

## X-Ray Absorption Lines Probe the Missing Half of the Cosmic Baryon Population

**Cosmologists believe that half of all ordinary matter in the present epoch is hidden as a web of highly ionized intergalactic gas. An x-ray analog of the Lyman  $\alpha$  forest of redshifted ultraviolet absorption lines promises to reveal that missing matter.**

The topsy-turvy character of the cosmos posited by the so-called concordance model is, by now, widely known: Matter constitutes less than a third of the cosmic matter–energy budget. And only about a sixth of that matter is the ordinary baryonic matter we know anything about. Quoted as an invariant fraction of the total matter–energy density in the expanding universe, the mean cosmic baryon density  $\Omega_b$  is confidently presumed to lie between 4 and 5%.

Less well known is the problem of the missing baryons in the present epoch, a small but embarrassing chink in the edifice of the concordance model. The model gets its name from the reassuring agreement of the cosmological parameters derived from a variety of independent observational regimes. The prediction of  $\Omega_b$  comes primarily from the abundance ratios of the lightest nuclear species, the theory of Big Bang nucleosynthesis, and the small anisotropies seen in the cosmic microwave background. Indeed, when astronomers look back to a few billion years after the Big Bang, they find almost all of the expected baryonic matter. But by the time the cosmos was 5 billion years old, about half of that matter had somehow become invisible to the usual observing techniques.

### Finding the missing baryons

A recent paper by Fabrizio Nicastro (Harvard–Smithsonian Center for Astrophysics) and coworkers reports the observation of x-ray absorption lines that appear to be the first clear sighting of the missing half of the baryon population.<sup>1</sup> How did the baryons disappear from sight, and why has it

been so hard to find them?

In a 1999 paper entitled “Where Are the Baryons?” Princeton theorists Renyue Cen and Jeremiah Ostriker pointed out the problem, proposed an explanation, and challenged observers to verify it.<sup>21</sup> They had performed a hydrodynamic computer simulation of cosmic evolution from about 2 billion years after the Big Bang to the present. Cosmologists label the time  $t$  since the Big Bang in terms of the redshift of light emitted at  $t$ , as we see it now. Roughly,  $t \approx 14 \text{ Gy}/(1+z)^{3/2}$ . The simulation covered the interval from  $z = 3$  to 0.

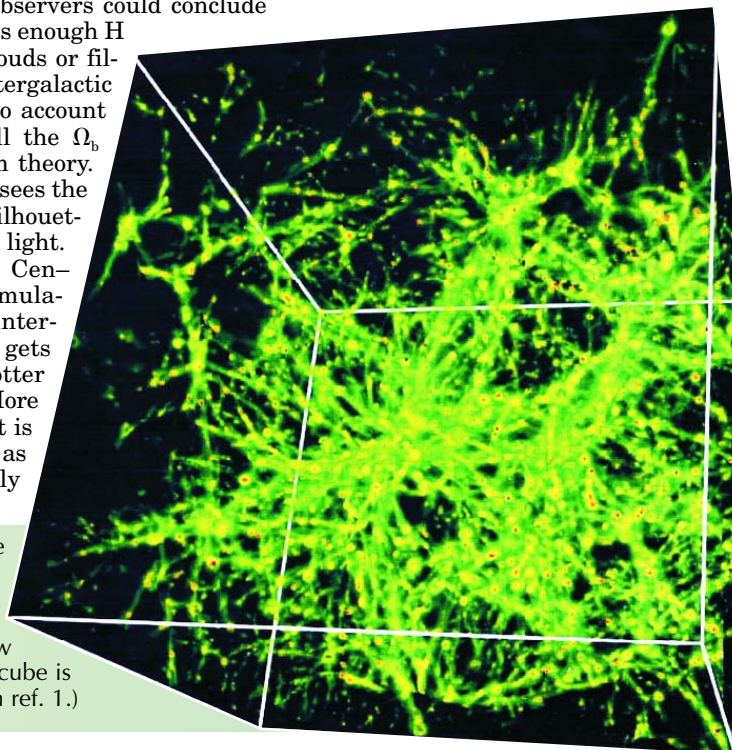
It’s known that at  $z = 3$  only about 5% of all the baryonic matter was in galaxies. Most of it was in accumulations of cool (below  $10^5 \text{ K}$ ) intergalactic hydrogen gas with enough neutral atomic H to yield detectable Lyman  $\alpha$  absorption lines in the UV and visual spectra of light from background quasars. From the so-called Lyman  $\alpha$  forest of such lines at many different values of  $z$ , observers could conclude that there was enough H in discrete clouds or filaments of intergalactic gas at  $z = 3$  to account for almost all the  $\Omega_b$  expected from theory. In effect, one sees the Ly  $\alpha$  clouds silhouetted in quasar light.

In the Cen–Ostriker simulation, the intergalactic gas gets steadily hotter after  $z = 3$ . More and more of it is shock heated as it repeatedly

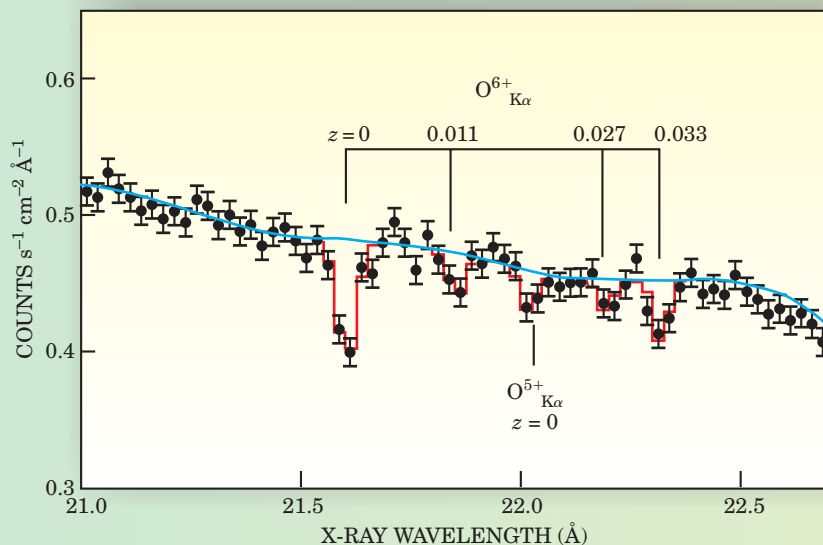
falls into gravitational potential wells of accumulated nonbaryonic “dark” matter. As the gas gets hotter, less and less of it remains un-ionized, so that Ly  $\alpha$  absorption lines become increasingly hard to see. In the present epoch, the Ly  $\alpha$  forest accounts for less than 30% of the presumed baryon density. Another 12% or so is visible in galaxies and in the x-ray emission of the very hot (above  $10^7 \text{ K}$ ) and relatively dense gas trapped in galaxy clusters.

Where are the rest of the baryons, and how can they be detected? Cen and Ostriker concluded that, after  $z = 1$ , almost half of the baryons in the cosmos have been residing in a “warm-hot intergalactic medium” (WHIM), a filamentary web of very-low-density gas—mostly hydrogen. With temperature ranging from  $10^5$  to  $10^7 \text{ K}$ , the WHIM is overwhelmingly ionized and therefore leaves no obvious trace in the Ly  $\alpha$  forest. Figure 1 shows the simulated distribution of the WHIM in the present epoch. The largest concentrations of galaxies occur at the nodes of this cosmic web.

“We worried that the WHIM might be an artifact of our simulation code, rather than a robust consequence of the concordance model,” says Ostriker.



**Figure 1. The warm-hot intergalactic medium** in the present epoch, as found in computer simulations of concordance-model cosmic evolution. The temperature of this diaphanous web of ionized gas (mostly hydrogen) ranges from  $10^5$  to  $10^7 \text{ K}$ . Galaxy clusters (shown yellow on the green gas) form particularly at web nodes. The cube is 80 million light years on a side. (Adapted from ref. 1.)



**Figure 2. Soft x-ray spectrum** of the blazar Markarian 421 shows absorption lines attributed to  $K\alpha$  transitions of highly ionized oxygen at several redshifts  $z$ . The  $O^{6+}$  lines at  $z = 0.011$  and  $0.027$ , in particular, are taken as evidence for absorption in foreground filaments of the putative warm-hot intergalactic medium. The blue and red curves show, respectively, the fitted blazar continuum and absorption lines. (Adapted from ref. 5.)

So he organized a collaboration of theorists doing concordance-model simulations with a number of different codes.<sup>3</sup> “To our relief,” he recalls, “they all found essentially the same WHIM.”

The WHIM isn’t seen in  $Ly\ \alpha$  absorption or emission because an ionized hydrogen atom is just a naked proton; it can cause colliding electrons to emit bremsstrahlung, but it has no excitable atomic states. The best hope for studying the WHIM is through its small admixture of oxygen. At WHIM temperatures, the predominant heavy-element ionization state is the helium-like configuration  $O^{6+}$ , which has a strong  $K\alpha$  absorption line at  $21.6\ \text{\AA}$  in the soft-x-ray regime.

One might think that the  $O^{6+}$  line would provide an x-ray analog of the  $Ly\ \alpha$  forest. It turns out, however, that the x-ray flux from quasars at cosmological distances is insufficient for unambiguous identification of redshifted foreground WHIM absorption lines by *Chandra* or *XMM-Newton*, the present generation of x-ray satellites. At UV wavelengths,  $O^{5+}$  absorption lines presumably from WHIM filaments have been identified at various redshifts.<sup>3</sup> But the less-ionized  $O^{5+}$  state is sufficiently populated for UV detection only at the low end of the WHIM temperature range.

### Illuminating the x-ray forest

Nicastro and company found a replacement for the too-meager x-ray flux of background quasars. Their observation of several clear x-ray absorption lines lets them venture an estimate of the WHIM’s contribution to the cosmic baryon density in the recent epoch. That estimate, albeit still very rough, is consistent with the 40 or 50% of baryons that theorists had labeled missing.

The Nicastro group’s trick was to avail itself of the extraordinary fleeting x-ray brilliance of Markarian 421, a relatively nearby blazar. Blazars are active galactic nuclei characterized by variable outbursts. At a distance of  $4 \times 10^8$  light years ( $z = 0.03$ ), Mkn 421, in its outburst phase, has an apparent x-ray brightness greater than that of any other known extragalactic source. Alerted by the all-sky monitor aboard the *Ross X-Ray Timing Explorer*, the group pointed *Chandra* at Mkn 421 on two dates in 2002 and 2003 for a total exposure of 60 hours. Happily, the blazar’s x-ray brilliance was at historic highs on those occasions.

Figure 2 shows the group’s principal finding:  $O^{6+}$   $K\alpha$  absorption lines at two distinct redshifts ( $z = 0.011$  and  $0.027$ ). These redshifts are taken to indicate the recessional velocities of absorbing WHIM filaments between us and Mkn 421 in the expanding universe. The two unredshifted lines indicate absorption in local gas. The line attributed to  $O^{6+}$  at  $z = 0.033$  is more problematic. A foreground absorption line’s  $z$  should be *smaller* than  $0.03$ , Mkn 421’s measured redshift. But the blazar’s  $z$  is poorly known.

The problem is more general. The blazar’s historic outbursts provided absorption lines that stand out clearly from the noise. But the provenance of each line is a subtler matter. The confident identification of a redshifted x-ray line with a particular ionization state depends crucially on finding several lines that fit the same  $z$ . That’s because of the observational degeneracy between  $z$  and transition energy. In addition to the oxygen lines, the Mkn 421 exposure yielded several weaker absorption lines that can be fitted by assuming they are nitrogen

$K\alpha$  lines at  $z = 0.011$  and  $0.027$ . But only one absorption line fits  $0.033$ .

The line of sight to Mkn 421 seems to pierce just two WHIM filaments. From the number of filaments a typical line of sight encounters per unit distance and the depths of the absorption lines at such encounters, one can estimate the WHIM’s oxygen population. But only one line of sight had been sampled, and Mkn 421 is not very far away. Therefore, the estimate by Nicastro and company suffers the statistical uncertainty of very small samples.

Furthermore, to translate the oxygen abundance into an overall baryon density, one must estimate the WHIM’s O/H abundance ratio. And that’s poorly known at present. An educated guess is that it’s about 10% of the Sun’s O/H ratio. But that could easily be wrong by a factor of two or three. Refining the O/H ratio at WHIM temperatures will require painstaking scrutiny of existing and new UV absorption data for traces of the one H atom in a million that’s neutral at  $10^6\ \text{K}$ .

Taking the O/H ratio to be 10% of the Sun’s and setting its large uncertainty aside, Nicastro and company estimate  $\Omega_b^W = 2.7^{+3.8}_{-1.9}\%$  for the WHIM’s baryonic contribution to the total cosmic mass-energy density. The best theoretical estimate of the total baryon density  $\Omega_b$  is  $(4.5 \pm 0.2)\%$ . In the present epoch, about half of those baryons had already been accounted for in galaxies, very hot cluster gas, the  $Ly\ \alpha$  forest, and the coolest fraction of the WHIM. So the estimate from the new WHIM x-ray lines, for all its uncertainty, is consistent with what cosmologists took to be missing.

How much better can one do? X-ray astronomers are unlikely to find another source that illuminates the WHIM for them as brilliantly as Mkn 421 can. Nicastro and coworkers have recently announced<sup>5</sup> the discovery of WHIM  $O^{6+}$  and carbon absorption lines along a second line of sight—this time to a quasar with 10 times Mkn 421’s redshift. Its much



lower x-ray brightness, however, makes for rather poor signal to noise.

The large-aperture x-ray telescopes needed to achieve good photon statistics along lines of sight to typical quasars are not expected before the next decade. For a given aperture, however, the sensitivity of an x-ray grating spectrometer improves as the square of the wavelength. "That's why we're now concentrating our search for WHIM lines on higher redshifts, while we're waiting for bigger telescopes," says Nicastro.

Andrzej Soltan (Copernicus Astronomical Center, Warsaw) and coworkers recently reported complementary evidence for the WHIM in the diffuse cosmic x-ray background.<sup>6</sup> Because the WHIM's mean density is only a handful of protons per cubic meter, its bremsstrahlung—which increases as density squared—would be too faint to see anywhere except near galaxies, where its density is expected to be highest. And that, indeed, is what Soltan and company find.

**Bertram Schwarzschild**

## References

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# A New Look at Electrons in Water Clusters Solves a Longstanding Riddle

**Influenced by cluster size and temperature, an electron can attach to the surface or be trapped internally.**

In 1962, Edwin Hart and John Boag of Argonne National Laboratory saw a novel absorption peak in the spectrum of water that had been blasted with high-energy electrons. They identified that peak as evidence for electrons in solution—solvated electrons. An individual water molecule, though, does not accept an electron. That means the solvation phenomenon is a cooperative one involving a number of molecules. To learn about the forces responsible for bulk solvation, chemists turned to tiny anionic (negatively charged) water clusters with tens of molecules or fewer. Cluster studies also enable scientists to explore how very small systems are fundamentally different from their bulk cousins.

By 1984, anionic clusters of water molecules had been successfully created in the lab. By decade's end, they had been subjected to theoretical and experimental studies. The result of those explorations was an inconclusive answer to a seemingly straightforward question: Are the electrons in modest-sized clusters bound to the surface or do they live inside? The puzzle was solved only recently when Daniel Neumark, his postdoc Jan Verlet, and colleagues from the University of California, Berkeley, formed distinct types of anionic-cluster isomers.<sup>1</sup> One, a metastable form, had properties consistent with surface binding; another suggested internal solvation.

## Two states living side by side

In the mid 1970s, Harvard University's Dudley Herschbach conceived the idea that studying charged water clusters would be a good way to learn

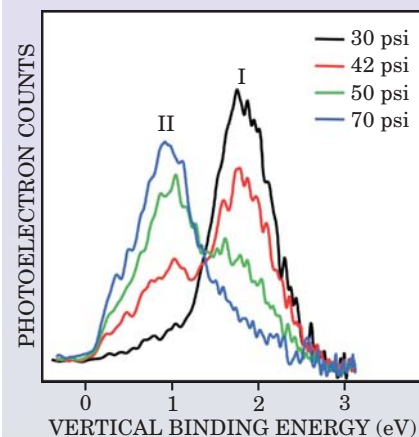
about bulk solvation. But Herschbach's group did not succeed in producing anionic water clusters. That feat was accomplished by Helmut Haberland, Doug Worsnop, and colleagues at the University of Freiburg, Germany, in 1984.<sup>2</sup>

Within a few years of the Haberland paper, Uzi Landman (Georgia Institute of Technology), Joshua Jortner (Tel Aviv University), and colleagues reported path-integral simulations that predicted the existence of surface states of excess electrons on smaller water clusters; the researchers also compared the energetics of electrons localized on the surface of a cluster with those that are inside.<sup>3</sup> The centerpiece of their approach was an effective electron-cluster interaction potential deduced with the help of scattering data. Landman and company concluded that for clusters with at most 32 water molecules, the surface state was energetically favored. Clusters with 32–64 molecules were in a transitional regime, and larger clusters favored internal electrons. For the clusters with electrons inside, the theorists predicted, the vertical binding energy would scale with the number of cluster molecules  $n$  and, when plotted against  $n^{-1/3}$ , would lie on a straight line. (In this usage, "vertical" means that an electron has been liberated, but the remaining neutral species has not had time to relax to its ground state.)

In the late 1980s, Kit Bowen (a former student of Herschbach's), James Coe, and others at Johns Hopkins University put the theoretical predictions to the test.<sup>4</sup> In their study of electrons solvated in water clusters with  $n$  ranging from 2 to 69, they

passed argon gas over water to scoop up clusters, and shot electrons into the carrier gas to make the cluster anions. After separating the clusters by mass, the group liberated electrons with laser photons of fixed energy and then measured the kinetic energies of the freed electrons. The difference between photon and kinetic energies is the vertical binding energy.

Bowen and company saw, when  $n \geq 11$ , the scaling behavior predicted for internal electrons. Moreover, the linear intercept was in good accord with the vertical binding energy for bulk solvated electrons. They did not see any transition at large  $n$  and concluded that they were looking at internally solvated electrons akin to the



**Increasing pressure**, as these  $(D_2O)_{50}$  data dramatically illustrate, changes the relative abundances of anionic isomeric states. The isomer labeled I has properties consistent with an internal electron, and the properties of isomer II suggest an electron localized on the surface. The lowest pressure, 30 psi, corresponds to  $2.1 \times 10^4$  Pa. (Adapted from ref. 1.)