The Emptiest Places

Space comes in degrees of emptiness, but even in the wasteland between galaxies it is not a complete void

By Evan Scannapieco, Patrick Petitjean and Tom Broadhurst

LIKE DEWDROPS ON A SPIDER'S WEB, galaxies collect on the filaments of material that stretch across the vast reaches of intergalactic space. Much of the history of the universe may have been determined by the give-and-take between galaxies and intergalactic gas. This artist's conception is based on computer simulations of the gas.

A trip from the earth to beyond the Milky Way is a journey to the emptiest places imaginable. Leaving the cozy confines of our solar system, we find ourselves in the interstellar regions of the galaxy. Here light from the nearest stars takes years to reach us, and the density of gas averages about one atom per cubic centimeter.

But we are headed to a place that is much more desolate. As we continue outward into the farthest reaches of the galactic disk, the stars are separated by dozens, then hundreds, of light-years, and the interstellar gas thins out 100-fold. Finally, passing into the vast inky blackness beyond the galaxy, we come upon a gas so tenuous that it scarcely seems worthy of the name, with an average density of only 10^{-5} atom per cubic centimeter.

In terms of density, the voyage from interplanetary to intergalactic space is more drastic than going from water into air. You might be forgiven for expecting that the end point of the trip, the deepest recesses of space, would give new meaning to the word "boring." Even astronomers used to think little of intergalactic space. Why bother with a thin gruel of atoms when the universe abounds in richly textured planets, luxurious galaxies and ravenous black holes?

But that attitude has been shifting. Far from an austere backwater, the intergalactic medium (IGM) is turning out to be the central staging area for cosmic evolution. The IGM predates galaxies. At early times, all matter took the form of a hot and all-pervading gas. Through the expansion of the universe, the gas cooled and condensed into the myriad galaxies found today. Anything left behind became ever more diffuse.

This much has been clear for several decades. Astronomers long assumed, however, that the details of the intergalactic gas were unimportant and that gravity alone called the shots in galaxy formation. According to the prevailing view, once the IGM had cooled from its hot, ionized state to a colder mixture of neutral hydrogen and helium, it offered no effective resistance to gravity. Places that had an unusually high density pulled in material at the expense of sparser regions—a process that continues unimpeded to this day. In this picture, the densities, positions and sizes of galaxies and larger structures depend only on the random primordial distribution of mass. Even if the medium had some internal complexity, a possibility that struck most researchers as unlikely, it exerted no effect on the truly interesting parts of the cosmos.

Yet the more astronomers began to uncover the properties of the gas, the more their observations came into conflict with this simple theory. They discovered that the IGM has an intricate history, including several important transitions intimately related to the formation of structure. And they found that this most delicate of materials is drawn out into a vast network of gaseous sheets and filaments, draped between the galaxies like a spider web.

These investigations began to gather momentum, and the past two years have seen an explosion of research activity. It is not easy, though, to study something that can barely be seen. Like detectives, astronomers are gathering indirect clues and carefully piecing them together to reveal the story of the gas between the galaxies.

Overview/*Intergalactic Medium*

- Near-Earth space, where astronauts roam, is nearly a vacuum by terrestrial standards, but the space between galaxies is even emptier, with a millionth the density. Astronomers once doubted that anything interesting could happen in such an incomprehensibly tenuous gas.
- Yet a steady accumulation of observations shows that this gas, known as the intergalactic medium, has undergone at least three dramatic transitions, with profound effects on the formation of galaxies and other cosmic structures.

Seeing the Forest for the Lines

THESE CLUES COME FROM four types of observational evidence: the cosmic microwave background radiation, quasar spectra, x-rays from galaxy clusters and magnetic field measurements. The microwave background provides a snapshot of the IGM at the moment it changed from ionized to neutral, approximately 300,000 years after the big bang, when the gas temperature had fallen to a few thousand kelvins. Patterns in this radiation are the starting point for all models of the IGM.

The second type of evidence involves quasars. Thought to be powered by young supermassive black holes, these extremely bright objects act as lighthouses that illuminate narrow stretches of intergalactic space. Material between us and a quasar absorbs light of specific wavelengths, leaving a telltale imprint on the quasar spectrum. Interpreting such spectra requires a degree of care. They contain lines at wavelengths that do not appear to correspond to any known substance. This discrepancy is thought to be a product of the expansion of the universe, which, by stretching the light waves, causes the spectral lines to move from their usual positions to longer wavelengths—a pro-

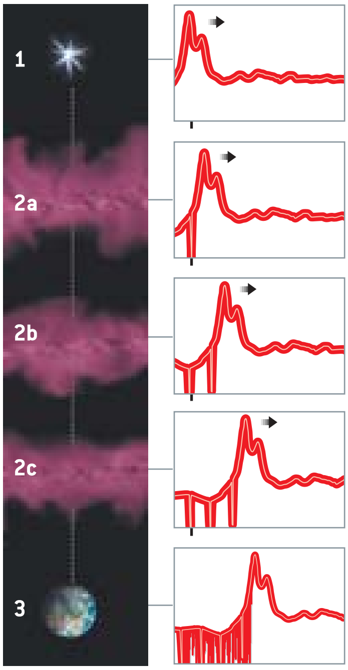
MARK A. GARLICK (*preceding pages*)

THE FOREST PRIMEVAL

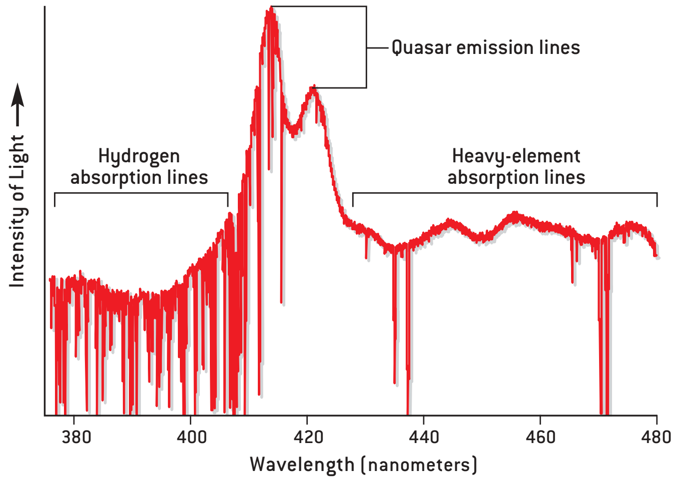
WISPY THOUGH IT MAY BE, intergalactic gas betrays its presence by distorting the light of other objects—particularly quasars, the brightest objects in the known universe. Acting like rose-tinted glasses, gas clouds block light at certain wavelengths but let the rest through. The process shows up as a series of absorption lines (*sharp dips*) in quasar spectra. A typical spectrum has so many such lines that metaphorically minded astronomers refer to them as the Lyman-alpha forest. *—E.S., P.P. and T.B.*

1 The light begins its journey with a fairly smooth spectrum (*red curve*). It peaks at a wavelength of 122 nanometers, referred to as Lyman alpha.

2 As the light travels toward the earth, two effects change the spectrum: cosmic expansion shifts it to longer wavelengths, and each hydrogen cloud takes a bite out of the spectrum (*sharp dip*). Each bite leaves a new spectral line at 122 nanometers, which later gets shifted along with the rest of the spectrum.



3 By the time the light arrives at the earth, the spectrum has been thoroughly chewed up, with hundreds of hydrogen lines and even the occasional line of a heavier element. In this spectrum of quasar HE 1122–1628, the original peak has been shifted from 122 to 414 nanometers—an indication of the quasar's distance.



cess known as redshifting. The farther away the subject is, the more the universe has expanded since the light began its journey and thus the greater the redshift.

The first quasar spectra were observed in the mid-1960s [see "The Absorption Lines of Quasi-Stellar Objects," by E. Margaret Burbidge and C. Roger Lynds; SCIENTIFIC AMERICAN, December 1970], but it was not until the late 1970s that detectors reached the sensitivity required to yield high-quality spectra. Alec Boksenberg, then at University College London, and Wallace L.W. Sargent of the California Institute of Technology realized that each spectrum had hundreds of absorption lines. On a graph it looks like a dense thicket of lines—hence the name that astronomers give to this phenomenon, the Lyman-alpha forest. The term "Lyman alpha" indicates that the lines appear to be produced by neutral hydrogen gas. That they occur in such profusion indicates that the space between us and the quasar is filled with hundreds of gas clouds, each at a different distance and therefore a different redshift [*see illustration above*].

Ironically, although neutral hydrogen neatly accounts for the lines, it can constitute only a small fraction of the clouds. Ionized hydrogen and helium must make up the bulk. This is because neutral gas naturally absorbs radiation at a range of wavelengths, as the random thermal motion of atoms leads to additional shifts in the spectrum. The mathematically ideal lines broaden into bands of noticeable width. In 1965 James E. Gunn and Bruce A. Peterson, both then at Caltech, showed that if a sufficient fraction of the IGM is neutral—more than one part in a million—the broadening would cause absorption lines of different clouds to overlap. Instead of a forest, astronomers would observe a continuous trough.

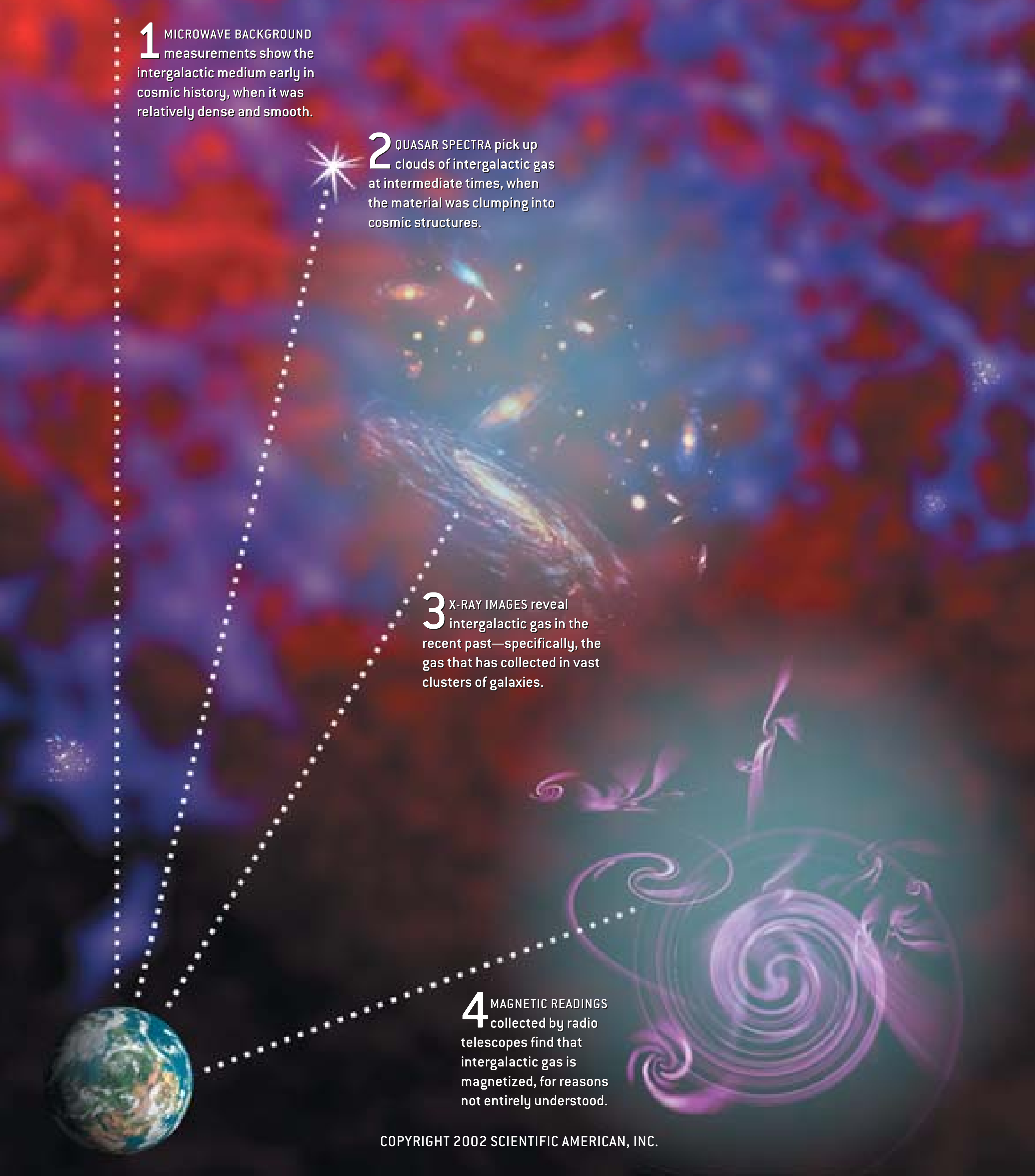
Thus, the simple presence of the Lyman-alpha forest proves that the cool, predominantly neutral IGM necessary for purely gravity-driven galaxy formation was relatively short-lived. Something must have reionized the gas before most quasars formed. An exciting recent discovery concerns one of the most distant and ancient quasars known, named SDSSpJ103027.10+052455.0, which was detected by the Sloan Digital Sky Survey, the most detailed effort yet made to map the sky. Last year Robert H. Becker of the University of California at Davis and his colleagues found an extended range of Lyman-alpha absorption in the spectrum of this object—perhaps the first observation of a trough as predicted by Gunn and Peterson. It may be a glimpse of the period when reionization was still under way.

Not only do quasar spectra tell us about the density and ionization of the IGM, they hint at how the material is distributed in space. In essence, each forestlike spectrum is a core sample through the universe. By comparing core samples with one another and with computer simulations of structure formation, astronomers have sought to reconstruct the full three-dimensional arrangement of matter. Gravitational lensing, whereby

DON DIXON (*illustration*); ALICIA CALLE (*left graphs*); LAURIE GRACE (*right graph*)

FOUR WAYS TO SEE THE UNSEEABLE

INTERGALACTIC GAS is nearly invisible, so astronomers cannot study it directly. Instead they must act as cosmic detectives, reconstructing the history of the gas from four main types of indirect clues.



the gravity of an intervening body bends the quasar light, can help in this process. The bending produces two core samples closer to each other than dumb chance would otherwise allow. In this way, Michael Rauch of the Carnegie Observatories in Pasadena, Calif., and Sargent and Thomas A. Barlow of Caltech measured gas motions within the IGM. They found that although most of the medium is quiescent, the densest patches have been stirred repeatedly by energetic events occurring every 100 million years or so.

In the past seven years, absorption-line studies have detected not only neutral hydrogen but also a smattering of heavier elements. Ionized carbon, with its characteristic "doublet" of twin absorption lines at wavelengths close to Lyman alpha, was the first of these elements to be observed, and others, notably magnesium and oxygen, have followed. In galaxies, atoms of these substances often clump into large molecules—that is, dust particles—that act to redden the light passing through them. No such reddening occurs in the Lyman-alpha clouds, indicating that the heavy elements there remain as individual atoms with a density of about one for every million hydrogen atoms. Although this is not a lot, it is enough to indicate that the IGM is not merely leftover material from galaxy formation. Elements synthesized by stars have somehow made their way out of galaxies and into the space between them.

Seeds of Construction

WHEREAS THE QUASAR SPECTRA probe small, tenuous clouds typically located at enormous distances from the Milky Way (and therefore seen as they were at a much earlier period in cosmic history), the third type of observation concerns itself with the opposite: massive, dense pockets of gas in the comparatively nearby universe. This gas resides in the largest gravitationally bound structures, the massive galaxy clusters. The name "galaxy clusters" is somewhat of a misnomer; these bodies are mostly hot plasma, with some galaxies thrown in like seeds in a watermelon. The ionized gas—nothing more than a compressed form of the intergalactic medium—has been heated to several million kelvins and shines brightly in x-rays. The Chandra X-ray Observatory and X-ray Multi-Mirror Mission have greatly improved our ability to study this gas.

In the conventional view of structure formation, the cluster gas was heated purely by gravitational collapse. If so, its temperature should be related to its mass and density and therefore to its luminosity; specifically, the luminosity should be proportional to the square of the temperature. Yet observations show that luminosity is proportional to temperature to the 3.5th power. Again, it seems that the IGM was the site of some kind of unexpected activity.

The fourth and final type of empirical finding concerns one of the most uncertain, yet potentially crucial, properties of the IGM: its magnetic structure. As electrons move through magnetized regions, they emit light at radio wavelengths. This emission is polarized in the same direction as the magnetic field. Unfortunately for observers, the low density of intergalactic gas makes the signal extremely weak. In 1989 Kwang-Tae Kim and Philipp P. Kronberg, both then at the University of Toronto, and their colleagues found a diffuse bridge of magnetized material that connects two clusters of galaxies, but such measurements have not extended into deeper reaches of space [see "Magnetic Anomalies," by George Musser; News and Analysis, SCIENTIFIC AMERICAN, August 2000]. For the most part, astronomers have relied on clues from large galaxies and clusters. Most spiral galaxies have magnetic fields that are sufficiently strong to affect the galaxies' formation and spin. Their ordered structure implies that a "seed" magnetic field predated the galaxy and strengthened as it took shape. On larger scales, radio studies have found diffuse magnetized gas in several nearby galaxy clusters. A clear implication is that the IGM as a whole is magnetized.

Take a Break

AS INCOMPLETE AS these four types of evidence are, they indicate that the IGM has undergone at least three dramatic changes over the course of cosmic time. The first transition, from ionized to neutral, is the best understood. Known as recombination, it was the event responsible for releasing the microwave background radiation.

The second transition, from neutral back to ionized, is murkier. This reionization may have been caused by quasars, by the stars in early galaxies or even perhaps by a hitherto undetected population of massive stars uniformly distributed through space [see "The First Stars in the Universe," by Richard B. Larson and Volker Bromm; SCIENTIFIC AMERICAN, December 2001]. Although the event seems to have had little effect on the formation of massive galaxies, it may have generated enough thermal pressure to impede the formation of smaller galaxies, complicating the simple picture of purely gravitational structure formation.

To determine which of the many possible sources of reionization played a role, astronomers have studied each in turn. The results are still inconclusive. The best observations of the stellar contribution involve the so-called Lyman-break galaxies, which take their name from a sharp cutoff in their spectra that occurs as neutral hydrogen within the galaxies absorbs starlight. For sufficiently distant galaxies, the break is redshifted from its usual position in the ultraviolet part of the spectrum to the visible part. By searching for a visible-light break, astronomers can identify distant galaxies without having to resort to tricky line-

THE AUTHORS

EVAN SCANNAPIECO, PATRICK PETITJEAN and *TOM BROADHURST* bring both theory and observation to the study of intergalactic space. Scannapieco and Broadhurst did the first theoretical analysis of the effect that galaxy outflows have on the formation of other galaxies. Scannapieco and Petitjean are working together on the clustering of heavy elements observed in quasar spectra. Scannapieco, who also dabbles in cosmology, works under the auspices of the National Science Foundation at the Arcetri Astrophysical Observatory in Florence and the Institute of Astrophysics in Paris. Petitjean is deputy director of the institute and a leader of the European research network on the intergalactic medium. Broadhurst, a visiting professor at the Hebrew University in Jerusalem, is the discoverer of some of the most distant known galaxies.

DON DIXON (opposite page)

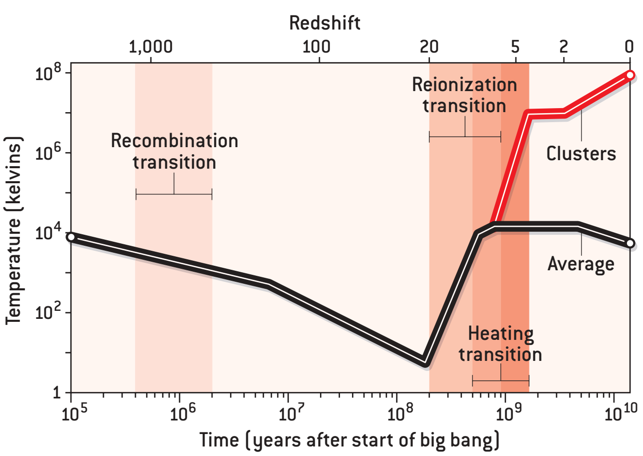
by-line redshift measurements. This technique, originally developed by Charles C. Steidel of Caltech and his colleagues, has enabled observers to build up sizable catalogues of distant galaxies—whose starlight may have helped reionize intergalactic gas. Unfortunately, the technique suffers from a selection effect: it tends to pick out only the brightest galaxies. Therefore, it does not capture the full stellar contribution to reionization.

Another method is to examine the abundance and distribution of heavy elements. If these elements are observed everywhere, the first objects were probably massive stars smoothly distributed in space. Quasars or dwarf galaxies would scatter the elements more unevenly. So far, however, measurements are too imprecise to provide much guidance. For now, the best scientists can do is to place limits on the spatial distribution of gas. They do so by combining quasar spectra with numerical simulations of structure formation. By adjusting the parameters of the simulation until the spectra match, modelers have drawn our picture of the cosmic web into clearer focus.

Blowout

THE THIRD IGM transformation, the one that accounts for the observed relation of luminosity and temperature in galaxy clusters, remains even more mysterious. The most convincing account dates to work by Nicholas Kaiser, then at Toronto, in 1991. He speculated that cluster gas was preheated to several million kelvins long before gravitational collapse began. This preheating would have reduced the density of the cluster gas, with the largest effect on the smaller clusters, in which gravity is weaker. The decrease in density would have led to lower luminosities and would have accentuated the dependence on temperature, which is related to cluster mass.

The most natural drivers of this preheating were supernova explosions. A rapid succession of supernovae blasts material out of galaxies, injecting not only energy but also heavy elements into the IGM. X-ray satellites have shown that the gas in galactic clusters is indeed enriched in these elements. Furthermore, the degree of enrichment is roughly the same no matter how young or old the clusters are, suggesting that the enrichment occurred early in the clusters' lives. Supernovae would naturally account for this abruptness, as the first wave of stars to form in a galaxy will explode within just a few million years.



THERMAL HISTORY of the intergalactic medium reveals three important transitions. Evidently the medium has both affected and been affected by the formation of cosmic structures, such as galaxy clusters. Observations indicate that the transitions occur at particular redshifts, which translate (with some uncertainty) into specific times.

The strongest evidence for the supernova mechanism involves direct observations of distant starbursting dwarf galaxies, which, lacking strong gravity, should be more susceptible to disruption by exploding stars. Max Pettini of the University of Cambridge, Steidel and Alice E. Shapley of Caltech and their collaborators combined galaxy spectra taken in both visible and infrared light. The visible-light spectra contained two sets of lines, one from hydrogen as it emitted light, the other from heavy elements as they absorbed the light of background objects. The infrared spectra contained one set of lines, which were emitted by gaseous nebulae within the galaxy.

Pettini and his colleagues found that these three sets of lines were redshifted by different amounts: the heavy elements by less than the galaxy, the hydrogen by more. In other words, relative to the center of the galaxy, the heavy elements are moving toward us at about 300 kilometers a second, whereas the hydrogen is moving away from us at the same velocity.

This pattern is strange and unexpected. The simplest interpretation is that material is streaming out of the galaxy—a cosmic wind blowing into space. This outflow contains both heavy elements and hydrogen, but in some regions the heavy elements are easier to see, and in other regions the hydrogen is easier to see. For the heavy elements to be visible, they must lie between us and the bulk of the galaxy; otherwise there would be no light for them to absorb. Thus, they must be moving away from the center of the galaxy. The reasoning is reversed for the hydrogen. For it to be visible it must also be moving away from the center but lie on the far side of the galaxy. That way its emitted light is redshifted beyond the wavelength at which intervening matter could block it [*see illustration on opposite page*].

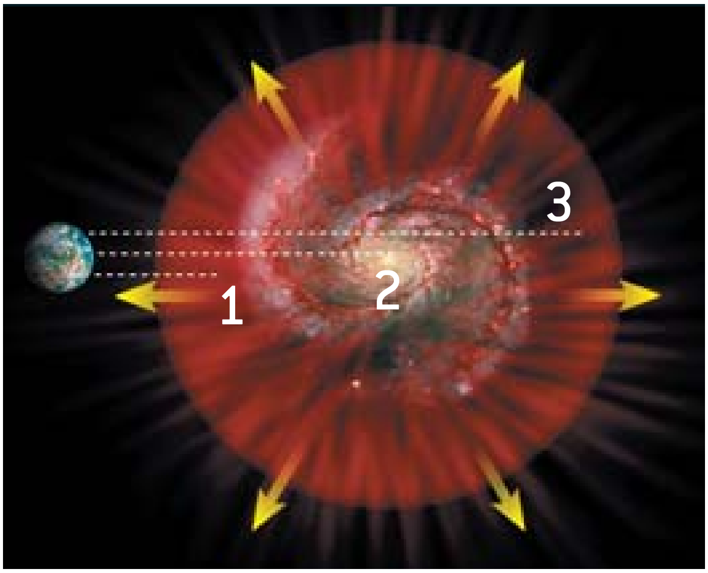
This pattern has been seen in all distant dwarf galaxies for which it is detectable, a fact that suggests that these outflows were once commonplace in the universe. Astronomers have seen gargantuan plumes of material from nearer galaxies as well. One particularly striking case is the dwarf galaxy NGC 1569, which was recently observed by Crystal Martin of the University of California at Santa Barbara and her colleagues. The team found that huge quantities of oxygen and other heavy elements are escaping from the galaxy in bubbles of multimillion-kelvin gas.

The winds stirred the densest regions of the IGM, magnetized vast regions of space and may even have suppressed the formation of small galaxies. The transformation wrought by outflows was much more severe than the earlier reionization. Whereas reionization kept galaxies smaller than a few hundred million solar masses from forming, outflows may have squelched galaxies 10 times larger. This process could resolve one of the most puzzling discrepancies of cosmology: simulations of structure formation predict many more small galaxies than actually exist [see "The Life Cycle of Galaxies," by Guinevere Kauffmann and Frank van den Bosch; SCIENTIFIC AMERICAN, June].

SARA CHEN

THE SHAPE OF THE WIND

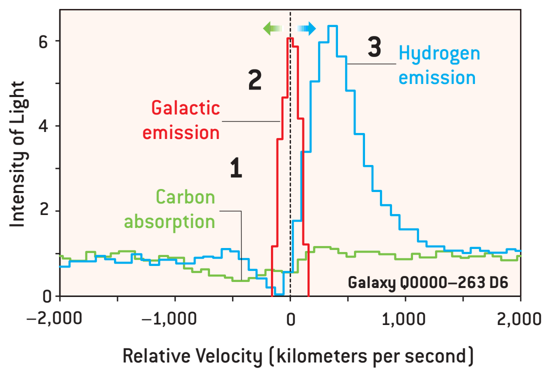
THE STRONGEST EVIDENCE that galaxies are blowing material into intergalactic space comes from studies of galaxy spectra. The wind shows up as a distinctive trio of spectral lines, representing the front (*1*), center (*2*) and rear (*3*) of the galaxy. Two are peaks, indicating emission; the other is a dip, indicating absorption. *—E.S., P.P. and T.B.*



1 As galactic light travels toward Earth, it passes through heavy elements such as carbon, which absorb certain wavelengths. This material is moving toward us, shifting the absorption to negative velocities with respect to the galaxy.

2 Nebulae within the galaxy itself emit infrared light, serving as a reference point.

3 Hydrogen on the far side of the galaxy emits light. The motion of the hydrogen away from us shifts the emission to positive velocities. This shift has the side effect of allowing the emission to pass through the galaxy without getting reabsorbed.



Exerting Self-Control

THUS, EACH GENERATION of objects alters the IGM, which in turn determines the properties of the next generation. The sources that reionized the universe generated enough thermal pressure to regulate their own formation, and the winds from starbursting galaxies may have been strong enough to nip other such galaxies in the bud. Analogous feedback processes occur within galaxies themselves, in which supernovae and ultraviolet starlight act on the interstellar gas out of which the next generation of stars forms [see "The Gas between the Stars," by Ronald J. Reynolds; SCIENTIFIC AMERICAN, January]. In fact, the concept of feedback is becoming a unifying theme in astronomy, seemingly repeating itself on all scales.

The four main types of observation are continually being complemented by new results and innovative methods. Observations of the microwave background radiation, for example, are now sensitive enough to detect the slight blurring caused by IGM material. Patchiness during reionization should scatter some of the microwave photons, and hot areas of the IGM, such as galaxy clusters, should further distort the radiation. The latter contribution, known as the Sunyaev-Zeldovich effect, has already been studied in individual clusters, and its broad-scale effect was tentatively detected by the Cosmic Background Imager experiment this past summer.

In an ingenious variation on quasar absorption-line studies, Kenneth R. Sembach of the Space Telescope Science Institute, Blair Savage and Bart Wakker of the University of Wisconsin–Madison and their colleagues have used the Far Ultraviolet Spectroscopic Explorer satellite to study the IGM in the immediate neighborhood of the Milky Way. Their observations indicate that nearby gas clouds are distributed in an uneven manner reminiscent of the cosmic web between galaxy clusters and yet are moving through a million-kelvin medium like the gas within clusters. Thus, the Local Group of galaxies may be surrounded by an extended corona of gas, whose properties are suggestive of both the most diffuse and the densest regions of the IGM. Similar hot regions could make up a hitherto unknown component of the IGM and account for a large fraction of its mass.

New studies such as these make it clear that the story of the intergalactic medium is only beginning to be told and that surprises await us. Like an intrepid intergalactic traveler, we have worked our way from the familiar solar neighborhood into the depths of the most desolate places imaginable. Our eyes are still adjusting to the unexpected and intricate beauty of the cosmic web that stretches across the emptiest places. SA

MORE TO EXPLORE

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DON DIXON (*illustration*); SARA CHEN (*graph*)