Where the Baryons Are
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ABSTRACT

A fair and complete accounting of cosmic baryons now appears possible, because most of them are in states which are either directly observable or reliably constrained by indirect arguments. More than three-quarters of the baryons are probably in hot ionized gas clustering, along with galaxies and dark matter, in the cosmic web. The rest are in galaxies, roughly equally distributed between old stellar populations and star-forming disk populations; within the latter, mass is distributed about equally between stars and (mostly neutral and molecular) gas. The total amount of matter agrees with that required for concordance of cosmic light element abundances with Standard Big Bang Nucleosynthesis, a neat result inviting deeper studies of baryon evolution.

1. Big Dave and the Big Bang

David Schramm loved baryons. He was fond of a few special baryons—those pesky ultra-high-energy cosmic rays, a few isotopes here and there in meteorite inclusions, the crystalline baryons above Aspen—but his greatest love was for the light elements, unmatched for their sheer quantity and energy. Dave’s whole personality expressed abundance, and his appetite was a match for an entire Hubble volume of hydrogen and helium, flavored with a little deuterium and helium-3, and a small but soothing trace of lithium-7. I think the deuterium was always his favorite kind; he was always looking for it and often phoned me up to ask if I’d found any more (or any less) recently.

2. The Baryon Budget

Tracking down baryons is of course a serious scientific issue. According to Standard Big Bang Nucleosynthesis, the composition of primordial matter depends on only one thing, the total amount of baryonic matter; so critical tests of cosmological theory revolve around nuclear abundances in primordial matter and the total density of baryons.
Fig. 1.— The Baryon Pie. This plot shows the rough division of baryons in different forms in the universe today. Note that about three-quarters of them are still in the intergalactic medium, and only a small fraction are in the most conspicuous stellar populations.

Table 1 shows a simple breakdown of the estimated density of baryons at the present epoch in all the forms where we have reasonably good direct or indirect estimates of their mean density. The typical errors in these estimates are still about a factor of two but the prospects are good for making these smaller. I summarize here the main issues; for more detail, discussion of errors, dependence on the Hubble constant, and detailed references to document the arguments below, the reader is referred to Fukugita, Hogan and Peebles (1998).

Table 1. Summary of baryon components today for $h_{70}=1$
### Baryonic Component $\Omega_i \times 10^3$ Source of Estimate

| Baryonic Component                  | $\Omega_i \times 10^3$ | Source of Estimate                               |
|-------------------------------------|-------------------------|--------------------------------------------------|
| Spheroid Stars                      | 2.6                     | Luminosity Density, $M/L$                         |
| Disk Stars                          | 0.86                    | Luminosity Density, $M/L$                         |
| Neutral Atomic Gas                  | 0.33                    | HI 21 cm surveys, Lyman-$\alpha$ absorption      |
| Molecular Gas                       | 0.30                    | CO surveys of galaxies                            |
| Ionized gas in clusters             | 2.6                     | X-ray emission                                    |
| Ionized gas around groups           | 14                      | Soft X-rays, extrapolation from clusters          |

Total at $z = 0$ $21 \times 2^{\pm 1}$
Some baryons are easy to spot, the most obvious being the shining stars. To estimate the density of matter in stars, we need to know the luminosity density and the mass-to-light ratio, both taking into account a particular waveband. The first quantity is directly measured to an accuracy of better than about 20% in blue light, but the mass-to-light ratio $M/L$ is not directly measured. For a single star of known mass, $M/L$ is known theoretically, but a stellar population contains some mixture of masses as well as a mass of dead remnants such as degenerate dwarfs, neutron stars and black holes which have accumulated over time. The traditional (over)simplified approach is to split stellar populations into two kinds, “disk” and “spheroid”, treating each one as if it were homogeneous, and splitting the light of galaxies up as belonging to one type or another. Disk populations are those associated with some current star formation, spheroid populations have had little star formation for about a Hubble time. Thus, the $M/L$ of a disk population can be estimated from our own region of the Milky Way, where we can actually count the faint stars that dominate the mass individually (and verify that the integral at low mass seems to turn over and converge); we can also estimate the total disk mass dynamically from vertical Oort oscillations in the disk. Spheroid populations can similarly be studied dynamically in the central parts of elliptical galaxies where the dark matter is negligible. The $M/L$ in blue light estimated in this way is about 6 and 1.5 respectively in solar units for the spheroid and disk populations, with errors of about 30%. Reassuringly, these numbers agree with those estimated from a priori models of the populations; the spheroid populations are heavier because their bright blue stars have burned out, and because they have more dark remnants.

While the total blue light coming from the two types of populations is comparable (slightly greater from disk stars, by about 30%), the amount of mass is about three times bigger in spheroid populations. These numbers are similar to those derived for many years by similar techniques. Further progress will come from a more sophisticated and detailed modeling of the stellar populations.

The second category is atomic gas. Here we start with a coarse census by quasar Lyman-$\alpha$ line absorption, a fairly unbiased sampling of all the atoms by random background light sources. Their statistics reveal that almost all the atoms are in high-column-density clouds, whose total atomic mass can be measured by HI 21 cm hyperfine emission. Unbiased surveys show that such high-column clouds are almost always associated with galaxies (although the stellar content is sometimes very low surface brightness). The error in this component is therefore rather small (less than 30%) because we have a good direct census of almost all the atoms. Note that it is only one-tenth the mass in stellar populations, although in the disk galaxies where it resides the atomic gas comprises on average about a third of the stellar mass.

The third category is molecular gas. This component is denser and cooler than the atomic one, and very closely correlated spatially with regions of star formation. The estimate of molecular gas mass is very uncertain; it is based on a rather small and relatively
uncontrolled sample of extragalactic detections, where the ratio of CO to HI mass is measured. The extrapolation to total molecular density (dominated by H$_2$) is uncertain as is the extrapolation to the general galaxy population. However the main qualitative result is almost certainly correct, that this component is comparable overall to the atomic phase; the two taken together are almost the same as the mass in stars in the galaxies where they reside.

This coincidence probably reflects a real physical connection. In most galaxies these three components (stars, atomic and molecular gas) probably form a coupled and self-regulating system of star formation from gas, with gas and energy being returned from the stellar population. The spheroid population results when the gas is used up or blown away, which can be seen happening in starbursts today and which happened some time ago for most of the baryonic mass in the central parts of galaxies.

The bulk of the baryons however seem never to have made it into the galaxies. We see the best evidence of this in galaxy clusters, in which the bulk of the baryons is seen as diffuse ionized gas. In these settings the gas is hot and dense enough to detect in X-ray emission as well as Comptonization of the microwave background radiation (the “Sunyaev-Zeldovich effect”; see Carlstrom (1999) for a summary of the recent progress). Estimated either way the ratio of ionized gas mass to total mass (about 0.08) or of ionized gas mass to spheroid star mass (about 6:1) appears fairly uniform from cluster to cluster. There is so much gas in the clusters that even though they represent a small fraction of all the galaxies (about 1/6 in the Fukugita et al. definition), their gas contributes as many baryons as all the stars in all the galaxies.

Many aspects of galaxy and structure formation are poorly understood, but one feature seems to be robust: the total mixture of stuff in galaxy clusters is a fair sample of the universe as a whole. This statement needs some qualification (there is some ejection, there is some segregation, etc.) but by and large we can use the situation in clusters as a guide to that in the universe as a whole. This argument can be employed in several ways; we can assume that nucleosynthesis is correct and estimate the density of matter (White et al. 1993), we can assume a constant mass-to-spheroid-star-mass ratio to estimate the total density of matter (a technique with a long history), or we can assume a constant baryon-to-star or baryon-to-mass ratio to estimate the global density of baryons. If we employ the latter extrapolations, we get a much bigger number for the baryon density than we have found within galaxies so far.

The best guess for where these baryons reside is in ionized gas very similar to the clusters, but gathered instead around the more typical dark matter condensations of the universe, around groups of galaxies. The gas is cooler and less dense than that of clusters, reflecting the smaller temperature and density typical of dark matter halos around typical groups of galaxies. Instead of temperatures in excess of 10$^7$K, the typical temperature is a few million degrees.
The bulk of the cosmic baryons thus seem to be parked in a form where we cannot study them easily. Gas at this temperature cools very inefficiently and radiates in soft X-rays which are notoriously difficult to detect. Some groups do indeed emit detectable thermal X-rays which could be the denser portion of this gas emerging above the backgrounds. There is a detected soft X-ray background which doubtless includes a contribution from the integrated light of all the groups of the universe, but this does not allow us to estimate the overall gas density unless we can estimate its overdensity, for example by detecting the extent of the emission around typical groups. It is also possible this gas will be detected in a few absorption lines of heavy elements (such as hydrogenic transitions of oxygen), in quasar spectra taken with large X-ray telescopes (e.g. Hellsten, Gnedin and Miralda-Escudé 1999). The density information will be combined in this case with abundance information.

The abundances of cluster gas and high-redshift absorbers add additional clues about the history of star formation, supernova enrichment, gas ejection from galaxies, and the universality of cluster baryons (Renzini 1999, Pettini 1999). The best guess is that the pervasive ionized gas is, like the gas in clusters, fairly enriched in metals, to perhaps one-third of the solar value. Thus the intergalactic gas contains not only most of the baryons in the universe but also most of the heavy elements.

3. Evolution of the Baryon Distribution

This state for the baryons is a natural outcome in current models of galaxy and structure formation. Once gas gets hot enough it has few coolants—everything is ionized except the rare heavy elements. In the cosmic setting, the heating and cooling of most of the gas become dominated by dynamical effects. Gravitation causes motion, collisions lead to shock heating, compression by infall leads to adiabatic heating, and cosmic expansion leads to adiabatic cooling. With no radiative cooling the gas achieves a steady-state distribution of temperatures determined by the cosmic web of dark matter which defines the gravitational potential. This evolution is seen in simulations (Cen and Ostriker 1999, Wadsley et al. 1999).

One important issue is not yet resolved by the simulations, and that is the overall efficiency of galaxy and star formation. The gas at early times is not so hot, and indeed passes through temperatures $10^{4-5}$K where the cooling is very efficient. What prevents all of the gas from collapsing at this time into the protogalactic lumps around then? Part of the story must be the feedback from star formation, like that we see at work today in galaxies: the formation of a few stars heats the remaining gas so that it does not fall in. However, it is not clear that this is even the dominant effect; another important ingredient is kinematical “heating”—the continuous mixing, stirring and tidal disruption that occurs in a hierarchy.
Fig. 2.— Histogram showing the distribution of gas temperatures at different epochs, from a simulation by Wadsley (1999). The qualitative trend is that the gas is gravitationally heated by clustering in the cosmic web; no other heat source was included in this model. At high redshift, most of the gas is around $10^4\text{K}$ and is readily visible in HI or HeII absorption; at late times, the cool phase remains but the bulk of the gas heats up to about $10^6\text{K}$ or more.

In some ways we have better information about the baryons at high redshift than we do at zero redshift, since we can directly observe the dominant phases of gas. Because the gas is cooler, hydrogen and helium are not entirely ionized and we can detect the small fraction left in the form of HI or HeII by Lyman-α absorption. The bulk of the baryons are in the diffuse, ionized protogalactic web of gravitationally-collapsing gas which create the “Lyman-α forest” in quasar spectra. The helium ions provide information supplementary to the HI since they are more abundant than HI, they are detectable in gas at lower density and higher temperature (in the “voids”), and their ionization state is constrained in a large region where the light of the target quasar dominates the radiation field; this information is now becoming obtainable with HST/STIS (Anderson et al. 1999, Heap et al. 1999). Together the HI and HeII can be used to paint a complete and compelling picture of the gas distribution at the time when most galaxy formation is happening. Hydrodynamical simulations reproduce the main features of the observed absorption and allow estimates of the mean density (Weinberg et al. 1997, Rauch et al. 1997, Zhang et al. 1997). A new technique based on HeII void absorption (Wadsley et al. 1999) gives an independent estimate, with ionizing radiation calibrated directly from the quasar light. From these estimates we infer that the bulk of the baryons at $z = 3$ are as predicted in the (mostly ionized) gas producing the absorption, and the total baryon density is about what we infer today. As sampling and modeling improves, the systematic sources of error will come under better control and these measurements will provide our best direct estimates of the total
baryon density. We already seem to have discovered that most of the baryons are now and have always been in diffuse gas.

4. Primordial and Unseen Baryons

The classical theory of Big Bang Nucleosynthesis cleanly predicts the composition of baryonic matter emerging from the early universe—four light element abundances (deuterium, helium, helium-3, and lithium-7) as a function of only one parameter, the ratio $\eta \equiv 10^{-10} \eta_{10}$ of baryons to photons. Once the background temperature is measured, specifying $\eta$ is equivalent to specifying the mean density of baryons, $\Omega_b h^2 = 7.45 \times 10^{-3} \eta_{10}$. (The theoretical predictions with errors are now available as a java calculator for those who wish make their own comparisons with observations: see Mendoza and Hogan 1999). The story on abundances (reviewed for example by Steigman 1999) is constantly shifting. Recent discussions of helium (Izotov et al. 1999) have raised previous limits slightly, and the primordial abundance of lithium (Ryan et al. 1999) may be lower than previously thought, bringing these elements into good concordance with each other. Although the central values of low estimates of the primordial deuterium (Burles and Tytler 1998ab, Kirkman et al. 1999) still prefer values of $\eta$ a higher than the other elements prefer, the full errors in these estimates allow a concordance. In spite of persistent debates about the correct values and errors to use, there always remains a comfortable spot giving reasonable concordance with current datasets (a spot which Dave Schramm always managed to find). This “sweet spot” has been remarkably stable for years, $\eta_{10} \approx 4 \pm 1$, $\Omega_b h^2 \approx 0.03 \pm 0.01$, squarely within the range from our tally of baryons, $0.01 \leq \Omega_b \leq 0.04$.

This is a very tidy result, suggesting that we may be close to a complete accounting of baryons. It may be further verified soon, with measurements of the microwave background anisotropy. If this is right, there are no other major repositories of baryons, and the dark matter really must be in some nonbaryonic form.

The basic ideas of Standard Big Bang Nucleosynthesis have held up for half a century. The modern theoretical structure it has been mature for three decades, although even today its predictions are subject to refinements. The most amazing thing about it is that nature’s real universe is so simple that according to the steadily mounting evidence, this maximally simple and symmetric model seems empirically to be an accurate description of what really happened in the early universe, starting about a second after the Big Bang, everywhere in the $10^3$ cubic Gigaparsecs encompassed within our past light cone. To some of us this simplicity was always a hope (but remains a surprise); to David Schramm, it was almost an article of faith, of which he was the most ardent evangelist.

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5. References

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Fig. 3.— A recent version of David Schramm’s favorite plot, from Izotov et al. 1999, who favor a concordance at a fairly high baryon density. Ryan et al. (1999) recently estimated a low primordial lithium abundance, arguing that $\eta_{10} \leq 4$. The direct tally of baryons yields estimates of $\eta_{10}$ from about 2 to about 5, in substantial agreement with the density expected from nucleosynthesis.
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