

ing to this picture, reconnection begins when the solar wind squeezes a part of the magnetotail from above and below the so-called X-line, the notional locus of a reconnection event (see figure 3). Magnetically entrained particles can't be compressed indefinitely. They resist when the region they occupy is about the same size as their radius of gyration about the field lines.

First to push back and demagnetize are the positively charged ions (mostly protons), whose gyroradius in the magnetotail is about 700 km. The electrons, meanwhile, continue inward, moving past the more or less stationary ions until they reach their much smaller gyroradius of about 20 km. It is in this small region, known as the electron diffusion region, that the electrons demagnetize and set off reconnection.

The drift of electrons relative to the ions creates a system of currents and magnetic fields akin to the classical Hall effect (see figure 3). Characteristically, the Hall fields are directed across, not along, the magnetotail and can exist well above the midplane of the magnetotail. In its chance encounter with the 1 April 1999 reconnection event, WIND detected both the Hall current and magnetic field. GEOTAIL, too, has observed Hall signatures,⁵ which would not be seen if

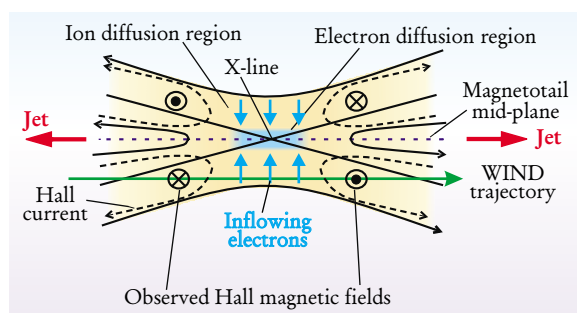


FIGURE 3. THE WIND SPACECRAFT flew through a reconnection event on 1 April 1999. Its trajectory, shown in green, took it through the Hall-like system of magnetic fields and electric currents established by inflowing electrons during reconnection. (Adapted from ref. 3.)

reconnection were mediated by anomalous resistivity.

Paradoxically, although WIND missed the electron diffusion region, the spacecraft's chance encounter underscores the importance of probing the region where electrons demagnetize. Pulling the electrons off their field lines requires an electric field, but reconnection, at least at the X-line, implies zero magnetic field and, with it, the possibility that electrons could short-circuit the electric field. Some kind of plasma instability might maintain the electric field, but simulations show that electrons tend to be kicked away from the X-line by the

Lorentz force, so an instability might not be needed.

Observing the electron diffusion region is one of the goals of NASA's Magnetospheric Multi-scale mission (MMS). Scheduled for launch in 2006, MMS consists of four identical spacecraft that will fly in a tetrahedral formation with a minimum separation of 10 km—fine enough, space physicists hope, to measure what they call the microphysics of reconnection in three dimensions. Meanwhile, another formation flyer, the European Space Agency's Cluster 2 mission, has been gleaned data in the magnetosphere since its launch last year.

WIND, however, might not witness another reconnection event. To save money, NASA plans to mothball the seven-year-old spacecraft.

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References

1. G. Paschmann et al., *Nature* **282**, 243 (1979).
2. T. D. Phan et al., *Nature* **404**, 848 (2000).
3. M. Øieroset, T. D. Phan, M. Fujimoto, R. P. Lin, R. P. Lepping, *Nature* **412**, 414 (2001).
4. B. U. Ö. Sonnerup, in *Solar System Plasma Physics*, vol. III, L. T. Lanzerotti, C. F. Kennel, E. N. Parker, eds., North-Holland, New York (1979), p.45.
5. T. Nagai et al., *J. Geophys. Res.* (in press).

Spectra of the Most Distant Quasars Elucidate the Reionization of the Cosmos

In 1965, just two years after quasars were first identified as cosmologically distant objects, James Gunn and Bruce Peterson at Caltech called attention to a peculiar spectroscopic aspect of these high-redshift beacons. Looking at the spectrum of a quasar with a redshift z of about 2, they pointed out that it did not exhibit a trough of total absorption on the blueward side of its prominent Lyman- α hydrogen emission peak. But if, as was generally supposed, the intergalactic medium between us and the quasar had lots of neutral atomic hydrogen, there would have to be such an absorption trough.

The absence of a "Gunn–Peterson trough" in any of the quasar spectra measured in the ensuing 35 years is the primary evidence we have that the intergalactic hydrogen is *not* neutral. It is, in fact, overwhelmingly ionized.

As cosmological epochs are reckoned, this ionized intergalactic medi-

Half a million years after the Big Bang, almost all the hydrogen in the cosmos was neutral. When and how did it all get reionized?

um has to be a rather recent state of affairs. The cosmic microwave background teaches us that, some 400 000 years after the Big Bang, the universe finally became cool enough for neutral hydrogen atoms to survive (see *PHYSICS TODAY*, July 2001, page 16). Astrophysicists have been striving for decades to pinpoint the time of the subsequent cosmic "reionization" phase transition—perhaps a billion years later—by looking at the spectra of ever more distant, higher-redshift quasars in search of one early enough to exhibit a Gunn–Peterson trough. The reionization time is an important parameter for models of the evolution of structure in the cosmos.

For the past year or two, this task

has been greatly aided by a byproduct of the prodigious Sloan Digital Sky Survey. Gunn, who has been at Princeton since 1968, is the Sloan survey's project scientist. The survey's principal task is to measure the redshifts—and hence the distances—of a million galaxies. But in the process, the survey has been identifying handfuls of the most distant quasars ever seen.¹

The trough, at last

Now we have a paper from the Sloan team reporting that their most distant quasar, with a z of 6.28, shows the first "clear detection of a complete Gunn–Peterson trough."² In a related paper,³ George Djorgovski and colleagues at Caltech, having taken a high-resolution look at the spectrum of a $z = 5.73$ quasar discovered by the Sloan survey last year, argue that residual dark patches in that spectrum are a signature of the final moments of the reionization transition.

Both these new papers suggest that the intergalactic medium was almost completely reionized at a redshift z_R of about 6. To circumvent various uncertainties, cosmologists like to specify moments in cosmic history by redshift rather than explicit time. If we see an emission line of a distant object redshifted by $z \equiv \Delta\lambda/\lambda_0$, where λ_0 is the rest-frame wavelength, we know that the linear scale of the expanding cosmos has grown by a factor $1+z$ since the time of emission. And, for most of cosmic history, that scale factor has been growing like $t^{2/3}$, where t is the time since the Big Bang. So, if the cosmos is now about 14 billion years old, a redshift of 6 corresponds roughly to a t of about 900 million years.

The transition from the hot primordial plasma to neutral hydrogen at about $t = 400\,000$ years ($z \approx 1200$) rendered the cosmos, for the first time, transparent to visible light (which was rapidly fading away as the temperature of the starless universe continued to fall) and to longer wavelengths. But the neutral hydrogen would not be so kind to the ultraviolet radiation from the first stars and accreting black holes that began to appear a few hundred million years later.

Lyman- α absorption

An expanding universe full of neutral hydrogen would have presented an opaque barrier to ultraviolet photons emitted with energies above 10.2 eV, the rest-frame Ly- α energy ($\lambda_0 = 1216$ Å). The Ly- α transition is the excitation of an electron from the ground state of atomic hydrogen to the first excited state. The Ly- α emission and absorption lines are both very strong. Even a very small residuum of neutral hydrogen presents a formidable absorption barrier. Photons that start out with energies above 10.2 eV are eventually redshifted down to the Ly- α energy by the cosmic expansion, and then promptly absorbed.

At a somewhat higher energy (13.6 eV, the limit of the Lyman spectroscopic series), an ultraviolet photon can ionize a hydrogen atom. Thus the ultraviolet radiation from the first protogalaxies and accreting black holes began to produce growing bubbles of ionized hydrogen in the neutral surrounding medium. Eventually, as time passed and galaxies proliferated, the merging of all these growing ionized bubbles is thought to have wrought a rather abrupt phase tran-

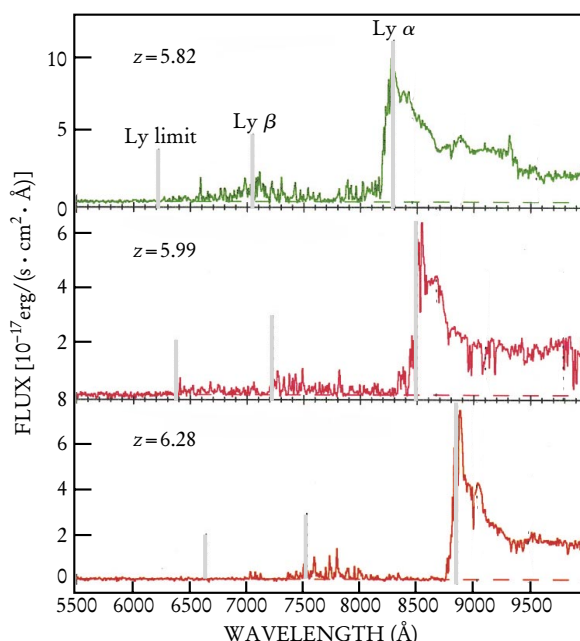


FIGURE 1. SPECTRA of the Sloan survey's three highest-redshift quasars, in the vicinity of the redshifted α and β lines of the hydrogen Lyman excitation series and the Lyman ionization limit. In the spectrum of the $z = 6.28$ quasar (bottom panel) the absence of any discernible flux between 8450 Å and the prominent Ly- α peak appears to be the first observation of a Gunn-Peterson trough. (Adapted from ref. 2.)

sition to the almost fully ionized intergalactic medium that surrounds us today.⁴ That is to say, the ultraviolet radiation from any source whose redshift is smaller than z_R will not be completely absorbed by neutral hydrogen as it makes its way to us through the intergalactic medium.

A useful exception to this general assertion is the so-called Lyman- α forest—a thicket of discrete absorption lines. This seemingly random jumble of black lines is due to Ly- α absorption of ultraviolet light from distant quasars by small residual pockets of neutral atomic hydrogen along the line of sight. If one such intervening pocket happens to sit at redshift z , we see the Ly- α absorption line it engenders redshifted by a factor $1+z$. This forest of discrete absorption lines in the ultraviolet continuum of a quasar spectrum is quite different from the wide, empty trough that would be produced by pervasive neutral hydrogen not confined to occasional pockets.

For two decades, the Ly- α forest has been a superb source of information about the intergalactic medium and the objects it envelops. (See PHYSICS TODAY, November 1987,

page 17.) The pockets of neutral hydrogen are still called Lyman- α clouds, but the “cloud” metaphor is now out of favor. The pockets are thought to be the fractally distributed regions of highest mass density in the gravitationally evolving structure in the intergalactic medium. The higher the local density, the more likely ionized atoms are to recombine with electrons to become neutral again. In cosmological models, the evolution of density fluctuations depends sensitively on what one assumes to be the admixture of cold and hot dark matter.

Quasar spectra

Figure 1 shows the Sloan survey's spectra of the three highest-redshift quasars found to date, taken in the group's follow-up measurements at the 10-m Keck II telescope on Hawaii's Mauna Kea. The ultraviolet region around the quasars' prominent Ly- α peaks is accessible to ground-based spectroscopy only because the high redshifts have transposed it into the visible and near infrared.

In the spectra of the $z = 5.82$ and 5.99 quasars, we see the Ly- α forest crowding right up to the quasar's Ly- α peak from its blueward (left) side. (At much lower redshifts, the forest is more obviously a collection of narrow absorption holes piercing an emission continuum. But at these high redshifts, the great number of intervening neutral-hydrogen pockets makes the forest look more like a jumble of small emission peaks.)

The $z = 6.28$ spectrum is different. Between 8450 Å and the precipitous beginning of the quasar's Ly- α emission peak, the spectral measurement is consistent with zero flux. This, then, appears to be the long-sought-after Gunn-Peterson trough. Its blueward margin at 8450 Å implies that any ultraviolet photon that redshifted down to the Ly- α energy before the time corresponding to $z = 5.95$ would have been promptly absorbed by neutral hydrogen. Given the sensitivity of the measurement, one can only say that the flux in the trough is dimmer by a factor of at least 150 than it would have been in the absence of intergalactic Ly- α absorption. To determine what that unabsorbed flux would have been, the Sloan group extrapolates from the essentially undimmed emission continuum on the redward shoulder of the Ly- α peak.

Even a small fraction of un-ionized hydrogen distributed throughout the intergalactic medium at $z \approx 6$ would have rendered the flux in the trough region undetectable. “Therefore,” the Sloan team cautions, “the existence of the Gunn–Peterson trough, by itself, does not indicate that the quasar is being observed prior to the reionization epoch.”² One has to consider how abrupt or gradual is the increase of absorption with increasing redshift. To that end, the team has looked at how the effective optical depth of the neutral hydrogen that’s absorbing the quasar light depends on the redshift at which the absorption is taking place (see figure 2). An optical depth of τ means that Ly- α absorption along the line of sight has dimmed the quasar’s ultraviolet emission by a factor of $e^{-\tau}$.

Figure 2 plots the optical depth for various z absorption intervals as calculated from the observed spectral intensity of the Sloan survey’s four highest-redshift quasars in the corresponding wavelength intervals blueward of the Ly- α emission peak.² The optical depth $\tau = 5$ for the highest z interval—corresponding to the reported Gunn–Peterson trough—is a lower limit, the trough showing no discernible flux.

The curve in the figure shows the gradual increase in optical depth one would get—in the absence of a reionization phase transition—simply

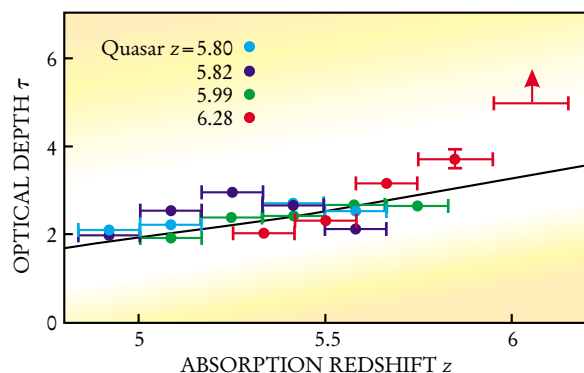


FIGURE 2. OPTICAL DEPTH due to Lyman- α absorption by neutral hydrogen grows as the redshift z at which the absorption took place increases. The data are from the spectra of the Sloan survey’s highest-redshift quasars. The rightmost data point, representing a spectral trough with no discernible flux, is a lower limit. With increasing z , the data pull away from the curve that shows what one expects simply from the greater abundance of Ly- α clouds at earlier times, suggesting that the intergalactic medium also had more neutral hydrogen in that epoch. (Adapted from ref. 2.)

from the expected increase in the number density of Ly- α clouds with increasing z . Above $z = 5.8$, the measured optical depths appear to be pulling away from the curve. So, above and beyond the greater abundance of Ly- α clouds at $z \gtrsim 6$, the intergalactic medium between the clouds in that epoch had a lot more

neutral hydrogen than it would have in the later epoch.

Djorgovski and company, having availed themselves of a six-hour exposure at the Keck II telescope to produce a very high signal-to-noise spectrum of the $z = 5.73$ quasar, found a revealing discontinuity that had not been evident in the earlier low-resolution spectrum: “a dramatic increase in the optical depth”³ on the blueward side of 7550 Å. They interpret this incipient spectral trough to mean that $z = 5.2$, the Ly- α absorption redshift corresponding to 7550 Å, is perhaps the last gasp of a rather extended reionization transition.

To map out the reionization of the cosmos in greater detail, observers will need more lines of sight to quasars at the highest redshifts. The Sloan survey expects ultimately to bag a total of about 20 quasars with $z \gtrsim 6$. If the reionization transition was far from uniform, different lines of sight may tell different stories.

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References

1. X. Fan et al., <http://arXiv.org/abs/astro-ph/0108063>, *Astron. J.* (in press).
2. R. H. Becker et al., <http://arXiv.org/abs/astro-ph/0108097>, *Astron. J.* (in press).
3. S. G. Djorgovski, S. Castro, D. Stern, A. Mahabal, <http://arXiv.org/abs/astro-ph/0108069>, *Astrophys. J. Lett.* (in press).
4. R. Barkana, A. Loeb, *Phys. Rep.* **349**, 125 (2001).

Buckyball Crystals Made to Superconduct at 117 K

The discovery in the early 1990s that C_{60} crystals could superconduct at temperatures of several tens of kelvins raised hopes that such “buckyballs” might rival the copper-oxide superconductors, whose T_c ’s go as high as 150 K under pressure. Those hopes have now been fulfilled.

The first C_{60} superconductors were made by incorporating alkali atoms into the spaces between the closely packed C_{60} spheres. These atoms acted as electron donors because their outer electrons were quickly stripped away by the buckyballs, which have a high affinity for electrons. Unfortunately, T_c seemed to reach a maximum of 40 K, obtained by doping C_{60} with rubidium atoms. Last year, while working at Bell Labs, Lucent Technologies, Jan Hendrik Schön (also of the University of Konstanz, Germany), Christian Kloc, and Bertram

By slipping molecules between C_{60} spheres in a crystal, researchers have raised the critical temperature as high as those of many copper-oxide superconductors.

Batlogg (now at ETH Zürich) took T_c up to 52 K by finding a way to inject holes instead of electrons (see PHYSICS TODAY, January 2001, page 15). Nice, but still far from the T_c region reached by the cuprates.

The achievement of 52 K was only a taste of things to come, however. The same Bell Labs–ETH team noted at the time that the T_c for electron-doped C_{60} increases with the size of the dopants: Larger dopants spread the C_{60} molecules farther apart and lead to higher values of T_c , by as much as a factor of 3 for a small percentage change in lattice spacing: When the

C_{60} molecules are farther apart, the energy bands grow narrower, so that the density of states—and concomitantly the T_c —gets higher. Perhaps, the trio reasoned, the same trend would also govern hole-doped crystals.

There was certainly room to expand the C_{60} crystal. Unlike in electron doping, in which electrons are brought in by the intercalated alkali atoms, the holes are added to the crystal electronically. The T_c of 52 K had been measured on a C_{60} crystal with excess holes but no intercalated atoms. For the new study, the researchers added neutral molecules to expand the crystal, hoping to realize the promised gain in T_c .

They have now succeeded in their quest.¹ By intercalating molecules of tribromomethane ($CHBr_3$) into the C_{60} lattice, the experimenters changed the cubic lattice constant from