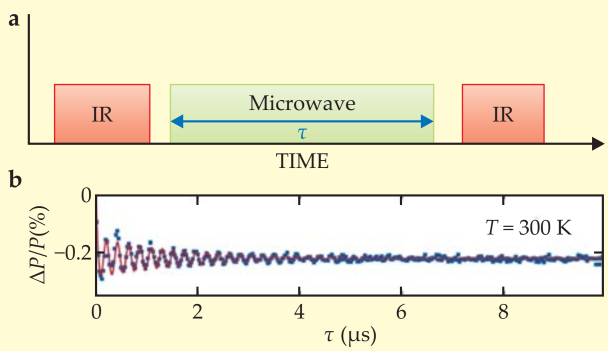

Figure 2. Coherent control. Applied to a sample of silicon carbide, the pulse sequence shown in **(a)**—an IR pulse followed by a microwave pulse of length τ followed by a second IR pulse—polarizes defect spins, rotates them, and then elicits a burst of photoluminescence that hints at their final orientation. Repeating the pulse sequence for various τ yields the data points (blue symbols) and fit (red curve) shown in **(b)**. The oscillations in photoluminescence intensity P suggest coherent rotations of the ensemble of electron spins. The data show the room-temperature response of one of SiC's as-yet unidentified defect structures. (Adapted from ref. 2.)

fluorescent probing. Applying a more sophisticated pulse sequence, the researchers showed they could coherently control spins for over 100 μs in chilled samples and for over 40 μs at room temperature. Provided SiC's defect spins can be flipped as swiftly as those of diamond's NV centers—that is, about once per nanosecond—a SiC qubit could conceivably survive thousands of quantum operations at room temperature.

All of the team's experiments were performed on defect ensembles; the millimeter-sized samples of SiC contain roughly 100 defects per cubic micron. Key to proving the defects' utility as qubits will be demonstrating that each one can be controlled individually. One challenge, says Awschalom, is detecting single photon emissions. That task is relatively straightforward in the visible but much more difficult in the IR. The researchers are now collaborating on that effort with NIST in Boulder, Colorado. Also key to realizing quantum devices will be demonstrating entanglement between multiple qubits and integrating them with photonic, electronic, and micromagnetic structures.

That the SiC defects emit in the near-IR and in the vicinity of fiber-optic bandwidths could ultimately prove a significant advantage. Says Awschalom, "It would mean that you could do quantum manipulation in the same material that's already being used for electronics, at telecommunications frequencies—and all at room temperature."

Jörg Wrachtrup (University of Stuttgart, Germany), who pioneered the manipulation of single-defect spin states in diamond, sees potential applications for SiC defects beyond quantum computing. He cites the defects' promise as ultrasensitive magnetometers. (See PHYSICS TODAY, August 2011, page 17.) Says Wrachtrup, "I could envision using tiny silicon carbide crystals to do micro- or nanoscale magnetic resonance imaging on cells and other biological systems. It really could open up a whole new world of scientific applications."

Ashley G. Smart

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A first glimpse of possibly primordial intergalactic gas

Before the first stars, there were presumably no nuclei heavier than lithium. But pristine gas without a trace of stellar contamination has been elusive.

Hydrogen, helium, and a minuscule trace of lithium are the only elements left over from the first minutes after the Big Bang, 13.7 billion years ago. The creation of all heavier elements, collectively called "metals" in astrophysicists' shorthand, had to await the coming of the first stars a few hundred million years later. So first-generation stars formed from pristine clouds of H and He. Only with their deaths was the cosmos first seeded with the metals they created.

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Bang nucleosynthesis (BBN). It's been impressively confirmed by the agreement between the predicted and measured cosmic abundance ratios of the various H and He isotopes (see PHYSICS TODAY, August 1996, page 17). But despite its general acceptance, the BBN scenario has come up against some frustrating nonobservations. No first-generation stars have yet been seen. Nor, until now, have observers found any intergalactic gas cloud free of detectable metallicity.

Metallicity, the quantitative measure of nonprimordial material in a star or gas cloud, is defined as the fraction of the system's mass contributed by elements heavier than helium. The metallicity Z of an intergalactic gas cloud can be measured by looking at telltale absorption lines in the continuum UV spectrum of a background quasar viewed through the cloud. The oldest quasars suitable for this task date back to within a billion years of the Big Bang. And yet none of the clouds thus examined revealed a metallicity less than 10^{-3} of $Z_{\odot}$, the Sun's metallicity. "This apparent metallicity floor, for both gas and the oldest stars, was so puzzling," says cosmologist Avi Loeb (Harvard University), "that some of us began to worry about the BBN model."

Now, however, a team led by Xavier Prochaska (University of California, Santa Cruz) has reported the detection of two intergalactic clouds of apparently pristine, zero-metallicity gas.[1] Using the high-resolution spectrometer on the 10-meter Keck I telescope in Hawaii, they found two high-redshift clouds that show no metal absorption lines whatsoever despite spectroscopic sensitivity down to $10^{-4}\,Z_{\odot}$. So even if those clouds are not in fact pristine, their metal abundances are smaller, by at least an order of magnitude, than any previously seen.

The two clouds, though far apart on the sky, both have redshifts z (not to be confused with metallicity Z) near 3.3, which means that they're being seen as they were about 2 billion years after the Big Bang. By then, most of the first-generation stars, presumed to have been much more massive than the Sun, would long since have died in supernovae, spewing out the metals they made. In any case, the quasars that shine through those apparently pristine clouds make clear that the clouds postdate a lot of galaxy formation.

So the new discovery bespeaks a surprisingly inhomogeneous distribution of the products of stellar nucleosynthesis in the early cosmos. And the clouds apparently untouched by that uneven dispersal provide cosmologists with a unique measurement of the primordial deuterium/hydrogen abundance ratio—a key BBN parameter—from an enclave unsullied by stellar processes.

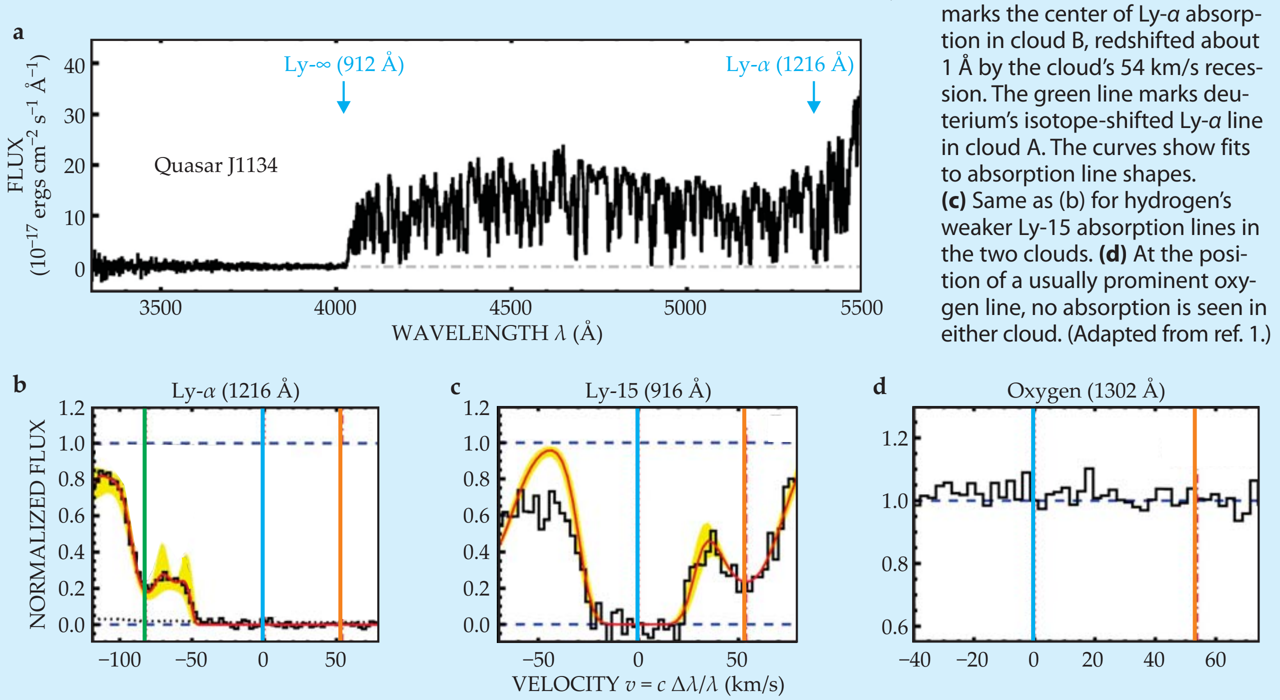
Telltale absorption lines

Prochaska, his graduate student Michele Fumagalli, and John O'Meara (St. Michael's College, Colchester, Vermont) had been spectroscopically observing high-z Lyman-limit systems to study the evolving metallicity of intergalactic gas in early epochs of star formation. An LLS is an intergalactic accumulation of gas with an atomic-hydrogen column density of order 10^{17}–10^{19} cm^{-2} through which one sees a background quasar. That range of column densities is particularly favorable for measuring intergalactic metallicity.

Figure 1a shows the absorption-riddled continuum emission spectrum of the background quasar in LLS1134—the more informative of the two LLS's reported in the team's new paper. Because the system's foreground absorber is at $z = 3.41$, the wavelengths of all the absorption features are stretched by a factor $(1 + z)$ from the UV into the visible.

The characteristic signature of an LLS, clearly seen in figure 1a, is the

Figure 1. Continuum UV emission spectrum of a quasar seen through a Lyman-limit system (LLS1134) of absorbing foreground clouds at redshift $z = 3.41$. **(a)** The highly redshifted spectrum has many lines due to absorption in the LLS. But the cutoff at 4022 Å shows the signature LLS opacity to all wavelengths shorter than hydrogen's Lyman-series limit (Ly-∞) of 912 Å in the absorber's rest frame. **(b)** Magnification of the spectrum around the 1216 Å Ly-α line (blue) in cloud A, the stronger absorber of the two that constitute this LLS. Wavelength is here labeled in terms of recessional velocity relative to cloud A. The orange line marks the center of Ly-α absorption in cloud B, redshifted about 1 Å by the cloud's 54 km/s recession. The green line marks deuterium's isotope-shifted Ly-α line in cloud A. The curves show fits to absorption line shapes. **(c)** Same as (b) for hydrogen's weaker Ly-15 absorption lines in the two clouds. **(d)** At the position of a usually prominent oxygen line, no absorption is seen in either cloud. (Adapted from ref. 1.)



Building ultralight lattices

DAN LITTLE/HRL LABORATORIES

The stiffness-to-weight ratio is an important figure of merit for structural engineers. But in the ultralight regime—at densities of 10 mg/cm^3 or less—few material options exist; one must turn to aerogels or foams. Architecture also matters: Both kinds of material form as a disordered network of cells whose random distribution renders the gel or solid far less stiff than one might predict based on its parent constituents—silica, carbon, polymer, or metal—in bulk form.

Fortunately, engineers have long known how to design structures whose order and symmetry enhance their mechanical properties. The Eiffel Tower, for instance, has a relative density—its mass per unit volume divided by the density of the iron in it—similar to that of aerogels, though the tower is clearly more structurally robust.[1] Extending such trusses and frames to the microscopic scale and yet processing them on the macroscopic scale is the vision behind a new method for making ultralow-density materials out of metallic microlattices.[2]

Developers Alan Jacobsen, Tobias Schaedler, and William Carter (all at HRL Laboratories, Malibu, California) and their colleagues start with a liquid photopolymer that solidifies when exposed to UV light. Passed through a patterned mask above the polymer, the light creates an interconnected, periodic array of fibers, each a few hundred microns thick, which the researchers then coat with a 100-nm film of nickel–phosphorus. They rinse the microlattice to etch away the polymer template, leaving a hollowed-out network of metal tubes. So diaphanous is the result that it can collapse under surface tension when lifted from the rinse bath; the lowest-density structures must be freeze dried.

The metallic microlattice, shown here atop a dandelion, could be made at a density as low as 0.9 mg/cm^3, below that of the lowest-density aerogels but with a Young's modulus—a measure of stiffness—nearly two orders of magnitude greater. Although the researchers opted for an octahedral unit cell, they could have created a variety of architectures by altering the mask pattern and the light's angle of incidence. The new method thus offers a greater level of flexibility than ones currently used to make metal foams and aerogels.

The method also allows control over the scale of lattice features, which can span six orders of magnitude—from millimeter-sized cells to micron-wide hollow tubes and their nanometer-thick walls. Indeed, the tiny thickness-to-diameter ratio, argue the researchers, is likely responsible for the materials' behavior in compression experiments. Astonishingly, the microlattice, though made of brittle nickel, recovers nearly completely—and repeatedly—after being squeezed to as little as 50% of its original size.

Metal foams and higher-density metal lattices deform plastically. But the hollow tubes in the new material act like soda straws, storing energy as they buckle elastically. "Even at stresses that crack a bending tube," says Carter, "the damage is rarely catastrophic and is localized on either side of the crack, leaving most of the tube undamaged."

Aerogels and metal foams have found widespread use in thermal insulation, acoustic and vibrational damping, battery electrodes, catalysts, and elsewhere (see the article by John Banhart and Denis Weaire in Physics Today, July 2002, page 37). Carter expects the new material to be useful in those applications and others such as tissue scaffolds and efficient heat exchangers. But at the moment, he and his colleagues are more interested in the interaction between material properties and architecture. The Young's modulus of a microlattice scales with the square of its density. But its value may be increased by fine-tuning the lattice parameters and by plating the polymer tubes with another material such as steel, ceramic, or high-strength carbon. **Mark Wilson**

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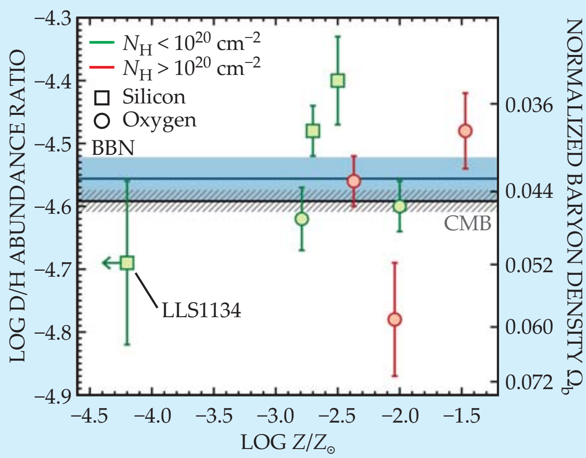

Figure 2. The primordial deuterium/hydrogen abundance ratio predicted from cosmic-microwave-background (CMB) data (hatched bar) is compared with direct measurements in a variety of high-redshift clouds, plotted as a function of their metallicities *Z*. The new LLS1134 datum has only an upper limit on *Z*. The right-hand axis translates D/H into cosmic baryon density according to Big Bang nucleosynthesis (BBN) theory, and the blue bar shows the new world average of D/H measurements. The measurements are consistent with the CMB baryon-density determination and with each other. There's no evident dependence of measured D/H on a cloud's hydrogen column density N_H, its *Z*, or the heavy element on which the *Z* measurement is primarily based. (Adapted from ref. 1.)

system's complete opacity to all photons more energetic than Ly-∞, the limiting energy of the Lyman series of UV atomic-hydrogen spectral lines. In the absorbing system's rest frame, the Ly-∞ wavelength is 912 Å, corresponding to hydrogen's 13.6 eV ionization energy.

Lyman-α, the strongest and most important of the Lyman absorption lines, marks the 10.2-eV Ly-α excitation from the H ground state to the first excited state. In the LLS1134 absorption spectrum, it's redshifted from 1216 Å, its rest-frame wavelength, to 5354 Å. The Ly-α line's precise position in the highly redshifted spectrum serves as a reference for identifying the other absorption lines of interest.

With the Keck I spectrometer's subangstrom resolution, the team was able to resolve individual Lyman absorption lines in LLS1134 all the way up to Ly-22. But model fitting of the line shapes showed each one to be a pair: a stronger absorption line with a weaker partner redshifted by only about 1 Å. The most straightforward interpretation of that doubling is that LLS1134 is really the superposition of a pair of separate clouds along the line of sight, the farther one (cloud B) receding from its more absorbing partner (cloud A) at a velocity of 54 km/s, corresponding to a tiny Δz of about 0.001 in the general cosmic expansion.

In that spirit, the magnified absorption spectrum near Ly-α and Ly-15 shown in figures 1b–c is plotted in terms of velocity $v = c\Delta\lambda/\lambda$. Zero velocity marks the spectral position of the line in cloud A. In each panel, a second absorption line, 54 km/s redward, is due to the same Lyman transition in cloud B. The strong Ly-α absorption is nearly total in both clouds, forming a continuous black trough. But the Ly-15 transition in cloud B yields only a shallow trough.

Deuterium but no metals

Figure 1b also exhibits a shallow trough, centered at $v = -82$ km/s. But that feature has nothing to do with clouds in relative motion. Instead it records Ly-α absorption in cloud A's small admixture of deuterium. The 82-km/s blueshift simply manifests the tiny isotope shift that makes the Ly-α excitation energy 0.03% bigger in D than in ordinary H. Cloud B yields no useful D absorption features.

From the depths of D absorption lines, the team concludes the D/H abundance ratio in cloud A is $10^{-4.7\pm0.1}$. That's not inconsistent with the average based on earlier measurements in half a dozen other low-metallicity clouds. Nor does the new measurement sport the smallest quoted uncertainty. It's noteworthy principally because it's the first D/H measurement in a system that might be pristine.

Despite the high sensitivity of the observations, cloud A revealed no absorption by metals. For example, figure 1d shows no discernable absorption at either the A or B spectral position of a usually prominent oxygen absorption line. But cloud B is clearly not pristine; it did exhibit some absorption by silicon and carbon. All the cloud A absorption lines, however, were attributable to H and its one stable heavy isotope. The

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undoubtedly significant He component in both clouds is not seen at optical frequencies because all its excitations remain in the UV even at these high redshifts.

"It's quite possible that the first generation of stars produced nothing heavier than oxygen," says Santa Cruz theorist Stan Woosley. "So I'm particularly impressed by the lack of carbon and oxygen."

Fumagalli and coworkers place an upper limit of $10^{-4.2}$ $Z_\odot$ on the metallicity of cloud A. The other apparently metal-free cloud, found by the team in a different LLS, has only about 15% of cloud A's column density. So its upper metallicity limit, $10^{-3.8}$ $Z_\odot$, is somewhat weaker.

Though each cloud, perhaps 100 light-years thick, was several orders of magnitude denser than the cosmic mean of 10^{-5} H atoms per cm^3 in that epoch, neither is thought to have been dense enough to form late first-generation stars. "But they may well be our first sighting of the so-called cool flows predicted by computer simulations of that epoch," says Prochaska. Those would be filamentary intergalactic streams of moderately dense, low-metallicity gas that flow into galactic halos and replenish the gas that sustains star formation.[2]

The primordial isotope ratio

The primordial D/H abundance ratio is particularly important to cosmologists because its predicted value depends sensitively on the cosmic mean baryon density. That density, usually given as Ω_b, the fraction of all mass and energy attributed to ordinary baryonic matter, is determined from cosmic-microwave-background (CMB) measurements to be $(4.5 \pm 0.1)\%$. (See PHYSICS TODAY, April 2003, page 21.) That predicts a D/H ratio of $10^{-4.6}$.

Stars can destroy D. So a long-standing question had been whether direct measurements of D/H in high-z clouds with small but nonzero metallicity reliably represent the primordial ratio. Figure 2 compares the CMB prediction with a variety of measurements at different metallicities, including the new measurement in LLS1134. They are all seen to be consistent, with no trend attributable to stellar destruction.

"So we can now conclude," says Fumagalli, "that deuterium abundances from quasar absorption-line systems are solid anchor points for models of galactic chemical evolution."

Bertram Schwarzschild

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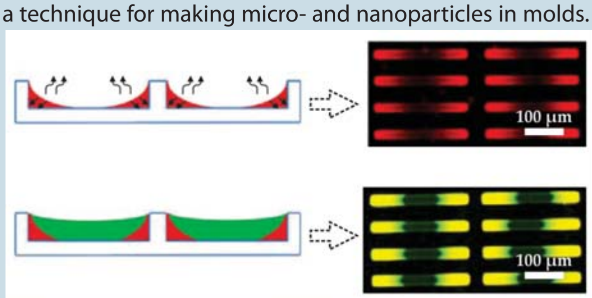
physics update

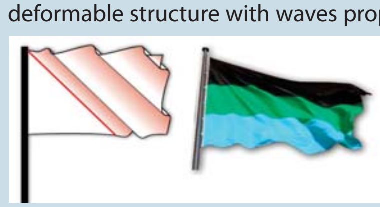
These items, with supplementary material, first appeared at http://www.physicstoday.org.

Molding many-faced particles. Scalable production of micron- and nanometer-sized particles with controlled sizes, shapes, and compositions is of interest for a host of applications. Toward that end, in 2005 Joseph DeSimone and colleagues (University of North Carolina, Chapel Hill) introduced PRINT—particle replication in nonwetting templates—a technique for making micro- and nanoparticles in molds.



The researchers fill an array of molds with an organic monomer liquid, use UV light to cure the liquid into a polymeric solid, extract the polymer particles using an adhesive film, and free them by dissolving the adhesive. In addition to pursuing various biomedical applications, DeSimone and colleagues have used PRINT to produce Janus particles: Hydrophobic on one side and hydrophilic on the other, the particles are interesting for the self-assembled structures they form (see the Quick Study by Steve Granick, Shan Jiang, and Qian Chen in PHYSICS TODAY, July 2009, page 68). The researchers fill the molds with a dilute solution of a hydrophilic monomer, evaporate off the solvent, and top off the molds with a hydrophobic monomer. Now, they've exploited capillary forces in rod-shaped molds to produce a wider range of multiphase particles. As shown in the figure, when the molds are filled with a hydrophilic solution and the solvent evaporated, the remaining liquid is drawn to the molds' ends; topping off with a hydrophobic monomer gives symmetric triblock particles. The researchers also created asymmetric triblock and diblock rods by spinning the partially filled molds in a centrifuge to drive some or all of the hydrophilic liquid to one end. (J.-Y. Wang et al., *J. Am. Chem. Soc.*, in press, doi:10.1021/ja2066187.) —JLM

Wrinkled roaches and flapping flags. For fluid dynamicists who seek a greater understanding of fluid–solid interactions, a flapping flag is a simple realization of a deformable structure with waves propagating in the direction of fluid flow. From models of such systems, researchers have determined, for example, that stiffer flags stretch nearly flat as they fly, as do those subjected to high fluid drag, whereas heavier flags form more and larger-amplitude wrinkles. Now, Jérôme Hœpffner at the Pierre and Marie Curie University in Paris and Yoshitsugu Naka at the University of Lille in France explain why the flag's wrinkles are oblique and how those oblique waves counterbalance gravitational forces. The researchers divide a flapping flag into two parts, as seen in the schematic and image: the pinned portion, represented by a right triangle, and the unpinned portion, which they call the roach, a term used for extra material on a sail. As the roach begins to collapse under its weight, it forms oblique waves, an observation that had not been explained by prior models. The researchers find that the flag's lift comes primarily from those waves. Aerodynamic forces act orthogonal to the wave-crests and impart the periodic rolling and snapping of the upper unpinned corner, which has been shown in old flags to suffer the greatest wear. (J. Hœpffner, Y. Naka, *Phys. Rev. Lett.* **107**, 194502, 2011.) —JNAM



Measuring morphological change. Objects alter their form in the course of such physical and biological processes as sedimentation and species differentiation. One