

# The elemental abundance pattern in a galaxy at $z = 2.626$

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The discovery of metal-poor stars<sup>1,2</sup> (where metal is any element more massive than helium) has enabled astronomers to probe the chemical enrichment history of the Milky Way<sup>3,4</sup>. More recently, element abundances in gas inside high-redshift galaxies has been probed through the absorption lines imprinted on the spectra of background quasars<sup>5–8</sup>, but these have typically yielded measurements of only a few elements. Furthermore, interpretation of these abundances is complicated by the fact that differential incorporation of metals into dust can produce an abundance pattern similar to that expected from nucleosynthesis by massive stars<sup>9</sup>. Here we report the observation of over 25 elements in a galaxy at redshift  $z = 2.626$ . With these data, we can examine nucleosynthetic processes independent of the uncertainty arising from depletion. We find that the galaxy was enriched mainly by massive stars ( $M > 15$  solar masses) and propose that it is the progenitor of a massive elliptical galaxy. The detailed abundance patterns suggest that boron is produced through processes that act independently of metallicity, and may require alternative mechanisms for the nucleosynthesis of germanium.

With the exception of the light elements (Li, Be, B and partly He) whose origin is linked to either Big Bang nucleosynthesis<sup>10</sup> or unique astrophysical processes<sup>11</sup>, the elements up to Fe on the periodic table are produced during the nuclear reactions that fuel stars or during the collapse of the stellar core and the resulting explosion defining a supernova<sup>12</sup>. Regarding supernovae, the current physical picture states that even-atomic-number (even- $Z$ ) nuclei—including the ‘ $\alpha$ -elements’ O, Ne, Mg, Si, S, Ar, and Ca—are synthesized by the supernovae of massive stars, whereas a substantial component of the Fe-peak elements are produced on significantly longer timescales in supernovae with lower mass progenitors. Therefore, comparisons between the  $\alpha$ -elements and the Fe-peak clarify the star-formation history and age of the galaxy<sup>13</sup>. The heavier elements—whose nuclei are energetically less favourable than Fe—require a significant source of free neutrons and the sequence of elements and isotopes created is very sensitive to the neutron capture rate relative to  $\beta$ -decay: the  $s$ -process ( $r$ -process) refers to a slow (fast) rate. To our knowledge, these heavier elements have never been detected outside our Galaxy and its nearest neighbours.

The galaxy discussed here was discovered<sup>14</sup> in absorption at  $z = 2.626$  along the sightline to the background quasar FJ081240.6+320808 (emission redshift  $z_{em} = 2.701$ ) via the signature damping wings of the Ly $\alpha$  profile that give the galaxy its classification—a damped Ly $\alpha$  system<sup>15</sup> (DLA). We obtained a moderate-resolution spectrum of FJ081240.6+320808 with the Echelle Spectrograph and Imager<sup>16</sup> on the Keck II telescope as part of a larger programme to survey the chemical enrichment history of the Universe<sup>17</sup>. The unusually strong metal-line absorption profiles of this galaxy led us to acquire follow-up observations of FJ081240.6+320808 with the HIRES echelle spectrograph<sup>18</sup> on Keck I. Our observations revealed a series of metal-line transitions (Fig. 1) previously undetected at high redshift which provide the most comprehensive set of elemental abundances available. By performing standard line-profile fitting and equivalent width measurements, we have measured gas-phase abundances for the

elements listed in Table 1. (See also the database at <http://kingpin.ucsd.edu/~hiresdla/>.) This DLA has the highest combined H I column density and metallicity ( $O/H \approx 1/3$  solar abundance) ever observed. We note that its redshift implies a strict upper limit to its age of 2.5 Gyr in any realistic cosmology.

The gas-phase abundances listed in Table 1 qualitatively follow the differential depletion pattern observed along the sightlines through the interstellar medium of the Milky Way galaxy<sup>19</sup>. Refractory elements like Fe, Ni and Cr must be highly depleted onto dust grains in this high redshift galaxy. The presence of strong C II\* and Cl I absorption suggests that the gas resides in a cold neutral medium characteristic of highly depleted gas in the Milky Way. Furthermore, the observation of significant Cl I requires at least a modest molecular hydrogen fraction<sup>20</sup>. To examine the underlying enrichment history of this galaxy we have applied empirical, conservative dust corrections (Table 1) derived from the depletion patterns of the Milky Way to the gas-phase abundances. Although these corrections are based on our limited knowledge of dust in the local Universe, we stress that the following discussion of nucleosynthesis is not sensitive to the corrections unless otherwise noted.

Figure 2 reveals the nucleosynthetic pattern of this galaxy where the dotted line compares the solar abundance pattern scaled to the oxygen metallicity of the galaxy. At the crudest level, the galaxy’s enrichment pattern resembles the Sun, indicating that their nucleosynthetic enrichment histories are not too dissimilar. Quantitatively, one might expect that the galaxy’s young age and relatively high metallicity would imply a nucleosynthetic pattern dominated by short-lived, massive stars. This presumption is supported by several lines of evidence. First, the  $\alpha$ -elements (O, Mg, Si) exhibit enhanced relative abundances compared to Zn, the only element representative of the Fe-peak not strongly incorporated into dust grains; O, Mg and Si are therefore presumably enhanced relative to the entire Fe-peak. This  $\alpha/Zn$  enhancement is suggestive of enrichment by massive stars. Second, the relative abundances of the  $\alpha$ -elements exhibit a trend of lower relative abundance at higher  $Z$  (for example,  $[O/S] \approx -0.3$ ). This trend reflects the detailed pro-

Table 1 Chemical abundances for the galaxy at  $z = 2.626$

Element	$[X/H]^*$	$\delta_{dust}^\dagger$	$[X/O]^\ddagger$
B	-0.57	0.1	-0.03
N	>-2.24	0.0	>-1.80
O	-0.54	0.1	0.00
Mg	-0.78	0.3	-0.04
Al	>-2.00	>0.5	>-1.06
Si	-0.91	0.3	-0.17
P	<-1.06	<0.3	<-0.32
S	-0.87	0.1	-0.33
Cl	-1.55	>0.0	>-1.11
Ti	-1.87	>0.7	>-0.73
Cr	-1.61	>0.7	>-0.47
Mn	<-1.85	0.7	<-0.71
Fe	-1.69	>0.7	>-0.55
Co	<-1.48	>0.7	>-0.34
Ni	-1.73	>0.7	>-0.59
Cu	<-1.11	>0.7	> 0.03
Zn	-0.91	0.2	-0.27
Ga	<-1.45	0.7	<-0.31
Ge	-0.92	0.3	-0.18
As	<0.26	0.0	<0.70
Kr	<-0.44	0.0	<0.00
Sn	<-0.27	0.0	<0.17
Pb	<-0.10	0.0	<0.34

\* Gas-phase abundances relative to solar on a logarithmic scale; for example,  $[X/H] = -1$  implies 1/10 solar abundance. Throughout the analysis we have adopted  $N(HI) = 10^{21.35} \text{ cm}^{-2}$  measured from a fit to the damped Ly $\alpha$  profile.

† Dust corrections estimated from the depletion patterns of Galactic gas with comparable depletion levels<sup>19</sup>. The values are added to the gas-phase abundances to yield the underlying nucleosynthetic pattern. In all cases, we have considered very conservative corrections.

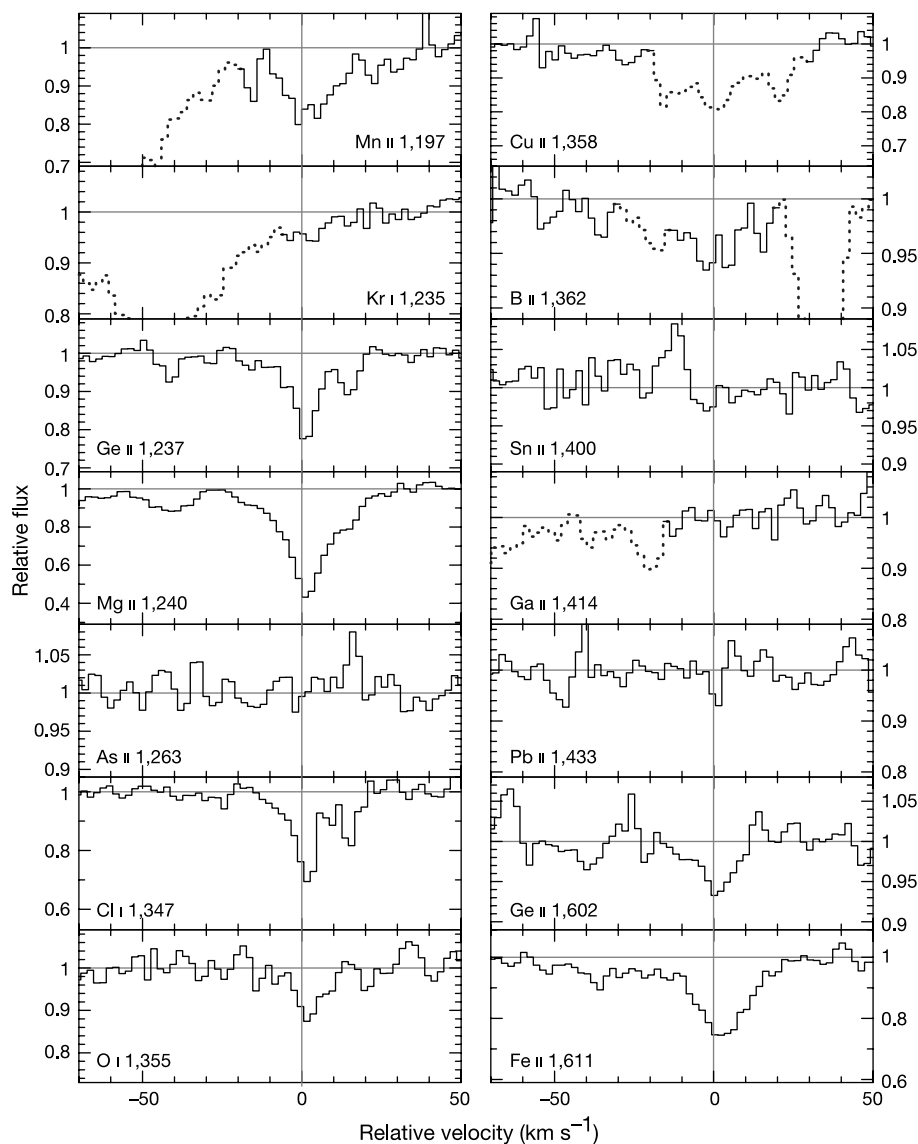
‡ Dust-corrected abundances on a solar logarithmic scale relative to O. These values express the nucleosynthetic pattern of this protogalaxy.

duction factors predicted for very massive stars<sup>21</sup> and their supernovae. Finally, all of the odd-*Z* elements show subsolar relative abundances marking the enhanced ‘odd–even effect’ indicative of massive supernovae. This includes  $[\text{Mn}/\text{Fe}] < -0.16$ ,  $[\text{Ga}/\text{Ge}] < -0.13$  and  $[\text{P}/\text{Si}] < -0.15$ .

The high metallicity and relative abundances of this galactic gas resemble stellar abundances observed in massive, early-type galaxies (for example, ellipticals) dominated by old stellar populations<sup>22</sup>. One might speculate, then, that this galaxy is the progenitor of one of these massive structures—which could explain its high metallicity at such an early epoch. In fact, its metallicity and dust content emission at  $z > 3$  that are the presumed progenitors of massive galaxies. The similarity in redshift, metallicity and relative abundances with the well-studied Lyman-break galaxy cB58 is

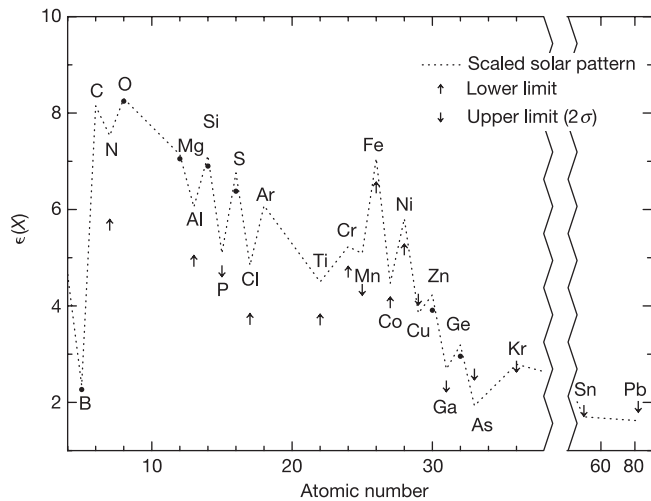
particularly noteworthy<sup>24</sup>. Furthermore, early-type galaxies may exhibit<sup>25</sup> an overabundance of Mg/Ca, which resembles the  $\alpha$ -element versus *Z* trend observed for this protogalaxy. Follow-up imaging and spectroscopy of the galaxies in the field surrounding FJ081240.6+320808 may help to reveal its stellar properties.

Our data place constraints on nucleosynthetic processes in the early Universe. The observations, for example, help to distinguish between processes where B production scales with the galaxy’s metallicity and processes that are independent of metallicity. The former theories (such as neutrino spallation in the carbon shells of supernovae<sup>26</sup> and the spallation of C and O nuclei accelerated by supernovae onto local interstellar gas<sup>27</sup>) predict that the B/O ratio will remain constant with O/H metallicity while the latter theories (such as p,n accelerated onto interstellar CNO seed nuclei) predict



**Figure 1** Sample of previously undetected metal-line transitions. Normalized absorption-line profiles related to the galaxy at  $z = 2.626$  toward FJ081240.6+320808 taken with the HIRES echelle spectrograph on the Keck I 10-m telescope ( $R \approx 45,000$ , signal-to-noise ratio  $\approx 30$  per  $2 \text{ km s}^{-1}$  pixel). With the exception of Fe II 1,611 and Mg II 1,240, none of these transitions have been detected outside of our Galaxy. Line blends with coincident absorption features are designated by dotted lines. The velocity  $v = 0 \text{ km s}^{-1}$  was arbitrarily defined to correspond to  $z = 2.6263$ . With the exception of Cl I, these

transitions correspond to the dominant ion of these elements in neutral hydrogen gas. Therefore, we convert the ionic column densities measured from these transitions into elemental abundances without ionization corrections. Although several transitions provide only upper limits to the elemental abundance (for example, Pb II 1,433, Ga II 1,414), the spectral regions are free from line-blends and future observations will yield detections or important limits.



**Figure 2** The nucleosynthetic enrichment pattern for a galaxy discovered in the early Universe. Dust-corrected elemental abundances for the protogalaxy at  $z = 2.626$  toward FJ081240.6+320808 on a logarithmic scale where hydrogen is defined to have abundance number  $\epsilon(X) = 12$ . The dust corrections were empirically derived from depletion patterns observed in the local Universe and were applied in a very conservative manner. This explains the lower limits to the Fe, Cr, Al, Co and Ni abundances and similarly the upper limit to Mn. Typical statistical errors are  $<0.1$  dex, that is, the size of the plot symbols (circles). The dotted line traces the solar abundance pattern scaled to match the observed oxygen abundance ( $[O/H] = -0.44$ , after dust correction). To zeroth order, the pattern of this high-redshift galaxy resembles that of the Sun; at finer detail, we note several important differences: see text for discussion.

that the B/O ratio will increase with increasing metallicity. The current observation of a solar B/O ratio in this approximately 1/3 solar metallicity gas argues for B synthesis independent of metallicity. Future observations could test this hypothesis in other galaxies and may allow a measurement of the  $^{10}\text{B}/^{11}\text{B}$  isotopic ratio, which will be critical to determining the relative importance of neutrino and cosmic ray spallation<sup>12</sup>.

In addition, the nearly solar Ge/O ratio we observe raises new challenges for the production of Ge. Although the s-process is expected to be a principal channel for Ge nucleosynthesis, the primary s-process site is during the ‘asymptotic giant branch’ phase of low-mass stars<sup>28</sup> whose lifetimes may exceed the age of this young galaxy. In addition to the s-process, supernovae with low-mass progenitors may produce a significant fraction of the Ge observed in our Galaxy. We have argued, however, that this high redshift galaxy is dominated by enrichment from massive stars, so the observed Ge/O ratio may support distinct physical processes (such as the neutrino-wind process<sup>29</sup>). These and related issues may be investigated by detecting or significantly lowering the current limits for Pb, Sn and Ga; Pb and Sn production are dominated by the s-process, whereas Ga may be produced in a similar fashion to Ge.

This galaxy also exhibits transitions of  $\text{C I}$ ,  $\text{C I}^*$ ,  $\text{C I}^{**}$ ,  $\text{C II}$ ,  $\text{C II}^*$ , and  $\text{Si II}^*$  that will yield an unparalleled analysis of its physical properties<sup>30</sup> (for example,  $\rho$ ,  $T$ , pressure, star formation rate) and an assessment of the cosmic microwave background temperature at  $z = 2.6$ . These observations will enable us to characterize the physical characteristics and star formation history of this young galaxy as well as provide detections or important limits on Ar, Ti, C, N, P, Pb, Sn, and possibly Kr and Fe. We could then test theories related to CNO and r-process nucleosynthesis.

Absorption-line studies of DLA provide the only means of examining elements beyond the Fe-peak outside the very local

Universe. The discovery of this galaxy indicates that similar abundance analyses will be possible in a small but non-negligible sample (about 2%) of high-redshift DLA. Finally, we report the discovery of a second DLA which should present an abundance analysis of about 20 elements including Ga, Ge, Cu and possibly B. This DLA is identified along the same sightline to FJ081240.6+320808 but at a cosmologically distinct redshift. □

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