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EARLY CHEMICAL EVOLUTION OF GALAXIES

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Abstract. Initial conditions are set by Big bang nucleosynthesis from which we know that 90 per cent of baryons are dark and have essentially unknown chemical composition. In our own Galaxy, there are many clues from individual stars in different populations whereas in elliptical galaxies the data largely come from integrated spectra, but these raise problems enough like the Mg/Fe and G-dwarf problems. Irregular and blue compact galaxies display the primary-secondary transition in N/O; this in turn may be relevant to element ratios observed in damped Lyman-α systems at high red-shift, which offer rather little evidence for pure SNII synthesis such as is found in the Galactic halo stars. A recent estimate of past star formation rates as a function of red-shift is presented and the appropriateness of the conventional conversion factor of 42 from SFR to metal production is discussed. For any reasonable value of this conversion factor, it is clear that most of the metals existing at $z = 2.5$ have yet to be detected.

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1. INTRODUCTION

Initial conditions set by Big Bang nucleosynthesis are $Y = .24$, $Z = 0$ for helium (e.g. Pagel 2000) and heavy elements respectively, D/H = 4×10^{-5} (Levshakov, Tytler & Burles 1998) and ^{7}Li/H = 1.7×10^{-10} (Bonifacio & Molaro 1997). The D/H ratio is the best indication of the overall density of baryons in the universe, which can be expressed as $0.03 \leq \Omega_B h_{70}^2 \leq 0.04$, similar to the density of Lyman-α forest gas at red-shifts 2 to 3 (Rauch et al. 1998), whereas the mass in visible stars in galaxies is given by $\Omega_* h_{70} \simeq 0.0035$ (Fukugita, Hogan & Peebles 1998), i.e. only 1/10 as much. Thus 90 per cent of baryonic matter is unseen and of unknown chemical composition, although it is reasonable to speculate that most of it is still intergalactic gas with Z now somewhere between 0.3 $Z_\odot$ (Mushotzky & Loewenstein 1997) and 0.1 $Z_\odot$ or less (Cen & Ostriker 1999).

The remainder of cosmic chemical evolution is the result of star formation, the history of which has been extensively studied by Madau and others (Madau et al. 1996; Steidel et al. 1999; Pettini 1999) using data from red-shift surveys, Lyman break galaxies etc. (see Figure 1). Thus we now have a fair idea about global star formation rates since $z = 4.5$, but ironically we do not know how to associate them with particular types of galaxies. The good news is that the integral over this version of the SFR history does come close to the estimated cosmic density of stars as given above, and it seems that about 1/4 of the stars were formed at red-shifts greater than 2.5, over 10^{10} years ago. This raises the question of what happened to all the metals they made, to which I return in the last section.

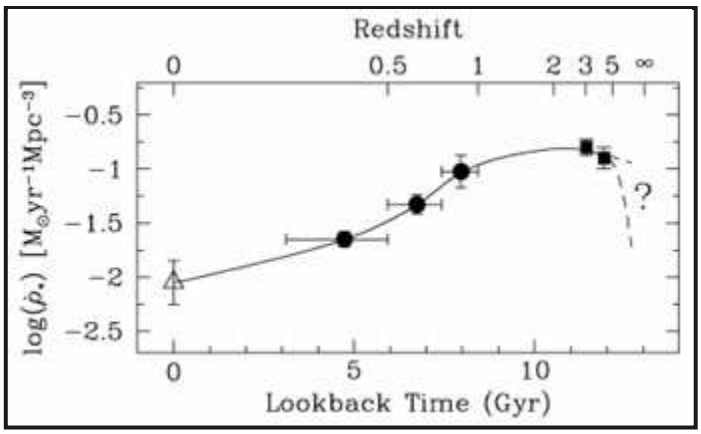

Figure 1. Global comoving star formation rate density vs. lookback time compiled from wide-angle ground-based surveys (Steidel et al. 1999 and references therein) assuming E-de S cosmology with h = 0.5, after Pettini (1999). Courtesy Max Pettini.

2. CHEMICAL EVOLUTION OF THE MILKY WAY

The Galactic halo, bulge and disk(s) are all relevant to early times, only the thin disk being younger than the bulge and thick disk. The respective roles of hierarchical clustering, mergers and monolithic collapse are still not very clear; probably all play a role, but the halo and bulge share a low specific angular momentum while the thick and thin disks share a high one and may result from later accretion of gas by the bulge, which would then resemble an E-galaxy. However, it is also possible that the bulge evolved from the disk by way of a bar.

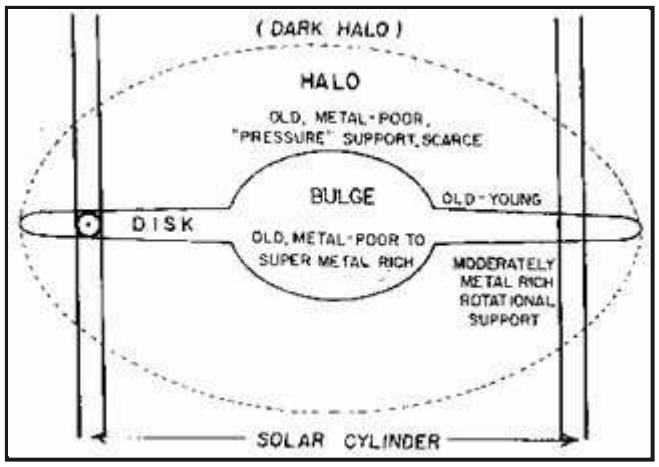

Figure 2. Schematic cross-section through the Galaxy.

In any case, the stellar dynamics of the halo favour what Thomas, Greggio & Bender (1999) refer to as a "fast clumpy collapse", basically the old idea of Eggen, Lynden-Bell & Sandage (1962) placed in the context of modern hierarchical clustering scenarios. One point of interest is the metallicity distribution function (MDF), recently extended to very low metallicities by Beers et al. (1998). The MDF is essentially the modified Simple-model type distribution originally noted by Hartwick (1976), with a peak at about 1/10 of the true yield, down to [Fe/H] $\simeq$ - 3. Below that it begins to fall off and there are virtually no stars (compared to a predicted number of about 10) below -4, which could represent enrichment either from a hypothetical Population III or from contamination of low-mass stars by a nearby supernova.

A significant clue to early Galactic chemical evolution comes from the relation between oxygen and α-particle elements, thought to come exclusively or mainly from type II supernovae, and iron, more than half of which in the Solar System comes from Type Ia. Fig 3 suggests that there is a plateau in O,α / Fe at low metallicities (assumed to represent early times), but there is currently a controversy in the case of oxygen. Abundances derived from the forbidden [OI] line, which is probably the most reliable source when it is not too weak, suggest a plateau, but from measurements of the near UV OH bands in dwarfs and subgiants, both Israelian, García Lopez & Rebolo (1998) and Boesgaard et al. (1999) have derived a rising trend with diminishing [Fe/H]

more or less following the open squares in the top panel of Figure 3. In contrast, Fulbright & Kraft (1999) have studied the [OI] spectral region in two of the extreme cases and find lower O/Fe ratios fitting the plateau. There are technical difficulties in both methods: the OH bands are subject to uncertainties in UV continuum absorption (cf. Balachandran & Bell 1998 on solar beryllium abundance) and effective temperature, while the forbidden line in the relevant cases is so very weak that the definition of the continuum becomes a crucial source of uncertainty.

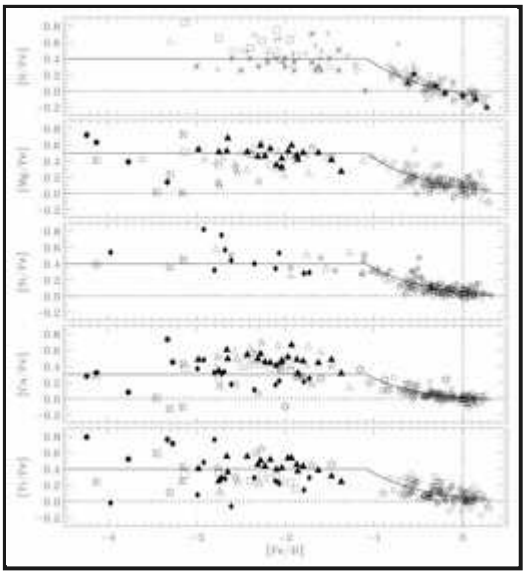

Figure 3. Abundance ratios of oxygen and α -elements to iron, plotted against [Fe/H] for stellar samples from the Galactic disk and halo, after Pagel & Tautvaisiene (1995). The solid line and curve represent a simple analytical Galactic chemical evolution model.

However this controversy comes out, the O, α enhancement is not universal, as has been shown, e.g. by Nissen & Schuster (1997); there are "anomalous" halo stars which have more solar-like element ratios even at quite low metallicities, a feature that is also found in the Magellanic Clouds and can be explained on the basis of slower star formation rates and effective yields diminished by outflows (e.g. Pagel & Tautvaisiene 1998). However, within the halo the presence of "anomalies" shows no obvious relation with extreme kinematic properties that might be signatures of a captured satellite (Stephens 1999).

Within the thick disk, the α / Fe ratio is remarkably uniform, even up to quite high metallicities, indicating an old "get rich quick" population. This is well brought out by the work of Fuhrmann (1998) on Mg, shown in Figure 4, and in a still unpublished study of oxygen by Gratton et al. (1996), and it may be that this trend is continued in the bulge (cf. Rich 1999). The data cast an interesting light on the formation of the thick disk, since they indicate a hiatus in star formation during which Fe/α increased but overall metallicity diminished, maybe from inflow of relatively unprocessed material, e.g. in a merger, before the stars now belonging to the thin disk were formed.

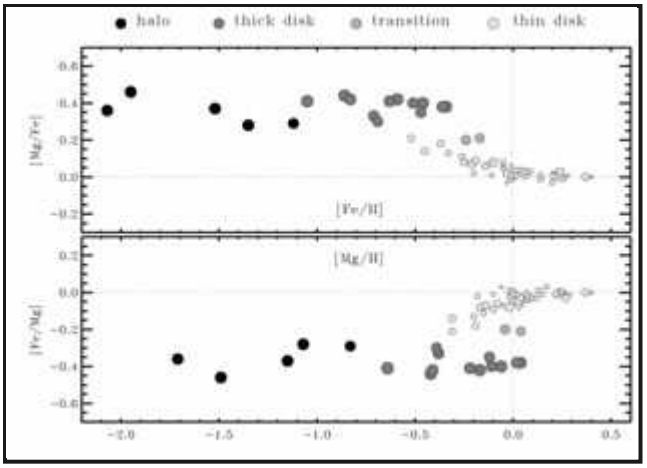

Figure 4. [Mg/Fe] vs [Fe/H] and [Fe/Mg] vs [Mg/H] for stars of the Galactic halo, thick disk and thin disk, after Fuhrmann (1998). Courtesy Klaus Fuhrmann.

Returning to the earliest stage of evolution of the Population II halo, when we consider a regime in which [Fe/H] < - 2.5 or so, we reach a stage where pollution by a single supernova becomes significant over a region the size of a globular cluster or superbubble of the order of $10^5\ M_\odot$. Metallicity (however defined) then becomes a poor clock and strange patterns appear, accompanied by significant scatter (McWilliam 1997). There are marked changes within the iron group, with Cr, Mn (and Cu) going down relative to iron and Co going up. Ryan, Norris & Beers (1996) suggest that at these low levels [Fe/H] is an increasing function of the mass of an individual supernova, and Tsujimoto & Shigeyama (1998) have estimated revised stellar yields as a function of progenitor mass on this basis. Most yields increase, with the conspicuous exception of the r-process, whose representative Eu/Fe has a large scatter and may be anti-correlated with [Fe/H]. Ba and Sr also mainly come from the r-process at these low metallicities and have even more scatter because the s-process can also contribute in evolved stars or stars with evolved companions. In a model recently put forward by Tsujimoto, Shigeyama & Yoshii (1999), stars form in superbubbles dominated by a single supernova, so that their composition is a weighted mean of the interstellar medium (with [Eu/Fe] $\simeq$ [α/Fe] = constant) and supernova ejecta. Fe/H increases with the mass of the supernova while Eu/Fe decreases leading to an anti-correlation with scatter superimposed until the ISM is sufficiently enriched to take over and normal Galactic chemical evolution proceeds.

Further evidence for inhomogeneity comes from the abundances of the light elements ^{6}Li, beryllium and boron, which show an unexpected "primary" behaviour - at least relative to iron - down to very low metallicities. This cannot be understood on the basis of spallation of interstellar CNO nuclei by primary cosmic ray protons and α-particles; these give a reasonable explanation for their abundances in the Sun and Population I stars in general but led to an expectation of secondary behaviour (Be,B/O $\propto$ O/H) with diminishing metallicity. [(1)] There are also energetic problems with the production by interstellar spallation at low metallicity (Ramaty et al. 1997). Thus various inhomogeneous processes have been proposed, beginning with the hypothesis of Duncan, Lambert & Lemke (1992) that fast CNO nuclei in primary cosmic rays are reponsible, and that their abundance is dominated by supernova ejecta rather than the interstellar medium. A more detailed model by Ramaty & Lingenfelter (1999) postulates an origin of of cosmic rays from acceleration of ions sputtered off dust grains in supernova ejecta by shocks within a superbubble. Thus the composition of cosmic rays is more or less constant and they dominate light element production at early times in the way suggested by Duncan, Lambert & Lemke.

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[1] With the large increase in O/Fe claimed by Israelian et al. and Boesgaard et al. there could be some semblance of secondary behaviour of the light elements after all, along with iron, magnesium, calcium etc; the likelihood of this depends on how the oxygen debate comes out. Back.

3. ELLIPTICAL GALAXIES

Most of our information on E-galaxies comes from colours and spectral features of integrated light interpreted with the aid of population synthesis models based on the theory of stellar evolution and a spectral library. A classical result is the correlation between the Lick Mg_2 index and central velocity dispersion (Bender 1992). For an old population, Mg_2 should be a good measure of the overall heavy-element abundance Z, dominated by oxygen and other α-elements, because Mg itself is one of

these and Mg and Si supply 2/3 of the free electrons providing H^- opacity in red-giant atmospheres. However, age is a complication and the correlation with iron is more problematic (cf. Figure 5). At face value, based on single stellar population (SSP) models by Worthey (1994) and by Buzzoni (1995), the nuclear *Z* or Mg abundance increases with depth of the potential well, whereas that of iron does not: the Mg/Fe dilemma. According to theoretical simulations by Thomas, Greggio & Bender (1999) and Thomas & Kauffmann (1999), the expectation would be that star formation goes on for longer in the bigger E-galaxies, making their weighted-mean age smaller and Mg/Fe smaller rather than larger.

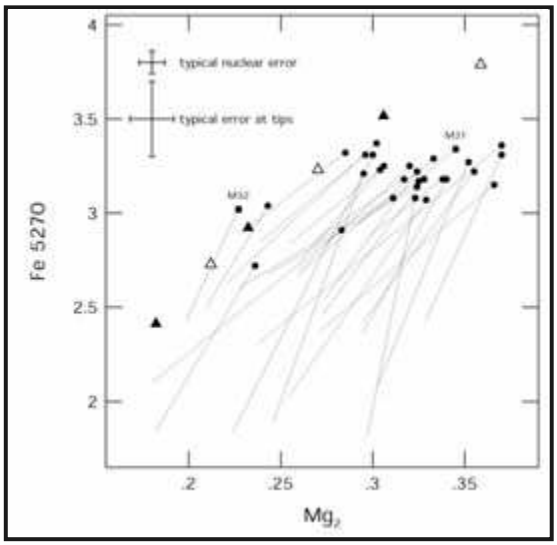

Figure 5. Plot of an iron feature against Mg_2. Filled circles and squares represent the nuclear regions (central 5 arcsec) of elliptical galaxies, while the sloping lines show the mean trend with galactocentric distance in each one. Triangles show model predictions for ages of 9 (solid) and 18 Gyr (open), based on SSP models that fit features in globular clusters assuming [Mg/Fe] = 0. A young model with [Fe/H] = 0 fits the nucleus of M 32 quite well, and the predicted trends with metallicity run roughly parallel to several of the observational lines, but the trend among nuclei is not fitted at all. After Worthey, Faber & Gonzalez (1992). Courtesy Guy Worthey.

There is also a "G-dwarf" problem, at least for nuclei, in the sense that SSP models fit the UV spectra better than those incorporating simple models of galactic chemical evolution (Bressan, Chiosi & Fagotto 1994; Worthey, Dorman & Jones 1996; Greggio 1997). One suggestion has been that the nuclei are pre-enriched with processed infalling material during a rapid clumpy collapse (Greggio 1997). The "concentration model" of Lynden-Bell (1975) may also be relevant to this situation, but according to Worthey, Dorman & Jones this is not just a nuclear problem.

Some notable results emerge from the recent study by Jørgensen (1999) of spectral features of galaxies in the Coma cluster. She confirms the existence of an age-metallicity relation as envisaged in the numerical simulations of Thomas & Kauffmann (1999), both for iron and magnesium, consistent with the view that galaxies with deep enough potential wells to hold on to their gas for longer reach higher metallicities. At any age, the galaxies with the highest velocity dispersions have the highest metallicity judged from magnesium, but for iron quite anomalously the opposite is the case, which makes one wonder about the calibration. Finally, Mg/Fe is independent of age and increases with velocity dispersion, which is hard to explain on the basis of the orthodox view of the unaided effects of a time lag for SNIa. Thomas (1999) has suggested that galactic nuclei may be affected by sporadic starbursts with a flat IMF.

The question of the IMF, or at least the yield, is also raised by the supply of iron and other elements to the X-ray gas in rich clusters of galaxies. Adapting an argument due to Renzini et al. (1993), we can start from the empirical finding of Arnaud et al. (1992) that the total mass of iron in the gas is proportional to the total optical luminosity of the E and S0 galaxies in the cluster according to

$$\frac{M_{\rm Fe}({\rm gas})}{L_*} = \frac{1}{55}\,\frac{M_\odot}{L_\odot}, \quad (1)$$

whence if $M_* / L_* \leq$ 10 solar units, then

$$\frac{M_{\rm Fe}({\rm gas})}{M_*} \geq 1.8 \times 10^{-3} = 1.5 Z_\odot({\rm Fe})$$

where the overall true yield [(2)] has been obtained by simply dividing the mass of iron by the mass of the stars; since the iron: oxygen ratio is about solar, the same result would have been obtained if we had considered oxygen instead of iron. This yield, however, is very high in comparison with values of $Z_\odot$ or slightly less that come up in studies of chemical evolution in the solar neighbourhood (e.g. Pagel & Tautvaisiene 1995), raising the question of whether such a high value is actually universal and the lesser yields found in other contexts just a consequence of mass loss from the systems. If so, it would be sufficient to enrich the intergalactic medium to the 1/3 of solar value postulated by Mushotsky & Loewenstein (1997).

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[2] Defined as the mass of newly synthesised and ejected heavy elements from a generation of stars divided by the mass remaining in long-lived stars and compact remnants (Searle & Sargent 1972). Back.

4. ABUNDANCES AT HIGH RED-SHIFT

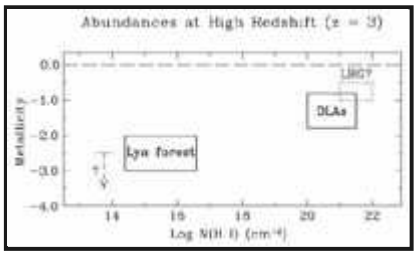

Figure 6. Summary of our current knowledge of abundances at high red-shift. Metallicity is on a log scale relative to solar and N(H I) is the column density of neutral hydrogen measured in the Lyman-α forest, damped Lyman-α systems and Lyman break galaxies, after Pettini (1999). Courtesy Max Pettini.

Naturally recent advances in studies of objects at high red-shift supply vital clues to the early evolution of galaxies, but, as Pettini (1999) has emphasised, our knowledge in this area is severely limited (see Figure 6), giving rise to serious observational selection effects. The Lyman forest comes from condensations in the intergalactic medium, possibly analogues of the high-velocity H I clouds seen today (Blitz et al. 1999), and represents the majority of the baryonic matter in the universe, while the damped Lyman-α (DLA) systems have a co-moving density similar to that of disk galaxies today. Then there are also the Lyman break galaxies, for which there is some information based on the strength of their stellar winds. Figure 7 shows the metallicities of DLA systems, based on zinc abundance, plotted against red-shift, after Pettini (1999). When column-density weighted means are formed in distinct red-shift bins, no evolution is detectable in the metallicity and there is no obvious way of identifying what sort of objects these systems will eventually become. Some clues could come from element:element ratios like N/O or α/Fe. Here the difficulty lies in correcting for depletion from the gas phase on to dust, which can be estimated (when not too large) from the ratio of Zn to Cr and Fe, since their intrinsic relative abundances are usually constant. According to Vladilo (1998) and Pettini et al. (1999a, b), the resulting relative abundances of silicon and iron are pretty much solar (or like the Magellanic Clouds and the "anomalous" halo stars referred to above), suggesting that they are destined to become Im galaxies rather than large spirals. The behaviour of N/Si vs Si/H also shows a resemblance to the behaviour of N/O vs. O/H in irregular and blue compact galaxies with perhaps an even greater scatter around the normal primary-secondary pattern than is found in irregulars and BCGs (Lu, Sargent & Barlow 1998).

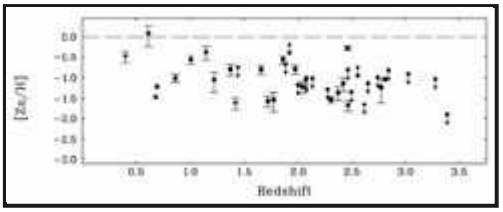

Figure 7. Zn abundance against red-shift for 40 DLAs from Pettini et al. (1999). Courtesy Max Pettini.

What are the consequences of the new star formation rate density (Fig 1) for "metal" production and global chemical evolution? To begin with, the SFR which I shall call $\dot{\rho}_*$(conv.) is based on the rest-frame UV luminosity density combined with a Salpeter power-law IMF between 0.1 and 100 $M_\odot$. The co-moving metal production-rate density is then usually deduced by dividing by the magic number of 42 (shades of *The Hitch-Hiker's Guide to the Galaxy*), which comes from models of supernova yields in the range of 10 to 100 $M_\odot$ or so, and I shall call this metal production rate $\dot{\rho}_Z$(conv.). The overall yield then amounts to

$$y = \frac{\dot{\rho}_Z(\mathrm{conv.})}{\alpha\dot{\rho}_*(\mathrm{conv.})} = \frac{1}{42\alpha} \simeq 0.03 \simeq 2Z_\odot, \quad (3)$$

where $\alpha \simeq 0.7$ is the lock-up fraction. Such a high yield is excessive for the solar neighbourhood (although it may be suitable for intra-cluster gas) and so people modelling Galactic chemical evolution generally either use a steeper slope, a smaller lower mass limit or assume that stars above 40 or 50 $M_\odot$ lock the bulk of their element production in black holes. So the true rate of "metal" production should be $\beta\ \dot{\rho}_Z$(conv.), where $\beta \leq 1$ is some correction factor depending on your favourite model o galactic chemical evolution. Finally, the true star formation rate density should be corrected by some factor γ, also ≤ 1, for the undoubted flattening of the IMF power law somewhere below 1 $M_\odot$, e.g. Fukugita, Hogan & Peebles (1998) have $\gamma = 0.65$, but this does not influence the conversion factor (at least to first order) because it is mainly just the massive stars that produce both the metals and the UV luminosity.

With these preliminaries, we can use the data supplied by Pettini (1999) to draw up the following inventory of stars and metals for the present epoch and for a red-shift of 2.5, assuming $\alpha = 0.67$, $\gamma = 0.65$.

Table 1. Inventory of stars and metals at $z = 0$ and $z = 2.5$

	$z = 0$	$z = 2.5$
$\rho_* = \alpha\,\gamma \int \dot{\rho}_*(conv.)\,dt$	$3.6 \times 10^8\ M_\odot\ Mpc^{-3}$	$9 \times 10^7\ M_\odot\ Mpc^{-3}$
$\Omega_* = \rho_* / 7.7 \times 10^{10}\ h_{50}^{\ 2}$	$.0047 h_{50}^{-2}$	$.0012 h_{50}^{-2}$
Ω_*(FHP 98)	$.0049 h_{50}^{-1}$	
$\rho_Z = y\,\rho_* = \beta \rho_* / (42 \alpha\,\gamma)$	$2.0 \times 10^7\ \beta\ M_\odot\ Mpc^{-3}$	$5 \times 10^6\ \beta\ M_\odot\ Mpc^{-3}$
Ω_Z (predicted)	$2.6 \times 10^{-4}\ \beta\ h_{50}^{-2}$	$6.5 \times 10^{-5}\ \beta\ h_{50}^{-2}$
Ω_Z (stars, $Z = Z_\odot$)	$1.0 \times 10^{-4}\ h_{50}^{-1}$	
Ω_Z (hot gas, $Z = 0.3 Z_\odot$)	$1.7 \times 10^{-4} h_{50}^{-1.5}$	
	-> $0.4 \leq \beta \leq 1$	
Ω_Z (DLA, $Z = 0.07 Z_\odot$)		$3 \times 10^{-6}\ h_{50}^{-1}$
Ω_Z (Ly. forest, $Z = 0.003 Z_\odot$)		$4 \times 10^{-6}\ h_{50}^{-2}$
Ω_Z (Ly. break gals, $Z = 0.3 Z_\odot$)		?
Ω_Z (hot gas)		?

The $z = 0$ column shows a fair degree of consistency. We can live with $\beta = 1$ if we wish to explain a metal content of intergalactic gas as high as suggested by Mushotzky & Loewenstein, or we can take this as a firm upper limit because we do not know if there is that much "metal" in intergalactic gas.

Somewhat more troubling questions arise at red-shift 2.5, however, as Pettini (1999) has already pointed out. It now seems that about a quarter of the stars have already been formed by then (in ellipticals, bulges and thick disks?), but known entries in the table only account for 10 per cent of the resulting metals (if $\beta = 1$) or 25 per cent (if $\beta = 0.4$). This is a good measure of the incompleteness in our knowledge of the distribution of the elements at substantial red-shifts.

I thank Max Pettini for supplying data and for enlightening discussions.

REFERENCES

1. Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L. & Vangioni-Flam, E. 1992, AA, 254, 49
2. Balachandran, S.C. & Bell, R.A. 1998, Nature, 392, 791
3. Beers, T.C., Rossi, S., Norris, J.E., Ryan, S.G., Molaro, P. & Rebolo, R. 1998, in *Primordial Nuclei and their Galactic Evolution*, N. Prantzos, M. Tosi & R. von Steiger (eds.), Sp. Sci. Rev., 84, 139
4. Bender, R. 1992, in IAU Symp. no. 149, *Stellar Populations of Galaxies*, B. Barbuy & A. Renzini (eds.), Kluwer, Dordrecht, p. 267
5. Blitz, L. 1999, in IAC Euroconference: *The Evolution of Galaxies on Cosmological Timescales*, J.E. Beckman & T.J. Mahoney (eds.), ASP Conf. Series, in press
6. Boesgaard, A., King, J.R., Deliyannis, C.P. & Vogt, S.S. 1999, AJ, 117, 492
7. Bonifacio, P. & Molaro, P. 1997, MNRAS, 285, 847
8. Bressan, A., Chiosi, C. & Fagotto, F. 1994, ApJS, 94, 63
9. Buzzoni, A. 1995, ApJS, 98, 69
10. Cen, R. & Ostriker, J.P. 1999, ApJ, 514, 1
11. Duncan,D., Lambert, D.L. & Lemke, M. 1992, ApJ, 401, 584
12. Eggen, O.J., Lynden-Bell, D. & Sandage, A.R. 1962, ApJ, 136, 748
13. Fuhrmann, K. 1998, AA, 338, 161
14. Fukugita, M., Hogan, C.J. & Peebles, P.J.E. 1998, ApJ, 503, 518
15. Fulbright, J.P. & Kraft, R.P. 1999, AJ, 118, 527
16. Gratton, R., Carretta, E., Matteucci, F. & Sneden, C. 1996, preprint
17. Greggio, L. 1997, MNRAS, 285, 151
18. Hartwick, F.D.A. 1976, ApJ, 209, 418

19. Israelian, G., García Lopez, R.J. & Rebolo, R. 1998, ApJ, 507, 805
20. Jørgensen, I. 1999, MNRAS, 306, 607
21. Levshakov, S., Tytler, D. & Burles, S. 1998, astro-ph/9812114, AJ, subm.
22. Lu, L., Sargent, W.L.W. & Barlow, T.A. 1998, AJ, 115, 55
23. Lynden-Bell, D. 1975, Vistas in Astr, 19, 299
24. McWilliam, A. 1997, ARAA, 35, 503
25. Madau, P., Ferguson, H.C., Dickinson, M.E. et al. 1996, MNRAS, 283, 1388
26. Mushotzky, R.F. & Loewenstein, M. 1997, ApJ, 481, L63
27. Nissen, P.E. & Schuster, W.A. 1997, AA, 326, 751
28. Pagel, B.E.J. 2000, Phys. Rep., in press
29. Pagel, B.E.J. & Tautvaisiene, G. 1995, MNRAS, 276, 505
30. Pagel, B.E.J. & Tautvaisiene, G. 1998, MNRAS, 299, 535
31. Pettini, M. 1999, in ESO Workshop: *Chemical Evolution from Zero to High Redshift*, J. Walsh & M. Rosa (eds.), Springer-Verlag, in press, astro-ph/9902173
32. Pettini, M., Ellison, S.L., Steidel, C.C. & Bowen, D.V. 1999a, ApJ, 510, 576
33. Pettini, M., Ellison, S.L., Steidel, C.C., Shapley, A.E. & Bowen, D.V. 1999b, preprint astro-ph/9910131, ApJ, in press
34. Ramaty, R., Kozlovsky, B., Lingenfelter, R. & Reeves, H. 1997, ApJ, 488, 730
35. Ramaty, R. & Lingenfelter, R. E. 1999, in *LiBeB, Cosmic Rays, and Related X- and γ-Rays*, R. Ramaty, E. Vangioni-Flam, M. Cassé & K. Olive (eds.), ASP Conf. Series, Vol. 171, p. 104
36. Rauch, M., Miralda-Escudé, J., Sargent, W.L.W. et al. 1998, ApJ, 489, 7
37. Renzini, A., Ciotti, L., D'Ercole, A. & Pellegrini, S. 1993, ApJ, 419, 52
38. Rich, R.M. 1999, in *Chemical Evolution from Zero to High Red-shift*, J. Walsh & M. Rosa (eds.), Springer-Verlag, in press
39. Ryan, S., Norris, J. & Beers, T.C. 1996, ApJ, 471, 254
40. Searle, L. & Sargent, W.L.W. 1972, ApJ, 173, 25
41. Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M. & Pettini, M. 1999, ApJ, in press, astro-ph/9811399
42. Stephens, A. 1999, AJ, 117, 1771
43. Thomas, D. 1999, MNRAS, in press, astro-ph/9901226
44. Thomas, D., Greggio, L. & Bender, R. 1999, MNRAS, 302, 537
45. Thomas, D. & Kauffmann, G. 1999, in *Spectrophotometric Dating of Stars and Galaxies*, I. Hubeny, S.Heap & R. Cornett (eds.), ASP Conf. Series, astro-ph/9906216
46. Tsujimoto, T. & Shigeyama, 1998, ApJL, 508, L151
47. Tsujimoto, T., Shigeyama, & Yoshii, Y. 1999, ApJL, in press, astro-ph/9905057
48. Vladilo, G. 1998, ApJ, 493, 583
49. Worthey, G. 1994, ApJS, 95, 107
50. Worthey, G., Dorman, B. & Jones, L.A. 1996, AJ, 112, 948
51. Worthey, G., Faber, S.M. & Gonzalez, J.J. 1992, ApJ, 398, 69