EVIDENCE FOR CHEMICAL EVOLUTION IN SPECTRA OF HIGH REDSHIFT GALAXIES *

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Abstract. Using a sample of 57 VLT FORS spectra in the redshift range $1.37 < z < 3.40$ and a comparison sample with 36 IUE spectra of local ($z \approx 0$) starburst galaxies we derive C IV equivalent width values and estimate metallicities of starburst galaxies as a function of redshift. Assuming that a calibration of the C IV equivalent widths in terms of the metallicity based on the local sample of starburst galaxies is applicable to high-z objects, we find a significant increase of the average metallicities from about $0.16\ Z_{\odot}$ at the cosmic epoch corresponding to $z \approx 3.2$ to about $0.42\ Z_{\odot}$ at $z \approx 2.3$. A significant further increase in metallicity during later epochs cannot be detected in our data. Compared to the local starburst galaxies our high-redshift objects tend to be overluminous for a given metallicity.

Keywords: galaxy evolution, stellar content

1. The Project

To answer the questions how galaxies have formed and evolved, it is necessary to understand the properties of the stellar population of the very first galaxies at early cosmic epochs. In orders to derive informations on galaxies in the early universe we obtained new high S/N spectra of galaxies with $z \leq 3.5$ in the FORS Deep Field (FDF; e.g. Heidt et al., 2001; Bender et al., 2001). To compare our results on the high-z universe with the local cosmos we also included a sample of local ($z \approx 0$) starburst galaxies. In the present report we describe results based on the C IV absorption line strength and their interpretation in terms of chemical evolution with cosmic age.

2. Sample selection and observations

During 6.5 nights of MOS and MXU observations with FORS1&2 at the VLT we obtained 300 object spectra with sufficient S/N to determine the type and redshift. Using the grism 150I and a slit width of 1" we covered the spectral range from 3400 to 10000 Å with a spectral resolution element of ≈ 25 Å. The data reduction is described in Noll et al. (2002). For the present investigation we selected 51 FDF galaxies showing absorption line spectra with an S/N > 10 per resolution element,

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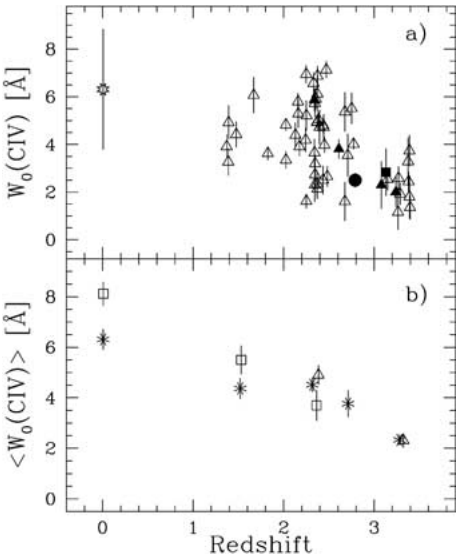

Figure 1. Measured C IV equivalent widths **a)** and averages of this value within selected z bins **b)** as a function of z. **a)**: Open star at $z \approx 0$: Average and 1σ rms scatter for the 36 local starburst galaxies. Open triangles – FDF galaxies. Filled triangles – Galaxies from cluster 1E0657-558. Filled circles and squares – Galaxies in the HDF-S and AXAF Deep Field, respectively. **b)**: Asterisks – all galaxies shown in Fig.1a. Open triangles and squares – FDF galaxies with magnitude $M_B \leq -22.28$ mag and -21.52 mag $\leq M_B \leq -20.38$ mag, respectively (see Fig. 2). The bars indicate the mean errors of the averages.

adequate for a meaningful quantitative analysis of the C IV resonance doublet. All these galaxies show typical starburst characteristics in their spectra such as intense (rest frame) UV continua and highly ionized metal absorption lines. We also added 6 additional FORS spectra which had been observed with the same setup during the FORS commissioning runs (Mehlert et al., 2001; Cristiani et al., 2000). The comparison sample of IUE low resolution spectra from the IUE archive* consists of 36 local ($z \approx 0$) starburst galaxies investigated by Heckman et al. (1998). They cover a similar rest-frame spectral range with a slightly better spectral resolution than our FORS spectra.

3. Results

C IV equivalent widths: High-excitation lines like C IV are produced mostly in stellar photospheres and winds and their strengths depend sensitively on the stellar metallicity (see Walborn et al., 1995; Heckman et al., 1998). Therefore, we measured the rest-frame equivalent widths W_0 of this feature for those galaxies with reliable spectroscopic redshifts $z > 1.35$ (i.e. galaxies where the C IV doublet was

* `http://ines.laeff.esa.es`

redshifted into our observed spectral range) as well as for the comparison sample of $z \approx 0$ starburst galaxies.

Figure 1a shows that our high-redshift galaxies with $z < 2.5$ have about the same average C IV equivalent widths and about the same scatter around the average as the local starburst galaxies. However, for redshifts larger than about 2.5 the average C IV equivalent widths and their scatter clearly decrease with z in our sample. In order to estimate the statistical significance of the effect, we calculated averages and their mean errors of the W_0(C IV) values for selected redshift bins. From Figure 1b it is clear that for the three bins with $z < 2.5$ no statistically significant differences are present. However, the difference between the local sample and our starburst galaxies with $z > 3.0$ is highly significant ($> 9\sigma$).

Metallicities: Since differences of the C IV line strength cannot be easily explained by population differences in the starburst galaxies, the observed decrease of the C IV equivalent width values for $z > 2.5$ can at present only be interpreted as a metallicity effect. Hence, the decrease of W_0(C IV) with z is expected to contain information on the evolution of the metal content of starburst galaxies with cosmic age. In order to derive a more quantitative measure of this metallicity evolution we calibrated the observed W_0(C IV) values in terms of the O/H ratios by using the oxygen abundances listed for 45 local starburst galaxies in Heckman et al. (1998). The metallicity derived obviously correlates with the measured W_0(C IV) values and the best linear least square fit to these data gives $\log Z/Z_\odot = 0.13(\pm 0.02) \times W_0(\mathrm{C\,IV}) - 1.10(\pm 0.12)$. Assuming that this correlation is also valid for our high-z starburst galaxies we can convert our observed C IV equivalent width values to metallicities. In this way we obtain for our starburst galaxies with $z > 3$ ($< z >= 3.24$) an average metallicity of about $0.16\,Z_\odot$ and for $< z >= 2.34$ a value of $0.42\,Z_\odot$. The corresponding local ($z = 0$) value would be $0.56\,Z_\odot$. In terms of cosmic time scales ($\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, $H_0 = 67$ km sec^{-1} Mpc^{-1}) this would correspond to an increase of the mean metallicity in starburst galaxies by a factor of 2.5 within ≈ 1 Gyr between cosmic ages of about 1.9 Gyrs and 2.9 Gyrs. For later epochs the data suggest only little further enrichment.

Luminosity effects: For local ($z \approx 0$) galaxies the metallicities are known to depend on the galaxies' blue and infrared luminosities, with luminous galaxies tending to have higher metallicities (see e.g. Kobulnicky and Zaritsky, 1999 and Heckman et al., 1998). To test whether at high redshifts a metallicity-luminosity correlation does exist and may affect the apparent metallicity evolution, we plotted in Figure 2 the absolute restframe B-magnitudes M_B of all high-redshift FDF galaxies as well as for the local starburst galaxies. From Fig. 2 we see that the local starburst galaxies indeed show the expected correlation between W_0(C IV) (our metallicity indicator) and the luminosity. For the high-redshift galaxies we cannot determine whether a metallicity-luminosity correlation does exist, since we do not have any faint objects in our high-z sample. But it is evident that the high-redshift

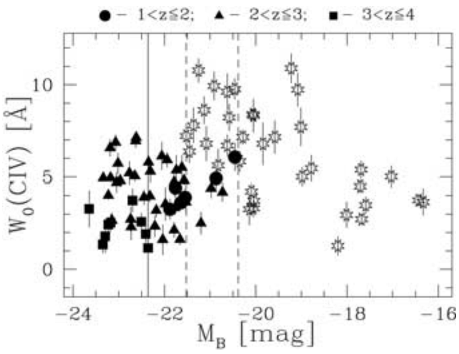

Figure 2. CIV equivalent widths of the local (open stars) and the high-z FDF (filled symbols) starburst galaxies versus the absolute B-magnitude. For the latter ones we indicated objects within the different redshift bins. The solid vertical line indicates $M_B = -22.36$ mag and the dashed vertical lines indicate $M_B = -21.52$ mag and $M_B = -20.38$ mag.

galaxies are on average overluminous for their metallicities as compared to local starburst galaxies. This agrees well with earlier results by Pettini et al. (2001) and Kobulnicky and Koo (2000) who find this trend for Lyman-break galaxies. Hence, if a metallicity-luminosity relation does exist at high redshifts, our data suggest that it has a clear offset to the local correlation, which seems to evolve with redshift. Moreover, it is obvious that for the high-redshift galaxies there is no correlation between the measured W_0(C IV) and the luminosity that may produce the observed metallicity evolution.

At high redshifts we do not have any faint objects in our sample, while in the local universe we do not find bright starburst galaxies. Thus we have to make sure that the observed metallicity evolution is not an artifact due to comparing different objects at different redshifts. Therefore we separately investigated all galaxies, which are brighter than the faintest one at $z \geq 3$ (which is $M_B = -22.36$ mag; solid line in Figure 2). In our sample we only find galaxies brighter than this limit for $z \geq 2$. From their average values of the measured W_0(C IV) (open triangles in Figure 1b) and the mean error it is obvious that this subsample shows the same trend with decreasing redshift as the total galaxy sample at $z \geq 2$. The same is true for all galaxies fainter than $M_B = -21.52$ mag (brightest local galaxy) and brighter than $M_B = -20.38$ mag (faintest galaxy with $z \geq 1$; open squares in Figure 1b). From these tests we conclude that the observed dependence of W_0(C IV) on redshift is not caused by luminosity effects.

References

Bender, R., Appenzeller, I. Böhm, A. et al.: 2001, in: S. Cristiani, A. Renzini and R. Williams (eds.), *the ESO/ECF/STScI Workshop on 'Deep Fields'*, p. 96.

Cristiani, S., Appenzeller, I., Arnouts, S. et al.: 2000, *A&A* **359**, 489.

Heckman, T.M., Robert, C., Leitherer, C. et al.: 1998, *ApJ* **503**, 646.

Heidt, J., Appenzeller, I. Bender, R. et al.: 2001, *Rev. Mod. Astron.* **14**: Dynamic Stability and Instabilities in the Universe, edited by Reinhard E. Schielicke, p. 209.
Kobulnicky, H.A. and Koo, D.C.: 2000, *ApJ* **545**, 712.
Kobulnicky, H.A. and Zaritsky, D.: 1999, *ApJ* **511**, 188.
Mehlert, D., Seitz, S., Saglia, R.P. et al.: 2001, *A&A* **379**, 96.
Noll, S., Mehlert, D., Appenzeller, I. et al.: 2002, in preparation.
Pettini, M., Shapley, A.E., Steidel, C.C. et al.: 2001, *ApJ* **554**, 981.
Walborn, N.R., Lennon, D.J., Haser, S.M. et al.: 1995, *PASP* **107**, 104.


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