Cosmic Matter Distribution: Cosmic Baryon Budget Revisited

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Abstract. The cosmic baryon budget is revisited using modern observations that have become available since our first publication. I also present an estimate for the heavy element abundance. An increased accuracy in the accounting of the baryon budget reveals 'missing baryons', which amount to $\approx 35\%$ of the total. This would provide an interesting test for models of the cosmic structure formation.

1. Introduction

The evolution of the Universe and the formation of cosmic structure redistribute dark matter and baryons. Thus the present day distribution of the matter reflects the history of the Universe, and gives us information as to how the cosmic structure formed. For this reason the matter distribution is taken as a useful constraint for models of formation of large-scale structure and galaxies. We have published an accounting of the cosmic baryon budget in 1998 (Fukugita, Hogan & Peebles 1998, hereafter FHP). Since then, much progress has been made in relevant observations, which include the *Sloan Digital Sky Survey* (SDSS: York et al. 2000), *Wilkinson Microwave Anisotropy Probe* (WMAP: Bennett et al. 2003), several HI surveys, and others. In this talk, I attempt to update the present-day baryon budget using modern data, and discuss some issues relevant to cosmic structure formation. We write the Hubble constant as $H_0 = 100h$ km s^{-1} Mpc^{-1}, but adopt $H_0 = 72$ km s^{-1} Mpc^{-1} when h is not explicitly denoted.

2. Baryons in stars

The basic data used to estimate baryons in stars are the luminosity function (LF) and the stellar mass to light ratio (M_s/L) of galaxies. The most accurate LF was derived from the SDSS for five colour bands (Blanton et al. 2001, 2003; Yasuda et al. 2003). The first LF from the SDSS given by Blanton et al. (2001) is based on earlier data for the northern equatorial stripe of approximately 200 square degrees, giving the global luminosity density $\mathcal{L}_r = (2.58 \pm 0.28) \times 10^8 h L_\odot (\text{Mpc})^{-3}$. It turned out, however, that the surface density of galaxies in this region for $r < 17.9$ mag is somewhat overdense compared to the mean. The *First Data Release* of the SDSS (Abazajian et al. 2003) now covers 2200 square degrees, and the LF derived from these data gives a somewhat smaller value $\mathcal{L}_r = (2.32 \pm 0.25) \times 10^8 h L_\odot (\text{Mpc})^{-3}$ (Yasuda et al. 2003; see also Blanton et

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al. 2003) in the r band. The corresponding luminosity density in the z band is $\mathcal{L}_z = (3.9 \pm 0.6) \times 10^8 h L_\odot (\mathrm{Mpc})^{-3}$.

The most extensive analysis for the stellar mass to light ratio is that by Kauffmann et al. (2003) using 10^5 SDSS galaxies. The estimate of the stellar mass using a population synthesis model depends on metallicity, age, and the star formation history, and also on the initial mass function (IMF). They estimated the probability distribution of each parameter in terms of the Bayesian analysis using five colour photometric data. In our consideration we limit to bright ($r < 15.9$) galaxies, the median redshift of which is 0.05. The value of $M/L_z \simeq 1.85$ for luminous galaxies with $M_z < M_z^* - 0.8$, and it decreases gradually to 0.65 for galaxies with $M_z \simeq M_z^* + 3$. The LF-weighted mean is $\langle M/L_z \rangle \simeq 1.5$ to which a 20% error is alloted.

There is still a significant uncertainty in the IMF, especially for the subsolar mass. Kauffmann et al. assumed the IMF of Kroupa (2001). Another typical IMF is that of Reid et al. (1999) from DENIS and 2MASS surveys. The former shows an increase of the IMF down to $M = 0.1 M_\odot$, whereas the latter flattens at $M \leq 1 M_\odot$. This leads to a 40% difference in the integrated mass. We take the geometric mean of the two as our central value, allowing for $\pm 20\%$ errors. The Kennicutt (1983) IMF gives the integrated mass close to our adopted value. The IMF for $< 0.1 M_\odot$ is even more uncertain, but the contribution from this region is small ($< 4\%$), provided that the IMF declines towards smaller masses (e.g., Burgasser et al. 2003). The value adopted here is 1.10 times that used in FHP, which employed the subsolar mass IMF of Gould, Bahcall & Flynn (1996). The Salpeter IMF, when cut off at $0.1 M_\odot$, gives the integrated mass 1.50 times the adopted value.

Assembling these inputs we obtain

$$\Omega_{\mathrm{star}} = 0.0025 \pm 0.0008, \tag{1}$$

which includes dead stars. This value is compared to $0.0019 - 0.0057$ of FHP. The error arises from the luminosity density ($\pm 15\%$), from M/L ($\pm 20\%$) and from IMF ($\pm 20\%$), which are added in quadrature.

3.   Metal abundance in stars

In the analysis of Kauffmann et al. (2003), the metallicity is also an output, but the results are not available. We here use the oxygen abundance determined from HII regions for nearby galaxies compiled by Kobulnicky & Zaritsky (1999). The metallicity shows a correlation with the luminosity of galaxies. Using oxygen as the metallicity indicator, integration over the LF in the B band yields,

$$Z = 10^{6.6 \pm 0.15} M_\odot \mathrm{Mpc}^{-3}, \tag{2}$$

where the solar composition is assumed. The zero point is set by the solar value, $\log[\mathrm{O/H}]+12 = 8.83$ at $(Z/X)_\odot = 0.0230$ (Grevesse & Sauvel 2000), or $Z_\odot = 0.0163$ using $X = 0.71$.

There is an additional storage of heavy elements in white dwarfs, which are liberated only by Type Ia supernovae. From the abundance of white dwarfs (Bahcall & Soneira 1980), we estimate the heavy element (C+O) abundance as

$$Z = 10^{7.6} M_\odot \mathrm{Mpc}^{-3}, \tag{3}$$

which is much larger than (2). Heavy elements frozen in neutron stars are also a large amount $\approx 10^{6.9} M_\odot \text{ Mpc}^{-3}$.

4. Neutral and molecular gas mass

FHP adopted the HI observation of optically selected galaxies by Rao and Briggs (1993), which yielded $\Omega_{\mathrm{HI}} = (2.1 \pm 0.6) \times 10^{-4}$ at $h = 0.72$. Since then, a number of blind HI surveys were carried out. Among them the largest sample (1000 galaxies) was obtained by the HIPASS survey (Zwaan et al. 2003), which gives $\Omega_{\mathrm{HI}} = (4.2 \pm 0.7) \times 10^{-4}$, twice higher than the value of Rao & Briggs. With the correction for helium (for both HI and H_2), the amount of atomic gas is

$$\Omega_{\mathrm{HI+HeI}} = (6.2 \pm 1.0) \times 10^{-4}. \tag{4}$$

The molecular hydrogen abundance is estimated from the CO survey of Keres, Yun & Young (2003):

$$\Omega_{\mathrm{H_2}} = 1.6 \pm 0.6 \times 10^{-4}. \tag{5}$$

This is compared to $\Omega_{\mathrm{H_2}} = 2.1 \pm 0.6 \times 10^{-4}$ (FHP) obtained by summing the mean H_2 abundance for each morphological class of galaxies (Young & Scoville 1991) weighted by the abundance of morphologically classified galaxies.

5. Hot gas in clusters

In FHP the hot gas abundance in clusters was estimated by integrating the cluster abundance for mass $M > 1 \times 10^{14} h M_\odot$ (Bahcall & Cen 1993) and multiplying the gas fraction obtained from X ray observations. The cluster mass was defined by the Abell radius. Now, the advancement in cluster studies allows us to use the mass within $r < r_{200}$, where r_{200} is the radius at which matter density $\rho = 200 \rho_{\mathrm{crit}}$. From a theoretical ground this may give a better measure for the mass of the virialised system. Reiprich & Böhringer (2002) estimated from the ROSAT All-Sky Survey that $\Omega_{\mathrm{cl}} = 0.012^{+0.003}_{-0.004}$ for clusters with mass larger than $M = 4.5 \times 10^{13} M_\odot$, which are visible with X rays.

The cosmic value of the baryon to total mass ratio from the WMAP (Spergel et al. 2003) is

$$\Omega_b/\Omega_m = 0.178(1 \pm 0.09). \tag{6}$$

We estimate the ratio of the stellar to total mass from the mean value of $M/L_B = (450 \pm 100)h$ and $M_s/L_B = 4.5(1 \pm 0.20)$, giving $M_s/M_{\mathrm{tot}} = 0.014(1 \pm 0.30)$. This is somewhat larger than the stellar mass density (1) divided by the total matter density from WMAP $\Omega_m = 0.26 \pm 0.05$: $\Omega_{\mathrm{star}}/\Omega_m = 0.010 \pm 0.004$. Assuming that the baryon to dark matter ratio in clusters agrees with the cosmic value and subtracting the stellar mass from the total baryonic mass, we estimate the hot gas abundance:

$$\Omega_{\mathrm{cl \ gas}} = 0.0020 \pm 0.0006. \tag{7}$$

The significant downward shift compared with FHP is due to the different definition of the radius with which the cluster mass is defined.

6.   Warm and cool plasma

FHP inferred the presence of copious warm and cool plasma based on the universality of the baryon to dark matter ratio at large scales, and suggested that this component fills the gap between the cosmic baryon abundance from Big Bang nucleosynthesis and that estimated from *observed* baryons in the local Universe. The evidence for abundant warm gas around galaxies was presented by the detection of O VI absorption in the UV spectrum (Tripp, Savage & Jenkins 2000). This year, WMAP gave an accurate estimate for the baryon abundance, which agrees with the value from the deuterium and helium abundance in Big Bang nucleosynthesis. This erases any doubts concerning the estimate of the cosmic baryon abundance from the nucleosynthesis argument.

We may estimate the abundance of baryons associated with galaxies from the mean M/L ratio and the LF of galaxies, assuming that the baryon to dark matter ratio is universal when averaged over large scales. The M/L of the Milky Way is known to be ≈ 100 at 200 kpc (e.g., Kuijken 2003). The analysis of Prada et al. (2003) (see also Zaritsky et al. 1997) using the motion of 3000 satellites around host galaxies derived from the SDSS yielded $\langle M/L \rangle = 120h$ at the 'virial radius'. The least model-dependent method to measure the mass associated with galaxies is to use gravitational lensing shear around those with known redshifts. McKay et al. (2001) estimated the galaxy mass using the SDSS sample, giving $\langle M/L_r \rangle = (170 \pm 21)h$ for $R < 260$ kpc from the r band data. (The i band data give a smaller value, and g band data give a larger value.)

These M/L values are significantly (by about a factor of 2) smaller than those for clusters. Taking the lensing value of $M/L_r = (170 \pm 20)h$ and the r band luminosity density, we estimate $\Omega_m = 0.14 \pm 0.02$ for the matter associated with galaxies (within the virial radius). This leads to $\Omega_b = 0.025$ when multiplied by the universal value of (6). Subtraction of Ω_s and $\Omega_{HI+HeI+H_2}$ gives

$$\Omega_{w/c\ gas} = 0.022 \pm 0.005 \tag{8}$$

for the warm baryon component around galaxies.

An alternative path to estimate the warm/cool baryon abundance is to subtract stars, neutral and hot ionised gas from the global baryon amount, which is accurately known after the WMAP observation:

$$\Omega_{w/c\ gas} = 0.044 - 0.0025 - 0.0020 - 0.0008 = 0.039 \pm 0.004. \tag{9}$$

The discrepancy of (8) and (9) implies 'missing baryons': the gap between the two estimates suggests the presence of baryons that are not immediately associated with galaxies. We do not count in (9) cool ($\approx 10^4$K) baryons in Lyman α clouds, which were estimated to give $\Omega = 0.002 \pm 0.001$ (FHP), but this contribution is much too small to fill the gap. These missing baryons may be in the vicinity of galaxies beyond a few hundreds of kpc, or associated with dark clumps which do not shine as galaxies, as they occur in CDM simulations (Ostriker et al. 2003). The two possibilities may not be necessarily exclusive to each other. A possibility is not excluded that the missing baryons are present as a highly ionised diffuse component, though this is not very likely (see below).

There is also a gap in the dark matter abundance between the cosmic value $\Omega_{dm} = 0.22$ and the amount associated with galaxies $\Omega_{dm} \approx 0.12$. According to

the hierarchical clustering calculation, we anticipate 15% of baryons are unbound $(M < 10^6 M_\odot)$ and 25% are in clumps of mass $10^6 M_\odot < M < 10^{10} M_\odot$. CDM simulations (Ostriker et al. 2003) predict a lot of dark, low mass clumps.

It would be interesting to note that if we adopt $M/L_r \simeq 320h$ ($M/L_B \simeq 450h$) of clusters as the universal M/L of galaxies to estimate the global mass density, we would obtain $\Omega_m \simeq 0.27$ which is consistent with the cosmic mass density from WMAP. This implies that dark clumps are integrated into clusters, leading to a large M/L ratio, compared to that for galaxies, for which those dark components are excluded from accounting. This suggests that the majority of dark clumps reside in outskirts of galaxies, or in filaments and groups of galaxies, so that dark matter component that is not counted in the estimate of $\mathcal{L} * \langle M/L \rangle$ is localised, rather than smoothly distributed through the Universe, and so are baryons.

7. Metal abundance outside stars

Taking the metallicity of interstellar gas given in Sect. 2, we find $Z \approx 1.5 \times 10^6 M_\odot$. For the cluster gas, we infer $Z \approx 1.6 \times 10^6 M_\odot$, adopting 1/3 solar. Very little is known for warm and hot plasma. If we assume the heavy element abundance of 0.01 solar as in globular clusters, or in typical Lyman α clouds, we get $Z \approx (0.5 - 0.9) \times 10^6 M_\odot$. Therefore, the metal abundance is dominated by that in dead stars in galaxies.

Table 1.   Summary of the cosmic baryon budget

component	FHP	new estimate
stars	0.0019−0.0057	0.0025±0.0008
HI+HeI gas	0.00025−0.00041	0.00062±0.00010
H_2 molecular gas	0.00023−0.00037	0.00016±0.00006
hot plasma in clusters	0.0014−0.0044	0.0020±0.0006
warm and cold plasma (by sum)	0.0072−0.030	0.022±0.005
(by subtr.)		0.037±0.004
total	0.011−0.041	0.044±0.004

8. Summary

In this report I have presented an updated accounting of the cosmic baryon budget, and have given an estimate for the heavy element abundance. The summary of the cosmic baryon budget is shown in Table 1. Each entry does not differ greatly from that given in FHP, but an increased accuracy reveals a missing baryon component which amounts to $(0.37 - 0.22)/0.44 \approx 35\%$ of the total. This would provide an interesting test for cosmic simulations of the structure formation.

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