

The most metal-poor damped Ly α system at $z < 3$: constraints on early nucleosynthesis

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Abstract

To constrain the conditions for very early nucleosynthesis in the Universe we compare the chemical enrichment pattern of an extremely metal-poor damped Lyman α (DLA) absorber with predictions from recent explosive nucleosynthesis models. For this, we have analyzed chemical abundances in the DLA at $z_{\text{abs}} = 2.6183$ toward the quasar Q0913+072 ($z_{\text{em}} = 2.785$) using public UVES/VLT high spectral resolution data. With $[\text{C}/\text{H}] = -2.83 \pm 0.05$, $[\text{N}/\text{H}] = -3.73 \pm 0.09$, and $[\text{O}/\text{H}] = -2.47 \pm 0.05$, this system represents one of the most metal-poor DLA systems investigated so far. The chemical evolution of this DLA is dominated by one or at most a few stellar generations. With reference to numerical model calculations, the chemical abundances in the DLA appear consistent with an enrichment from a single starburst of a zero-metallicity population (Pop III) of massive stars ($\sim 10 - 50 M_{\odot}$) exploding as core-collapse Supernovae (SNe) with $E = 10^{51}$ erg, i.e., the classical Type II Supernovae (SNe II), and possibly Hypernovae (HNe) as well.

Introduction

Recent theoretical studies (e.g., Omukai & Palla 2003) predict that the first (Pop III) stars must have been very massive ($\sim 100 - 600 M_{\odot}$), thus indicate a top-heavy initial mass function (IMF). Stellar evolution studies (Heger & Woosley 2002) show that primordial stars with main-sequence masses between $\sim 50 - 140 M_{\odot}$ and above $\sim 260 M_{\odot}$ inevitably collapse into black holes and are unable to eject their metals. Hence, only primordial stars of $\sim 140 - 260 M_{\odot}$, exploding as pair-instability supernovae (PISNe), or stars below $\sim 50 M_{\odot}$, exploding as "ordinary" core-collapse SNe, will eventually enrich the interstellar (ISM) and subsequently the intergalactic medium (IGM).

Fate of massive stars

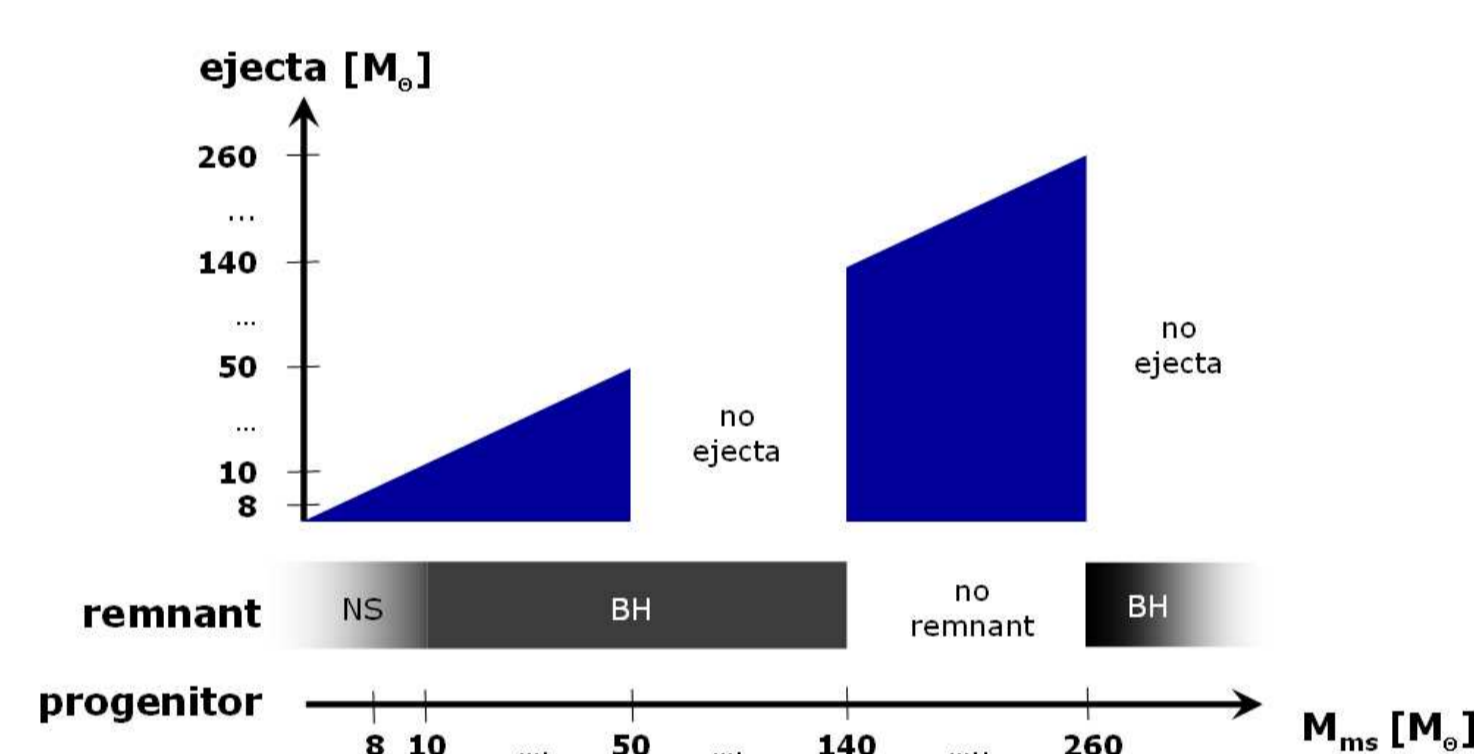


Fig. 1. From the above sketch we can see that only stars with progenitors of in the mass range of $M_{\text{ms}} \approx 10 - 50 M_{\odot}$ and $\approx 140 - 260 M_{\odot}$ do contribute to the chemical enrichment (Heger & Woosley 2002). Although the luminosities of galaxies depend primarily on stars of masses $\approx 1 M_{\odot}$, metal enrichment and feedback effects on galactic scales depend on the number of stars with masses above $\sim 10 M_{\odot}$ (Ciardi & Ferrara 2004).

nucleosynthesis (Oh et al. 2001) for Pop III stars could solve this disagreement. In order to constrain the mass range for Pop III stars with chemical feedback effects on galactic scales, we analyze the abundance pattern of an extremely metal poor protogalactic structure at high redshift by quasar absorption-line spectroscopy.

Quasar absorption-line (QAL) systems are important objects to study the IGM at low and high redshifts. Metal abundance measurements in QALs at high redshift are particularly important to learn about the first generations of stars in the Universe, as these objects should have left a characteristic signature in the abundance pattern of chemically young systems.

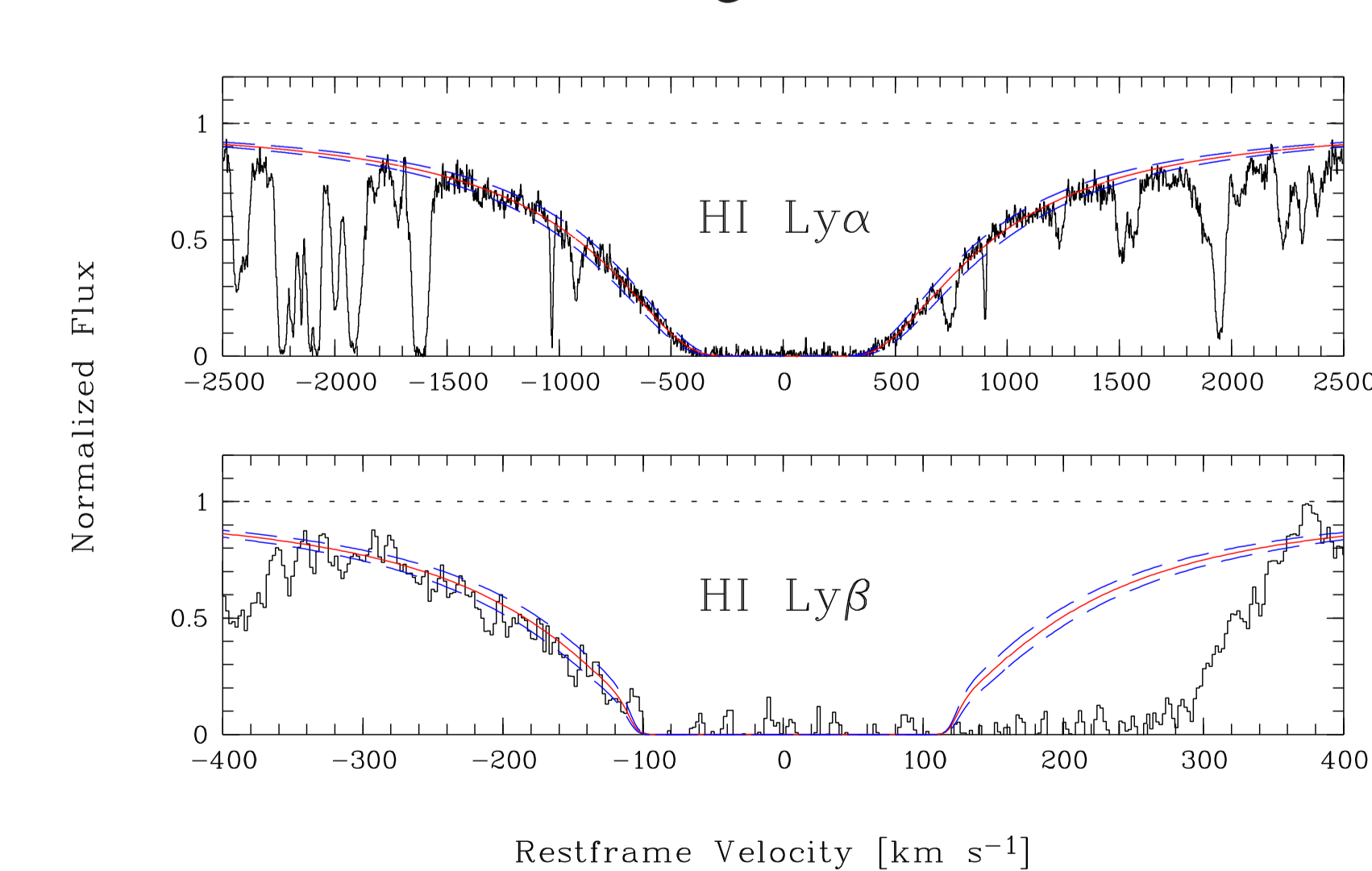


Fig. 2. DLA at $z_{\text{abs}} = 2.6183$ toward the quasar Q0913+072 ($z_{\text{em}} = 2.785$): Lyman α and β are shown in velocity space where the velocity rest frame was set at $z=2.6183$.

in stars, in the past it must have been in the form of gas. The DLA system we discuss is characterized by a very low overall metallicity. It exhibits an abundance pattern that points to an enrichment of only one or at most a few stellar generations. Thus, the UVES high resolution data of the DLA toward Q0913+072 provide us with a unique insight into the early enrichment history of a proto-galactic structure at $z \approx 2.6$.

It has been proposed (Bromm et al. 2001; Schneider et al. 2002) that metal enrichment is the mechanism responsible for a transition from a top-heavy to a more conventional power-law IMF as observed in the present-day Universe. The metallicity is believed to reach a critical value at $[M_{\text{cr}}/\text{H}] \approx -4$, marking a transition mode from a high-mass to a low-mass fragmentation mode of the protostellar gas cloud. Conversely, recent observations of hyper metal-poor (HMP) stars (e.g., HE0107-5240 with $[\text{Fe}/\text{H}] = -5.2$ or HE1327-2326 with $[\text{Fe}/\text{H}] = -5.4$) might, at first sight, rule out a top-heavy IMF for Pop III stars. Other scenarios like a bimodal IMF (Nakamura & Umemura 2001; Omukai & Yoshii 2003), binary star formation, or a nonstandard

Damped Lyman α absorbers (DLA) are QAL systems with large hydrogen column densities ($N(\text{H}) \geq 2 \times 10^{20} \text{cm}^{-2}$); they are most suitable for studies of the chemical evolution at high redshift (Péroux et al. 2003). Number statistics of DLA systems imply that these objects dominate the neutral gas content of the Universe at $z > 1$ (Lanzetta et al. 1995; Wolfe et al. 1995; Rao & Turnshek 2000). While the observable baryonic content of today's galaxies is concentrated

Data & Analysis

The quasar Q0913+072 was observed by the VLT UV-Visual Echelle Spectrograph (UVES), providing a high-resolution ($R \sim 45,000$) spectrum. The raw data were reduced using the UVES data pipeline implemented in the ESO-MIDAS software package. The signal-to-noise ratio in the whole spectrum ($\sim 3,500\text{\AA} - 10,200\text{\AA}$) is generally very high and gains a maximum of ~ 150 per resolution element for $\lambda \lesssim 4000\text{\AA}$. These data are public and can be found in the UVES database of ESO's Science Archive Facility^a.

The data were analyzed with the program FITLYMAN (Fontana & Ballester 1995) in the ESO-MIDAS software package, using a χ^2 minimization algorithm for Voigt-profile fitting. Simultaneous fitting procedures and the high resolution spectrum allow us to determine the column density N and the doppler parameter $b = (b_{\text{therm}}^2 + b_{\text{turb}}^2)^{1/2}$, which in our case is dominated by the turbulent term, with high accuracy.

^ahttp://archive.eso.org

Results & Discussion

Species	Transition lines used	$\log N(X) \pm \sigma_{\log N}$	$[\text{X}/\text{H}] \pm \sigma_{[\text{X}/\text{H}]}$
C II	1036,1334	14.05 ± 0.01	-2.83 ± 0.05
N I	1199	12.58 ± 0.07	-3.73 ± 0.09
O I	1039,1302	14.58 ± 0.01	-2.47 ± 0.05
Al II	1670	11.84 ± 0.02	-3.01 ± 0.05
Si II	1304,1526	13.35 ± 0.01	-2.57 ± 0.05
Fe II	1096,2344,2600	13.09 ± 0.01	-2.77 ± 0.05
Fe III	1122	$\leq 13.33 \pm 0.01$	
Ni II	1370	$\leq 12.17 \pm 0.18$	$\leq -2.44 \pm 0.19$

Table 1. Summary of chemical abundances using the common notation $[\text{X}/\text{H}] = \log(N(\text{X})/N(\text{H})) - \log(N(\text{X})/N(\text{H}))_{\odot}$.

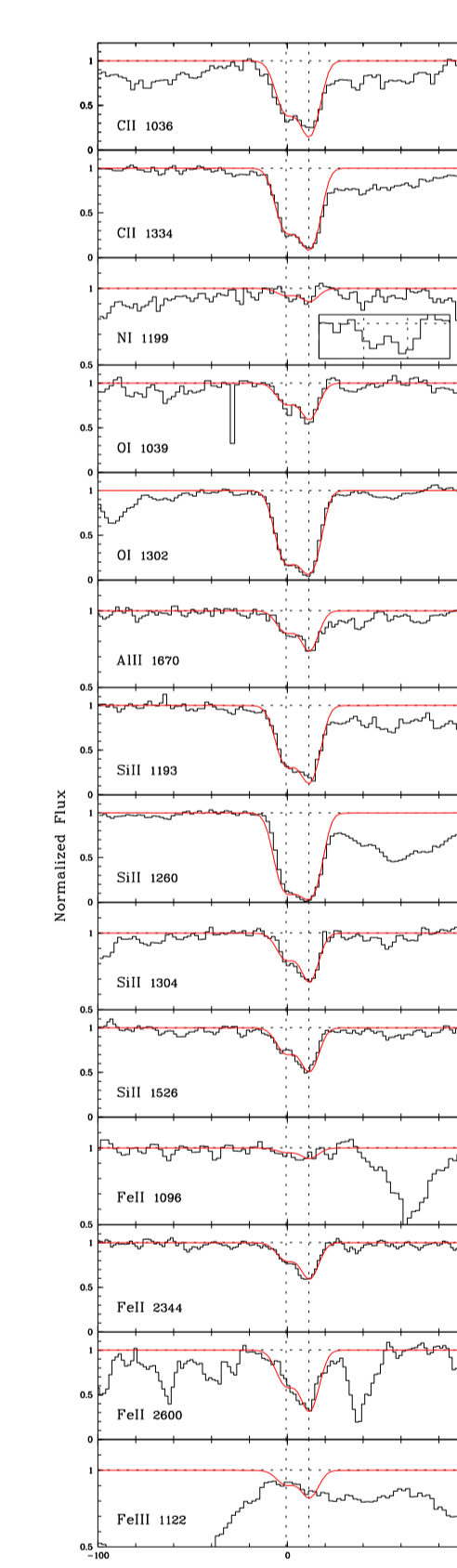


Fig. 3. Detected absorption for different ions.

In a recent paper Daigne et al. (2004) have modeled the chemical evolution of condensed cosmic structures (galaxies) and the IGM as a function of redshift including the process of reionization. They consider various different SFRs and IMFs for the progenitor stars that drive the metal enrichment in the early Universe. Following their calculations, a bimodal (or top-heavy) IMF with a moderate mass range of $40 - 100 M_{\odot}$ yields to both, the required number of ionizing photons to reionize the Universe at $z = 17$, and the correct chemical composition of nucleosynthesis products of these stars to match the observations of metal abundances in metal-poor halo stars and in the IGM. When comparing the mass fractions of C, N, O, Si, and Fe presented in their models with those derived for the DLA toward Q0913+072 we find that the abundances of these elements in the DLA are slightly (< 1 dex, typically) above the values predicted for the IGM at $z = 2.6$, but substantially lower than what is expected for the ISM in galaxies at that redshift. This implies that the DLA toward Q0913+072 represents a protogalactic structure that has just recently formed, so that local star formation activity in this system had not enough time to significantly enhance the abundance level above that of the surrounding IGM. The DLA system at $z = 2.6183$ toward Q0913+072 is characterized by a very low overall metal abundance ($[\text{Z}/\text{H}] = [\text{O}/\text{H}] = -2.47$), a pronounced deficiency of nitrogen ($[\text{N}/\text{H}] = -3.73$), and a mild underabundance of carbon ($[\text{C}/\text{H}] = -2.83$). These values mark this system as the most metal-poor DLA observed in the redshift range $2 < z < 3$. We further report this absorber to be the first DLA at present date with a reliable carbon measurement. The low nitrogen abundance implies that this system has not yet attained the full level of primary nitrogen enrichment. We do not expect our results to be altered due to dust depletion or photoionization effects.

Comparing the metal abundance pattern of the DLA system at $z = 2.6183$ toward Q0913+072 with yields from explosive nucleosynthesis model calculations, we conclude that the most likely scenario for the observed abundance pattern was massive (but not super-massive) Pop III stars with $M_{\text{ms}} \approx 10 - 50 M_{\odot}$, exploding as core-collapse SNe/HNe. Any significant contribution from PISNe can be excluded. Scenarios of progenitor stars with a non-zero metallicity, a top-heavy IMF, other explosion mechanism like SNe Ia or PISNe, or a combination the foregoing, can not explain the observed chemical abundance pattern.

$z_{\text{abs}} = 2.6183$ corresponds to a lookback time of 11.1 Gyr (i.e., to an age of the Universe of 2.5 Gyr at that redshift)^a. Given the very low abundance, the chemical evolution of this system is lagging behind the evolution of other DLA systems at similar redshifts. This DLA can be compared with the nearby dwarf galaxy *I Zwicky 18*, which contains no stars older than 0.5 Myr. Either these kind of galaxies have formed just recently, or they have been existing as protogalactic structures for a time as long as 13 Gyr.

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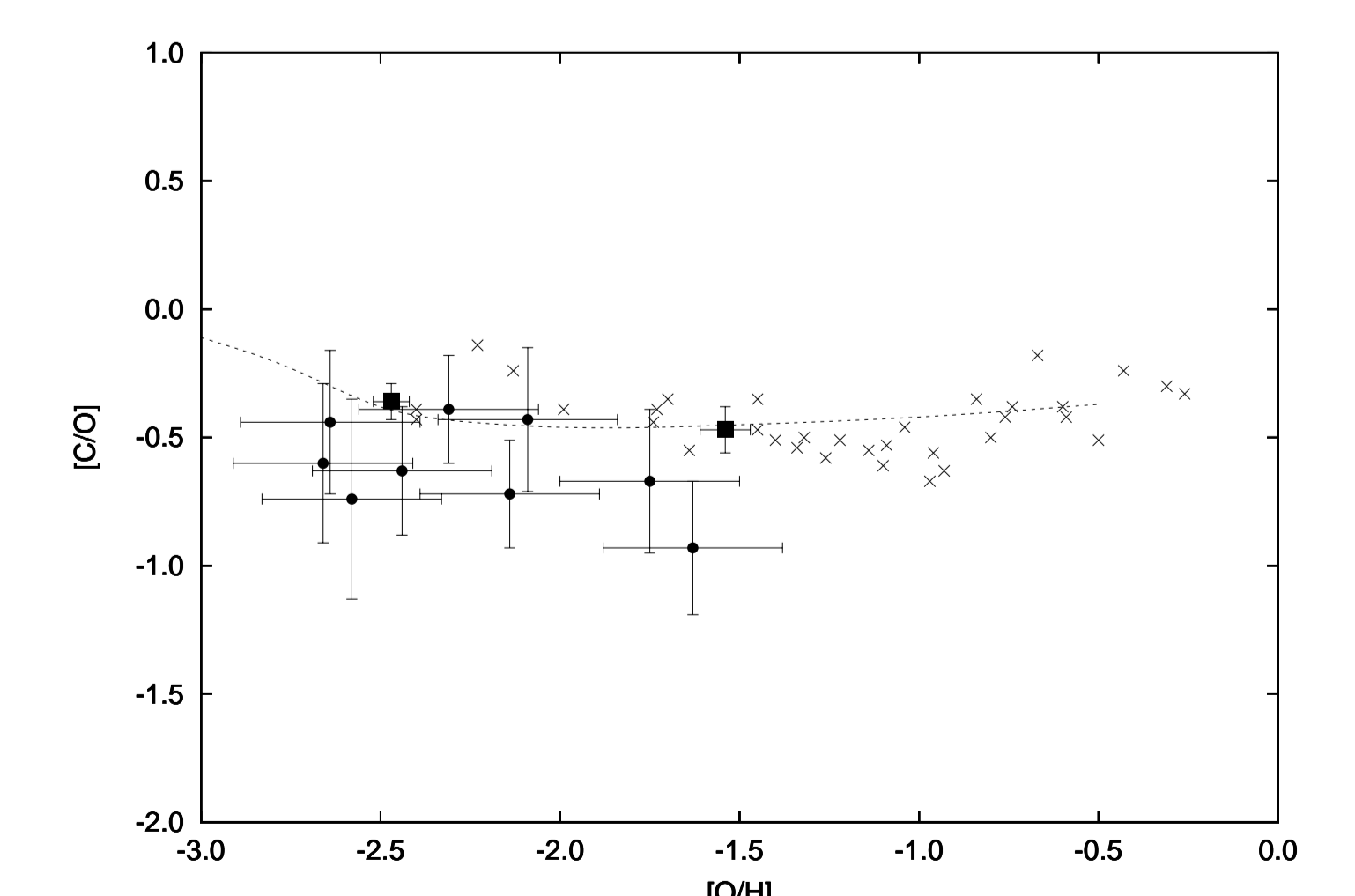


Fig. 4. We compare the only two existing carbon abundance measurements in DLA systems (squares) with extremely metal-poor halo stars (crosses) from Akerman et al. (2004), and (circles) from Spite et al. (2005). The dashed line shows predictions from Pop III stars (Chieffi & Limongi 2002) for an IMF with $M_{\text{ms}} \geq 10 M_{\odot}$.

^ausing $H_0 = 71 \text{ km s}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\text{tot}} = 1$