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Cosmic Baryon Density from Primordial Nucleosynthesis and Other Evidence

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Abstract. I comment on primordial abundances, their implications for cosmic baryon density (all are consistent with $4 \leq \eta_{10} \leq 5$), the nature of baryonic dark matter (probably mainly hot intergalactic gas), its metallicity and implications for the overall yield. Recent estimates of the cosmic star formation rate as a function of red-shift are discussed in the light of the present-day densities of stars and heavy elements.

1. Introduction

It has been recognised for a long time that a 'low' primordial deuterium abundance of a few $\times 10^{-5}$ implies the existence of both baryonic and non-baryonic dark matter, since $\Omega_{\rm vis} < \Omega_{\rm bbns} < \Omega_{\rm M}$ (see Table). Some of this baryonic dark matter (BDM) could be in the form of low surface-brightness galaxies (Bristow & Phillipps 1994), but from the results reported at this and other conferences it seems that these are likely to make only a minor contribution over and above what has been taken into account already (cf. Fukugita, Hogan & Peebles 1998). In this talk I give an update on estimates of primordial abundances, which seem to be converging to well-defined limits on the baryon density, and compare that density with estimates based on other arguments. The existence of substantial quantities of BDM, now thought to reside mainly in the form of intergalactic hot gas, raises interesting questions about its metallicity and the likely existence of 'dark metals', which in turn have implications for the cosmic history of star formation which has recently undergone intensive study on the basis of optical red-shift surveys, UV drop-out galaxies in the Hubble Deep Field and elsewhere, and infra-red and sub-mm observations. The upshot is that there may well be a substantial amount of 'dark' metals residing in intergalactic gas, and comparison of this with the density of visible stars leads to estimates of the yield that are substantially higher than what one normally assumes for the solar neighbourhood.

2. Primordial abundances

2.1. Deuterium and ^{3}He

The primordial D/H ratio is the chief test of baryonic density because of its steep negative dependence thereon. Extrapolations of the well-determined value of 1.6×10^{-5} in the local interstellar medium (Linsky et al. 1993) to a primordial value give only rather vague limits: Hata et al. (1996), updating an argument by Yang et al. (1984) based on solar D + ^{3}He, give 95% confidence limits 10^5 $(D/H)_P = 3.5^{+2.7}_{-1.8}$. A recent detection of the D I hyperfine structure line in the Galactic anti-centre gives a D/H ratio $(3.9 \pm 1) \times 10^{-5}$ (Chengalur, Braun & Burton 1997), which is an alternative lower limit in a region that has undergone less astration than the solar neighbourhood. More precise estimates of the primordial value are available in principle from direct measurements of D/H in Lyman-limit absorption-line systems in front of quasars, which can be expected to have essentially primordial chemical composition, but only a few systems are suitable from the spectroscopic point of view and there has been some controversy with both high ($\sim 2 \times 10^{-4}$) and low values ($\sim 2 \times 10^{-5}$) reported. The best estimates for two high red-shift systems ($z = 2.5$ and 3.6) observed with the Keck Telescope give D/H = $(3.4 \pm 0.3) \times 10^{-5}$ (Burles & Tytler 1998ab), but Webb et al. (1997) have found a high value in a system with $z = 0.7$ observed with IUE and HST, as well as a low one in another system at $z \simeq 0.5$. These results have encouraged speculations that there might be cosmic variations in η (Jedamzik & Fuller 1995; Copi, Olive & Schramm 1996) or in neutrino degeneracy (Dolgov & Pagel 1997), but doubts have been raised as to whether the differences are real: Levshakov, Kegel & Takahara (1998ab) have argued that the conventional microturbulent approximation used in simulating line profiles is invalid in these systems and have found solutions involving mesoturbulence with lopsided velocity distributions that give the same D/H ratio, 4.1×10^{-5}, in all three of the prominent cases. It is possible, therefore, that the data are homing in on a universal primordial deuterium abundance somewhere between 3 and 5 $\times 10^{-5}$, which implies that the baryonic density parameter η_{10} is between 4 and 6, or $0.015 \leq \Omega_b h^2 \leq 0.022$.

This result implies that D in the interstellar medium has been destroyed by a factor between 2 and 3, which is reasonable from the point of view of Galactic chemical evolution. One might then expect a corresponding increase in the abundance of ^{3}He, resulting from D destruction and some fresh production. However, the latest results on ^{3}He in Galactic H II regions (Balser et al. 1998) give a 'plateau' with abundances equal within errors to the proto-solar value $^3He/H \simeq 1.5 \times 10^{-5}$ over a wide range of Galactocentric distances and metallicities indicating an apparent balance between production and destruction. Should this value be identified with the primordial one, they estimate a corresponding value of $\eta_{10} = 3.2^{+4.4}_{-1.9}$, consistent with the value derived from deuterium. The existence of 'extra mixing' in giant stars leading to significant ^{3}He destruction has substantial support from carbon isotope ratios in red giants (Hogan 1995; Charbonnel & do Nascimento 1998), and it seems that production and destruction may be nearly in balance (Sackmann & Boothroyd 1998).

2.2. Helium-4

The primordial helium abundance is not a good measure of baryon density, to which it is comparatively insensitive, but it is an important test of consistency and of N_ν, the number of relativistic neutrino types present at BBNS, which there are good grounds for believing to be 3. The most accurate estimates come from measurements of recombination emission lines in extragalactic H II regions as a function of oxygen (and nitrogen) abundance representing the heavy-element fraction Z and extrapolating linearly to $Z = 0$ (Peimbert & Torres-Peimbert 1974). Over the years, such studies have often led to a rather low value $Y_P \simeq 0.23$ (e.g. Lequeux et al. 1979; Pagel et al. 1992; Skillman & Kennicutt 1993; Skillman et al. 1994), which raised doubts in some quarters as to the viability of conventional BBNS theory (Hata et al. 1995), and to rather high values of 3 or more for $\Delta Y/\Delta Z$.

Pagel et al. (1992) noted that there could be systematic errors of various sorts and suggested a 95% confidence upper limit of 0.242; Olive, Skillman & Steigman (1997) and Hogan, Olive & Scully (1997) suggested a similar limits of 0.242 to 0.244. The assumption of such a limit has been criticised on various grounds which were mostly spurious (e.g. Sasselov & Goldwirth 1995), but the critics' conclusions now seem to have been correct if for the wrong reasons. The trouble centres in large part on the blue compact galaxy I Zw 18, where it has been shown by Izotov & Thuan (1998) and by Vílchez & Iglesias-Páramo (1998) that there was a greater effect of underlying stellar absorption lines than we had allowed for. There are also other difficulties with the lowest-metallicity H II regions arising from their high electron temperatures and the resulting sensitivity of collisional-excitation corrections to the electron density. We used densities based on [S II] (the only method available in 1992), whereas Izotov, Thuan & Lipovetsky (1997), Izotov & Thuan (1998) and Izotov et al. (1999) have produced a more homogeneous set of data than was previously available and use ratios of helium lines with different sensitivities to collisional and radiative transfer effects, resulting in $Y_P = 0.2452 \pm 0.0009$, slightly above the upper limits that were previously suggested. This is probably a better value than ours, but the error bar looks very optimistic. I should prefer to conclude that the primordial helium abundance is between 0.24 and 0.25, corresponding to η_{10} between 2.5 and 8.5, and thus quite compatible with the the deuterium result within the standard BBNS framework.

2.3. Lithium-7

The final piece of the BBNS jig-saw is ^{7}Li. Bonifacio & Molaro (1997), using improved model atmospheres, especially with regard to the effective-temperature determination from the infra-red flux method of Blackwell et al. (1990), find the Spite plateau to be remarkably well defined for [Fe/H] < -1 and $T_{\rm eff} > 5700$ K, with $12 + \log$ Li/H $= 2.24 \pm 0.05$ (syst.). The same authors have measured a subordinate Li I line in HD 140283, checking its concordance with the resonance doublet and thereby ruling out significant non-LTE effects (Bonifacio & Molaro 1998). Destruction factors in the stellar atmospheres are severely constrained by this tightness and by the presence of ^{6}Li in HD 84937 (Smith, Lambert & Nissen 1993), and they are estimated in any case to be less than 0.2 dex (Vauclair & Charbonnel 1998), so that it now seems reasonable to take this as the primordial lithium abundance. Owing to the bimodal dependence of lithium on η, this leads to two solutions corresponding to low η and high D/H and to high η and low D/H respectively. The low-η solution now seems unlikely in view of the results for D and ^{4}He reported above, while the high-η solution gives $3 \leq \eta_{10} \leq 5$. Combining this with the the deduction from D/H, we end up with $4 \leq \eta_{10} \leq 5$, or $0.015 \leq \Omega_{\rm B} h^2 \leq 0.018$.

3. Abundances of different forms of matter

The attached Table gives estimates of the smoothed-out cosmic densities of different forms of (mostly baryonic) matter deduced from estimates of mass:light ratios combined with luminosity densities from red-shift surveys and other evidence and arguments. They are given as Ω, normalised to a Hubble parameter of 70 km s^{-1} Mpc^{-1}, which seems to be the fashionable value of the month. Figures on the left of the two columns are taken from Persic & Salucci (1992), while those on the right are from the more recent work of Fukugita, Hogan & Peebles (1998).

The two estimates of the amount of mass in the form of stars are not very different, amounting to only a tenth of the total from BBNS, and in the Persic & Salucci estimates allowing for gas does not make a great difference. At high red-shifts, a substantial part of the stellar population is accounted for by the damped Ly-α population, whereas all the baryonic matter is accounted for by ionized gas associated with the Lyman forest (Rauch et al. 1998). The subsequent fate of this (presumably largely intergalactic) ionized gas has been uncertain, but it has now been suggested that it still exists in the form of hot, rarefied intergalactic gas today (Cen & Ostriker 1998). The density of this hot intergalactic gas was previously derived on the assumption that it bears the same relation to field and group elliptical galaxies as does hot gas to elliptical galaxies in clusters (Mushotzky & Loewenstein 1997; Fukugita, Hogan & Peebles 1998), and the resulting overall density of stars plus gas is then $0.021\,h_{70}^{-1.5}$, which is within striking distance of the BBNS-derived total density of $(0.03 \text{ to } 0.04)h_{70}^{-2}$.

There is thus the possibility that the dark baryonic matter can all be accounted for, but there is another issue associated with its chemical composition. If it is primordial, then most of the 'metals' in the universe are in stars and can be accounted for on the basis of conventional galactic chemical evolution theory with overall yields comparable to solar abundances, although larger yields may be needed in cluster ellipticals to account for the metallicity of intra-cluster gas (e.g. Pagel 1997). Mushotzky & Loewenstein argue, on the other hand, that the metallicity of diffuse intergalactic gas should be the same as in the intra-cluster gas, i.e. about 1/3 solar, and in this case the yield averaged over the whole universe has to be 2.5 times larger than solar abundance.

4. Implications for overall star formation history

Cosmic star formation rates as a function of red-shift have been intensively studied in the last few years on the basis of Hα surveys, red-shift surveys and UV drop-out galaxies in the Hubble Deep Field and elsewhere. According to Madau, Pozzetti & Dickinson (1998), optical and near IR data are well accounted for by a co-moving star formation rate (SFR) in units of $h_{50}M_{\odot}$ yr^{-1} Mpc^{-3} rising from 0.01 at $z=0$ to a peak of 0.1 at $z \simeq 1.5$ and then declining exponentially to reach 0.02 at $z=5$, assuming a Salpeter IMF with a lower limit of 0.1 $M_{\odot}$ and SMC-type dust in a foreground screen with $E_{B-V}=0.1$. These figures are likely underestimates by a factor of 2 or so, according to extinction corrections based on supplementary near-IR and radio observations of Canada-France red-shift survey fields by Hammer & Flores (1998) and on G$-$R colours of HDF UV

Inventory of cosmic baryons and 'metals'

Densities expressed as Ω,
in units of $\rho_{\rm crit} = 1.54 \times 10^{11} h_{70}^2\, M_\odot\, {\rm Mpc}^{-3}$

All baryons from BBNS (D/H = 3.4×10^{-5} [a])	$0.035\, h_{70}^{-2}$	
Stars in spheroids	.0015 [b]	$.0026\, h_{70}^{-1}$ [c]
Stars in disks	.0007 [b]	$.0009\, h_{70}^{-1}$ [c]
Total stars	.0022 [b]	$.0035\, h_{70}^{-1}$ [c]
Cluster hot gas	$.0006\, h_{70}^{-1.3}$ [b]	$.0026\, h_{70}^{-1.5}$ [c]
Group/field hot gas	$.0002\, h_{70}^{-1.3}$ [b]	$.014\, h_{70}^{-1.5}$ [c]
Total stars + gas	$.003\, h_{70}^{-0.4}$ [b]	$.021\, h_{70}^{-1.5}$ [c]
Machos		?? [c]
Ω_Z (stars, $Z = 0.02$ [d])	4.4×10^{-5} [b]	$7 \times 10^{-5}\, h_{70}^{-1}$ [c]
Ω_Z (hot gas, $Z = .006$)	$5.0 \times 10^{-6}\, h_{70}^{-1.3}$ [b]	$1.0 \times 10^{-4}\, h_{70}^{-1.5}$ [c]
		$1.2 \times 10^{-4}\, h_{70}^{-1.3}$ [e]
Yield ρ_Z/ρ_*	$.022\, h_{70}^{-0.2}$ [b]	$.051\, h_{70}^{-0.3}$ [c]
Damped Ly-α	$.0015\, h_{70}^{-1}$ [c,f]	
Ly-α forest	$.04\, h_{70}^{-1.5}$ [c,g]	
Gals + DM halos (M/L = $210\, h_{70}$)	0.25 [c,h]	
All matter ($f_{\rm B} = .056\, h^{-1.5}$)	$0.37\, h_{70}^{-0.5}$ [c,i]	

[a] Burles & Tytler 1998
[b] Persic & Salucci 1992
[c] Fukugita, Hogan & Peebles 1998
[d] Edmunds & Phillipps 1997
[e] Mushotzky & Loewenstein 1997
[f] Storrie-Lombardi, Irwin & MacMahon 1996
[g] Rauch et al. 1998
[h] Bahcall, Lubin & Dorman 1995
[i] White & Fabian 1995

drop-out galaxies by Pettini et al. (1997). Similar numbers up to $z = 1$ result from a UV-selected galaxy red-shift survey by Treyer et al. (1998).

The resulting model is one among many discussed by Blain et al. (1998), who refer to it as Peak-G (peaking at $z \simeq 2$). According to their computations, it ends up with a present-day stellar density parameter $\Omega_* h_{50}^2 = 0.01$ or $\Omega_* h_{70}^2 = 0.005$, slightly higher than the figure of 0.0035 in the Table, but not disastrously so. With a typical heavy-element yield of 0.02, this gives $\Omega_Z h_{70}^2 \simeq 10^{-4}$, which would account for 1/2 of the Ω_Z given in the Table, including diffuse intergalactic gas. There is thus a choice between (a) assuming somewhat lower abundances in the diffuse intergalactic gas, which is quite reasonable in view of the existence of relatively young dwarf galaxies with low metallicity; (b) assuming a higher stellar density than suggested in the Table (LSB galaxies, intergalactic stars?); and (c) assuming a larger yield, e.g. from a top-heavy IMF. This higher yield is probably needed anyway for elliptical galaxies in clusters, but the new evidence suggests that it could be more universal.

Far infra-red and submm observations, notably with the SCUBA detector on JCMT, together with new COBE data on the submm diffuse background, are very important as probes of high red-shift star formation in galaxies hidden by dust because of the negative K-corrections. These have so far given rise to widely divergent interpretations, however. Lilly et al. (1998) find from their studies of CFRS fields that about 1/2 of star formation and metal production occurs in obscured souces with a similar red-shift distribution to the one derived from optical data, which agrees with the peaking model discussed above. Blain et al., on the other hand, present 'anvil' models based on the submm observations which imply substantially higher star formation rates, at least for $z > 1$, resulting in predicted present-day star densities that are nearly an order of magnitude higher ($\Omega_* \simeq 0.03 h_{70}^{-2} \simeq \Omega_{\rm bbns}$!) and in significant disagreement with counts of observable stars. Blain et al. discuss possible reasons for this disagreement, which include a contribution from AGNs and a top-heavy IMF. In the latter case, the cosmic metal density is more closely related to the measured luminosity density than is either of them to the total SFR by mass, so that the predicted metal density at the present time provides a more specific test of the models. The submm-based models discussed by Blain et al. typically give $\Omega_Z h_{70}^2 \simeq 5 \times 10^{-4}$, which is 2.5 times too much for the estimates in the Table. Putting this another way, this figure would require all baryonic matter (most of which is presumably diffuse gas) to have a mean abundance of 0.7 solar, and that does not look very likely. It is not clear whether there could be a sufficiently large AGN contribution to fill the gap.

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