

UV survey finds 40% of the baryons missing from the nearby universe

Most baryons exist in the near vacuum between clusters of galaxies. Accounting for all the baryons continues to challenge astronomers.

By the time the universe was three minutes old, all the baryonic building blocks of normal matter had formed. As the young universe aged, a minority of those primordial baryons—a few percent—joined clumps of the far more abundant dark matter to condense and form the first galaxies.

Those galaxies grew by merging with each other. They grouped together in clusters. New generations of stars sprang from the gas left by their predecessors' explosive demise. Throughout those processes, which are still going on, the overall distribution of baryons more or less persisted: Most baryons remain outside galaxy clusters.

Astronomers have confidence in their predictions of how much baryonic matter formed in the Big Bang. And their observations of luminous matter indicate how much baryonic matter lies in stars, galaxies, and galaxy clusters. What's been harder to determine is the baryonic content of the intergalactic medium.

In principle, accounting observationally for all the IGM baryons is straightforward. Both the density fluctuations that led to the first galaxies and the mergers that formed their successors have squeezed dark and baryonic matter into a foamy network of widely spaced nodes, the galaxy clusters, connected by wispy filaments, the IGM. See figure 1.

Almost inevitably, a line of sight to a distant quasar passes through a succession of filaments at different redshifts. The potentially observable result is a quasar spectrum imprinted with absorption lines at helpfully discrete wavelengths. From the lines' depths, one can infer the amount and distribution of the absorbing gas.

Where those lines show up in the electromagnetic spectrum depends not only on redshift but also on the temperature of the absorbing gas and the atomic species. At redshifts of 2 to 6, cold, neutral hydrogen absorbs at the Lyman- α

transition in the near-UV and optical.

Astronomers discovered those lines, dubbed the Lyman- α forest, in the 1970s when 4-m telescopes equipped with photon-counting spectrometers came on line. With plausible assumptions about the ionization state of the clouds, they balanced the baryon budget: What was produced in the Big Bang matched the total seen in stars, galaxies, and the Lyman- α forest.

But a problem appeared. At lower redshifts, the Lyman- α forest thins out. The cold, neutral clouds that balance the baryon budget at higher redshifts are less abundant in the universe's old, close-in neighborhoods. An apparent deficit had opened.

Hints of a solution emerged in the late 1990s when Renyue Cen and Jeremiah Ostriker of Princeton University tracked the fate of the IGM with a hydrodynamic computer simulation.¹ Their simulation, which spanned redshifts from 3 to 0, showed that the large-scale collapsing and squeezing that forms the universe's foamy structure also shock-heats the IGM's baryons. As

the universe ages, the IGM's temperature climbs.

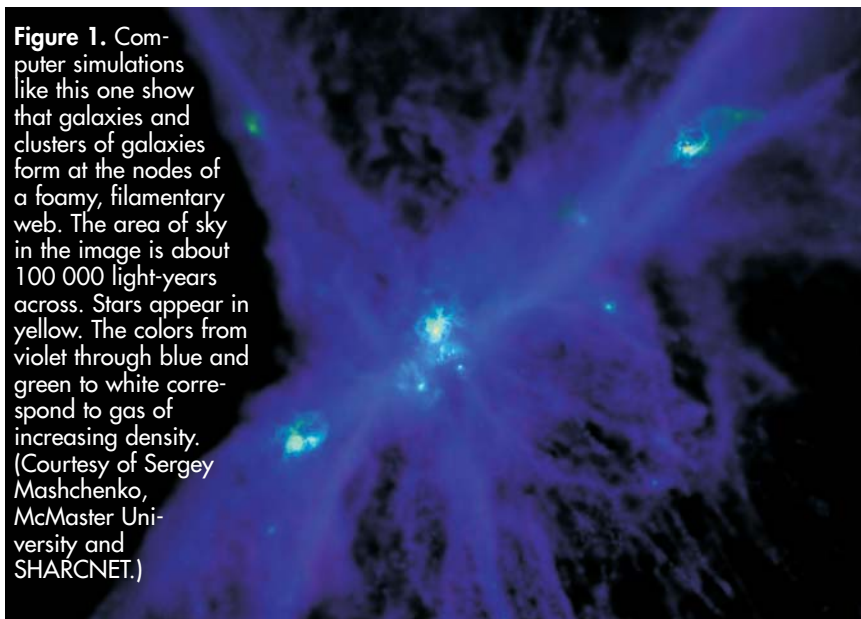
At the lowest redshifts, shock-heated hydrogen and other elements are ionized. Their absorption lines pass out of the optical and into the far-UV and x ray. The baryons weren't missing from the nearby IGM; they were just too hot to see—at least with the instruments and telescopes of the past century.

Now, Charles Danforth and Michael Shull of the University of Colorado at Boulder have used the UV spectrometers aboard the *Far Ultraviolet Spectroscopic Explorer* (FUSE) and the *Hubble Space Telescope* (HST) to survey quasar absorption lines in the IGM. Their survey has turned up 40% of the missing baryons in the nearby universe.² The rest, they and others say, lie in even hotter x-ray-emitting gas. New missions, such as NASA's *Constellation-X* and ESA's *X-ray Evolving Universe Spectroscopy*, are expected to find some of them.

Lines of sight

To look for the missing baryons, Danforth and Shull combed through

Figure 1. Computer simulations like this one show that galaxies and clusters of galaxies form at the nodes of a foamy, filamentary web. The area of sky in the image is about 100 000 light-years across. Stars appear in yellow. The colors from violet through blue and green to white correspond to gas of increasing density. (Courtesy of Sergey Mashchenko, McMaster University and SHARCNET.)



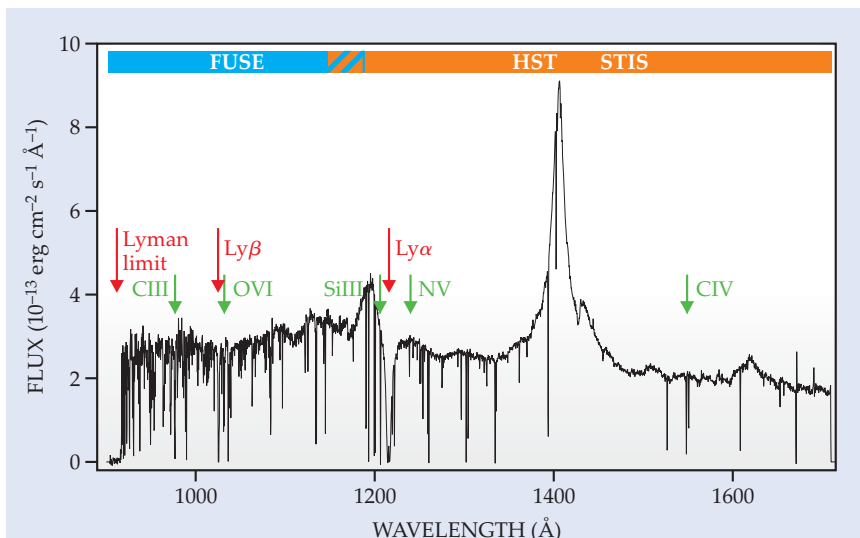


Figure 2. The UV spectrum from the quasar PG 1211+143 as observed by the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST). The broad peaks originate from the quasar itself, whereas the narrow absorption lines originate from filaments or clouds of gas that lie at various redshifts between Earth and the quasar. (Courtesy of Charles Danforth, University of Colorado.)

36 quasar spectra taken in the UV by *FUSE* and *HST*. The sample is fixed for now: The *FUSE* mission, which began in 1999, ended last year when one of its gyroscopes failed and, although *HST* is still in orbit, its UV spectrometer fell victim in 2004 to an electrical fault.

Not all the spectra yielded usable data. Some were too noisy. Others came from quasars that were too close: Their lines of sight didn't pass through enough absorbing filaments to yield a significant sample. And for a handful of more distant quasars, the lines of sight passed through so many absorbers that reliably assigning redshifts proved impossible.

The final sample included 28 quasars and hundreds of absorption lines from various atomic species and from redshifts up to 0.4. Figure 2 shows an example. Finding several absorbing filaments at different redshifts in such a spectrum might seem daunting. Atomic physics helps. Corrected for redshift, lines from a given species will always appear at the same wavelengths.

To identify an absorption line, Danforth and Shull would proceed iteratively. First they'd assume a line belonged to Lyman- α and then look for Lyman- β at the same redshift. If they found it, they'd look for lines from other species at the same redshift.

In addition to Lyman- α , Danforth and Shull found lines from six different ionic species: O^{5+} , N^{4+} , C^{2+} , Si^{3+} , Si^{2+} , and Fe^{2+} .

The lines appear to arise from two

distinct thermal phases. The majority phase, traced by Lyman- α , is in the form of photoionized gas at 10^4 K; it closes 30% of the baryon deficit. The minority phase, traced by O^{5+} and the other ions, is in the form of shock-heated gas at 10^5 to 10^6 K; it closes 10% of the baryon deficit.

The abundances of oxygen, carbon, and other elements made in stars are surprisingly high: about 0.1 of the solar values. Evidently, stellar material travels millions of light-years from its original galactic host.

Shocked—shocked

It would have been a surprise if all the missing baryons turned up in the warm, UV-absorbing gas that Danforth and Shull found. Simulations by Cen and Ostriker and by others predict that some gas, especially the gas closest to the sites of newly merged galaxies, should be at tens of millions of degrees. At that temperature, oxygen and carbon become more highly ionized and their absorption lines pass into the x-ray band.

Chandra and *XMM-Newton* can barely detect those x-ray absorption lines. The two observatories have yielded weak and contradictory evidence. On the other hand, an *XMM-Newton* image recently analyzed by Norbert Werner of SRON Netherlands Institute for Space Research and his collaborators revealed faint hot gas between two clusters of galaxies, Abell 222 and Abell 223.³ One observation

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constitutes consistent, but not compelling, evidence of the whereabouts of the last slice of missing baryons.

Beyond the satisfaction of balancing the baryon budget, what would observations of the warm and hot IGM reveal about the universe? The number of absorbers that Danforth and Shull have found agrees with the number of filaments that simulations predict. Those simulations, and their underlying assumptions, will be tested further as the sensitivity of observations and the

power of computers improve.

Observations of the nearby IGM could also help astronomers tackle one of their most pressing and difficult problems: the role of feedback in galaxy formation. One expects the formation of large-scale structure to heat the IGM as galaxies form, but not necessarily to enrich it. The presence of stellar material deep in the IGM suggests that galaxies could influence the formation of other galaxies by expelling hot, energetic gas into the IGM.

Fourteen billion years after the Big Bang, the universe remains a violent place.

Charles Day

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Statistical mechanics elucidates constraints on the ultimate accuracy of biochemical sensing

Some biochemical interactions are akin to detecting a sporadic signal against a noisy background.

In biology textbooks, the way proteins work is often depicted by what looks like a set of puzzle pieces. A small piece, a regulator molecule, say, fits into a large piece, an enzyme, say. The enzyme's shape then changes to one that fits snugly around a medium-sized piece, the enzyme's substrate.

Those cartoons are meant to convey the exquisite specificity of biochemical reactions. Of the myriad reactions inside a cell, a given enzyme catalyzes just one. Not surprisingly, the picture doesn't tell the whole story. What's missing is the physical setting.

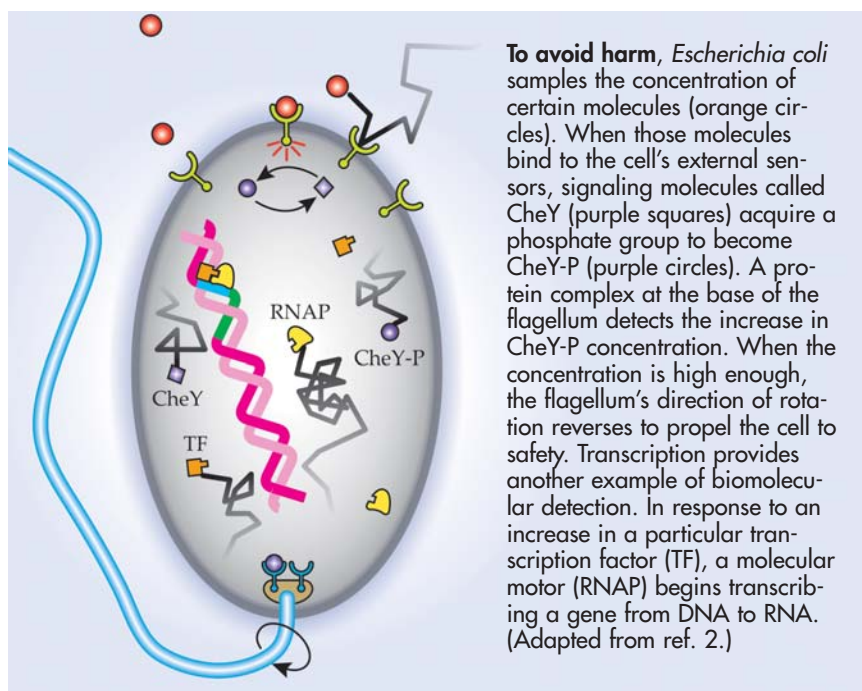
"In the world of a cell as small as a bacterium," wrote Howard Berg and Edward Purcell in a classic 1977 paper,¹ "transport of molecules is effected by diffusion, rather than bulk flow; movement is resisted by viscosity, not inertia; the energy of thermal fluctuation, kT , is large enough to perturb the cell's motion."

Under those conditions, the turning off of genes by transcription factors or the response to caffeine molecules of a neuron, just two examples, both resemble the sampling of a signal. Although the detector, the protein, responds more or less promptly to its target, fluctuations in its environment limit its accuracy.

Berg and Purcell derived an expression for how accurately a sensor of radius a can determine in time τ the mean concentration c of a target molecule whose diffusion coefficient is D :

$$\Delta c/c = 1/(Dac\tau)^{1/2}.$$

Berg and Purcell's analysis treated the sensor as a sticky sphere: Every target that hits the sensor sticks to it. But real proteins are like flexible scaffolds that fluctuate between two or more metastable configurations. And real target molecules bind and



unbind at different kinetic rates.

In 2005 William Bialek of Princeton University and Sima Setayeshgar of Indiana University incorporated those complications into a reanalysis of limiting sensitivity. Metastability and kinetics, they found, contribute an additional, always positive term to $\Delta c/c$. Berg and Purcell's expression can therefore be thought of as a noise floor: Real systems are less accurate than Berg and Purcell's model; they can never be more accurate.²

Now, Bialek and Setayeshgar have taken a further step toward accounting for the complexities of real biomolecular sensors: cooperativity.³ A cooperative biomolecule consists of two or more identical subunits arranged symmetrically. The binding of one target molecule

to one subunit alters the molecule's configuration and makes binding a second target more favorable. The more subunits a molecule contains, the greater the cooperative boost to binding.

Human hemoglobin, whose job is to scoop up oxygen and ferry it to cells that need it, has four subunits. Cooperative interactions among them result in a steep dependence of the fraction of occupied binding sites on the ambient oxygen concentration. In sensor proteins, cooperative interactions enhance sensitivity. Even a tiny change in concentration will boost the average number of sensors in a particular state. But can cooperative gain, which, in principle, is arbitrarily high, overcome background noise?