 CONSTRAINTS ON GALAXY FORMATION FROM DEEP GALAXY REDSHIFT SURVEYS AND QUASAR ABSORPTION LINE STUDIES

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Magnitude-limited galaxy redshift surveys are now providing large samples of galaxies to beyond $z = 2$, while color-selected and emission-line-selected samples are finding galaxies to $z = 4.7$. A broad picture is emerging of galaxy formation peaking in the $z = 1$ range, which ties in with the metallicity and density evolution seen in the quasar absorption lines. We still have no direct information beyond $z = 5$, but the ionization of the IGM at this redshift argues for activity prior to this time. The metallicities of around 0.01 solar which appear to be relatively ubiquitous in quasar absorption lines beyond $z = 2$, even in very low column density clouds, could be a relict of this period.

1 Introduction

A consistent picture of galaxy formation and evolution is emerging from combining faint galaxy properties obtained from deep galaxy surveys with what has been learned from quasar absorption line studies. At $z > 2$ a large fraction of the baryon density of the universe appears in quasar absorption line clouds stretching over neutral hydrogen column densities from $10^{12}$ cm$^{-2}$ to $10^{22}$ cm$^{-2}$. This material has largely vanished by the present time, presumably converting into stars. Studies of the metallicity and ionization of the baryonic material in absorbing clouds provide evidence for small amounts of early enrichment followed by a much more rapid rise below redshifts of about 2. At the same time, nearly complete spectroscopic surveys are yielding information on the star-formation history of galaxies, with evidence of substantial evolution in the properties of individual galaxies out to redshifts of one, where there are many massive galaxies which are dominated by the light of massive star formation. These also show that the total star-formation rates in the universe were highest near $z = 0.5-1$ and were lower at higher redshifts, although sub-galactic or near-galactic sized star-forming galaxies exist at least to redshift 4.7 [refs. 1, 2] and presumably extend beyond $z = 5$. 
2 Early Metals?

One of the first results to emerge from the HIRES spectrograph on the Keck telescope was the detection of many weak C\textsc{iv} lines corresponding to relatively low column density Lyman alpha forest lines. This provided confirmation of previous suggestions that there might be fairly regular metal enrichment in such systems. Currently, as is summarised in Fig. 1, we know that nearly all clouds with \(N(\text{H} \textsc{i}) > 10^{15} \text{ cm}^{-2}\) and a large fraction of those with \(N(\text{H} \textsc{i}) > 3 \times 10^{14} \text{ cm}^{-2}\) are detected in C\textsc{iv}. The issue of whether yet lower column density clouds may be chemically unenriched remains open since current sensitivity limits would not detect such clouds in C\textsc{iv} at the expected column densities.

Figure 1: C\textsc{iv} versus H\textsc{i} column density for all systems with \(N(\text{H} \textsc{i}) > 5 \times 10^{14} \text{ cm}^{-2}\) at \(3.135 < z < 3.60\) toward Q1422+231 (diamonds) and for \(N(\text{H} \textsc{i}) \geq 1.5 \times 10^{15} \text{ cm}^{-2}\) at \(z > 2.95\) toward Q0014+813 (triangles). Also shown (open squares) is C\textsc{iv}/H\textsc{i} in all Lyman limit systems (open boxes) toward eight quasars. The dashed line shows the typical 2 \(\sigma\) detection limit for C\textsc{iv} in Q1422+231. The solid lines show model calculations of C\textsc{iv}/H\textsc{i} for \(\Gamma = 10^{-2.7}\) (lower), \(\Gamma = 10^{-1.7}\) (upper) and the dotted line the model for \(\Gamma = 10^{-0.7}\), and a metallicity of \(10^{-2}\) solar, and illustrate that the difference between the higher and lower column density systems is not solely a radiative transfer effect but must arise from a higher ionization parameter or higher metallicity in the weaker clouds.

Remarkably the metallicity in the forest clouds of around 0.01 solar is similar to that seen in partial Lyman limit system clouds with \(N(\text{H} \textsc{i}) = 10^{17}\).
cm$^{-2}$ (Fig. 1) and in the $z > 2$ damped Ly$\alpha$ systems with $N$(H$I$)$=10^{21}$ cm$^{-2}$ [ref. 11]. There is also some evidence that the forest clouds show enhancement of the alpha process elements versus the Fe process elements as may also be the case in the damped Ly$\alpha$ systems paralleling the abundances in the low metallicity stars in the Galactic halo.

This relatively ubiquitous enrichment clearly has powerful implications for understanding the early stages of the heavy element formation. Essentially it requires that along any line of sight through a forest cloud we must see a relatively uniform (at least to order of magnitude) enhancement, or alternatively expressed, that the covering factor of metal-enriched portions of the clouds must be near unity. On smaller scales there may, of course, be lower metallicity pockets or unenriched regions.

We may, of course, be seeing directly the early stages of star formation in the halos of forming galaxies but it is also possible, perhaps even likely, that we may be seeing relics left over from subgalactic star formation in the dark ages at $z > 5$. If this is true, this metallicity and the fact that the IGM is ionized at $z = 5$ represent the two pieces of information we have about this period. Even in the $z = 5$ era [ref. 12] it is not easy to understand the uniformity since, based on simple cooling arguments, substantial star formation is only expected in near Galactic sized clumps.

3 Galaxy Redshift Distributions

Currently, large and near-complete redshift samples exist to $B = 24.5$, $I = 23$ and $K = 20$ as is summarised in Fig. 2 in the left hand panels. These surveys extend to about $z = 2$ and show that there is a very substantial evolution in the properties of the galaxies even by redshift one. By $z = 1$ there are many large galaxies whose colors and emission line properties show that they are dominated by massive star formation.

This may be most cleanly seen in the $K$-selected surveys which do not have the bias against early type galaxies at $z = 1 - 4$ which is present even in red optical samples. Fig. 3 shows the rest equivalent width of the [OII] 3727 line versus absolute $K$ magnitude in various redshift slices. This figure shows an interesting and (at least for a simple minded CDM theorist) somewhat surprising effect. Galaxies whose light is dominated by massive star formation typically have [OII] equivalent widths in excess of 25Å [ref. 14], and we can see from Fig. 3 that there are very few such galaxies at any $K$ luminosity at the present time. However at $z = 0.2$ there are small galaxies (the blue dwarfs) which fall into the category of rapid star formers, and as we move to higher redshift more and more massive galaxies appear to be [OII] luminous until at
Figure 2: The left hand panels show the redshift magnitude diagrams for near complete spectroscopic samples in the $K$, $I$ (Kron Cousins) and $B$ bands. The data is taken from the Autofib sample of Ellis et al. and the Hawaii survey for the $B$ sample, the CFRS survey and the Hawaii survey for the $I$ band and the Glazebrook sample and the Hawaii sample also for the $K$ band. For the $K$ band we have extended the sample beyond the completeness limit of $K = 20$ shown by the dotted line. The right hand panels show the spectroscopically identified objects given in Cohen et al. and Steidel et al. in the Hubble Deep Field as triangles. The remaining objects are shown at color estimated redshifts using a six color estimator with the four Hubble Deep Field colors and two IR colors ($J$ and $H+K$). This color estimator agrees well with all the measured spectroscopic redshifts. The solid and dashed lines show an unevolving Im (solid) and Sb (dashed) galaxy with $M_K = -25.8$, $M_I = -23.5$ and $M_B = -22$ for $H_0 = 50$ km s$^{-1}$/Mpc and $q_0 = 0.5$. 

\[ \text{Figure 2:} \]
Figure 3: Rest-frame [O II] equivalent width versus absolute rest $K$ magnitude and redshift for the $K < 20$ sample. In the lowest redshift interval (lower left panel) very few galaxies have strong [O II] lines or are undergoing rapid star formation ($\text{EW}([\text{O} \text{II}]) \sim 25$ Å). At higher redshifts, progressively more massive galaxies are undergoing rapid formation, until at $z > 1$ the locus of rapidly forming galaxies reaches a luminosity near $M_K^* \sim -25$. The absolute magnitudes are calculated for $q_0 = 0.5$ and $H_0 = 50 \text{ km s}^{-1}\text{Mpc}^{-1}$.

At $z > 1$ we see many near L* galaxies ($M_K^* = -25.1$) in this category. There are very few super L* galaxies at any redshift as can be seen from Fig. 2. Rather, galaxies seem to regulate at this value in their earlier stages. An $M_I = -23.5$ galaxy has an $AB$ magnitude of $-23$ and would be produced by a star formation rate of about 100 $M_\odot/\text{yr}$ [ref. 17]. This could easily form a massive galaxy if it persisted until $z = 1$.

In order to push this to higher redshifts we can construct color-estimated redshifts from the Hubble Deep Field (HDF) as was discussed by a number of groups at the conference and in the literature [22, 23]. The color estimates are not straightforward, particularly at the faint end where galaxies generally become very blue, and use of only the four Hubble colors can make this very uncertain. The estimates can be made somewhat more robust by ex-
Figure 4: The left panel shows the extragalactic background light (EBL) contribution of the $I < 26$ galaxy sample in the HDF as a function of wavelength (solid line). Also shown is the same quantity computed for a $K < 22$ sample (triangles), an $I < 24.5$ sample (crosses) and a $B < 25.5$ sample (boxes) in the Hawaii survey fields. The dashed lines show the expected UV surface brightness required to form the local metal density with the range reflecting the uncertainty in the metal density estimates. The right hand panel shows the evolution of the EBL per unit redshift at a wavelength of $3000(1+z)\,\text{Å}$ versus redshift in the $I < 23$ spectroscopic sample of the Hawaii fields (dotted line), in the $I < 23$ color estimated sample in the HDF (Dot-dash), and in the $I < 26$ color estimated sample in the HDF (solid line).

4 The history of galaxy formation

The integrated extragalactic background light (EBL) from the galaxies in the HDF is shown over the $3000\,\text{Å}$–$20000\,\text{Å}$ range in the left panel of Fig. 4 where it is compared with the integrated EBL in $B$, $I$, and $K$-selected samples from the Hawaii Galaxy Survey fields. The extra depth of the HDF does not...
greatly increase the EBL, although the shape is slightly bluer, since the number counts strongly converge in the red light density, while in the blue they only logarithmically diverge.

The ultraviolet EBL is a direct measure of the metal density production which may be compared with the local value of the metal density in the universe, whose rather uncertain range is shown by the dashed lines. When sliced by redshift it therefore produces a direct history of the star formation in the universe. This method has a considerable advantage over the method of constructing the UV light density as a function of redshift which was discussed by a number of speakers at the conference. The EBL technique measures the integrated production of metals either in total or in a given redshift interval independent of cosmology. By contrast, the UV luminosity density measures the production rate and is sensitive to the cosmology adopted. It must also be integrated back to study the total production.

As has been known for some years there is enough ultraviolet light to account for most of the current galaxies in relatively recent formation. The spectroscopic or color-estimated redshift distributions allow us to expand this result by slicing in the redshift direction. In the right-hand panel we show the EBL per unit redshift at a wavelength of 3000(1+z)Å as a function of redshift. The dotted line shows this for the $I < 23$ sample in the Hawaii Survey Fields using full spectroscopic data, while the dashed-dotted line shows the $I < 23$ sample for the HDF using the color-estimated redshifts. The agreement is satisfactory. The solid line then shows the $I < 26$ sample from the HDF. As can be seen by comparing the $I < 23$ sample with the $I < 26$ sample, the $I < 23$ sample maps the ultraviolet EBL well to just beyond $z = 1$ so that the $I < 26$ sample should be good to around $z = 3$. The fall-off in the $I < 26$ curve is therefore real and most star formation has taken place at $z \lesssim 1.5$. As can be seen from the thin dashed lines, the total amount of star formation agrees with the present metal density range. At the present redshift the larger area Hawaii Survey suggests that the star formation rate has begun to turn down.

From Fig. 4 we can see that most of the star formation occurs after $z = 1.5$ though it is probably beginning to die out by $z = 0$. As we have seen in section 3 below $z = 1$ most of this star formation is in relatively evolved galaxies. The redshift range for the formation matches that in which the baryons in the quasar absorption line systems vanish and is also broadly consistent with the general history of chemical evolution and star formation in our own galaxy.
Acknowledgments

This work was primarily supported by grants AR-06377.06-94A, GO-5401.01-93A and GO-05922.0194A from STScI. I would like to thank Richard Ellis for supplying the autofib data in machine form and Esther Hu for assistance.

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