The Metallicity of $0.5 < z < 1$ Field Galaxies

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**Abstract.** We are undertaking a program to measure emission line ratios in a selected sample of $0.5 < z < 1.0$ CFRS starforming galaxies in order to compute their Interstellar Medium metallicities. The latter are derived by means of the empirically-calibrated $R_{23}$ estimator introduced by Pagel et al. (1979). Here we focus on a subsample of 15 galaxies with $L_{H\beta} > 1.2 \times 10^{41}$ erg s$^{-1}$. In addition to the optical CFHT spectra discussed in Carollo & Lilly (2001), where a preliminary account of this work can be found, in this paper we also refer to new $J$-band Keck spectroscopy of the $H\alpha$ and [NII]6583 lines for several objects. These lines allow us to break the degeneracy between low ($\lesssim 0.1 Z_\odot$) and high ($\gtrsim 0.5 Z_\odot$) metallicity of the $R_{23}$ estimator, and put on solid ground the finding that the $0.5 < z < 1.0$ blue galaxies in the high-$L_{H\beta}$ sample are significantly metal-enriched ($Z \gtrsim 0.3 Z_\odot$ up to $Z_\odot$). Therefore, our results do not support previous suggestions in which the $0.5 < z < 1.0$ starforming galaxies are dwarf galaxies brightened by large bursts of star-formation, but support instead a picture where at least a significant fraction of them evolves to become today’s massive metal-rich systems.

1. **Introduction**

The Canada-France Redshift Survey (CFRS; Lilly et al. 1995a) and other similar surveys have shown evolutionary changes in the field galaxy population over the redshift interval $0 < z < 1$. At $z \sim 1$ a substantial population of $L \sim L^*$, blue galaxies with small sizes and irregular morphologies (Brinchmann et al. 1998, hereafter B98; Lilly et al. 1998; hereafter L98) appears, a population that is largely absent in the local Universe.

Studies that have provided e.g., the morphologies and sizes of the $z \sim 1$ field blue galaxies (e.g. B98; L98), and their internal kinematics have suggested that these blue galaxies have generally the irregular morphologies (B98), small sizes
(3-5 \, h_{50}^{-1} \, \text{Mpc}, \text{L98}) \text{ and low velocity dispersions } \sigma < 100 \, \text{km s}^{-1} \text{ (Guzman et al. 1997; Vogt et al. 1997; Mallen-Ornelas et al. 1999) that are usually associated in the local Universe with galaxies 2-3 magnitudes further down the luminosity function. These results support at first sight a scenario where the } z \sim 1 \text{ blue galaxies are dwarf galaxies substantially brightened by a burst of star formation. There are still, however, major gaps in our knowledge of galaxies in the } 0.5 < z < 1.0 \text{ redshift regime, and it is possible that this interpretation of the morphologies and the kinematic data is incorrect. Not least, the possibility that the small-blue-irregular galaxies are the cores of more massive galaxies cannot be ruled out at this stage. For example, the } K \text{-luminosities of typical blue galaxies at } z \sim 0.8 \text{ are comparable to those of today’s massive galaxies, leading to suggestions that at least some of these blue objects may be indeed the progenitors of massive systems (Cowie et al. 1996).}

Detailed astrophysical diagnostics are needed to discriminate between the two scenarios. The metallicity of the interstellar medium (ISM) of distant star-forming field galaxies is particularly important, both as a general indicator of the evolutionary state of these systems, and as a constraint on their possible present-day descendants. No information has been available about the ISM metallicities of galaxies in the } 0.5 < z < 1.0 \text{ redshift regime. We have therefore begun a program of systematic emission line spectroscopy of CFRS galaxies to determine their ISM metallicity, and to study how the metal content in these systems correlates with galaxy luminosity, star-formation rate, structure and morphology. Our program uses the } R_{23} = (\text{[OII]}3727 + \text{[OIII]}4959 + 5007)/H\beta \text{ metallicity estimator (Pagel et al. 1979; see also Kobulnicky et al. 1999 for a detailed description of the potential accuracy that can be obtained in using } R_{23} \text{ to measure metallicities of unresolved galaxies at high redshifts). The lines required to measure } R_{23} \text{ are shifted into the } 5000 \, \text{Å} - 1 \, \mu \text{m wavelength region for } 0.5 < z < 1. \text{ A reversal in } R_{23} \text{ occurs however at } Z \sim 0.3Z_\odot \text{ due to cooling effects (so a low- and a high-metallicity solution are associated with most values of } R_{23}), \text{ and the } \text{[OIII]}5007/\text{[NII]}6584 \text{ ratio is required to break this degeneracy (Kobulnicky et al. 1999). Our program therefore includes supplementary spectroscopy of } H\alpha, \text{[NII]}6584 \text{ and } \text{[SII]}6717,6731 \text{ lines (which, for } 0.5 < z < 1, \text{ are shifted into the near-infrared } J\text{-band) for reddening determinations, AGN discrimination and breaking of the } R_{23}\text{-degeneracy with metallicity through the } \text{[OIII]}/\text{[NII]} \text{ ratio.}

In this paper we use deep } 0.5 < \lambda < 1.0 \mu \text{m multi-object spectrophotometry collected at the Canada-France-Hawaii Telescope in March 2000 (already published in Carollo & Lilly 2001), and refer to complementary } J\text{-band spectroscopy that we have in the meanwhile acquired with NIRSPEC at Keck for five objects in the optical sample (in preparation). We use } H_0 = 50 \, \text{Mpc/Km/s and } q_0 = 0.5 \text{.}

2. The Sample

The target galaxies were selected from the CFRS to have, in addition to the original } I_{AB} < 22.5 \text{ photometric selection, an } \text{[OII]}3727 \text{ flux } > 7 \times 10^{-17} \text{ erg s}^{-1}\text{cm}^{-2}, \text{ so as to ensure strong enough lines for a measurement of the } R_{23} \text{ parameter. 34 such objects were observed in our first CFHT observing run. The } H\beta \text{ luminosity is however likely to be better related to the star-formation}
rate than the [OII] flux. Unfortunately, H\(\beta\) measurements were not available beforehand, so an approximation to an \(H\beta\)-luminosity selected sample could only be constructed a posteriori. The current optical analysis is therefore based on the 15 out of 34 objects with H\(\beta\) luminosities above \(L_{H\beta} > 1.2 \times 10^{41}\) erg s\(^{-1}\). This high-\(L_{H\beta}\) selection well samples the ‘blue’ starforming CFRS galaxy population.

Three high redshift galaxies in the original sample of 34 had upper limits to their H\(\beta\) luminosities which were above our \(L_{H\beta} = 1.2 \times 10^{41}\) erg s\(^{-1}\) threshold, possibly putting these systems into the high-\(L_{H\beta}\) sub-sample that is discussed in this paper. The line ratios for these galaxies are necessarily uncertain; however, we have included these systems in the figures for completeness, and assigned to them the range of line ratios that they would have if their H\(\beta\) luminosities were indeed above our threshold. We have however identified these three objects with different symbols, as a reminder that they may well not belong to the high-\(L_{H\beta}\) sub-sample.

### 3. Results and Discussion

Figures 1a and 1b show the [OIII]5007/[OII]3727 versus \(R_{23}\) relation for the local field sample of Jansen et al. (2000) and the high-\(L_{H\beta}\) CFRS galaxies of our sample, respectively. In the figures, the solid and dashed lines are lines of constant metallicity. From left to right, the dashed lines indicate increasing metallicities from 0.02\(Z_\odot\) to 0.2\(Z_\odot\). At \(Z \sim 0.3Z_\odot\), the reversal of \(R_{23}\) occurs, and the curves of constant metallicity then follow the solid-line sequence in which \(Z\) rises up to about 3\(Z_\odot\) from right back to left. The \(Z = Z_\odot\) curve is highlighted with a thicker linewidth. In order to appropriately compare the local and the high-\(z\) samples, the local Jansen et al. galaxies which have \(L_{H\beta} > 1.2 \times 10^{41}\) erg s\(^{-1}\) are identified with large circles; local galaxies with smaller
$H\beta$ luminosities are represented by small circles. Furthermore, in Figure 1a, filled symbols represent objects which have a flux ratio $[OIII]5007/[NII]6584 > 2$ and thus metallicities $Z \lesssim 0.5Z_\odot$, and empty symbols indicate objects with higher metallicities, as indicated by a flux ratio $[OIII]5007/[NII]6584 < 2$ (see Edmunds & Pagel 1984). In Figure 1b, the high-$z$ galaxies are represented by the filled squares, with the exception of the three objects which may or may not be in the sample on account of their H$\beta$ upper limits (empty squares). The fiducial dotted-line box in both panels encompasses the bulk of the Jansen’s galaxies. The arrows represent the direction in which the points of the diagram would shift due to reddening by dust (as described by Cardelli et al. 1989); the length of the arrows refer to an $E(B-V) = 0.3$ magnitudes at $z = 0.7$.

The high redshift galaxies fall in the $R_{23}$ versus $[OIII]/[OII]$ plane in locations that are occupied by galaxies in the local Jansen et al. (2000) sample. Furthermore, most of the high redshift sample selected to have $L_{H\beta} > 1.2 \times 10^{41}$ erg s$^{-1}$ occupies the same restricted location in the $R_{23}$ versus $[OIII]/[OII]$ plane as do the objects in the local Universe with similarly high $H\beta$ luminosities. At both epochs, galaxies selected to have the same H$\beta$ luminosities exhibit the same range of $R_{23}$ and $[OIII]/[OII]$. Two objects have, within the error bars, $R_{23} \sim 7$, the value that is non-degeneratively associated with intermediate metallicities $Z \sim 0.3Z_\odot$. These two objects were excluded from the discussion in Carollo & Lilly (2001) due to their $[NeIII]3869$ emission that made them good candidates for AGN activity. The $Z$-degenerate $R_{23}$ values that are measured for the remaining high-$z$ galaxies indicate either rather low ($\lesssim 0.1Z_\odot$) or rather high ($\sim Z_\odot$) metallicities for these systems.

The similarity between most of the high-redshift galaxies and the low-redshift sample is further illustrated in Figure 2, which shows the relationship between $R_{23}$ and continuum luminosity $M_B$. There is a startling similarity between the high-$z$ and the local galaxies on this diagram. There is little evidence for an evolutionary change in the relationship between metallicity (as estimated from $R_{23}$) and the line and continuum luminosities for high-$L_{H\beta}$ field galaxies between $z \sim 0$ and $z \sim 1$. The two $[NeIII]$ emitters are the only two systems out of 15 which may indicate a different relationship, i.e. one produced by substantial brightening of lower $Z$ systems.

$J$-band spectroscopy is available for five of the 15 galaxies, including the two $[NeIII]$ emitters. These new data provide the intensity of the $[NII]6584$ emission line, and enable us to compute the degeneracy-breaking $[OIII]5007/[NII]6584$ ratio. Three of the five objects have $[OIII]5007/[NII]6584$ ratios that undoubtedly place them on the high-metallicity branch of the $R_{23}$ parameter, with a metallicity of $\gtrsim 0.5Z_\odot$ up to solar. The remaining two objects are the two $[NeIII]$ emitters, which are proven to be ‘normal’ star forming galaxies (rather than AGN) and confirmed to have the intermediate, $Z \sim 0.3Z_\odot$ value indicated, within the errorbars, by the $R_{23}$ parameter.

The near-infrared data therefore demonstrate a high, i.e. about solar metallicity for at least some objects in our $0.5 < z < 1$ high-$L_{H\beta}$ sample. The HST morphology of one of these high-metallicity objects is that of a regular two-armed spiral (Schade et al. 1995), and so it is possibly not surprising that this galaxy has a high metal content. It may be that our high-$L_{H\beta}$ selection favours large well-formed galaxies relative to the general blue CFRS population. How-
Figure 2. The $R_{23}$ versus absolute $B$ magnitude relation for the galaxies in the local universe (circles) and those in the $0.5 < z < 1$ redshift regime (squares). Symbols are as in Figures 1a and 1b, and are explained in the text.
ever, there is no indication that this is the case from the HST morphology of three additional objects for which the HST data are available (Lilly & Carollo 2001). More importantly, a second object among the three with confirmed high metallicity and HST morphology shows the irregularity and compactness typical of the blue galaxy population at those redshifts.

Of course, until we obtain the infrared spectroscopy for the entire sample, the $R_{23}$ degeneracy with $Z$ does not allow us to prove on what branch — i.e., the low- or the high-metallicity one — each individual high-$z$ galaxy lies, and the possibility remains that some objects have indeed very low metallicities $Z \lesssim 0.1Z_\odot$, making them strong candidates for star bursting dwarfs. However, at this stage, the confirmation that at least a large fraction of the high-$L_{H\beta}$ $0.5 < z < 1$ star forming galaxies has high metallicities within $\sim 40$-$50\%$ of solar contrast the idea that these systems are all low mass, i.e., low metallicity dwarfs brightened by substantial luminosity evolution. In contrast, the metallicity data seem to suggest that at least a large fraction of these small irregular galaxies are in fact the progenitors of today’s massive, metal-rich galaxies, but seen in an earlier phase of their evolution when they were already significantly metal-rich but morphologically more disturbed and smaller.

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