The missing metals problem. I. How many metals are in submm galaxies?

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ABSTRACT
At redshifts larger than 2, a large fraction (80%) of the metals are apparently yet undetected. We use a sample of sub-mm selected galaxies (SMGs) with molecular gas and dynamical mass measurements from the literature to put constraints on the contribution of such galaxies to the total metal budget. Compared to Lyman break galaxies (LBGs), for example, SMGs are rarer (by a factor of 10 or more), but contain much more gas and are more metal rich. For SMGs brighter than 3 mJy, we estimate that SMGs contain only ≲9% of the metals when we combine the observed dynamical masses ($<M_{\text{dyn}}>$~few×$10^{11}$ M$_{\odot}$), number density ($n \approx 10^{-4}$ Mpc$^{-3}$), observed gas metallicity ($Z \approx 1-2Z_{\odot}$), and observed gas fractions ($f_{\text{gas}} \approx 40\%$) assuming a molecular to neutral hydrogen ratio of 1. Including SMGs fainter than 3 mJy, we estimate that SMGs contain about ≲15% of the metals, where our incompleteness correction is estimated from the dust mass function. Our results are strong upper limits given that high gas fractions and high overall metallicity are mutually exclusive. In summary, SMGs make a significant contribution to the metal budget (≲15%) but not sufficient to solve the ‘missing metals problem’. A consequence of our results is that SMGs can only add ≈ 3.5% to Ω$_{\text{DLA}}$, and can not be the source of a significant population of dusty DLAs.

Key words: cosmology: observations — galaxies: high-redshift — galaxies: evolution

1 INTRODUCTION
A direct consequence of star-formation and, in particular, of the star-formation history (SFH) (Lilly et al. 1996; Madau et al. 1996; Giavalisco et al. 2004; Hopkins 2004, and others) is the production of heavy elements, known as metals. Indeed, for a given initial mass function (IMF), the total expected amount of metals $p_{Z,\text{expected}}$ formed by a given time $t$ is simply the integral of the star formation density (SFD) $\dot{\rho}_s(t)$ times $<p_z>$, where $<p_z>$ is the mean stellar yield (Songaila et al. 1990; Madau et al. 1996): $p_{Z,\text{expected}} = <p_z> \int_0^t dt \dot{\rho}_s(t)$ . Using a Salpeter IMF and the type II stellar yields (for solar metallicity) $p_s(m)$ from Woosley & Weaver (1995), Madau et al. (1996) found that $<p_z> = \frac{1}{12}$ or 2.4%. Using the SFH parameterized (in a LCDM cosmology) either as in Cole et al. (2001) or by a constant star formation rate (SFR) beyond $z = 2$, we find that the total co-moving metal density is $p_{Z,\text{expected}} \approx 4.0 \times 10^{-6}$ M$_{\odot}$ Mpc$^{-3}$, after integrating the SFH over the redshift $z$ range from 4 to 2. This is about 25% of the $z = 0$ metals.

But at redshifts $z \sim 3$, our knowledge of the cosmic metal budget is still highly incomplete. Indeed, only a small fraction (20%) of the budget is actually seen when one adds the contribution of the Ly$\alpha$ forest ($N_{\text{H}1} = 10^{13-17}$ cm$^{-2}$), damped Ly$\alpha$ absorbers (DLAs) ($N_{\text{H}1} > 10^{20.3}$ cm$^{-2}$), and galaxies such as Lyman break galaxies (LBGs) (Pettini et al. 1994; Pagel 2002; Pettini 2003; Wolfe et al. 2003).

To account for the remaining 80% of Eq. (1) or the “missing metals,” there are two likely possibilities, as pointed out by Pettini (2003). Either they are in a galaxy population not yet accounted for in the budget of Pettini (2003), or they are in a hot phase which is currently difficult to detect. In Bouché et al. (2005, hereafter paper III), we discuss further the missing metal problem and the latter alternative. In this paper and in Bouché et al. (2004) (paper II), we discuss the former. In paper II, we discuss the contribution of both the $z \sim 2.2$ UV selected galaxies, “BX” (Steidel et al. 2004),...
and near-IR selected galaxies (e.g. Franx et al. 2003). In this paper, we discuss submm selected galaxies (SMGs). SMGs are potentially good candidates for hiding metals given that they are both gas and metal rich. For instance, Dunne et al. (2003) hereafter D03) explored the contribution of SMGs to the metal budget using the dust mass function (DMF) of high redshift (z ≃ 2–3) submm galaxies constructed from deep blank field SCUBA surveys. From the DMF, D03 inferred, using chemical models, the co-moving density of metals and baryons associated with the ISM of submm galaxies (SMGs). They concluded that all of the remaining metals (80%) are in the ISM of SMGs and that the mere existence of SMGs is enough to close the metal budget.

Recently, the gas content and metallicity of SMGs have been directly estimated or constrained in a few cases (Genzel et al. 2003; Neri et al. 2004; Greve et al. 2003; Tecza et al. 2004; Swinbank et al. 2004). These measurements now allow us to put more direct limits on the contribution of SMGs to the cosmic metal budget. In this paper, we will show that indeed SMGs contribute significantly to the metal budget, but their contribution is ≲ 10% and, even optimistically, cannot be more than ≲ 20%. In paper II, we show that z ∼ 2.2 galaxies contribute significantly to the metal budget, up to 15–20%. Thus, combining all the known galaxy populations at z > 2, there is about 50% of the metal budget that has been accounted for. In paper III, we will explore whether the remaining metals have been expelled from small galaxies into the IGM (i.e. into a hot non-detectable phase).

In section 3 we compare our results to those of D03 in a ΛCDM cosmology. In the remainder of this paper, we used H₀ = 70 h70 km s⁻¹ Mpc⁻¹, Ω₅₀ = 0.3 and Ω₇₀ = 0.7.

2 HOW MANY METALS IN SMGS?

In this section, we use the recent observations of gas content (H₂) and dynamical masses of 7 SMGs (Genzel et al. 2003; Tecza et al. 2004; Greve et al. 2005) to put constraints on the contribution of the SMGs to the metal budget. We first summarize the observations.

2.1 Properties of SMGs

Recent measurement of the dynamical and gas masses of currently known a dozen z ∼ 2.5 submm sources have been made from CO line emission (some resolved) using both OVRO and the IRAM Plateau de Bure interferometer (e.g. Greve et al. 1999; Genzel et al. 2003; Neri et al. 2003, Greve et al. 2002). They have redshifts spanning 1.0–3.3, bolometric luminosities Lbol ∼ 10^{11} L⊙, and have large molecular mass Mgas ∼ 2 × 10^{10} M⊙ and dynamical masses Mdyn ∼ 0.5 × 10^{11} M⊙. From the compilation by Greve et al. (2003), we find that out of the dozen SMG with CO detections, 7 meet the following two criteria: (i) z > 2 and (ii) an intrinsic (de-lensed) S850 flux > 3 mJy. The redshift cut-off is natural given the aims of this paper, and the flux threshold corresponds to the one used by D03 (see section 3). We note that SMMJ14011+152, with an intrinsic S850 flux of 2.9 mJy, could be included in our sample if the magnification is slightly smaller. Our mean values do not change significantly if one includes SMMJ14011+1152.

The properties of these sources are listed in Table 1. One can see from the table that, on average, ∼ 20% (and up to 50% for J014111) of the dynamical mass of SMGs is made of molecular (H₂) gas. Excluding SMMJ014111, the averaged gas mass, velocity width and dynamical masses are Mgas = 4.0 × 10^{10} M⊙, FWHM ≃ 700 km s⁻¹, Mdyn ≃ 2.1 × 10^{11} M⊙, respectively (see the bottom of Table 1).

Very few SMGs have had their gas phase metallicities measured or constrained. In the case of J14011, Tecza et al. (2004) used the near-infrared integral field spectrometer, SPIFFI (now SINFONI) on the ESO-VLT to measure the nebular emission line ratios of J14011. Using the classical optical diagnostic ratio, R₂₃ = [OII] / [OIII], Tecza et al. (2004) inferred a metallicity of +0.27 ± 0.15 dex (Z ∼ 1.9 ± 0.5 Z⊙). Swinbank et al. (2004) used long-slit spectroscopy to measure the [NII] / Hα ratio to infer metallicities using the calibration of Pettini & Pagel (2004). The median of their sample is slightly below solar. Broadly speaking, SMGs have metallicities close to solar and up to ∼ 2 Z⊙.

In order to estimate the total metal contribution of submm galaxies, it is necessary to estimate the true number density of SMGs corrected for the “duty cycle,” the fraction of cosmic time over which submm galaxies are observed. Genzel et al. (2003) estimated the raw co-moving density n of SMGs to be ∼ 10⁻⁵ h₇₀ Mpc⁻³ from the observed area covered by the SCLS and the estimated redshift range 1 < z < 5. The duty cycle of SMGs can be constrained directly from the gas depletion time scale.

Genzel et al. (2003) showed that such a luminous galaxy (with a SFR ∼ 500 M⊙ yr⁻¹) would use up its gas in approximately 4 × 10⁶ yr and make ∼ 2 × 10¹¹ M⊙ of stars. Tecza et al. (2004) estimated an age for J14011+0252 of ≥ 200 Myrs from the strength of its Balmer break. Using a SMG time scale of 4 × 10⁸ yr, and assuming that SMGs are evenly distributed over 1 < z < 5 (≃ 4.5 Gyr), this would imply that SMGs are ‘on’ 10% of the time or have a duty cycle r of 0.1. Thus, the co-moving density is at least n ≥ 1.3 × 10⁻⁴ h₀³ Mpc⁻³ (n ∼ 1.3 Mpc⁻³).

Independently, Chapman et al. (2003) estimated a raw co-moving density n of z ∼ 2.5 SMGs above L₁₀₁₀ = 10^{12.5} M⊙ of n ≃ 10⁻⁵ h₀³ Mpc⁻³ using measured redshifts of radio identified SMGs. Chapman et al. (2003) modeled the redshift distribution of SMGs with a Gaussian distribution of width σ_z ∼ 1.3 (covering ∼ 1 Gyr), and assumed a time scale of 10⁷ yr, yielding a similar duty cycle r of 0.1. Thus, the true co-moving space density estimated by two groups, n = 1.3 × 10⁻⁴ h₀³ Mpc⁻³.

Another way to estimate the duty cycle of SMGs is to use their clustering strength (as pointed out by Chapman et al. 2003) and Fig. 1. Both panels show the co-moving number density of sources vs. redshift. In the left panel, lines of constant halo mass log M_h = 14, 13, 11, 10, 9 are shown. In the right panel, lines of constant clustering amplitude r₀ = 15, 10, 8, 6, 4, 2 Mpc (from bottom to top) are shown. Blain et al. 2004 estimated the SMG auto-correlation length r₀ = 7 h⁻¹ Mpc (represented by the star), from which one would infer a halo co-moving abundance density of n ∼ 1 × 10⁻⁴ h₀³ Mpc⁻³.
The metals in SMGs

Table 1. Gas masses and dynamical masses of SMGs with $z > 2$ and an intrinsic flux $S_{850}$ greater than 3 mJy. The average quantities are shown. References: (1) Genzel et al. (2003), (2) Neri et al. (2003), (3) Greve et al. (2005), (4) Tecza et al. (2004), (5) Swinbank et al. (2004).

| Name                  | $S_{850}$ a (mJy) | $z_{CO}$ | $M_{gas}$ b $\times 10^{10} M_\odot$ | FWHM c km s$^{-1}$ | $M_{dyn}$ d $\times 10^{10} M_\odot$ | Refs | [O/H] e | Refs |
|-----------------------|-------------------|----------|--------------------------------------|-------------------|--------------------------------------|------|---------|------|
| SMMJ02399−0136        | 9.6               | 2.8076   | 6.0                                  | 1100              | 60                                   | 1    | 3       | 6/9  |
| SMMJ09431+4700        | 8.8               | 3.3460   | 2.0                                  | 420               | 5/7                                  | 2,3  | 3       | 6/9  |
| SMMJ131201+4242       | 6.2               | 3.308    | 4.2                                  | 530               | 12                                   | 3    | 3       | 6/9  |
| (SMMJ14011+1152 f)    | 2.9               | 2.5652   | 3.4                                  | 190               | 6                                    | 1,3  | 0.3     | 4    |
| SMMJ16358+4057        | 8.2               | 2.3853   | 5.6                                  | 840               | 9/35                                 | 2,3  | 3       | 6/9  |
| SMMJ16366+4105        | 10.7              | 2.450    | 4.6                                  | 870               | 9/37                                 | 2,3  | 0.1     | 5    |
| SMMJ16371+4053        | 10.5              | 2.380    | 2.4                                  | 830               | 34                                   | 3    | -0.1    | 5    |
| SMMJ22174+0015        | 6.3               | 3.099    | 3                                    | 780               | 28                                   | 3    | 3       | 6/9  |

average g: 8.6 $\pm$ 1.55 767±226 21±21/30±17

a Intrinsic submm fluxes.
b Molecular gas masses from CO line emission.
c Full width at half maximum of the CO line.
d Dynamical masses for the inclination $i = 45$ and using $h_{70} = 1$.
e [O/H] metallicities using (O/H)$_\odot$ from Asplund et al. (2004).
f The amplification of this source was revised from 2.5 to $\sim 5$ (Smail & et al. 2005) moving it just below our threshold of 3 mJy.
g Excluding SMM14011+1152.

Figure 1. Left: Co-moving number density of sources vs. redshift. Lines of constant halo mass are shown by the contours for $\log M_h = 14$, 13, 11, 10, 9, from bottom to top. The filled square shows the observed number density of SMGs, $n \approx 1 \times 10^{-5} h^3$ Mpc$^{-3}$, with the uncertainty and redshift coverage represented by the dark shaded area. Right: Same as left, but the contours represent lines of constant clustering amplitude $r_0 = 15$, 10, 8, 6, 4, 2 Mpc (bottom to top). The correlation length of SMGs ($r_0 \approx 7$ h$^{-1}$ Mpc [Blain et al. 2004]) is shown by the star. The halo mass inferred from the clustering is $\approx 10^{12.5} M_\odot$. Given that the observed $n$ (left panel, solid square) is lower than the one inferred from the clustering (star) by a factor of $\sim 10$, the duty cycle of SMGs is about $\sim 0.1$. The number density of SMGs corrected for the duty cycle is shown by the light shaded area in both panels. Both panels were produced using the Press-Schechter formalism of Mo & White (2002).

$10^{-4} h_{70}^3$ Mpc$^{-3}$ (light shaded area). This is $\approx 10$ times larger than the observed number density ($n \sim 1 \times 10^{-5}$ Mpc$^{-3}$, dark shaded area). These two numbers can be reconciled if SMGs are short lived, with a “duty cycle” of the order of 0.1. Nonetheless, the several methods of estimating the duty cycle of SMGs agree to within a factor of a few.

2.2 Consequences of SMGs properties
From the observed properties of SMGs (summarized in Table I), in this section, we derive the co-moving baryonic density and co-moving metal densities in SMGs (summarized in Table II).

The dynamical masses of SMGs cover the range $2-3 \times 10^{11} h_{70}^{-3} M_\odot$ (Table I) and assuming that this mass is...
entirely baryonic, the co-moving baryonic density in submm galaxies is observed to be:

$$\rho_{b, \text{obs}} \sim 2.7 \times 10^2 \, h_{70}^2 \left(\frac{r}{0.1}\right)^{-1} \, M_\odot \, \text{Mpc}^{-3}. \quad (2)$$

The observed mean gas mass $$M_{\text{gas}}$$ of $$\sim 4.0 \times 10^9 \, M_\odot$$ corresponds to a gas fraction $$f_g = 20\%$$ and a gas (molecular) co-moving density of $$\rho_{\text{gas, SMG}} = 5.2 \times 10^6 \, h_{70}^2 M_\odot \, \text{Mpc}^{-3}$$.

Naturally, the ISM of the SMGs contains also an unknown amount of neutral gas (H$^1$). Since we do not know the neutral to molecular ratios, it is difficult to make a robust estimate of the total potential reservoir of gaseous material. In the local Universe, Kereš et al. (2003) have estimated the neutral to molecular ratios, it is difficult to make a robust estimate of the total potential reservoir of gaseous material.

3 THE DUST MASS FUNCTION AND ITS IMPLICATIONS

D03 took a very different approach. They used submm data from published deep blank field SCUBA surveys and constructed the dust mass function (DMF) of high redshift galaxies. From the DMF, they inferred, using chemical models, the co-moving density of metals and baryons associated with the ISM of galaxies. They assumed a dust temperature of $$\sim 25 \, K$$ from Dey et al. (1999). Because the dust mass is a strong function of the dust temperature, a lower (higher) dust temperature 20 K (30 K) will increase (decrease) their mass estimates by a factor of about two (D03).

D03 argued that most of the dust mass in SMGs would be a low temperature ($T_d \sim 20 \, K$) component. We note that the recent observations of Chapman et al. (2005) favor higher dust temperature ($T_d \sim 35 \, K$). D03 also used the dust mass opacity measured at 125$$\mu$$m and extrapolated it to submm wavelengths using a $$\lambda^{-\beta}$$ dependence with $$\beta = 2$$ (from their local survey Dunne & Eales 2001). We now discuss their results, which are summarized in Table 2.

3.1 DMF all

D03 find that the DMF function is well described by a Schechter function with the parameters $$M^*_d = 4.7 \times 10^7 M_\odot$$, $$\phi_d^* = 8.9 \times 10^{-4} \, \text{Mpc}^{-3}$$, and $$\alpha = -1.08$$ in a $$\Lambda = 0.7$$ cosmology. The integral of the DMF gives the co-moving density of dust

$$\rho_d = \Gamma(2+\alpha) M^*_d \phi_d^* = 4.39 \times 10^5 \, M_\odot \, \text{Mpc}^{-3} \, h_{75}^{-2}.$$  

From $$\rho_d$$, they assumed that 40% ($$\eta = 0.4$$) of the ISM metals are locked into dust grains, yielding a metal density:

$$\rho_{Z, \text{DMF}} = 1.1 \times 10^6 \, h_{70} \frac{4}{\eta} \, M_\odot \, \text{Mpc}^{-3},$$

i.e., about 27% of the cosmic metal budget. The apparent discrepancy between that number and the original conclusion of D03, namely that SMGs contain $$\geq 70\%$$ of the cosmic metal density, is due to the different cosmology assumed.

A strong lower limit comes from $$\eta = 1$$, i.e. assuming 100% of the metals are locked onto the submm emitting dust grains. In that case, at least 11% of the metals are in the ISM of SMGs. Note that (i) this does not include the metals in stars, and (ii) it will not depend on the chemical evolution models discussed below.

D03 used a “closed-box” chemical evolution model (Edmunds & Eales 1998) to convert the dust content into a total baryonic content. They find that SMGs contribute a baryonic co-moving density of about:

$$\rho_{b, \text{DMF}} \approx 7.2 \times 10^7 \, h_{70} \, M_\odot \, \text{Mpc}^{-3}.$$  

In these chemical evolution models, they have assumed that the submm sources are observed at their maximum dust mass, i.e., at the peak of the dust mass to baryonic mass ratio. Thus their baryonic mass density is a strong lower limit. This peak occurs at a gas fraction of roughly 50%.

1 D03 used a $$\Omega_M = 1$$ cosmology throughout their paper. In the remainder of this paper, we used their DMF in a $$\Omega_M = 0.3$$, $$\Lambda = 0.7$$ cosmology. This lowers their cosmic densities ($$\rho_{b, \text{DMF}} = 1.3 \times 10^8 \, h_{75} \, M_\odot \, \text{Mpc}^{-3}$$, $$\rho_{Z, \text{DMF}} = 1.9 \times 10^6 \, h_{75} \, M_\odot \, \text{Mpc}^{-3}$$) by a factor 1.7. The global factor between our cosmology and D03 is 1.8 including the change from $$h_{75}$$ to $$h_{70}$$. 

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Table 2. Baryons and metal cosmic densities in SMGs from this paper.

| Baryons            | \(\rho (M_\odot \, h_{70}^{-1} \, \text{Mpc}^{-3})\) | \(\rho / \rho_\odot\) | \(\rho / \rho_\odot\) (%) | Note | \(Z/Z_\odot\) | \(\rho_Z (M_\odot \, h_{70}^{-1} \, \text{Mpc}^{-3})\) | \(\rho_Z / \rho_\odot\) | \(\rho_Z / \rho_Z,\text{tot}\) (%) |
|-------------------|-----------------------------|------------------|-----------------------|------|------------|-----------------------------|------------------|-----------------------------|
| Stars < \(z < 4\) | 1.21 \times 10^8 h_{70}^{-2} | 0.000890 h_{70}^{-2} | 2.02 \int \text{SFR}^a | 1.25\(^b\) | 4.00 \times 10^6 | 2.94 \times 10^{-5} | 100 |

SMGs > 3 mJy:

- SMGs Baryons | 2.73 \times 10^7 h_{70}^{-2} | 0.000201 h_{70}^{-2} | 0.46 |
- SMGs ISM (H2) | 5.16 \times 10^6 h_{70}^{-2} | 0.00038 h_{70}^{-2} | 0.09 \(f_g = 19\%\) |
- \(>\) ISM (H2+HI) | 1.03 \times 10^7 h_{70}^{-2} | 0.000076 h_{70}^{-2} | 0.17 \(f_g = 38\%\) | 1.9 | 3.63 \times 10^5 | 2.67 \times 10^{-6} | 9.1 |

\(^a\)Cosmic stellar density calculated from the integrated SFH taking into account a recycled fraction of \(R = 0.28\). \(f_g\) is the gas fraction.

\(^b\)Averaged yield (= \(1/42 = 1.25 \, Z_\odot\)) for type II SN with \(m > 10 \, M_\odot\) [Madau et al. 1996].

Table 3. Results from the dust mass function (D03). Numbers in bold are taken from D03 and corrected for our cosmology.

| Baryons          | \(\rho (M_\odot \, h_{70}^{-1} \, \text{Mpc}^{-3})\) | \(\rho / \rho_\odot\) | \(\rho / \rho_\odot\) (%) | Note | \(Z/Z_\odot\) | \(\rho_Z (M_\odot \, h_{70}^{-1} \, \text{Mpc}^{-3})\) | \(\rho_Z / \rho_\odot\) | \(\rho_Z / \rho_Z,\text{tot}\) (%) |
|------------------|-----------------------------|------------------|-----------------------|------|------------|-----------------------------|------------------|-----------------------------|
| Stars < \(z < 4\) | 1.21 \times 10^8 h_{70}^{-2} | 0.000890 h_{70}^{-2} | 2.02 \int \text{SFR}^a | 1.25\(^b\) | 4.00 \times 10^6 | 2.94 \times 10^{-5} | 100 |

SMGs dust (DMF)

- 4.39 \times 10^5 h_{70}^{-1} | 0.000003 h_{70}^{-1} | 0.01 |
- ISM | 7.65 \times 10^7 h_{70}^{-1} | 0.00052 h_{70}^{-1} | 1.28 |
- Stars | 3.82 \times 10^7 h_{70}^{-1} | 0.00281 h_{70}^{-1} | 0.64 \(\eta = 0.4\) | 1.52 | 1.10 \times 10^6 | 8.07 \times 10^{-6} | 27.4 |
- ISM | 2.24 \times 10^7 h_{70}^{-1} | 0.00164 h_{70}^{-1} | 0.37 | 6.42 \times 10^5 | 4.72 \times 10^{-6} | 16.0 |
- Stars | 2.24 \times 10^7 h_{70}^{-1} | 0.00164 h_{70}^{-1} | 0.37 < \(>\) 0.33 | \(1.41 \times 10^5\) | 1.80 \times 10^{-6} | 3.5 |

\(^a\)Cosmic stellar density calculated from the integrated SFH taking into account a recycled fraction of \(R = 0.28\). \(\eta = 0.4\) is the fraction of the ISM metals that are assumed to be locked onto dust grains.

\(^b\)Averaged yield (= \(1/42 = 1.25 \, Z_\odot\)) for type II SN with \(m > 10 \, M_\odot\) [Madau et al. 1996].

3.2 DMF bright

In order to compare this prediction to the observed properties of SMGs discussed in section 2, one needs to compare the cosmic baryonic and metal densities of flux selected SMGs to the DMF with a similar flux limit. The D03 integrated the DMF down to \(S_{650} > 3\, \text{mJy}\), but quoted only the stellar mass density (\(\rho_{\text{star}} = 2.24 \times 10^7 \, h_{70}^2 \, M_\odot \, \text{Mpc}^{-3}\), half of the baryons) and stellar metal density (\(\rho_{Z,\text{star}} = 1.4 \times 10^7 \, h_{70}^2 \, M_\odot \, \text{Mpc}^{-3}\))^2. Thus, the cosmic baryon density for bright (with \(S_{650} > 3\, \text{mJy}\)) submm sources of (twice the stellar density):

\[ \rho_{b, \text{DMF,3mJy}} \approx 4.2 \times 10^7 \, h_{70}^2 \, M_\odot \, \text{Mpc}^{-3} \]  

i.e., \(\sim 0.6\) times the number quoted in Eq. 5 providing the completeness factor. We then scale the total metal density (Eq. 4) by this 0.6 factor to infer the metal cosmic density in sources with \(S_{650} > 3\, \text{mJy}\):

\[ \rho_{Z, \text{DMF,3mJy}} \approx 6.4 \times 10^7 \, h_{70}^2 \, M_\odot \, \text{Mpc}^{-3} \]  

or about \(\sim 16\%\) of the estimated cosmic metal density (Eq. 4).

If one compares the baryonic and metal densities predicted from the DMF (Eqs. 5 6) with the observed baryonic and metal densities (Eqs. 2 3), we conclude that the predictions from the DMF (in a \(\Lambda\) cosmology) were over-estimated by a factor of at least 2. This factor can be easily accounted for if one uses a higher dust temperature (\(T_d \approx 35\, \text{K}\)), as indicated by the observations of [Chapman et al. 2003].

4 SUMMARY & DISCUSSION

SMGs are gas- (gas fraction 20–50%) and metal-rich galaxies (\(Z/Z_\odot \geq 1\)). Therefore, they are potentially good candidates for harboring the missing metals. From the observed gas
fraction $\sim 40\%$, dynamical mass $M_{\text{dyn}}$, and mean metallicity of $\gtrsim Z_{\odot}$ (supported by [Tecza et al. 2004] of 7 SMGs brighter than $S_{850} > 3$ mJy, we show that

- Based on the dynamical masses of SMGs assuming a 100% baryon fraction with $< Z > \approx Z_{\odot}$, SMGs can not contribute more than 9% of the expected cosmic metal density;
- Based the observed high gas fractions and observed high ISM metallicities $Z \gg Z_{\odot}$, SMGs can not contribute more than 9% of the expected cosmic metal density;
- the total contribution of SMGs, correcting for incompleteness (section 3.2), is $\frac{1}{3}$ times the contribution of SMGs brighter than 3 mJy, or $\lesssim 15\%$;
- our results imply that SMGs can only add $\approx 3.5\%$ to $\Omega_{\text{DLA}}$. Thus SMGs cannot harbor the dusty DLAs of Vladilo & Péroux (2004).

Early estimates of the contribution of the SMGs to the metal budget from the DMF were overestimated. The discrepancy however is mainly due to the assumed cosmology and to the low dust temperature used by D03 ($T_d \approx 25$ K).

We do agree with the conclusion of D03 that SMGs make a significant contribution to the cosmic metal budget, just not enough to solve the “missing metals problem”.

We are still far from closing the metal budget, however. In addition to $\lesssim 9\%$ of the metals that are in SMGs, 5% are in $z \sim 3$ LBGs (Pettini 2003), $\approx 15-20\%$ in $z \sim 2.2$ galaxies (see paper II), 8% in the forest (but see paper III), and 5% in DLAs $^3$.

Taking our results on SMGs at face-value, and ignoring the issue of double-counting, roughly 50% of the metals have been accounted for (see also paper III).

We are exploring two main avenues in trying to close the missing metals problem. Following Pettini (2003), either another population of galaxies has not yet been accounted for or there is a significant reservoir of metals in the IGM that has not been detected. A substantial fraction of the missing metals may be hidden in a very hot, collisionally ionized gas. Based on simple order-of-magnitude calculations, in paper III, we will discuss the possibility that the remaining missing metals could have been ejected from small galaxies via galactic outflows into the IGM in a hot ($T > 10^6$ K) that is difficult to detect using observed properties of local galaxies.

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$^3$ Dusty DLAs [Vladilo & Péroux 2004], missed in current spectroscopic DLA surveys (current DLA samples show small molecular and dust contents, e.g. [Ellison et al. 2003] Murphy & Liske 2004), could amount to an additional 17% (paper III). These would be in a separate population from SMGs given that the amount of H i in SMGs is less than 3–4% of $\Omega_{\text{DLA}}$.

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