STAR FORMATION AND METAL PRODUCTION IN THE EARLY UNIVERSE

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Recent advances in our understanding of star formation and the associated production of heavy elements at high redshift are reviewed. First, the host galaxies of star-formation regions at redshift $2-4$ are characterized, and a comparison with their local counterparts is made. Then the properties of the stellar content in these objects are summarized. A major theme is the interaction and feedback between star formation and the dynamical state of the interstellar medium of the host galaxy. Star formation enriches the interstellar medium with chemically processed material and may be able to drive the galaxy ISM into the intergalactic medium via powerful superwinds. The chemical composition of star-forming galaxies at high redshift is compared to abundances derived for damped Lyman-α absorbers and the Lyman-α forest. A consistent scenario for the metal production can be derived if the heavy elements produced in star-forming galaxies leave their formation sites and are effectively dispersed in the universe by a yet to be determined mechanism.

THE GALAXY POPULATION AT HIGH REDSHIFT

One of the most notable recent breakthroughs in observational cosmology was the direct verification of star formation in galaxies at an epoch when the universe was young. This progress was made possible largely due to our better understanding of the restframe ultraviolet (UV) light emitted by star forming galaxies in the local and distant universe.

The Hubble Deep Fields North and South are among the most influential astronomical images ever taken (Ferguson, Dickinson, & Williams 2000). The images for the two Hubble Deep Fields (HDFs) were obtained in four passbands and cover the wavelength range 2500 to 9000 Å, with follow-up observations in the near-infrared (IR). They are suitable for performing a deep optical census of the universe at the highest angular resolution. At low redshift, $z < 1$, the comoving volume sampled in the HDF field of view is rather small, and only about 20 $L^\star$ galaxies are expected for a local galaxy luminosity function. The HDF exposures are deep enough to detect essentially all $L^\star$ galaxies with redshifts up to $z = 3$. In this case meaningful statistics can be done: the HDF comoving volume $\times$ the luminosity function predicts about 500 $L^\star$ galaxies, all of which can be detected even allowing for some light loss due to dust absorption.

The morphologies of the galaxies seen in the HDFs resemble those of local peculiar late-type spiral and irregular galaxies with approximately $L^\star$ luminosities. There are very few, if any, ellipticals and spirals with bulges and disks at $z > 2$. Since these types are abundant at $z < 1$, their formation must have occurred at redshifts between 1 and 2. Therefore the Hubble sequence as we know it was created at $1 < z < 2$.

Combination of the optical HDFs with HST NICMOS Deep Fields at 1.1 μm and 1.6 μm allows an evaluation of the importance of morphological K-corrections. Ferguson et al. (2000) compared galaxies viewed at optical and near-IR wavelengths in the HDFs. Despite some differences, the overall morphologies in the optical and near-IR are remarkably similar. This suggests that K-corrections are insignificant and that dust does not have a major effect on the galaxy morphologies (Dickinson 2000). The possibility exists that some galaxies are obscured from view *both* in the optical and near-infrared due to large amounts of dust. The galaxies detected by SCUBA in the sub-mm region may fall into this category (Hughes et al. 1998). However, it is unlikely that this population *dominates* the star formation and metal production at $z \approx 3$ (Ferguson 1999). If the SCUBA galaxies are at $z \approx 3$ (which is subject to debate), it is a distinct population and not the red tail of the HDF galaxies with large dust obscuration.

The dust attenuation in those galaxies which are actually detected can be estimated from their spectral energy distribution and a comparison with model spectra. Generally, the observed colors suggest star-forming galaxies with ages of order 10^8 yr and reddening $0.1 < E(B-V) < 0.4$ if the starburst attenuation law of Calzetti, Kinney, & Storchi-Bergmann (1994) is adopted. The corresponding attenuation of the V flux is about a factor of 3 to 10. Taking into account the reddening corrections, the luminosities are approximately $L^\star$-like, consistent with viral-mass estimates from emission lines in the infrared.

In summary, the galaxy population at redshift around 3 has morphologies similar to those of luminous late-type/irregular galaxies. The galaxies are actively forming stars, and they show signs of dust obscuration with optical attenuation factors between 5 and 10.

STAR FORMATION IN THE LOCAL AND DISTANT UNIVERSE

Galaxy morphologies and colors allow an overall estimate of the stellar content of galaxies at high redshift. Spectroscopy of representative examples provides more quantitative insight. Steidel and collaborators identified bona fide star-forming galaxies suitable for spectroscopy by pre-selecting them from their strong Lyman breaks. The restframe UV spectra of these galaxies turn out to be quite similar to those of local star-forming galaxies (Steidel et al. 1996). This supports the view that the properties of the late-type/irregular galaxies seen in the HDF are similar to those of UV-selected star-forming galaxies in the local universe. Therefore we can apply locally calibrated techniques to derive the rates of star formation and metal production at high redshift.

Before discussing the properties of a high redshift star-forming galaxy in detail, I will review some key results found for the local galaxy population — assuming an extrapolution to high redshift is justified, for the reasons given before. A particularly well-studied local example is the interacting (merging?) system NGC 1741. Conti, Leitherer, & Vacca (1996) proposed this galaxy as a template to be used for comparison with distant star-forming galaxies. NGC 1741 is at a distance of 50 Mpc, its luminosity is close to $L^\star$, and the metallicity is $\frac{1}{4}$ $Z_\odot$. The star formation is concentrated in a ~500 pc large region where the star-formation *intensity* per unit surface is almost 3 orders of magnitude higher than in our Galaxy. Hot, massive stars with masses above 10 $M_\odot$ are currently forming at rate producing an ionizing photon output 100 times that of the 30 Doradus region. Yet, the stellar mass function in the NGC 1741 starburst and in 30 Doradus are very similar: both follow the classical Salpeter power law (Johnson et al. 1999). In the optical, the morphology of NGC 1741 shows a disturbed disk composed of intermediate-age stars, with the starburst region offset at the periphery. When observed in the UV at 2200 Å, the starburst completely dominates, and an irregular morphology is suggested. Hibbard & Vacca (1997) simulated the appearance of NGC 1741 and similar objects when projected at high redshift; NGC 1741 would look very similar to the irregular, clumpy $L^\star$ galaxies observed in the HDFs.

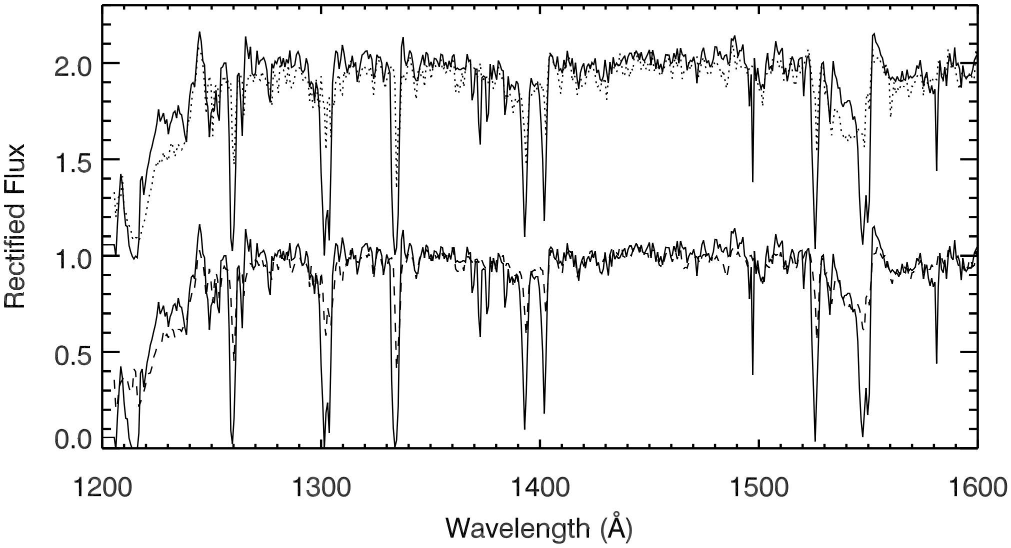

Figure 1: Comparison between the observed spectrum of MS 1512-cB58 (solid lines) and two synthetic models at $Z = \frac{1}{4}$ $Z_\odot$ (lower; dashed) and $Z = Z_\odot$ (upper; dotted). The models have continuous star formation, age 100 Myr, and Salpeter IMF between 1 and 100 $M_\odot$. Adopted from Leitherer et al. (2000).

Moving back to the high-redshift universe, the galaxy MS 1512-cB58 has become the Rosetta Stone for spectroscopic studies. This object was originally discovered in the CNOC cluster redshift survey by Yee et al. (1996) and subsequently found to be a lensed star-forming galaxy (Seitz et al. 1998) at a redshift of $z = 2.7$. Its star-formation history and general properties were explored by Ellingson et al. (1996), de Mello et al. (2000), Pettini et al. (2000), and Teplitz et al. (2000). The star-formation intensity in MS 1512-cB58 is a few $M_\odot$ yr^{-1} kpc^{-2}, almost identical to the value derived for NGC 1741. In MS 1512-cB58, however, the star formation is likely to extend all over the disk, leading to a total rate of $\sim 10^2$ $M_\odot$ yr^{-1}. This is close to the maximum rate possible when the total gas mass is converted into stars on a dynamical timescale.

Apart from the spatial extent of the star formation, the stellar population in MS 1512-cB58 seems quite similar to that of NGC 1741 and other local starburst galaxies. In Figure 1 a comparison is shown between a restframe UV spectrum of MS 1512-cB58 (Pettini et al. 2000) and synthetic models with a standard stellar initial mass function, which fits local starburst galaxies (Leitherer et al. 2000). The agreement between the observations and the modeled low-Z (lower) spectrum is excellent. The stellar-wind features N V λ1240, Si IV λ1400, and C IV λ1550 are reproduced quite well, except for the narrow interstellar contributions. The mismatch of the interstellar components is expected since the interstellar lines in MS 1512-cB58 are broadened by macroturbulence and blending of multiple components due the energy input from stellar winds and supernovae in starbursts. Generally, the interstellar medium (ISM) in starburst galaxies is more turbulent than in, e.g., the Milky Way and the Magellanic Clouds so that even saturated lines are stronger in starbursts (Heckman & Leitherer 1997). The comparison in Fig. 1 indicates that the overall spectral fit at $\frac{1}{4}$ $Z_\odot$ is much improved over that with solar composition. Therefore the conclusion is that MS 1512-cB58, which is observed at a redshift corresponding to an age of the universe of about 2 Gyr, has an LMC/SMC-like chemical composition.

The chemical composition of MS 1512-cB58 and high-redshift galaxies in general is difficult to determine. Due to their redshift, a traditional emission-line analysis is not feasible since some of the key diagnostic lines, like [O III] λ4363, are inaccessible from the ground and/or are too faint. Nevertheless, Teplitz et al. (2000) were able to estimate an oxygen abundance $\frac{1}{3}$ $Z_\odot$ from near-IR spectroscopy, using the approximate R_{23} method (e.g., Kobulnicky, Kennicutt, & Pizagno 1999). Pettini et al. (2000) analyzed weak interstellar absorption lines of Si II, S II, and Ni II to infer an abundance of about $\frac{1}{4}$ $Z_\odot$. Each of these analyses may be quite uncertain, but taken together, they give firm evidence for a relatively high metallicity in MS 1512-cB58.

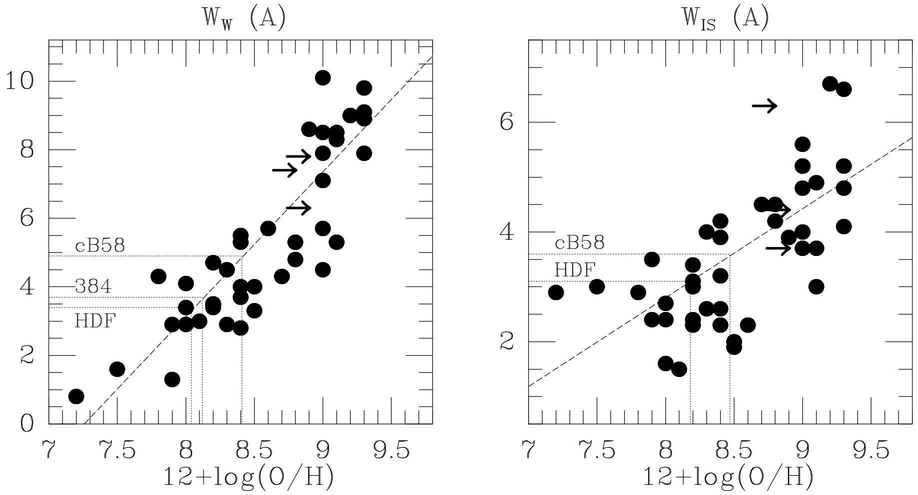

Figure 2: Correlation of the mean stellar-wind (left) and interstellar (right) line equivalent widths with metallicity. Full circles: measurements for the local galaxy sample; arrows: upper limits; dashed line: least squares fit to the data points; dotted lines: observed equivalent widths of MS 1512-cB58, the object 384, and the HDF sample and corresponding metallicities. Adopted from Leitherer (1999).

MS 1512-cB58 fits rather well the general correlation between the equivalent widths of the UV interstellar (like Si II or C II) and stellar-wind (like Si IV or C IV) lines and metallicity discussed by Leitherer (1999). MS 1512-cB58 is added to this relation in Figure 2. The metallicities of MS 1512-cB58 and other high-z galaxies are in the range $8.0 < 12 + \log(O/H) < 8.9$, with average values close to those of the LMC and SMC. This range is in reasonable agreement with other estimates.

FEEDBACK BETWEEN STAR FORMATION AND THE INTERSTELLAR MEDIUM

Close inspection of Figure 1 shows that the interstellar lines, such as Si II λ1526, are not only broadened due to the dynamics and structure of the ISM, but also blueshifted with respect to the model fiducials. Pettini et al. (2000) measure velocity offsets of 200 km s^{-1}. Since the interstellar lines are almost black in their cores, indicating large covering factors, we are witnessing a large-scale outflow of the galactic ISM. Together with the column density of (mildly saturated) interstellar lines, an outflow rate of order 10^2 M$_\odot$ yr^{-1} is found. This rate is surprisingly similar to the derived star-formation rate.

I will return back to the nearby universe in order to compare MS 1512-cB58 with a local paradigm. He 2-10, a blue compact dwarf galaxy, has been the subject of numerous investigations since Allen, Wright, & Goss (1976) first found signatures of Wolf-Rayet stars in its optical spectrum. At a distance of 9 Mpc, He 2-10 is relatively nearby, and has an optical diameter of about 2.8 kpc (Johnson et al. 2000). An HST GHRS spectrum of the this galaxy is shown in Figure 3. In this figure the observed spectrum of He 2-10 is compared to a model spectrum for a starburst age of 4 Myr. Apparently all *stellar* photospheric and wind lines are reproduced extremely well by the model. Compare, for instance, the blue wings of the Si IV λ1400 and C IV λ1550 wind lines, the standard indicators for massive stars. On the other hand, the deep, narrow interstellar absorptions are much broader and more blueshifted in the observations than in the model. The lines are purely interstellar, arising in the interstellar medium in and around the starburst. The sharp interstellar lines seen in the model spectra can be used to measure the outflow velocity in He 2-10, suggesting a bulk motion of at least –360 km s^{-1}. The energy source are almost certainly winds and supernovae. They are capable of initiating large-scale outflows of interstellar gas via so-called galactic superwinds (Chevalier & Clegg 1985). Johnson et al. (2000) estimate that the mass-loss rate of the interstellar medium is quite similar to the star-formation rate in He 2-10. Taken at face value, this suggests that the available gas reservoir will not only be depleted by the star-formation process but, more importantly, by removal of interstellar material. Starbursts may determine their own fate by their prodigious release of kinetic energy into the interstellar medium.

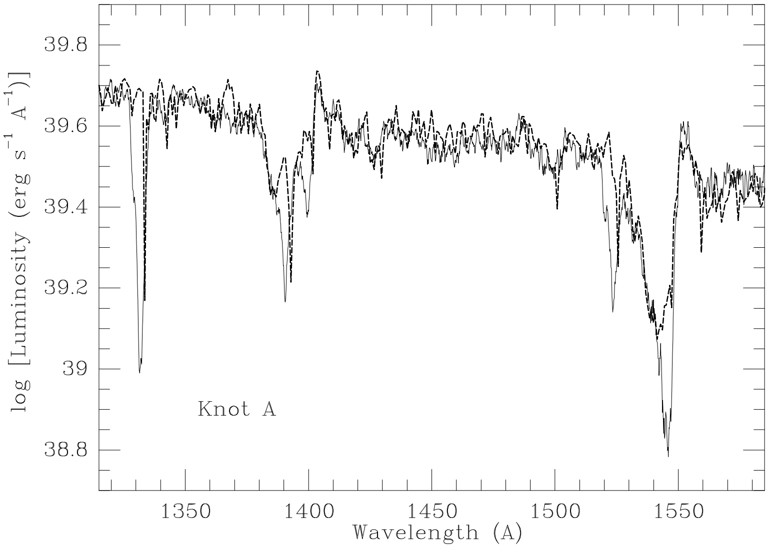

Figure 3: HST GHRS spectrum of He 2-10. The dashed spectrum is a model fit to the *broad* stellar lines. The *narrow* interstellar lines are offset by ∼400 km s^{-1}. From Johnson et al. (2000).

The dynamical state of the ISM in He 2-10 (and in other local starburst galaxies — see González Delgado et al. 1998) is remarkably similar to that in MS 1512-cB58. This suggests that regions of active star formation generally affect the dynamics of the galactic ISM via non-thermal energy input and remove the interstellar gas locally, possibly initiating global outflows. An important observational consequence is that the line widths of interstellar lines are more sensitive to the stirring by stellar winds and supernova explosions than to the bulk motion of the gas in the gravitational potential of the galaxy. Therefore these lines are not suitable to estimate the virialized mass (Heckman & Leitherer 1997).

GALACTIC SUPERWINDS

The combined effect of stellar winds and supernovae overpressurizes the surrounding gas, producing a hot ($10^7 - 10^8$ K), expanding (∼10^2 km s^{-1}) cavity in the ISM. As discussed in Leitherer et al. (1999), the relative importance of stellar winds and supernovae is a function of the age and metallicity of the starburst. For typical starburst parameters, the rate of supply of mechanical energy is of order 1% of the bolometric luminosity of the starburst and typically 10 to 30% of the Lyman continuum luminosity. Some fraction of this mechanical energy may be radiated away by dense shock-heated material inside the starburst. However, observations of superwinds imply that a significant fraction is available to drive the outflow and that radiation losses are not important enough to stall the flow. The hot wind-blown bubble keeps expanding, thereby driving the ambient cold interstellar material from the star-formation site. This outflowing cold material is seen in the blueshifted narrow absorption lines in Figures 1 and 3. Typical sizes of starburst regions are tens to hundreds of parsecs. The regions are often (but not always) in the centers of the host galaxies. If there is a preferred axis, such as in a disk galaxy, the bubble will preferentially expand along the maximum pressure gradient, which is the minor axis of the galaxy. After a few scale heights (∼kpc), Rayleigh-Taylor instabilities set in, the bubble wall leaks, and the hot interior material can escape into the galactic halo. The dynamical evolution of such galactic superwinds was discussed, e.g., by Tomisaka & Bregman (1993) and Suchkov et al. (1994, 1996).

Galactic superwinds are able to transport dust and chemically enriched material from the star-formation sites into the galactic halo. The ultimate fate of the superwind depends on the starburst geometry (Tenorio-Tagle et al. 1999), the mass of the galaxy (Ferrara & Tolstoy 2000), and on the properties of the halo (Ferrara, Pettini, & Shchekinov 2000). The material may fall back onto the galaxy disk or become unbound, with the second alternative being more likely in less massive galaxies.

After a characteristic time the outflow will reach pressure equilibrium with the ambient intergalactic medium (IGM) at some distance R_e from the galaxy. Hydrodynamic models by Ferrara et al. (2000) predict $R_\mathrm{e} \approx 50$ kpc. This is small in comparison with the separation of objects with mass $\sim 10^{10}$ $\mathrm{M}_\odot$ formed in the early universe according to Cold Dark Matter models, which is of order 1 Mpc. Therefore, in the absence of an additional dispersal process, the metals transported out of the galaxies by superwinds essentially stay close to their birthplace from a cosmological point of view. It is not unreasonable to assume that additional dispersal mechanisms exist. Large-scale diffusion processes in the IGM, peculiar motions of galaxies, and galaxy-galaxy mergers and interactions all tend to disperse the ejected metals into larger volumes. An alternative scenario was proposed by Gnedin (1998). Protogalaxies can merge at large velocity in a head-on collision. Stars and dark matter experience significantly different forces than the gas. As a result, the two components have different spatial distributions, and the gas, which has already been enriched in metals by the first generations of stars, escapes into the IGM. Currently both models are considered viable mechanisms for the dispersal of metals in the early universe.

Whatever dispersal mechanism operates, an approximate picture for the star formation, metal production, and pollution of the IGM at high redshift is beginning to emerge:

- Late-type/irregular galaxies with peculiar morphologies at redshift around 3 are forming stars at high rates, but otherwise have properties similar to those in the local universe.
- Stellar winds and supernova explosions are an efficient mechanism to transport heavy elements from the galaxy centers to the halos, and possibly into the IGM.
- Depending on the existence of a dispersal mechanism (or if protogalaxy mergers are important), the metals are distributed over large volumes and pollute the IGM early in the evolution of the universe.

METAL ABUNDANCES AT HIGH REDSHIFT

Observational constraints on the chemical composition of galaxies at high redshift are still rather scarce. This contrasts with the state of knowledge of the heavy-element abundances in the IGM. The situation is summarized in Figure 4. In addition to the previously discussed Lyman-break galaxies, as the star-forming galaxies at high redshift are referred to, the figure contains damped Lyman-α (DLA) systems and the Lyman-α forest.

DLA systems are thought to be the cross sections of the outer regions and halos of (proto)-galaxies seen along the sightlines of quasars. DLA systems may trace the halos of star-forming galaxies but such galaxies are unlikely to account for the majority of the systems. One argument against DLA systems being halos of galaxies with active star formation is the redshift dependence of the zinc abundance (an element with negligible depletion and ionization corrections) in DLAs (Pettini 2000). No redshift evolution of the column density weighted metallicity is found. This is contrary to the expectation from chemical models of galaxies, whose metallicity should steadily rise to $\sim\mathrm{Z}_\odot$ at $z = 0$ (Pei & Fall 1995). Most likely, DLA systems arise from a diverse population of galaxies, and various selection effects are conspiring, such as selective dust obscuration of the more metal-rich and more actively star-forming galaxies. It is therefore difficult to relate the metal production in star-forming galaxies at high z to the metallicities in DLA systems.

The Lyman-α forest is predicted by cold dark matter models to result from structure formation in the presence of an ionizing background (Weinberg, Katz, & Hernquist 1998). The Lyman-α forest had long been thought to be truly primordial but recent Keck spectroscopy revealed weak but significant C IV λ1550 absorption in almost all sight lines with H I columns above 10^{15} cm^{-2} (Cowie et al. 1995). The corresponding carbon abundances strongly depend on the ionization correction but are thought to be about $\frac{1}{30}$ $Z_\odot$. It is worth highlighting that already at a redshift of 3 the IGM has a carbon abundance which is higher than that of very metal-poor stars in the halo of our Galaxy (Wheeler, Sneden, & Truran 1989).

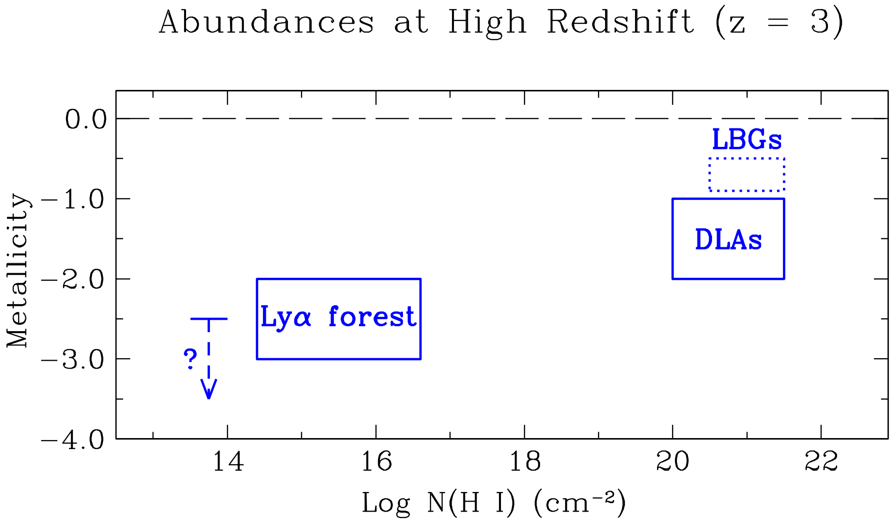

Figure 4: Summary of our current knowledge of abundances at high redshift. Plotted are metallicity (relative to solar) vs. H I column density. The approximate location of Lyman-break galaxies, damped Lyman-α systems, and the Lyman-α forest is indicated by boxes. Adopted from Pettini (2000).

The high metal abundance in the IGM clearly requires enrichment early in the evolution of the universe. The metals could have been produced by a first generation of Population III stars which are capable to account for the amount of metals, and at the same time could have provided copious ionizing photons, as metal and photon production are closely correlated. Alternatively, star-forming galaxies with redshift at and above 3 could be the production sites of the metals seen in the universe. Even at a redshift of ~3, the average chemical composition of Lyman-break galaxies is about $\frac{1}{4}$ $Z_\odot$. It is likely that the metals are removed from the star-formation sites by galactic superwinds. If they can be effectively dispersed and mixed outside the galaxies, the metals seen in the Lyman-α forest may have their origin in galaxies similar to, e.g., MS 1512-cB58.

EPILOGUE: THE FIRST GENERATION OF STARS?

A previously unexpected discovery is the relatively high metal abundance of star-forming galaxies at $z \approx 3$. Already at that redshift and a correspondingly young age of the universe of about 2 Gyr, multiple stellar generations must have been at work to built up the metal content.

Where is the first generation of stars? Dickinson et al. (2000) discovered an extremely red object in the HDF North whose spectral energy distribution is consistent with a star-forming galaxy with its Lyman break in the J band. If this interpretation turns out to be true, the object could be a young galaxy at $z > 10$ forming its first stellar generation. Spectroscopic verification of this hypothesis will be a challenge for the more distant future.

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