feedback in these larger systems. But perhaps we will be guided by observations. Small galaxies older than 1 billion years may be detectable with the Next Generation Space Telescope, if not by 8-m telescopes on the ground (*9*).

The very first generation of stars, although few in number, nonetheless played a crucial formative role in the emergence of all later structures. The calculations by Abel *et al.* go some way toward dispelling the mystery and uncertainty that surrounds them.

References
1. R. H. Becker *et al.*, *Astrophys. J.*, in press (available at http://xxx.lanl.gov/abs/astro-ph/0108097).
2. X. Fan *et al.*, in preparation (available at http://xxx.lanl.gov/abs/astro-ph/0111184).
3. T. Abel, G. L. Bryan, M. L. Norman, *Science* **295**, 93 (2002); published online 15 November 2001 (10.1126/science.1063991).
4. V. Bromm, P. S. Coppi, R. B. Larson, *Astrophys. J.* **527**, L5 (1999).
5. F. Nakamura, M. Umemura, *Astrophys. J.* **548**, 19 (2001).
6. T. Abel, G. L. Bryan, M. L. Norman, *Astrophys. J.* **540**, 39 (2000).
7. A. Heger, S. E. Woosley, *Astrophys. J.*, in press (available at http://xxx.lanl.gov/abs/astro-ph/0107037).
8. P. Madau, M. J. Rees, *Astrophys. J.* **551**, L27 (2001).
9. R. Barkana, A. Loeb, *Phys. Rep.* **349**, 125 (2001).

PERSPECTIVES: DEVELOPMENT

Carbohydrate Recognition in Spermatogenesis

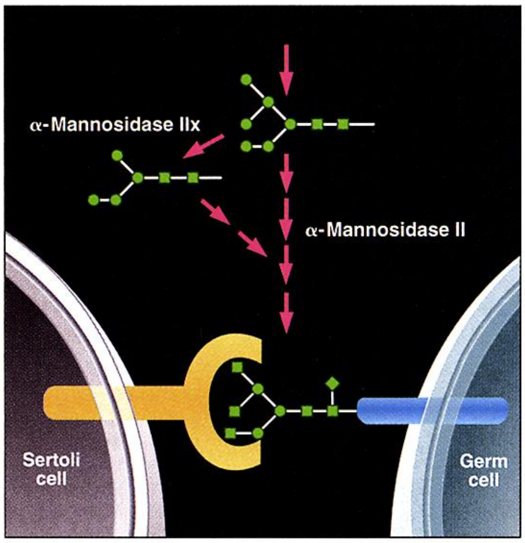
Takashi Muramatsu

Carbohydrates linked to proteins or lipids in the plasma membrane are involved in cellular processes as varied as embryonic development and the recruitment of white blood cells to sites of inflammation (*1–3*). On page 124 of this issue, Akama *et al.* (*4*) identify a unique carbohydrate, required for spermatogenesis in the mouse, that enables male germ cells to adhere to Sertoli cells in the testis.

Chains of sugar molecules (oligosaccharides) linked to proteins through an asparagine residue are described as N-linked. To form complex N-linked carbohydrate, a long sugar chain is transferred to the protein, is "trimmed" (*1, 5*) and then further embellished by the addition of sugars, such as *N*-acetylglucosamine (GlcNAc), galactose (Gal), fucose, and sialic acid. The enzyme α-mannosidase II is important for the final processing step in the formation of complex carbohydrate. When mice are engineered to lack the gene encoding α-mannosidase II, their red blood cells (but not other cells and tissues) lose the ability to make complex carbohydrate (*6*). The mice also develop dyserythropoietic anemia, which resembles human congenital dyserythropoietic anemia type II. The other cells and tissues of the mutant mouse retain their ability to make complex carbohydrate, probably because they produce an alternative enzyme, α-mannosidase IIx.

Akama *et al.* (*4*) report that male mice lacking the α-mannosidase IIx gene, which is predominantly expressed by male germ cells, exhibit almost complete suppression of fertility. This result complements the finding that the chemical swainsonine, which inhibits both α-mannosidase II and IIx, causes male sterility. By staining with labeled lectin, the authors discovered that a sugar structure present on male wild-type germ cells was almost undetectable on the germ cells of mice lacking α-mannosidase IIx.

So, what happened to the germ cell carbohydrate in the mutant mice? Akama *et al.* used high-performance liquid chromatographic mapping to separate enzymatically released N-linked oligosaccharides from the testes of wild-type and mutant animals (*7*). They were able to determine the structure of the N-linked oligosaccharides from the change in elution position after digestion with glycosidases. Their analysis revealed a marked decrease in oligosaccharides with GlcNAc at the terminus, but not those with galactose at the terminus, in testes from mutant mice. In an in vitro assay, the investigators then tested the effect of each oligosaccharide on the adhesion of male germ cells to Sertoli cells. They found that a unique oligosaccharide with a GlcNAc residue at



A spoonful of sugar. A newly identified carbohydrate on male germ cells enables them to bind to Sertoli cells in the mouse testis. The enzymes α-mannosidase II and α-mannosidase IIx process oligosaccharides to form the complex carbohydrate attached to proteins. Only α-mannosidase IIx is able to produce complex carbohydrate containing oligosaccharide chains that terminate in GlcNAc (square) and fucose (diamond), rather than mannose (circle) or galactose (not shown). It is this unique oligosaccharide that germ cells use to adhere to Sertoli cells, although the molecule on Sertoli cells (possibly a lectin) that recognizes this sugar has not yet been identified.

The author is in the Department of Biochemistry, Nagoya University School of Medicine, Nagoya 466-8550, Japan. E-mail: tmurama@med.nagoya-u.ac.jp