tions are known—one at 223 K involving a change in symmetry and one at 423 K involving a change in unit-cell size—and although the experimenters took care not to heat or cool their sample to either of those temperatures, they thought that they would see something akin to one of them and that their experiment would probe the transition's microscopic mechanism.

To check the x-ray results, colleagues Benjamin Freyer and Mirabelle Prémont-Schwarz used ultrafast IR spectroscopy to probe the system's vibrational modes. They found that the bending mode of the NH_4^+ ion decreased in intensity, and then increased again, over the same time scale as the electron–proton transfer shown in the diffraction studies. They also confirmed that the system returned to its equilibrium structure within 500 ps—well before the next pump pulse was due to arrive 1 ms later.

That the team was able to see the motion of single electrons and protons is extremely promising; light atoms such as hydrogen are often invisible in diffraction studies. Still, the x-ray researchers are working with mechanical engineering colleagues on campus to further improve the experiment's x-ray flux. They plan to turn their attention to the transition-metal complexes relevant to photovoltaic cells.

Johanna Miller

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Radio waves map matter without counting galaxies

A new technique for charting the large-scale structure of the universe has received its first experimental demonstration.

As everyone except movie directors knows, sound doesn't travel in outer space. But there was a time, spanning the first 380 000 years after the Big Bang, when acoustic waves did traverse the cosmos, which was filled with hot, dense plasma. As the plasma cooled and neutral atoms formed, the waves suddenly stopped propagating. Their mass-density pattern froze in place, and the denser regions eventually contracted under their own weight to form galaxy clusters.

Cosmologists are interested in studying that density pattern—the so-called baryonic acoustic oscillations (BAOs)—as a way of tracing the universe's expansion. (See the article by Daniel Eisenstein and Charles Bennett, PHYSICS TODAY, April 2008, page 44.) Observations of distant supernovae have led to the surprising conclusion that the expansion is accelerating under the influence of an enigmatic dark energy. (See the article by Saul Perlmutter, PHYSICS TODAY, April 2003, page 53.) But the expansion trajectory is poorly constrained. BAO observations could add further confirmation to the acceleration and perhaps provide some clues

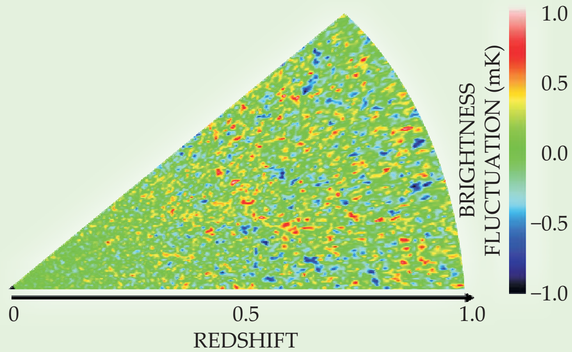


Figure 1. Simulation showing large-scale structure as it would appear in an intensity map of the 21-cm hydrogen emission. Red spots indicate greater-than-average density; blue indicates lower-than-average density. (Adapted from ref. 1.)

about dark energy's nature. The observations would need to cover an enormous volume of space, extending to redshift z of at least 1.

Surveys of relatively nearby galaxies (with $z < 0.3$) have turned up evidence of the BAOs, but not with enough precision to draw any cosmological conclusions. And galaxy surveys are laborious: Each galaxy (in a sample of hundreds of thousands or millions) must be separately resolved so that its redshift can be inferred from its spectral features. Extending the surveys to greater distances is even more difficult and time consuming, since distant galaxies are fainter and more numerous than nearby ones, and much of their light is shifted out of the visible band into the IR, where it is absorbed by Earth's atmosphere.

A potentially more efficient technique, dubbed "intensity mapping," is to focus not on the visible light produced by stars but on the radio waves emitted by interstellar atomic hydrogen gas.[1] Radio observations can't easily resolve distant galaxies, but they don't have to. Since the 21-cm emission is an isolated spectral line (corresponding to hydrogen's spin-flip transition), blobs of mass at different distances can be detected simultaneously: They have different redshifts, so they show up at different frequencies. And the spatial resolution would still be sufficient to detect the BAOs, as shown in the simulated intensity map in figure 1.

But hydrogen is not the only radio emitter in the universe: Other sources, both terrestrial and celestial, dwarf its signal by a factor of 1000. Now a team of four researchers—Tzu-Ching Chang of Academia Sinica in Taiwan and the University of Toronto, Ue-Li Pen also of Toronto, and Kevin Bandura and Jeffrey Peterson of Carnegie Mellon University—has demonstrated that the hydrogen signal can in fact be extracted over redshifts from 0.5 to 1.1. The researchers conducted RF observations over some of the few patches of sky whose galaxies had already been mapped at those distances. They then processed the data to remove the nonhydrogen contribution. The remaining signal showed significant correlation with the known galaxy density—meaning that the team was indeed detecting hydrogen from distant galaxies.[2]

Back in time

Much is known about what the universe looked like at the moment the acoustic waves stopped propagating, because the cosmic microwave background originated at the same time. Spatial variations in the CMB intensity reflect the mass-density pattern imprinted by the sound waves as they froze in place. (See PHYSICS TODAY, April 2003, page 21.) The CMB fluctuations exhibit a correlation on the angular scale of 0.6°, equivalent to a correlation length, at the time of their formation, of about 440 000 light-years, the distance the sound waves traveled during the plasma epoch, helped along by the expansion of the universe.

Today that correlation length has grown to 480 million light-years, so galaxy clusters are slightly more likely to be 480 Mly apart than one would expect if they were distributed randomly. By measuring that "standard ruler" over a range of redshifts, one should be able to track the expansion of the universe in a way that complements the "standard candle" of the supernovae data.

The 21-cm hydrogen line can potentially provide information not only about the BAOs near $z = 1$ but also about the earlier era of reionization (with z between 6 and 20), when stars and galaxies were just starting to form, and about the even earlier "cosmic dark ages" when there were no stars at all. Several new facilities are being constructed for observing the very distant hydrogen, and theorists have analyzed what the measurements would mean,[3] but until now the 21-cm emission had never been isolated at a redshift beyond 0.24.

Hunting for hydrogen

In 2007 Chang, Pen, and Peterson met at a conference and decided to work together on intensity mapping. They began with a theoretical analysis in which they showed that intensity mapping with existing radio telescopes could potentially improve the constraints on cosmological parameters related to dark energy.[4] Then they analyzed radio and optical data taken by the HIPASS survey (HI Parkes All-Sky Survey) to show that 21-cm emission is correlated with the distribution of galaxy clusters in our local neighborhood ($z < 0.04$).[5] Now they've obtained

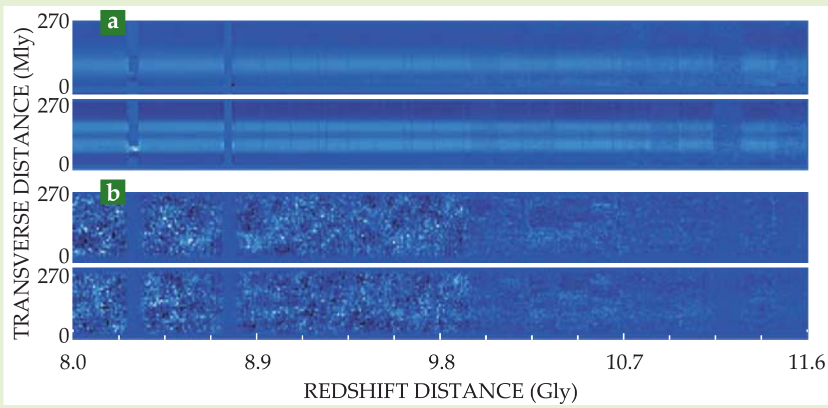
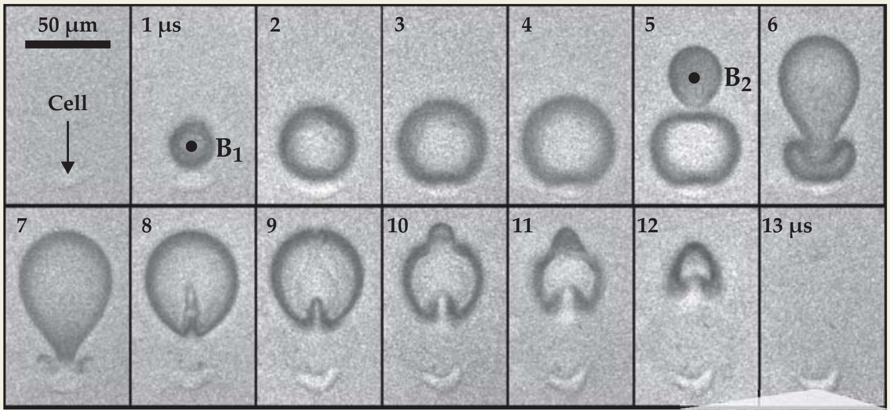


Figure 2. Radio flux over two slices through the intensity map over a redshift range of 0.70–1.12. **(a)** Before nonhydrogen sources are removed, they overwhelm the hydrogen signal. The vertical stripes are caused by terrestrial signals such as television broadcasts, and the horizontal stripes are created by astronomical synchrotron radiation. **(b)** Removal of continuum sources reveals the hydrogen signal. (Adapted from ref. 2.)

Laser-generated bubbles take aim at a cell membrane



Ever since World War I, when Lord Rayleigh laid the theoretical foundations for the dynamics of collapsing bubbles that were eroding the propeller blades on the Royal Navy's ships and submarines, experiments have borne out the violent nature of the cavitation process. During a bubble's collapse, the gas inside it can reach temperatures of more than 15 000 K—as hot as the surface of a star—and the energy can be released in the form of shock waves, heat, light, or turbulent vortices and high-speed jets of fluid. (See the article by Detlef Lohse in PHYSICS TODAY, February 2003, page 36.)

For decades, medical researchers have worked to harness that energy release for therapeutic applications such as the disintegration of cancerous tumors using focused ultrasound (see the article by Gail ter Haar in PHYSICS TODAY, December 2001, page 29) and the delivery of drugs or genes into living cells (see PHYSICS TODAY, December 2005, page 22). Although studies have demonstrated that cavitating bubbles can rupture nearby cells, thanks to the high shear and pressure forces that their expansion and collapse generate in surrounding fluid, a complete understanding of the bubble–cell interaction and how best to control it remains elusive.

Duke University researchers Georgy Sankin, Fang Yuan, and Pei Zhong have now developed an experimental approach to opening a cell's membrane that entails carefully manipulating the fluid dynamics around it.[1] The key to their approach is the use of two laser-generated bubbles that act in concert to direct a tiny jet of fluid into a target cell.

This high-speed sequence of photographs captures the process. The researchers focus two 5-ns laser pulses, each about 30 μJ, near one of thousands of cancer cells held in a microfluidic chamber. Heat from the first laser pulse vaporizes a pocket of liquid, which expands adiabatically into a microbubble (B_1). After 4 μs the second pulse creates another microbubble (B_2), 40 microns away, whose own rapid expansion causes the collapse of the first by pressing against it. Both bubbles lose their spherical symmetry, with B_2 drawn into the wake left by the collapsing B_1. The asymmetric collapse of both bubbles gives rise to two localized microjets that shoot in opposite directions along the bubbles' axis: the first, between 6 and 7 μs, a downward-directed thin fluid spike that pricks a 2-μm pore in the cell, and the second, between 8 and 11 μs, an upward-directed spike.

As one camera captures the bubbles' interaction, a second records the fluid dynamics from tiny polystyrene tracers caught up in the flow. The particle image velocimetry (PIV) indicates that, as B_1 collapses, fluid rushes in from both sides. Zhong argues that the higher pressure there, along with a higher surface tension due to greater local curvature, causes the lower edge of B_2 to then collapse faster than the rest of it at 8 μs. Indeed, the resulting microjet is so forceful that a nipple appears on the opposite side of the bubble.

According to the PIV measurements, a microjet typically flows at 10 m/s and sets up a pair of vortices—one clockwise, the other counterclockwise in the image plane—that can spin as rapidly as 350 000 s^{-1} and persist for hundreds of microseconds. The jet-induced flow and vorticity generate a shear stress of about 1 kPa, which stretches and bends the cell membrane.

"The beauty of the Duke experiment," says Nanyang Technological University's Claus-Dieter Ohl, "is the level of control and precision it offers in a microfluidic setting." The researchers can adjust the bubbles' positions, separation, and orientation relative to any cell of interest. What's more, the flexibility of their setup allows them to photograph the bubble dynamics simultaneously either with the PIV measurements—at about a million frames per second—or with measurements that capture the subsequent uptake and diffusion of dye molecules into the ruptured cell over a minute's time.

Afterward, the team can chemically preserve the cell, mark its location with a laser spot burned on the Petri dish, and easily find the pore for later microscopy, as shown in the final image.

Mark Wilson

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their own data at the Robert C. Byrd Green Bank Telescope (GBT) in West Virginia for *z* between 0.5 and 1.1. They chose two regions of sky, each 0.5° by 2°, that had been cataloged by the DEEP2 optical redshift survey.

The GBT is a steerable, directional telescope—an enormous satellite dish, basically—with a 0.25°-wide beam. The researchers used it in "drift scan mode": Keeping the telescope stationary, they allowed Earth's rotation to drag the beam through the field of interest. Scanning one square-degree patch once with a series of such tracks took 36 minutes; they recorded data for a total of 15 hours.

The sought-after hydrogen signal was overwhelmed by terrestrial radio waves (television broadcasts and cellphone signals with frequencies of 670 to 930 MHz) and by astronomical synchrotron radiation (produced whenever relativistic electrons encounter magnetic fields). Terrestrial-sourced radio waves are more or less localized in frequency, but not in position; they're also strongly polarized. The researchers removed the brightest terrestrial signals by discarding all the data points that were more than 2% polarized. That meant cutting stripes out of their data plots that amounted to about 5% of their data. Residual signals show up as vertical stripes in figure 2a; to mitigate those, they subtracted the mean flux in each spectral channel.

Space-based radio emissions, on the other hand, show up as horizontal stripes, localized in position and weakly dependent on frequency. To remove them, the researchers used a matrix-algebra technique, called a principal component analysis, to decompose their data into a sum of components, each the product of a function of frequency times a function of position. The strongest components, they figured, probably represented the unwanted synchrotron sources. They removed those and retained only the weaker components that contained most of the hydrogen signal. The result is shown in figure 2b.

That done, the researchers calculated the cross-correlation of their data and the DEEP2 galaxy density. The two were correlated up to length scales of 40 Mly—quantitatively similar to the DEEP2 data's autocorrelation. That means that the extracted signal measures much the same thing as the galaxy survey: The teasing out of the hydrogen contribution was a success.

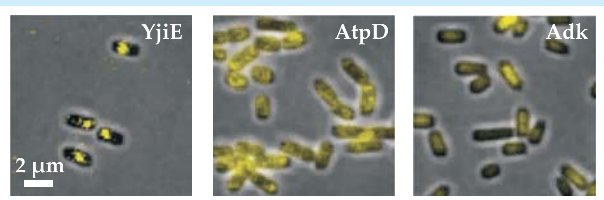
There's a long way to go, though, before intensity mapping can provide any

physics update

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

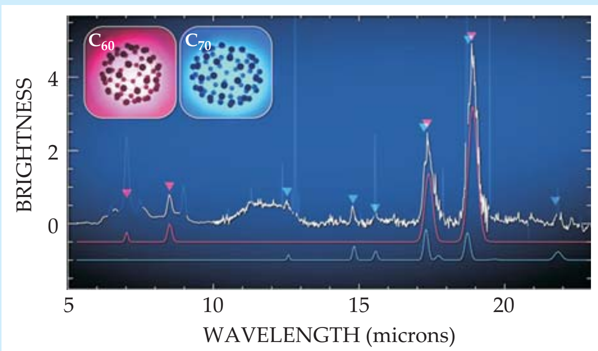
Muonic Lamb shift. Willis Lamb's 1947 measurement of the tiny splitting between the 2*s* and 2*p* states of atomic hydrogen gave a crucial impetus to the development of quantum electrodynamics (QED). That "Lamb shift" from the Dirac hydrogen spectrum is a 4-μeV increase in the 2*s* energy level due primarily to vacuum fluctuations of the electromagnetic field. Now Randolf Pohl (Max Plank Institute for Quantum Optics, Garching, Germany) and coworkers at the Paul Scherrer Institute (PSI) in Switzerland have finally measured the analogue of the Lamb shift in the muonic H atom—a proton orbited by a μ^- instead of an e^-. Muons live only microseconds, but they are 200 times heavier than electrons, and their atomic orbits are correspondingly tighter. The muonic Lamb shift is about 200 meV, and its precise value is particularly sensitive to the proton's finite size. The PSI experiment was accomplished with precision laser excitation of μ^- p atoms created by an intense μ^- beam stopping in a small volume of H_2 gas at very low pressure. The team measured the muonic Lamb shift to a part in 10^5 and compared it with elaborate QED calculations that parameterize the proton's finite size with an effective charge radius R_p. They find an R_p about 4% smaller than that measured, with less precision, by conventional H spectroscopy and e^-–p scattering experiments. The discrepancy is 5 standard deviations. Either the proton really is smaller than previously thought, argue Pohl and company, or there's something wrong with the QED calculations or their input constants. But the proton is a quark composite whose size and shape are quantum-chromodynamic manifestations beyond the purview of QED. Several QCD theorists suggest that at the extraordinary precision achieved by the PSI experiment, it may not be possible to describe proton-size effects adequately with a single length parameter. (R. Pohl et al., *Nature* **466**, 213, 2010.) —BMS

The noisy expression of genes into proteins. Genetic information is transcribed from DNA to RNA and translated from RNA to make proteins. Because each step entails a modest number of molecules, gene expression, as the DNA-to-protein conversion is termed, is inevitably noisy: Identical genes in identical cells don't yield identical numbers of proteins. But how noisy? Sunney Xie of Harvard University and his collaborators have used single-molecule fluorescence microscopy and microfluidics to find out.



They started by modifying the DNA of *Escherichia coli* to create 1018 different strains of the single-celled bacterium. In each strain, the code for a yellow fluorescent protein (YFP) was inserted after the gene for a different protein. To see the rate at which one gene is expressed in one cell of one strain, you'd illuminate the cell with a laser and measure the YFP emission through a microscope. To gather gene-expression statistics for a sample of cells from all 1018 strains, the Harvard team sent streams of cells through channels cut in a microfluidic chip and imaged them. The figure shows sample images for three proteins, YjiE, AtpD, and Adk. Ninety-six strains could be processed at once at a total throughput of 160 cells per second. The team found that the least abundant proteins appear at 10^{-1} molecules per cell; the most abundant, at 10^4 per cell. Gene expression is indeed noisy, but with a twist. As you'd expect, the least abundant proteins have the largest cell-to-cell fluctuations. But for proteins whose mean abundance is 10 per cell or higher, the expression noise saturates, presumably because the various molecules that mediate gene expression inside a cell are in limited supply. (Y. Taniguchi et al., *Science* **329**, 533, 2010.) —CD

Space buckyballs. The field of nanotechnology is in part rooted in the 1985 Nobel Prize–winning laboratory synthesis of buckyballs—the soccer-ball-shaped carbon molecule C_{60}—by Rice University chemists Richard Smalley and Robert Curl and their collaborator, University of Sussex chemist Harold Kroto. The synthesis was guided by Kroto's hypothesis that complex carbon chains could naturally form in the interstellar medium of aging carbon-rich, hydrogen-poor giant branch stars. Now, 25 years later, Jan Cami at the University of Western Ontario and his colleagues have reported the clearest evidence yet of such complex carbon structures in space. The research team analyzed IR spectroscopic data—collected by the *Spitzer Space Telescope*—of the circumstellar region of a planetary nebula known as Tc 1. As the image shows, the spectrum contains several prominent peaks of C_{60} (red arrows) and peaks of the rugby-ball-shaped C_{70} (blue arrows); both molecules were uncharged and in the solid phase. Previous spectra of other carbon-rich planetary nebulae indicated strong emission peaks of volatile polycyclic hydrocarbons, which were completely absent in the monitored region of Tc 1.



cosmologically significant conclusions. The radio data's autocorrelation—the quantity that should eventually reveal the BAO peak at 480 Mly—was so noisy that it wasn't statistically different from zero. But Chang notes, "The situation has improved since late 2009, since digital TVs no longer occupy the 700-MHz frequency range." With 300 more observing hours at the GBT, she and her colleagues are now mapping a larger area of sky—about 50 square degrees—which they'll use as a test for even larger surveys aimed at BAO measurement. And they hope to get funding to build a dedicated intensity-mapping telescope that's as big as the GBT. Peterson, Bandura, and others have already built a prototype.

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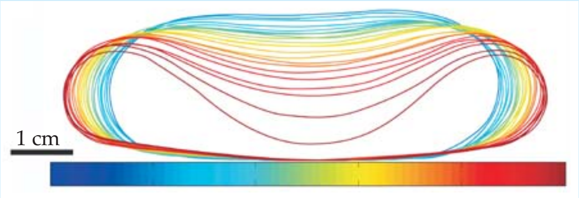
Cami and his colleagues suggest that the planetary nebula may have ejected its hydrogen envelope a few thousand years ago and that a recent thermal pulse prompted the ejection of the pure carbon dust they're now observing. (J. Cami et al., *Science*, in press, doi:10.1126/science.1192035.) —JNAM

Rolling ribbons get the bends. For thousands of years, children have delighted in hoop rolling. Certainly, most of them have not considered that the rings are subject to gravitational and inertial forces; in any case, the hoops are stiff enough that they maintain their circular form despite those forces. But what happens to a rolling hoop that's not so stiff? John Bush of the MIT mathematics department, along with visiting student Pascal Raux and colleagues, has answered that question in a recent study of more general systems—rolling bands that may be wider than they are high. Bush and company's work was both experimental and theoretical. In their experimental investigations they took pictures of a vinyl polysiloxane loop placed on the inner surface of a rotating drum. The figure shows how the form of a representative loop changes as the drum speed is increased; blue corresponds to low speeds; red, high. In their theoretical work, the investigators confirmed the intuitive idea that the rolling band deforms as the inertial or gravitational force overwhelms the internal stiffness force. Indeed, if either gravity or inertial effects



are strong enough, the top of the band can make contact with the bottom; new forces then come into play and the team's analysis is no longer valid. Rolling droplets, tumbling blood cells, and carbon nanotubes deformed by van der Waals forces, the authors note, all display similar shapes to the rolling ribbons; the dynamics of those varied systems may be elucidated by the relatively simple ribbon study. (P. S. Raux et al., *Phys. Rev. Lett.* **105**, 044301, 2010.) —SKB

Bali's beating gong. At the heart of the Balinese percussive orchestra known as a gamelan is the large gong called the *gong ageng wadon*. It features a large, protruding dome or boss in the middle; when the boss is struck with a padded mallet, the gong produces a pronounced acoustic beating or *ombak* (meaning "wave"), as can be heard in the online version of this item. Using acoustical and vibrometric analyses, David Krueger and his colleagues at Brigham Young University have studied the sources of the ombak. Although some beating was found to come from asymmetric vibration modes with closely spaced frequencies, those appear to contribute mostly to the gong's timbre. The more significant contribution arises from the gong's nonlinear structural response. Its two dominant vibration modes, both axially symmetric, have nearly a 2:1 frequency ratio. That relationship gives the gong its perceived pitch, but the ratio isn't exact. So when the gong is struck, causing displacements large enough to produce overtones, the fundamental generates harmonics and interacts with the second axisymmetric mode to yield sum and difference frequencies. The resulting sound spectrum features strong peaks of similar amplitudes that are spaced only a few hertz apart and give rise to the distinctive sound of ombak. (D. W. Krueger, K. L. Gee, J. Grimshaw, *J. Acoust. Soc. Am.* **128**, EL8, 2010.) —RJF

Directly imaged exoplanet challenges formation models. Two years ago, astronomers in Canada directly imaged what seemed to be a gas giant planet in a very distant orbit—more than 300 times the Earth–Sun distance of one astronomical unit (AU)—around a star much like our Sun. (For comparison, Jupiter's orbit is 5.2 AU, Neptune's is 30 AU.) Such a scenario poses difficulties for all the major planet-formation models in current use: core accretion, gravitational instability, and fragmentation of a pre-stellar core. The main difficulty is that either much larger objects, like another star, or much smaller ones are expected at such a great distance. Now, with further observations in hand from the Gemini North telescope and its adaptive optics, University of Toronto astronomers Ray Jayawardhana, Marten van Kerkwijk, and David Lafrenière (now at the University of Montreal) have confirmed the puzzle: The planet, with about eight times the mass of Jupiter, is moving through space gravitationally bound to the parent star, known by its nickname 1RXS 1609. Besides astrometric observations, the direct imaging (shown here) along with spectroscopic and photometric data allowed the researchers to further characterize the planet and confirm that no other large planets are farther out in the system. A mere toddler at only 5 million years old, 1RXS 1609 is about 500 light-years away. Hundreds of other exoplanets have been discovered in recent years, but this one is expected to keep theorists busy for some time. (D. Lafrenière, R. Jayawardhana, M. H. van Kerkwijk, *Astrophys. J.* **719**, 497, 2010.) —SGB