THE ELEMENTAL ABUNDANCE PATTERN IN A GALAXY AT Z = 2.626

JASON X. PROCHASKA
UCO/Lick Observatory
University of California, Santa Cruz; Santa Cruz, CA 95064 (xavier@ucolick.org)

AND

J. CHRISTOPHER HOWK & ARTHUR M. WOLFE
Department of Physics, and Center for Astrophysics and Space Sciences
University of California, San Diego; C-0424; La Jolla, CA 92093

The discovery of metal-poor stars\(^1,2\) (where metal is any element more massive than helium) has enabled astronomers to probe the chemical enrichment history of the Milky Way\(^3,4\). More recently, element abundances in gas inside high-redshift galaxies has been probed through the absorption lines imprinted on the spectra of background quasars\(^5–8\), 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\(^9\). Here we report the observation of over 25 elements in a galaxy at \(z = 2.626\). With these data, we can examine nucleosynthetic processes independent of the uncertainty arising from depletion. We find that the galaxy was enriched mainly by 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\(^10\) or unique astrophysical processes\(^11\), the elements through Fe are produced during the nuclear reactions which fuel stars or during the collapse of the stellar core and the resulting explosion defining a supernovae (SN)\(^12\). Regarding supernovae, the current physical picture states that even-Z nuclei including the ‘\(\alpha\)-elements’ O, Ne, Mg, Si, S, Ar, and Ca are synthesized by the SN of massive stars whereas a substantial component of the Fe-peak elements are produced on significantly longer timescales, in SN with lower mass progenitors. Therefore, comparisons between the \(\alpha\)-elements and the Fe-peak reflect on the star formation history and age of the galaxy\(^13\). The heavier elements – whose nuclei are energetically less favorable 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 date, these heavier elements have never been detected outside our Galaxy and its nearest neighbors.

The galaxy central to this Letter was discovered\(^14\) in absorption at redshift \(z = 2.626\) along the sightline to the background quasar FJ081240.6+320808 (emission redshift \(z_{\text{em}} = 2.701\)) via the signature damping wings of the Ly\(\alpha\) profile which give the galaxy its classification – a damped Ly\(\alpha\) system\(^15\) (DLA). We obtained a moderate resolution spectrum of FJ081240.6+320808 with the Echellette Spectrograph and Imager\(^16\) on the Keck II telescope as part of a larger program to survey the chemical enrichment history of the universe\(^17\). 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\(^18\) on Keck I. Our observations revealed a series of metal-line transitions (Figure 1) previously undetected at high redshift which provide the most comprehensive set of elemental abundances to date. By performing standard line-profile fitting and equivalent width measurements, we have measured gas-phase abundances for the elements listed in Table 1. This DLA has the highest combined HI column density and metallicity (\(O/H \approx 1/3\) solar abundance) ever observed. Remarkably, its redshift implies a strict upper limit to its age of 2.5 Gyr in any realistic cosmology.

The gas-phase abundances listed in column 2 of Table 1 qualitatively follow the differential depletion pattern observed along the sightlines through the interstellar medium of the Milky Way galaxy\(^19\). Refractory elements like Fe, Ni, and Cr must be highly depleted onto dust grains in this high redshift galaxy. The presence of strong CII\(^+\) and CII absorption suggests the gas resides in a cold neutral medium characteristic of highly depleted gas in the Milky Way. Furthermore, the observation of significant CI requires at least a modest molecular hydrogen fraction\(^20\). To examine the underlying enrichment history of this galaxy we have applied empirical, \textit{conservative} dust corrections (column 3) 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; this point is both comforting and impressive given its age and distinction from our current universe. 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 severely incorporated into dust grains. 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 abun-
The elemental abundance pattern in a galaxy at \( z = 2.626 \)

### Table 1

| Elm | \( [X/H] \) | \( \Delta \phi \) | \( [X/O] \) |
|-----|-------------|-------------|-------------|
| 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      |

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

\( b \) Dust corrections estimated from the depletion patterns of Galactic gas with comparable depletion levels\(^{39} \). The values are added to the gas-phase abundances to yield the underlying nucleosynthetic pattern. In all cases, we have considered very conservative corrections.

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

dow that are independent of metallicity. The former theories (e.g., neutrino spallation in the carbon shells of SN\(^{26} \), the spallation of C and O nuclei accelerated by SN onto local interstellar gas\(^{27} \)) predict the B/O ratio remains constant with O/H metallicity while the latter (e.g., p,n accelerated onto interstellar CNO seed nuclei) predict the B/O ratio increases with increasing metallicity. The current observation of a solar B/O ratio in this \( \approx 1/3 \) solar metallicity gas argue for B synthesis independent of metallicity. Future observations will test this hypothesis in other galaxies and may allow a measurement of the \(^{10}\text{B}/^{11}\text{B} \) isotopic ratio critical to determining the relative importance of neutrino and cosmic ray spallation\(^{12} \).

The impact of our observations is particularly powerful when interpreted under the light of the young age of this galaxy. For example, the nearly solar Ge/O ratio 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\(^{28} \) whose lifetimes may exceed the age of this galaxy. In addition to the s-process, SN 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, therefore the observed Ge/O ratio may argue for a distinct physical processes (e.g. the neutrino-wind process\(^{29} \)). These and related issues will 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 while Ga may be produced in a similar fashion to Ge.

This galaxy is also special for exhibiting transitions of CI, C\(^1\)*, C\(^1\)**, CII, CII*, and SiII* which will yield an unparalleled analysis of its physical properties\(^{30} \) (e.g., \( \rho, T, \) 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 F. In turn, we will 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 similar abundance analyses will be possible in a small but non-negligible sample (\( \approx 2\% \)) of high redshift DLA. In closing, we report the discovery of a second DLA which should present an abundance analysis of \( \approx 20 \) elements including Ga, Ge, Cu and possibly B. Remarkably, this DLA is identified along the same sightline to FJ081240.6+320808 but at a cosmologically distinct redshift.

These observations were made with the W.M. Keck Telescope. The Keck Observatory is a joint facility of the University of California, the California Institute of Technology, and NASA. The author wishes to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. JCH recognizes support from a NASA grant to UC San Diego.
Fig. 1.— Sample of previously undetected metal-line transitions: Normalized absorption-line profiles related to the galaxy at $z = 2.626$ toward F108124.6+320808 taken with the HIRES echelle spectrograph on the Keck I 10m telescope ($R \approx 45000$, S/N $\approx 30$ per 2 km/s pixel). With the exception of Fe II 1611 and Mg II 1240, none of these transitions have been detected outside of our Galaxy. Line blends with coincident absorption features are designated by dotted lines. The velocity $v = 0$ km s$^{-1}$ was arbitrarily defined to correspond to $z = 2.6263$. With the exception of C 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 (e.g. Pb II 1433, Ga II 1414), the spectral regions are free from line-blends and future observations will yield detections or important limits.
The elemental abundance pattern in a galaxy at $z = 2.626$.

Fig. 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 $\epsilon(X) = 12$. 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, i.e., the size of the plot symbols. 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 our Sun indicating their nucleosynthetic enrichment histories are not too dissimilar. At finer detail, one notes several important differences: (i) $(O, Mg, Si)$ are enhanced relative to Zn and therefore presumably to the entire Fe-peak. This enhancements is indicative of enrichment by massive stars; (ii) The $\alpha$-elements show lower relative abundance at higher Z (e.g. $[O/S] \approx -0.3$), matching the detailed production factors of nucleosynthesis in massive stars and their SN; (iii) there is an enhanced ‘odd-even effect’ with P, Ga and Mn showing sub-solar relative abundances relative to Si, Ge, and Fe. Finally, we emphasize the solar B/O and nearly solar Ge/O ratios. The former observation argues against the ‘secondary’ production of B which predict the B/O ratio scales with metallicity and for ‘primary’ B production. Meanwhile, the Ge/O ratio may challenge current theories for the production of Ge particularly when one considers the young age (less than 2.5 Gyr) of the galaxy and the likelihood that it was primarily enriched by massive stars.
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