(such as *Ets1*, *Gata3*, and *Tcf1*) and boost the expression of natural killer cell lineage–associated genes (including *Id2*, *Il2rb*, and *Nfil3*). They also gained the capacity to grow in response to IL-2, and transcriptionally and functionally resembled normal cytokine-activated natural killer cells. As such, Li *et al*. (*4*) refer to these cells as induced T–to–natural killer (ITNK) cells, which could potently eliminate tumor cells in vitro and in vivo. Remarkably, mature T cells could also be "reprogrammed" to ITNKs, although they retained some signatures of their T cell origin. Whether these ITNK cells recognize antigen via the T cell receptor is not known. Thus, Bcl11b appears critical for maintaining T cell identity throughout the T cell life span. Moreover, because of their robust proliferative capacities, ITNK could represent a potential source for therapies.

The three studies suggest a revised model of early T cell lineage commitment with Bcl11b as the focal point (see the figure). Signals through Notch1 are critical for initiating T cell specification at the early DN stage. Li *et al*. (*4*) show that Notch regulates Bcl11b expression, which is critical for repressing myeloid and natural killer cell potential. Nevertheless, because Bcl11b-deficient precursors do not regain B cell potential, another transcription factor must be involved in T cell specification.

Although IL-7 is essential for early thymocyte survival and proliferation (*12*), the results of Ikawa *et al*. (*3*) suggest that it must also be attenuated to allow Bcl11b–mediated T cell development. How can this paradox be resolved? It is likely that an IL-7 "niche" in the thymus is limited, as suggested by the discrete anatomical placement of IL-7–producing thymic epithelial cells (*13*). When IL-7 becomes limiting, DN2 cells must receive other survival signals or else die. This instance of IL-7 deprivation could increase Bcl11b expression [which in turn would repress *Il7r* expression (*2*)], thereby establishing a feedforward loop for subsequent T cell commitment. In this way, overgrowth of the IL-7 niche would result in default T cell progression and further maturation in an IL-7–independent manner. As a corollary, early thymocytes from IL-7–deficient mice (while severely reduced) might progress more rapidly through the DN2-DN3 transition and show unusually high Bcl11b expression.

The gene targets of Bcl11b that promote T cell development are yet to be defined. Similarly, the molecular determinants of the T cell "signature" defined by Bcl11b in mature T cells are largely unknown. How is T cell identity maintained? As IL-7 is a central mediator of peripheral lymphocyte homeostasis, it will be interesting to learn whether Bcl11b regulation of cytokine receptor sensitivity also operates in the maintenance of diverse peripheral T cell subsets.

References

1. C. V. Laiosa, M. Stadtfeld, T. Graf, *Annu. Rev. Immunol.* **24**, 705 (2006).
2. L. Li, M. Leid, E. V. Rothenberg, *Science* **329**, 89 (2010).
3. T. Ikawa *et al., Science* **329**, 93 (2010).
4. P. Li *et al., Science* **329**, 85 (2010); published online 10 June 2010 (10.1126/science.1188063).
5. F. Radtke *et al.*, *Immunity* **10**, 547 (1999).
6. U. Koch *et al.*, *J. Exp. Med.* **205**, 2515 (2008).
7. K. Hozumi *et al.*, *J. Exp. Med.* **205**, 2507 (2008).
8. E. V. Rothenberg, *Nat. Immunol.* **8**, 441 (2007).
9. Y. Wakabayashi *et al.*, *Nat. Immunol.* **4**, 533 (2003).
10. J. Inoue *et al.*, *J. Immunol.* **176**, 5871 (2006).
11. H. Wada *et al.*, *Nature* **452**, 768 (2008).
12. U. von Freeden-Jeffry *et al.*, *J. Exp. Med.* **181**, 1519 (1995).
13. N. L. Alves *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1512 (2009).

10.1126/science.1191664

CHEMISTRY

To Cool or Not to Cool

Volker Bromm

Precision measurements of chemical processes are providing a clearer picture of how the universe evolved.

One of the tantalizing questions in modern cosmology concerns how the first stars formed at the end of the cosmic dark ages, a few hundred million years after the Big Bang. It has long been realized that their emergence must have set into motion the rapid transformation of the early universe from an exceedingly simple initial state into one of ever-increasing complexity (*1*). On page 69 of this issue, Kreckel *et al*. (*2*) present a combination of laboratory and numerical astrophysics to provide an improved value for the production rate of molecular hydrogen (H_2), one of the key physical processes that governed the formation of the first stars.

A picture of primordial star formation has emerged, based on sophisticated supercomputer simulations, in which the first stars were predominantly very massive, with typical masses a few hundred times that of the Sun (*3*). At the core of this picture lies the argument that the primordial gas, consisting only of the hydrogen and helium made in the Big Bang itself, can only cool via the excitation of low-energy rotational transitions in H_2. This is not a very efficient cooling mechanism, however, resulting in temperatures of about 200 to 300 K within the pristine star-forming clouds compared to the 10 K found in present-day giant molecular clouds, where stars form in our Milky Way galaxy. In modeling the first stars, a crucial ingredient is the amount of H_2 produced. Until now, the corresponding production rate was subject to substantial disagreements between different theoretical calculations and experiments. The results of Kreckel *et al*. remove this lingering uncertainty. Indeed, it is a fascinating aspect of this study that microphysical processes can have such large-scale, cosmological implications.

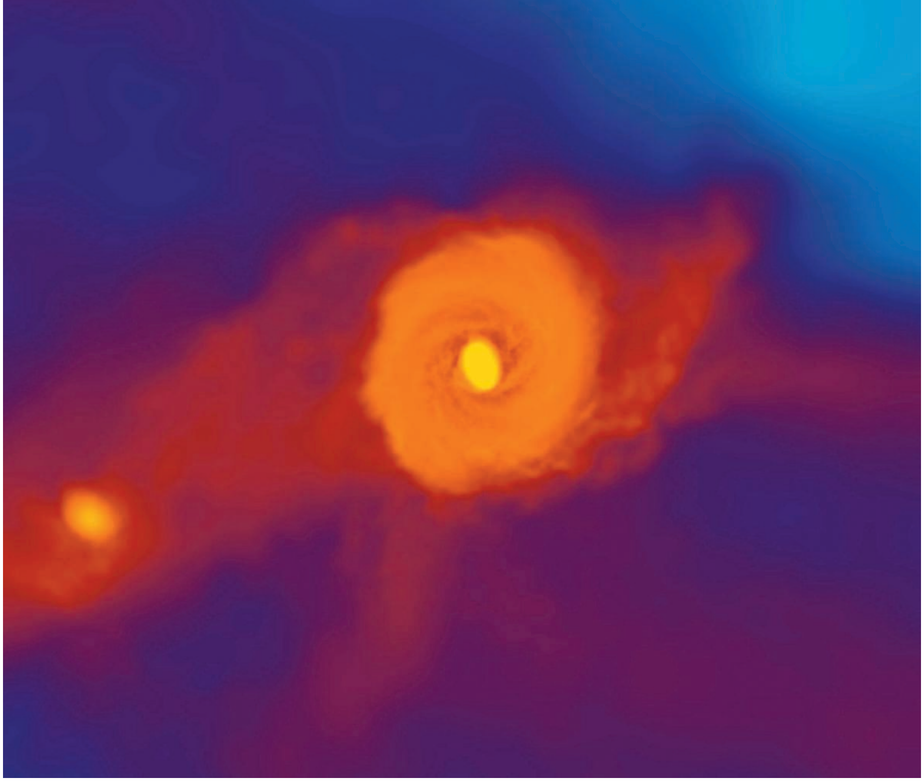
The typical mass range of the first stars is so important because it determines how they shaped early cosmic evolution via feedback effects. For example, the emission of energetic ultraviolet radiation from their surfaces strongly depends on stellar mass. Emitted photons were able to ionize the neutral hydrogen in the surrounding intergalactic medium, thus initiating the protracted process of cosmic "reionization." Understanding this process is a crucial goal, as it was the last global phase transition in the history of the universe, transforming a completely neutral hydrogen-helium gas into the almost fully ionized plasma observed around us today (*4*). After reionization, different regions in the universe evolved largely independently of each other. Reionization left a number of observable signatures behind whose strength and character depends on the contribution from the first stars. The most important signature is the optical depth to Thomson scattering, a process that describes how often a photon of the cosmic microwave background interacts with free electrons along its path of propagation. The free electrons in turn are created by the ionizing radiation from stars, and the cumulative optical depth is thus a measure

---

Department of Astronomy, University of Texas, Austin, TX 78712, USA. E-mail: vbromm@astro.as.utexas.edu

of star formation throughout cosmic time. The Wilkinson Microwave Anisotropy Probe (WMAP) has determined this quantity with high precision (*5*), indicating that a few percent of the total signal measured by WMAP may be attributable to the first stars.

The first stars were also responsible for enriching the pristine, pure H/He gas with the first heavy chemical elements. Again, the nature of this initial enrichment event is sensitive to the mass of the first stars, as differences in progenitor masses translate into different classes of supernova explosions that have particular nucleosynthetic element patterns (*6*). One intriguing possibility is that a fraction of primordial stars died in a particular kind of explosion, called a hyperenergetic pair-instability supernova (PISN). Such events are predicted to leave behind no compact remnant, neither a neutron star nor a black hole, and would therefore release the entire amount of heavy elements produced in their interior into the surrounding cosmic gas. A PISN would therefore constitute a very efficient mechanism to rapidly enrich the early universe with heavy elements, just a few million years after the first stars appeared (*7*, *8*). The PISN idea existed only as a theoretical scenario (*9*, *10*), but recently, a promising candidate for such an unusual explosion was discovered in a nearby small galaxy (*11*). This discovery greatly strengthens the case for such extreme explosions to have occurred in the early universe.



Primordial galaxy. A supercomputer frame showing how the pristine hydrogen and helium gas has assembled in the center of one of the first galaxies, 500 million years after the Big Bang. The prominent disk is a few thousand light years across, with a massive gas cloud in the very center. This cloud is expected to fragment and give rise to a massive cluster of stars, possibly bright enough to be observable with the JWST. Future simulations will include the new Kreckel *et al*. results.

The process investigated by Kreckel *et al.* may be important not only for the formation of the first stars, but also of the first galaxies (see the figure). Within the current standard model of cosmological structure formation, dominated by cold (slow-moving) dark matter particles, structures are predicted to form hierarchically from the bottom up, so that smaller systems merge into ones of ever-increasing mass. The first stars are expected to emerge in small dark matter halos, as single stars or members of a small group. To form galaxies, more massive halos are needed with a correspondingly larger amount of gas for star formation, so that systems of stars can be built up. The primordial gas condensing inside the first galaxies may have been able to cool to lower temperatures, and the masses of the resulting stars would be consequently smaller. The additional cooling boost would come from the hydrogen deuteride (HD) molecule, where one deuterium atom replaces one of the hydrogen atoms in conventional H_2 (*12*). Whether this additional cooling mechanism will be important depends on the H_2 formation rate. Now that Kreckel *et al*. have provided a reliable value for this key process, theorists can follow the thermal history of the gas as it collapses into the first galaxies with much greater confidence. Incorporating the relevant microphysics into computer models will enable improved simulations of the assembly process of primordial galaxies, and of the star formation ensuing in them.

Making realistic predictions for the properties of the first galaxies is important in preparing for the James Webb Space Telescope (JWST) launch, planned for 2014. The JWST will have exquisite sensitivity in the near-infrared waveband, where the bulk of the radiation from very distant sources lies. Despite its unprecedented sensitivity, the JWST will not be able to detect individual primordial stars, but it would be able to image clusters containing a large number of them, and such clusters may arise inside the first galaxies. Predicting the overall energy output and the color of such primordial star clusters is highly dependent on the stellar mass, and therefore on the cooling processes that initiate the star formation process. A second reason why understanding the first galaxies matters is that they are the likely sites for the formation of the first low-mass stars. Such stars evolve sufficiently slowly that they are still around today, 13 billion years after their birth. Astronomers can hunt for local fossils of the cosmic dark ages in the halo of our Milky Way, an approach often termed "stellar archaeology" (*13*). The idea is to scrutinize the elemental abundance patterns observed in their atmospheres, and to infer the properties of the first supernovae that produced these elements. The final goal is to indirectly determine the mass of the first stars.

The key to unlocking the mysteries of our cosmic beginnings relies on precision measurements carried out by atomic and molecular physicists in laboratories here on Earth. The increased power of our computer models and the enhanced sensitivity of our telescopes will continue to feed the need for such precision experiments.

References and Notes

1. R. Barkana, A. Loeb, *Phys. Rep.* **349**, 125 (2001).
2. H. Kreckel *et al*., *Science* **329**, 69 (2010).
3. V. Bromm, N. Yoshida, L. Hernquist, C. F. McKee, *Nature* **459**, 49 (2009).
4. X. Fan, C. L. Carilli, B. Keating, *Annu. Rev. Astron. Astrophys.* **44**, 415 (2006).
5. E. Komatsu *et al*., *Astrophys. J. Suppl. Ser.* **180**, 330 (2009).
6. N. Iwamoto, H. Umeda, N. Tominaga, K. Nomoto, K. Maeda, *Science* **309**, 451 (2005).
7. J. H. Wise, T. Abel, *Astrophys. J.* **685**, 40 (2008).
8. T. H. Greif, S. C. O. Glover, V. Bromm, R. S. Klessen, *Astrophys. J.* **716**, 510 (2010).
9. Z. Barkat, G. Rakavy, N. Sack, *Phys. Rev. Lett.* **18**, 379 (1967).
10. A. Heger, S. E. Woosley, *Astrophys. J.* **567**, 532 (2002).
11. A. Gal-Yam *et al*., *Nature* **462**, 624 (2009).
12. J. L. Johnson, V. Bromm, *Mon. Not. R. Astron. Soc.* **366**, 247 (2006).
13. A. Frebel, J. L. Johnson, V. Bromm, *Mon. Not. R. Astron. Soc.* **392**, L50 (2009).

14. Supported by NSF grant AST-0708795 and NASA ATFP grant NNX08AL43G.

10.1126/science.1192014

CREDIT: A. PAWLIK, M. MILOSAVLJEVIĆ, V. BROMM/TEXAS ADVANCED COMPUTING CENTER