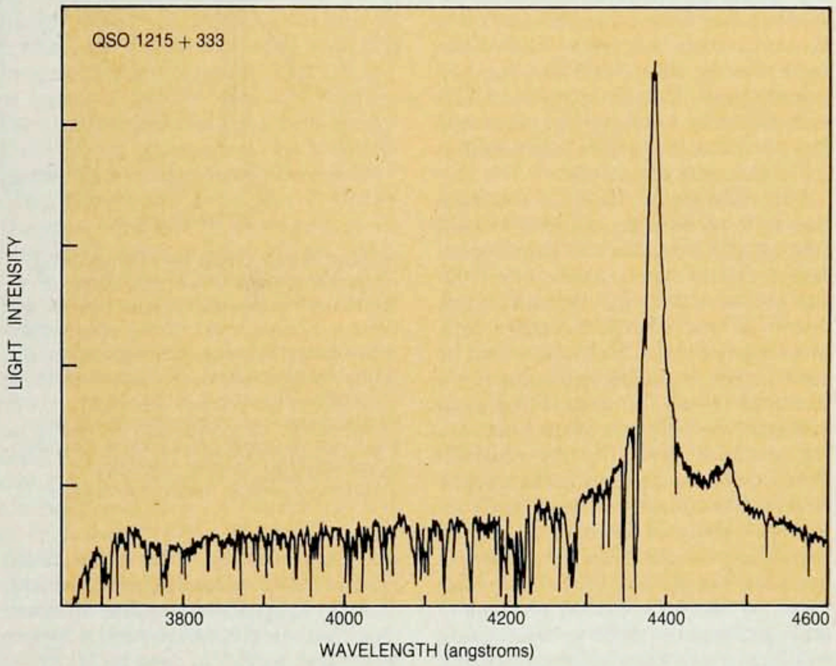
# PROBING THE EARLY UNIVERSE WITH QUASAR LIGHT

A powerful new cosmological probe is coming of age, giving us access to regions so remote that we have seen nothing of them less luminous than their quasars. But quasars are as atypical as they are wondrous. We've only seen a few thousand. To study the structure and evolution of the cosmos, one wants to look at the less ostentatious, ordinary inhabitants of the distant realms—galaxies and aggregates of hydrogen gas.

The new technique exploits the unique brilliance of quasars to render fainter objects between us and them visible, in effect silhouetted in the quasar light. The "silhouette" is spectroscopic: One looks at absorption lines filtered out of a quasar's light by atoms of hydrogen and heavier elements in intervening aggregates of gas along the line of sight. A workshop entitled Quasar Absorption Lines: Probing the Universe, convened in May by the Space Telescope Science Institute in Baltimore, attested to the great interest and progress in this very young field. In fact, the investigation of quasar absorption lines has been designated one of only three objectives granted special priority as "key projects" for the Hubble Space Telescope, whose launch is currently scheduled for the summer of 1989.




**Lyman α 'forest'** of hydrogen absorption lines seen in the visible spectrum of a quasar whose redshift $z$ is 2.60. The most prominent peak is the quasar's own 1216-Å Ly $\alpha$ hydrogen emission line, redshifted here to 4380 Å. Only on the blueward (left) side of this emission peak do we see the forest of dozens of Ly $\alpha$ absorption lines due to intervening "Lyman $\alpha$ clouds" of hydrogen at various distances (redshifts) along the line of sight between us and the quasar. This spectrum, taken by J. Bechtold at the Multiple Mirror Telescope on Mount Hopkins, Arizona, has a resolution of 1 Å.

On the cosmic scale, redshift is the essential measure of distance and age. It is usually designated by $z$, the fractional Doppler wavelength shift $\Delta\lambda/\lambda_0$, where $\lambda_0$ is the wavelength as seen by an observer at rest with respect to the source of the emission or absorption line. A few weeks ago Paul Hewett and his Cambridge University coworkers discovered a quasar with a record $z$ of 4.43, an incredible redshift implying that the cosmos was only 18% its present diameter when that light was emitted, less than 2 billion years after the Big Bang. Ordinary galaxies, by contrast, are difficult to study much beyond a redshift of 0.1. Thus the fascinating reports of galaxy distributions showing bubbly froths, filaments and great voids (PHYSICS TODAY, May 1986, page 17) are all restricted to the very "recent" past; these galaxies are a billion light years away, at most. For those who want to know about galaxies and the intergalactic medium in much earlier days, we now have a powerful new source of previously unattainable information.

Looking at quasar spectra, we see three classes of absorption lines. One of these classes—the broad absorption troughs seen for a small fraction of quasars—is believed to be due to the material associated with the quasar itself, rather than the intervening cosmic regions. It is thus not relevant to this discussion. The other two classes are:

▷ The "Lyman $\alpha$ forest" of myriad hydrogen absorption lines at different redshifts corresponding to intergalactic hydrogen clouds at various distances along the line of sight

▷ Absorption lines due to "heavy elements"—mostly ionized carbon, silicon and magnesium—also seen at several redshifts, but far fewer than in the forest of Ly $\alpha$ hydrogen lines.

The heavy element lines are thought to result from extended halos, disks or clouds of gas associated with galaxies near the line of sight. Thus the Ly $\alpha$ lines tell us about the intergalactic medium, while the heavy element lines tell us about galaxies too far away to see. The two stories are quite different.

## The Lyman α forest

The existence of the Lyman $\alpha$ forest

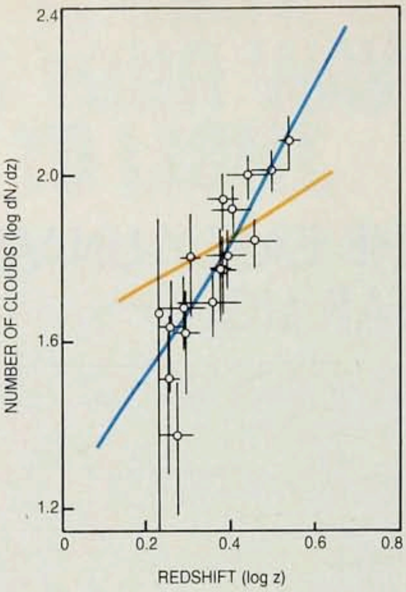
© 1987 American Institute of Physics

has been known since 1971, but only in this decade have improvements in spectroscopic resolution led to a concerted study of this extraordinary information from far away. The Ly $\alpha$ line of atomic hydrogen, signaling a transition between the ground state and the first excited electron state, is seen in the laboratory at 1216 Å in the ultraviolet. For a quasar at $z = 2$, the Ly $\alpha$ emission line is redshifted by a factor of three into the visible. For ground-based observation this is all to the good, because the ozone layer surrounding those of us who don't live in Antarctica prevents ultraviolet light shorter than 3000 Å from getting through. Furthermore the detectors typically employed at telescope foci for this work tend to lose sensitivity in the near ultraviolet.

The redshift of the Ly $\alpha$ emission line tells us how far away the emitting quasar was. On the short-wavelength side of this emission line from the quasar itself, one typically finds dozens of less redshifted narrow Ly $\alpha$ absorption lines. Each such line, it seems clear, is due to absorption by a localized "cloud" of neutral hydrogen along the line of sight at an intervening distance given by its redshift. Being closer to us than is the quasar source, the clouds are receding from us less rapidly in the general cosmic expansion; so their Ly $\alpha$ transitions are less redshifted. The light captured by the Ly $\alpha$ excitation of neutral hydrogen in such a cloud came not from the quasar's Ly $\alpha$ emission, but rather from its shorter-wavelength uv continuum, which appears redshifted to the cloud. The closing of our ultraviolet "window" at 3000 Å means that one cannot investigate absorption lines with ground-based telescopes for quasars with $z$ less than about 1.7. This is a long-range technique.

The systematic investigation of the Ly $\alpha$ forest began in earnest with the work of Wallace Sargent (Caltech) and his colleagues Alec Boksenberg (Royal Greenwich Observatory), David Tytler (now at Columbia) and the late Peter Young in 1980. From the profile of an absorption line one can deduce the "column density" of the absorber—the number density of absorbing atoms times the length along the line of sight. This turns out to be about $10^{-14}$ cm$^{-2}$ for a typical Ly $\alpha$ cloud. But the observed column density only tells us about *neutral* hydrogen. Ionized atomic hydrogen, that is to say, naked protons, cannot absorb ultraviolet.

A column density of only $10^{-14}$ neutral hydrogen atoms per cm$^2$ is a hundred times too tenuous to block




**Number of Ly α clouds** per unit redshift is observed to grow as we look at higher redshift $z$—further back in time. The blue curve is a power law fit to the data, which grows faster than one can account for simply by the expansion of the universe (orange). One needs some sort of evolutionary mechanism to explain why these clouds appear to become rarer with increasing age. (Figure from Bruce Peterson, Australian National University.)

out the ionizing ultraviolet background that pervades intergalactic space in these distant realms (of time). One can calculate that such a hydrogen cloud would in fact be 99.999% ionized. That is to say, the cloud is presumed to have $10^5$ bare protons for each of the neutral hydrogen atoms absorbing the ultraviolet.

To complete the picture, one needs to know how big these Lyman $\alpha$ clouds are. In 1984 Craig Foltz and his University of Arizona colleagues Ray Weymann (now director of the Mount Wilson and Las Campanas Observatories), Hermann Röser and Frederic Chaffee demonstrated rather convincingly that the clouds are of galactic dimension—a few times $10^4$ light years across. They invoked a pair of quasar images that are believed to be a double image of a single quasar produced by gravitational lensing due to a galaxy astride the line of sight. Noting that many (but not all) of the Ly $\alpha$ absorption lines of the two images are common to both, with identical redshifts, they argued that many of the intervening Ly $\alpha$ clouds must cover both lines of sight, curving around opposite sides of the galactic lens. If the clouds were much smaller than galaxies, this would hardly occur. Conversely, if the clouds were much larger than galaxies, even more of the absorption lines would be paired. Hence the conclusion that the Ly $\alpha$ clouds are about the same size as the (unseen) lensing galaxy.

From this size estimate, the observed column densities and the calculated ratio of ionized to neutral hydrogen, one concludes that the Ly $\alpha$ clouds have typical masses $10^7$ to $10^8$ times that of the Sun, not unlike the masses of dwarf galaxies such as the Magellanic Clouds. By balancing heating and cooling mechanisms one estimates their temperatures to be a "warm" 30 000 K. But because the clouds are so tenuous—only one ion or atom for every 10 liters—the atoms rarely experience collisions. Thus, even at 30 000 K, almost all the neutral atoms are in the ground state; one sees no evidence of absorption from excited states. Nor does one see any evidence for anything but hydrogen. With the exception of helium, one assumes that Ly $\alpha$ clouds are essentially free of heavier atoms. Helium would have to be present if these clouds are of primordial composition, but the telltale helium lines are too far in the ultraviolet to be seen from the ground. The Space Telescope will tell us whether the hydrogen/helium ratio of the Ly $\alpha$ clouds is indeed primordial.

## What holds the clouds together?

Hydrogen gas clouds with these properties are much too small to be held together by their own gravity. Sargent and company originally suggested that they are confined by the pressure of a surrounding, all-pervasive intergalactic gaseous medium, less dense but hotter than the Ly $\alpha$ clouds themselves. Six years before the Ly $\alpha$ forest was seen, James Gunn and Bruce Peterson (then at Caltech) pointed out that the absence of any significant Ly $\alpha$ trough in the quasar ultraviolet continuum tells us that there's exceedingly little neutral hydrogen in intergalactic space. "Now we know there's *some*, and it's patchy—confined in the Lyman $\alpha$ clouds," says Princeton theorist Jeremiah Ostriker. The intergalactic medium confining the clouds, he asserts, must be even more ionized than the clouds themselves; it would have almost no neutral hydrogen. "This is very similar to the situation within our own Galaxy," Ostriker points out, "where clouds of atomic hydrogen are confined by a hotter, less dense surrounding medium." Just as the discovery of this interstellar medium has contributed crucially to our understanding of star formation, he suggests, our investigation of the intergalactic medium should help us understand galaxy formation.

Ostriker and his colleague Satoru Ikeuchi (now at the University of Tokyo) have carried out detailed calculations supporting the observers' original conjecture that the Ly $\alpha$ clouds are pressure confined, and providing a scenario for their creation.[1] The clouds, they argue, arise from the fragmentation of unstable shock-heated shells originating in great explosions—for example, the cumulative effect of many supernovae in a young "star-burst" galaxy. Larger explosions of this kind, Ostriker and Ikeuchi suggest, may have produced the bubbly distribution of galaxies observed recently by John Huchra (Harvard–Smithsonian Center for Astrophysics) and his colleagues. Somewhat less energetic explosions, they contend, result in smaller fragments, not massive enough to bind themselves gravitationally and form galaxies. They become the Ly $\alpha$ clouds. Shock heating of the surrounding medium provides their confinement. The Rayleigh–Taylor instability that would generate this fragmentation was found by Ethan Vishniac (University of Texas) in 1983. This scenario, Ostriker tells us, yields masses, sizes, temperatures and velocity dispersions in good agreement with observation. Similar calculations have recently been done by Vishniac and his colleague Gary Bust,[2] and by Leonid Ozernoy[3] (Harvard–Smithsonian Center for Astrophysics). When he was still at the Lebedev Physics Institute in Moscow in 1983, Ozernoy and his colleague Victor Chernomordik claimed to see a subtle pairing of Ly $\alpha$ absorption lines at very small redshift separations, suggesting that one is seeing in individual quasar absorption spectra the effect of pairs of clouds on opposite sides of expanding shells traversed by the line of sight. Ostriker agrees that such pairs of clouds should exist in principle, but he thinks the available data as yet inconclusive.

## Clustering

Galaxies are well known to cluster together, forming structures as large as $10^8$ light years. A key parameter of such clustering is the characteristic length of the two-point correlation function evaluated from galaxy surveys by James Peebles (Princeton) and his colleagues. This galactic correlation length is observed to be about 15 million light years at small redshifts, that is to say, in the local, modern universe. Sargent and his colleagues have been looking since 1980 for a nonvanishing correlation length among the Ly $\alpha$ clouds. They have as yet found none. The redshift values of the Ly $\alpha$ lines in a given quasar absorption spectrum appear to be randomly placed without spatial correlation. Unlike the case for galaxies, the presence of a Ly $\alpha$ cloud at one point in space does not seem to affect the probability of finding another nearby. Sargent and company see no hint of the correlation at small redshift separations implied by Ozernoy's pairing of clouds. Furthermore, Martin Rees and Robert Carswell at Cambridge University have recently reported[4] that the cosmic distribution of Lyman $\alpha$ clouds does not display the spectacular voids one finds in the distribution of galaxies. In his PhD thesis this year, Carswell's student John Webb (now at Leyden) presents the first evidence of some degree of clustering among Ly $\alpha$ clouds. But their spatial correlation is certainly far weaker than what we see among galaxies.

Though there is general agreement about the size, mass and ionization of the Ly $\alpha$ clouds, there is no consensus on pressure confinement. The other leading school of thought argues that the clouds are held together by the gravitational force of concentrations of cold dark matter. Cold dark matter, made of undetected exotic particles, has been widely invoked to bring the mean mass density of the cosmos up to its critical closure value (PHYSICS TODAY, May, page 17). What we see in telescopes is too little by at least an order of magnitude; and the hydrogen in Ly $\alpha$ clouds and their surroundings doesn't add much more.

Joseph Silk (Berkeley), Richard Bond (Canadian Institute for Theoretical Astrophysics, Toronto) and Alex Szalay (Johns Hopkins) have recently proposed[5] that small perturbations in the primordial distribution of cold dark matter produce the Ly $\alpha$ clouds in a scenario of collapse and reexpansion. "We don't need to invoke a hypothetical, unobserved confining medium," Silk told us. "Nor do we need any gravitational support. The clouds, in our picture, are freely expanding, thus offering a natural explanation for the fact that we see fewer and fewer of them at smaller [later] redshifts." An alternative cold dark matter model put forward by Rees[6] has a somewhat easier time explaining the striking density contrast between the Ly $\alpha$ clouds and the elusive surrounding medium. Rees would have the Ly $\alpha$ clouds sitting in gravitational potential wells produced by "mini-halos" of surrounding cold dark matter. It is not yet obvious that this picture would explain why we see more and more clouds with increasing redshift. The rate at which $dN/dz$, the number density of Ly $\alpha$ clouds per unit redshift, is seen to increase with $z$ is much too fast to be explained simply by the expansion of the universe. One must invoke some sort of evolution. Either there were more of these clouds in early days, or they were larger. In the Ostriker–Ikeuchi scenario, more and more of the absorbing neutral hydrogen is ionized away as time goes on.

Surprisingly, this *general* increase of cloud population as one looks back in time (redshift) is not entirely true of the spectrum of individual quasars. Carswell and his coworkers pointed out in 1982 that when one looks at any one spectrum one sees an apparently paradoxical "proximity effect." As the forest of absorption lines approaches close to the $z$ of the quasar itself (the Ly $\alpha$ emission line), the density of absorption lines peters out. They suggested that this effect is due to the very strong ultraviolet flux in the immediate vicinity of the quasar. Ly $\alpha$ clouds that come too close are so heavily ionized that they don't retain enough neutral hydrogen to be effective absorbers.

Ostriker and his Princeton colleagues Robert Duncan and Stanislaw Bajtlik have been exploiting the details of this proximity effect as a unique probe of the general background ultraviolet radiation field at these early times. The rate at which Ly $\alpha$ ionization falls off as one backs away from a quasar of known output is a measure of the ionizing flux of ultraviolet coming from sources *other* than that quasar. This general background radiation is presumed to come from all the other quasars and galaxies. The epoch for which $z$ is between 2 and 4, with its many quasars and young galaxies, was bathed in a much more intense intergalactic uv flux than we see today.

The analysis of Bajtlik and company[7] finds a somewhat higher ultraviolet flux than had been expected. Perhaps, Ostriker suggests, there were more quasars in that era than we know about, or the galaxies were putting out more uv than we imagined. "This probing of the metagalactic ultraviolet flux at high $z$ is the most important result to date," Sargent told us. "My main project on the 200-inch Palomar telescope next year will be to get more detailed data on the proximity effect."

## Heavy element absorption lines

A typical quasar absorption spectrum shows about 50 Ly $\alpha$ lines, but only a few heavy element lines. This is taken to mean that Lyman $\alpha$ clouds are far more prevalent along a random line of sight than are the galactic halos or disks one credits for the heavy element absorption. The mix of elements one sees in the lines—mostly carbon, silicon and magnesium—is similar to what one sees in the interstellar medium of our galaxy. Clearly this is not primordial gas, as one supposes the Ly $\alpha$ clouds to be.

The heavy element lines are in general the result of absorption in perigalactic halos or disks, or even nearby clouds, much larger than the galaxies with which they are associated. One assumes this because a random line of sight to a quasar has only a very small chance of passing directly through the heart of a galaxy. Given the population density of galaxies, one needs to fatten their geometric cross sections by an order of magnitude to get a few heavy element absorption lines in almost every quasar spectrum.

This interpretation of the heavy element lines, originally proposed by John Bahcall and Lyman Spitzer 15 years ago, was greatly strengthened by work presented at the Baltimore workshop in May by Jacqueline Bergeron (Institut de Astrophysique, Paris). Searching for galaxies *near* the line of sight to quasars with heavy element lines, Bergeron was able, in about 80% of cases, to find such a galaxy with the same redshift as the heavy metal absorption line. These are galaxies very far away, not easily seen unless you're looking very hard with excellent equipment. Their redshifts are in the $z$ range from 0.5 to 0.8. For Ly $\alpha$ lines, such redshifts are too small to bring the line into the visible. But for these longer-wavelength heavy element lines they suffice.

Having proven the case, one can henceforth record such distant galaxies without arduous telescope searches, simply by looking at quasar absorption lines; and one can go out to even more-redshifted galaxies, far beyond the direct reach of telescopes. Thus one can study how the clustering of galaxies has evolved over long cosmological time spans.

Sargent, Boksenberg and Charles Steidel (Caltech) have just completed a determination of the two-point galactic correlation function for the epoch around $z = 2$, when the cosmos was one-third its present (linear) size. From the redshift clustering of heavy element absorption lines, they find a correlation length of about 5 million light years, as compared with Peebles' 15 million light year value for the modern era. One expects the correlation length to grow with time, as the cosmos expands and gravity reaches out to gather in more distant objects. But the rate of growth depends strongly on the cosmological model. The new correlation length determination at $z = 2$, Sargent told us, is in reasonable agreement with the simplest such model, in which the correlation length scales like $(1+z)^{-5/3}$.

The correlation length is only a crude parameter; it provides little detail about the configuration of galaxy clusters. Sargent and Steidel are availing themselves of a recent serendipitous discovery[8] by Peter Jakobsen and his colleagues at the European Southern Observatory and the European Space Agency to map out an ancient supercluster at least 300 million light years across. Jakobsen and coworkers had observed that a pair of quasars adjacent on the sky, but well separated in redshift, shared an implausible number of heavy element absorption lines with almost identical redshifts. Sargent and Steidel have concluded[9] that the two lines of sight are intercepted at a very skew angle by a wall of galaxies, seen almost edge on, so that the galactic halos through which they pass are clustered in the same narrow redshift interval. To delineate this large structure still further, both groups have been looking for related absorption lines in other quasars nearby. Sargent told us that the wall of galaxies appears to be about 30 million light years thick and at least 300 million light years in extent. This is larger than any structure we have seen directly with telescopes, and it dates back to a time when the cosmos was only about 3 billion years old.

## Piercing galactic hearts

A special subset of the heavy element absorbing systems has received particular attention from Arthur Wolfe (University of Pittsburgh), David Turnshek (Space Telescope Science Institute) and their colleagues Harding Smith and Ross Cohen (University of California, San Diego).[10] It turns out that about a fifth of the heavy element absorbing systems seen at large redshift are associated with Ly $\alpha$ absorbing lines so strong that one can deduce a neutral-hydrogen column density greater than $10^{20}$ $cm^{-2}$. That is to say, such a system has at least 1000 times more neutral hydrogen along the line of sight than does a typical heavy element absorber. Apparently in these special "damped Lyman $\alpha$" systems we are looking directly through the heart of a distant, young intervening galaxy. The more typical heavy element absorbing system, where the line of sight to the quasar behind only passes through the galaxy's extended halo, tells us little about the central gas disk that plays a crucial role in galactic evolution.

"We can't hope to see stars in galaxies at these distances," Turnshek told us, "but looking at absorption in their central gas disks as far back as $z = 3.3$, we have a unique handle on the evolution of galaxies from a few billion years after the Big Bang." For example, the group has been able to conclude that stellar populations were already "polluting the interstellar medium" with heavy elements at this early epoch. But the molecular gases and dust we see nowadays had not yet formed. A somewhat surprising result, Wolfe told us, was the discovery of significant magnetic fields in most of these high-redshift damped Ly $\alpha$ systems—as seen by the Faraday rotation of polarized quasar light. The prevalent dynamo model of galactic magnetic fields leads one to expect that the fields do not form until much later, after a galaxy has completed several full rotations.

Wolfe and his colleagues conclude that these central galactic disks of hydrogen gas held the bulk of ordinary matter in the redshift epoch from 3 to 2—far more than the Ly $\alpha$ clouds or the extended galactic halos accounted for. They observe that the diameters of these disks were then more than twice as large as they are today. As they have shrunk, most of the mass of gas has found its way into stars.

—Bertram Schwarzschild

## References


1. S. Ikeuchi, J. Ostriker, Astrophys. J. **301**, 522 (1986).
2. E. Vishniac, G. Bust, Astrophys. J. **319**, 14 (1987).
3. L. Ozernoy, Observatory **106**, 168 (1986).
4. M. Rees, R. Carswell, Mon. Not. R. Astron. Soc. **224**, 13p (1987).
5. J. R. Bond, A. Szalay, J. Silk, Astrophys. J., to be published.
6. M. Rees, Mon. Not. R. Astron. Soc. **218**, 25p (1986).
7. S. Bajtlik, R. Duncan, J. Ostriker, Astrophys. J., to be published.
8. P. Jakobsen, M. Perryman, M. Ulrich, F. Machetto, S. Di Serego Alighieri, Astrophys. J. Lett. **303**, L27 (1986).
9. W. Sargent, C. Steidel, Caltech preprint (1987).
10. A. Wolfe, D. Turnshek, H. E. Smith, D. R. Cohen, Astrophys. J. Suppl. **61**, 249 (1986). ■