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METALS IN THE UNIVERSE AND DIFFUSE BACKGROUND RADIATION

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Abstract. An attempt is made to guess the overall cosmic abundance of "metals" and the contribution made by the energy released in their production to the total intensity of extragalactic background light (EBL). With a comparable or somewhat larger amount coming from white dwarfs, and a probably quite modest contribution from AGNs, one can fairly easily account for the lower end of the range of existing estimates for the total EBL intensity (50 to 60 nwt m^{-2} $sterad^{-1}$), but it seems more difficult should some higher estimates (90 to 100 in the same units) prove to be correct.

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1. INTRODUCTION

There are certain more or less well or badly determined integral constraints on the past history of star formation in the universe. These include

- Cosmic baryon density Ω_B, now fairly well determined both from primordial deuterium (O'Meara et al 2001) and from the CMB fluctuation spectrum (e.g. Turner 2001).
- Cosmic mass density of stars Ω_*, rather less well determined as it involves a combination of luminosity-density measurements with an IMF and evolutionary population synthesis models.
- Extragalactic background light (EBL) intensity, now known within a factor of 2 or so from COBE (FIRAS and DIRBE) and galaxy counts in the optical and near IR (e.g. Gispert, Lagache & Puget 2000).
- Cosmic abundance of "metals", Ω_Z, due to the heavy-element content of stars, the interstellar medium and the intergalactic medium, a quantity that is very poorly known and largely a matter of guesswork. In this talk I shall nevertheless make some guesses, so that at least one can see more easily how things relate to one another. In particular, the metallicity Z_{IGM} of the intergalactic medium has tended to be either neglected or underestimated in models of the past star formation rate, and it is of interest to ask about its relation with EBL.

2. THE COSMIC INVENTORY

A useful starting point is the cosmic baryon budget drawn up by Fukugita, Hogan & Peebles (1998), hereinafter FHP, shown in

the accompanying table. The total from Big Bang nucleosynthesis (BBNS) adopted here agrees quite well with the amount of intergalactic gas at a red-shift of 2 to 3 deduced from the Lyman forest, but exceeds the present-day stellar (plus cold gas) density by an order of magnitude. (1)

Table 1. Inventory of cosmic baryons and "metals"
Densities expressed as Ω, in units of $\rho_{crit} = 1.54 \times 10^{11}\ h_{70}^{2}\ M_{\odot}\ \mathrm{Mpc}^{-3}$

All baryons from BBNS ($D/H = 3 \times 10^{-5}$ [a])	$0.04\ h_{70}^{-2}$
Stars in spheroids	$0.0026\ h_{70}^{-1}$ [b]
Stars in disks	$0.0009\ h_{70}^{-1}$ [b]
Total stars	$0.0035\ h_{70}^{-1}$ [b]
Cluster hot gas	$0.0026\ h_{70}^{-1.5}$ [b]
Group/field hot gas	$0.014\ h_{70}^{-1.5}$ [b] ($0.004 h_{75}^{-1}$ in O VI systems [c])
Total stars + gas	$0.021\ h_{70}^{-1.5}$ [b]
Machos + LSB gals	?? [b]
Ω_Z (stars, $Z = 0.02$ [d])	$7 \times 10^{-5}\ h_{70}^{-1}$
Ω_Z (hot gas, $Z = .006$)	$1.0 \times 10^{-4}\ h_{70}^{-1.5}$ [b]
	$1.2 \times 10^{-4}\ h_{70}^{-1.3}$ [e]
Yield ρ_Z / ρ_*	$0.051\ h_{70}^{-0.3}$ ($\backsimeq 3 Z_{\odot}$!)
Damped Ly-α (H I)	$0.0015\ h_{70}^{-1}$ [b, f]
Ly-α forest (H^+)	$0.04\ h_{70}^{-2}$ [b, g]
Gals + DM halos ($M/L = 210\ h_{70}$)	0.25 [b, h]
All matter ($f_B = .056\ h^{-1.5}$)	$0.37\ h_{70}^{-0.5}$ [b, i]

[a] O'Meara et al 200l; but see also Pettini & Bowen 2001; [b] Fukugita, Hogan & Peebles 1998; [c] Tripp, Savage & Jenkins 2000; [d] Edmunds & Phillipps 1997; [e] Mushotzky & Loewenstein 1997; [f] Storrie-Lombardi, Irwin & MacMahon 1996; [g] Rauch, Miralda-Escudé, Sargent et al 1998; [h] Bahcall, Lubin & Dorman 1995; [i] White & Fabian 1995.

FHP pointed out that a dominant and uncertain contribution to the baryon budget comes from intergalactic ionized gas, not readily detectable because of its high temperature and low density. The number which I quote is based on the assumption that the spheroid star-to-gravitational mass ratio and baryon fraction are the same in clusters and the field, an assumption that had also been used previously by Mushotzky & Loewenstein (1997). The resulting total star-plus-gas density is within spitting distance of Ω_B from BBNS, but leaves a significant-looking shortfall which may be made up by some combination of MACHOs and low surface-brightness galaxies; it is not clear that a significant contribution from the latter has been ruled out (cf O'Neil 2000).

[1] The stellar density taken here from FHP is based on B-luminosity density estimates and might be revised upwards by 50 per cent in light of SDSS commissioning data (Blanton et al 2000) or downwards by 20 per cent in light of 2dF red-shifts plus 2MASS K-magnitudes (Cole et al 2000); in either case we are following FHP in assuming the IMF by Gould, Bahcall & Flynn (1996), which has 0.7 times the M / L_V ratio for old stellar populations compared to a Salpeter function with lower cutoff at 0.15 $M_\odot$. Back.

3. GLOBAL ABUNDANCES AND YIELDS

We now have the tricky task of estimating the total heavy-element content of the universe. Considering stars alone, it seems reasonable to adopt solar Z as an average, but the total may be dominated by the still unseen intergalactic gas, which Mushotzky & Loewenstein argue to have the same composition as the hotter, denser gas seen in clusters of galaxies, i.e. about 1/3 solar. (2) It could be the case, though, that the metallicity of the IGM is substantially lower in light of the metallicity-density relation predicted by Cen & Ostriker (1999) and in that of the low metallicities found in low red-shift Ly-α clouds by Shull et al (1998). Against this, we have neglected any metals contained in LSB galaxies or whatever makes up the shortfall between Ω_{IGM} and Ω_B, so we are being conservative in our estimate of Ω_Z.

The mass of heavy elements in the universe is related to that of stars through the yield, defined as the mass of "metals" synthesised and ejected by a generation of stars divided by the mass left in form of long-lived stars or compact remnants (Searle & Sargent 1972). The yield may be predicted by a combination of an IMF with models of stellar yields as a function of mass, or deduced empirically by applying a galactic chemical evolution (GCE) model to a particular region like the solar neighbourhood and comparing with abundance data. E.g. Fig 1 shows an abundance distribution function for the solar neighbourhood plotted in a form where in generic GCE models the maximum of the curve gives the yield directly, and it is a bit below $Z_\odot$. Similar values are predicted theoretically using fairly steep IMFs like that of Scalo (1986). In Table 1, on the other hand, if we divide the mass of metals by the mass of stars, we get a substantially higher value, corresponding to a more top-heavy IMF.

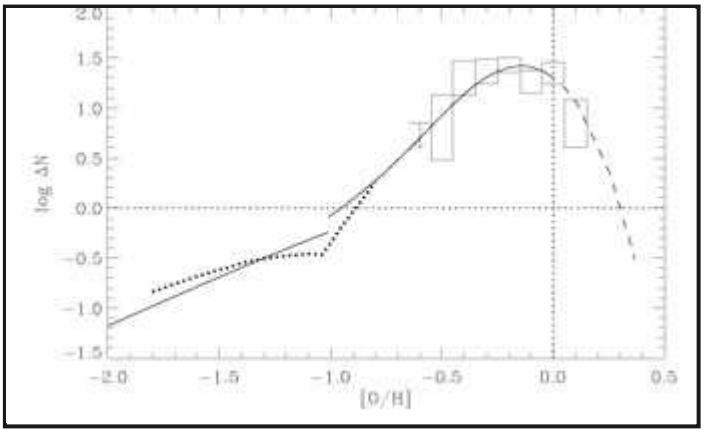

Figure 1. Oxygen abundance distribution function in the solar neighbourhood, after Pagel & Tautvaisiene (1995).

There are two other indications for a top-heavy IMF, one local and one in clusters of galaxies themselves. The local one is an investigation by Scalo (1998) of open clusters in the Milky Way and the LMC, where he plots the IMF slopes found as a function of stellar mass. The scatter is large, but on average he finds a Salpeter slope above $0.7M_\odot$ and a virtually flat relation (in the sense dN / $d\log m \simeq 0$) below, which could quite easily account for the sort of yield found in Table 1. The other indication is just the converse of the argument we have already used in guessing the abundance in the IGM: the mass of iron in the intra-cluster gas is found (Arnaud et al 1992) to be

$$M_{Fe}/L_V = 0.018 M_\odot/L_\odot, \quad (1)$$

where L_V is the luminosity of E and S0 galaxies in the cluster. As has been pointed out by Renzini et al (1993) and Pagel (1997), given a mass:light ratio less than 10, we then have

$$M_{\rm Fe}({\rm gas})/M_* \geq 1.8\times10^{-3} \;=\; 1.6Z_\odot({\rm Fe}) \quad (2)$$

$$M_{\rm Fe}(*)/M_* \;\simeq\; Z_\odot({\rm Fe}) \quad (3)$$

$${\rm Yield} = M_{\rm Fe}({\rm total})/M_* \;\geq\; 2.6Z_\odot. \quad (4)$$

The argument is very simple; the issue is just whether such high yields are universal or confined to elliptical galaxies in clusters.

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[2] This refers to iron abundance, the relation of which to the more energetically relevant quantity *Z* is open to some doubt. Papers given at this conference indicate an SNIa-type mixture in the immediate surroundings of cD galaxies with maybe a more SNII-like mixture in the intra-cluster medium in general; for simplicity I assume the mixture to be solar. Back.

4. COSMIC STAR FORMATION AND CHEMICAL EVOLUTION: GCE vs HDF

The deduction of past star formation rates from rest-frame UV radiation in the Hubble and other deep fields as a function of red-shift is tied to "metal" production through the Lilly-Cowie theorem (Lilly & Cowie 1987):

$$\rho_{\rm L}(z) \;=\; \nu_{\rm H}\rho_{\nu\ {\rm UV}}(z) = \frac{1}{\epsilon}L_{\rm FIR}(z) \quad (5)$$

$$\;=\; 0.007c^2\dot\rho_{\rm Z}(z)(1+a)\beta^{-1} \quad (6)$$

$$\;=\; 0.018c^2\dot\rho_{\rm Z}({\rm conv.}), \quad (7)$$

where $(1 + a) \simeq 2.6$ is a correction factor to allow for production of helium as well as conventional metals and β (probably between about 1/2 and 1) allows for nucleosynthesis products falling back into black-hole remnants from the higher-mass stars. ϵ is the fraction of total energy output absorbed and re-radiated by dust and $\nu_{\rm H}$ is the frequency at the Lyman limit (assuming a flat spectrum at lower frequencies). The advantage of this formulation is that the relationship is fairly insensitive to details of the IMF.

Eq (7) is the same as eq (13) of Madau et al (1996), so I refer to the metal-growth rate derived in this way as $\dot\rho_{\rm Z}$(conventional).

Assuming a Salpeter IMF from 0.1 to 100 $M_\odot$ with all stars above 10 $M_\odot$ expelling their synthetic products in SN explosions, one then derives a conventional SFR density through multiplication with the magic number 42:

$$\dot\rho_*({\rm conv.}) = 42\dot\rho_{\rm Z}({\rm conv.}) = 42\rho_{\rm L}/.018{\rm c}^2. \quad (8)$$

In general, we shall have

$$\dot\rho_*({\rm true}) = \gamma\dot\rho_*({\rm conv.}), \quad (9)$$

where γ is some factor. E.g., for the IMF adopted by FHP, γ = 0.67, whereas for the Kroupa-Scalo one (Kroupa et al 1993) γ = 2.5.

Finally, the present stellar density is derived by integrating over the past SFR and allowing for stellar mass loss in the meantime, and the metal density is related to this through the yield, *p*:

$$\rho_*(0,{\rm true}) \;=\; \alpha\gamma\int\dot\rho_*({\rm conv.}){\rm dt} \quad (10)$$

$$\rho_{\rm Z}(0,{\rm true}) \;=\; p\rho_*(0,{\rm true}) = \left(\frac{2.6}{1+a}\right)\frac{\beta}{42}\int\dot\rho_*({\rm conv.}){\rm dt} \quad (11)$$

(where α is the lockup fraction), whence (if a = 1.6)

$$p = \frac{\beta}{42\alpha\gamma}, \quad (12)$$

which can be compared with $Z_\odot \simeq 1/60$. It was pointed out by Madau et al (1996) that the Salpeter slope gives a better fit to the present-day stellar density than one gets from the steeper one - a result that is virtually independent of the low-mass cutoff if one assumes a power-law IMF.

Eq (8), duly corrected for absorption, forms the basis for numerous discussions of the cosmic past star-formation rate or "Madau plot". Among the more plausible ones are those given by Pettini (1999) shown in Fig 2 and by Rowan-Robinson (2000), which leads to similar results and is shown to explain the far IR data. Taking γ = 0.62 (corresponding to a Salpeter IMF that is flat below $0.7M_\odot$) rather than Pettini's value of 0.4 (for an IMF truncated at $1M_\odot$), and α = 0.7, we get the data in the following table.

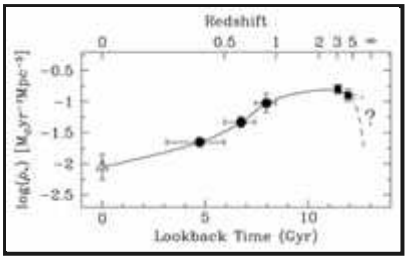

Figure 2. Global comoving star formation rate density vs. lookback time compiled from wide-angle ground-based surveys (Steidel et al. 1999 and references therein) assuming E-de S cosmology with h = 0.5, after Pettini (1999) . Courtesy Max Pettini.

Table 2 indicates that the known stars are roughly accounted for by the history shown in Fig 2 (or by Rowan-Robinson) and the metals also if β is close to unity, i.e. the full range of stellar masses expel their nucleosynthesis products. At the very least, β has to be 1/2, to account for metals in stars alone. The other point arising from the table, made by Pettini, is that at a red-shift of 2.5, 1/4 of the stars and metals have already been formed, but we do not know where the resulting metals reside.

Table 2. Inventory of stars and metals at $z = 0$ and $z = 2.5$

	$z = 0$	$z = 2.5$
$\rho_* = \alpha\gamma\int\dot{\rho}_*(conv.)\,dt$	$3.6 \times 10^8\ M_\odot\ Mpc^{-3}$	$9 \times 10^7\ M_\odot\ Mpc^{-3}$
$\Omega_* = \rho_* / 1.54 \times 10^{11}\ h_{70}^{\ 2}$	$.0024 h_{70}^{-2}$	$6 \times 10^{-4}\ h_{70}^{-2}$
Ω_*(FHP 98)	$.0035 h_{70}^{-1}$	
$\rho_Z = p\,\rho_* = \beta\rho_* / (42\alpha\gamma)$	$2.0 \times 10^7\ \beta\ M_\odot\ Mpc^{-3}$	$5 \times 10^6\ \beta\ M_\odot$ Mpc^{-3}
Ω_Z (predicted)	$1.3 \times 10^{-4}\ \beta\ h_{70}^{-2}$	$3.2 \times 10^{-5}\ \beta\ h_{70}^{-2}$
Ω_Z (stars, $Z = Z_\odot$)	$7 \times 10^{-5}\ h_{70}^{-1}$	
Ω_Z (hot gas, $Z = 0.3Z_\odot$)	$1.0 \times 10^{-4} h_{70}^{-1.5}$	
	-> $0.5 \le \beta \le 1.3$	
Ω_Z (DLA, $Z = 0.07Z_\odot$)		$2 \times 10^{-6}\ h_{70}^{-1}$
Ω_Z (Ly. forest, $Z = 0.003Z_\odot$)		$1 \times 10^{-6}\ h_{70}^{-2}$
Ω_Z (Ly. break gals, $Z = 0.3Z_\odot$)		?
Ω_Z (hot gas)		?

5. EXTRAGALACTIC BACKGROUND LIGHT

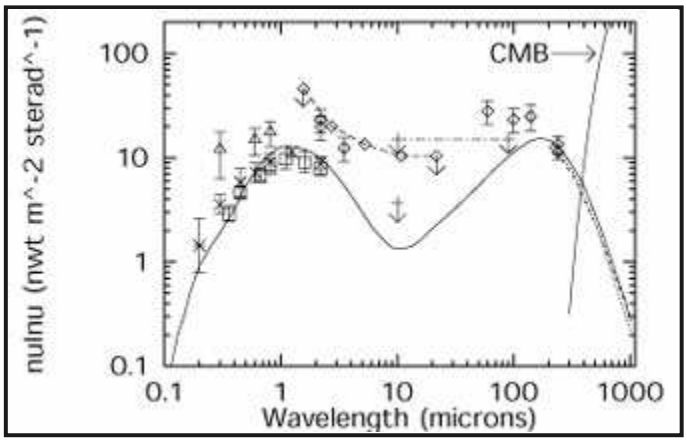

Figure 3. Spectrum of extragalactic background light, based on COBE data after Hauser 2001 (diamonds with error bars, dotted and short-dash curves), Madau & Pozzetti 2000 (squares), Totani et al 2001 (crosses), Bernstein, Freedman & Madore 2001 (triangles) and Armand et al 1994 (asterisk). The broken-line curve (Biller et al 1998) and horizontal dash-dot line (Hauser 2001) show upper limits based on lack of attenuation of high-energy γ-rays from AGNs and the solid curve is from the model by Pei, Fall & Hauser (1999). The arrow showing an upper limit at 10μm is from unpublished thesis work by A. Barrau, cited by Gispard, Lagache & Puget (2000).

Fig 3 shows the spectrum of extragalactic background light (EBL) with the model fit by Pei, Fall & Hauser (1999). Gispert, Lagache & Puget (2000) have estimated the total EBL $\int I_\nu\, d\nu$ based on observation to lie within the following limits:

$\lambda \leq 6\mu$m:	20 to 40	nwt	m^{-2}	$sterad^{-1}$
$\lambda > 6\mu$m:	40 to 50	"	"	"
Total:	60 to 90	"	"	"

(The total from the model of Pei, Fall & Hauser (1999) is 55 in these units.)

We use the estimates of stellar and metal densities in Tables 1 and 2 together with eq (7) and an assumption about the mean red-shift of metal formation to derive the EBL contributions from:

- Metals in stars; $Z = Z_{\odot} = 0.02$:

$$\rho_Z(*) = 7 \times 10^{-34} h_{70} \ \mathrm{gm\ cm^{-3}} \quad (13)$$

$$I = \frac{0.018 c^3 \rho_Z \beta^{-1}}{4\pi\langle 1+z\rangle} = \langle \frac{3}{1+z} \rangle \beta^{-1} \rho_Z \times 1.3 \times 10^{34} \quad (14)$$

$$\simeq 9\beta^{-1} h_{70} \ \mathrm{nwt\ m^{-2}\, sterad^{-1}}. \quad (15)$$

- Metals in diffuse gas/dark baryons, $Z \backsimeq 0.007$:

$$\rho_Z = \Omega_Z \rho_{\mathrm{crit}} = 1.2 \times 10^{-33} {h_{70}}^{0.7} \beta \ \mathrm{gm\ cm^{-3}}. \quad (16)$$

$$I = 16\, h_{70}^{0.7} \ \mathrm{nwt\ m^{-2}\, sterad^{-1}}. \quad (17)$$

- Helium, carbon etc in white dwarfs and red-giant interiors.

  Here we use eq (6) without the $(1 + a)$, since most of the nuclear energy is already released on reaching this stage. Assuming most stars to belong to an old population so that

$$\rho_{\mathrm{WD}} \simeq 0.1\rho_* = 3.5 \times 10^{33} h_{70} \ \mathrm{gm\ cm^{-3}}, \quad (18)$$

$$I = \frac{0.007 c^3 \rho_{\mathrm{WD}}}{4\pi\langle 1+z\rangle} = \langle \frac{3}{1+z} \rangle 5 \times 10^{33} \rho_{\mathrm{WD}}. \quad (19)$$

$$= 18\, h_{70} \ \mathrm{nwt\ m^{-2}\, sterad^{-1}}. \quad (20)$$

- AGN contribution

  Madau & Pozzetti (2000) and Brusa, Comastri & Vignali (2001) have made estimates of the AGN contribution to EBL based on the the abundance of massive black holes and that of obscured hard X-ray sources, respectively. They agree that the contribution is quite small, of order 5 nwt m^{-2} $sterad^{-1}$.

The upshot is that these readily identifiable contributions add up to 48 nwt m^{-2} $sterad^{-1}$, well within range (given the obvious uncertainties in mean z and other parameters) of the lower estimate given at the beginning of this section. It is interesting to note that white dwarfs and intergalactic metals come out as the major contributors, either one predominating over metallicity in known stars. To reach the higher estimate may involve some more stretching of the parameters.

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