THE N/Si ABUNDANCE RATIO IN 15 DAMPED Lyα GALAXIES: IMPLICATIONS FOR THE ORIGIN OF NITROGEN

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ABSTRACT

Calculations derived from Galactic chemical evolution models indicate that there should be considerable scatter in the observed N/O ratios at a fixed metallicity (O/H) for galaxies with very low metallicities, due to the delayed release of primary N from intermediate-mass stars relative to that of O from short-lived massive stars. Moreover, the scatter should increase progressively as metallicity decreases. Such effects have not been convincingly demonstrated by observations of H II regions in nearby metal-poor galaxies, raising doubts about the time-delay model of primary N production. Pettini et al. and Lipman et al. realized the utility of high-redshift damped Lyα galaxies for gaining further insights into the origin of N, and discussed abundances in three damped Lyα galaxies. Since abundance measurements for O are generally unavailable for damped Lyα galaxies, they used N/Si or N/S in place of N/O, under the reasonable assumption that the abundance ratios O/Si and O/S are the same as solar in damped Lyα galaxies. We discuss observations of heavy-element abundances in 15 high-redshift (z > 2) damped Lyα galaxies, many of which have metallicities comparable to or lower than the lowest metallicity galaxy known locally (I Zw 18). We find that the N/Si ratios in damped Lyα galaxies exhibit a very large scatter (∼1 dex) at [Si/H] ∼ −2 and that there is some indication that the scatter increases with decreasing metallicity. Consideration of various sources of uncertainty suggests that they are not likely the main causes of the large scatter. These results provide strong support for the time-delay model of primary N production in intermediate-mass stars if, indeed, O/Si ≃ solar in damped Lyα galaxies.

Key words: galaxies: abundances — quasars: absorption lines

1. INTRODUCTION

The element nitrogen is undoubtedly synthesized from carbon and oxygen through the CNO cycle in stellar interiors. However, the details of the nucleosynthesis (i.e., the mass range of the stars and their stage of evolution) are uncertain. According to current theory, "primary" nitrogen production occurs in the asymptotic giant branch phase of the evolution of intermediate-mass stars (3–8 M☉), when thermal pulses bring C-rich material from the He-burning shell up into the hydrogen-burning shell (Renzini & Voli 1981). The N subsequently synthesized in the hydrogen-burning shell is later dispersed into the interstellar medium through stellar winds. The N produced in this manner is considered "primary," because its production does not require the initial heavy-element content of the stars to provide the seed C nuclei. The synthesis of N can also occur through the CNO cycle in main-sequence stars of any mass that contain an initial supply of heavy elements. The amount of N produced in this latter manner depends on the initial metallicity of the stars; hence, this mechanism is described as "secondary." Galactic chemical evolution models predict that the N/O abundance ratio should be independent of the overall heavy-element abundance (N/O independent of O/H) for primary N production. On the other hand, it is expected that N/O ∝ O/H for secondary production (Pagel & Patchett 1975; Edmunds 1990). For stellar systems with normal initial mass functions, there should necessarily be a time delay between the release of primary N from intermediate-mass stars and O from short-lived massive stars. The delay can be as large as 5 × 10⁸ yr, which is expected to introduce a large scatter in the N/O ratio at low O/H (Garnett 1990; Pilyugin 1993; Marconi, Matteucci, & Tosi 1994). The scatter in N/O is also expected to increase with decreasing metallicity, as the effects of the time delay become relatively more important.

There are many observational investigations of the origin of nitrogen in the literature. In particular, Vila-Costa & Edmunds (1993) summarized the then-existing observations of abundances in H II regions of nearby spiral and dwarf irregular galaxies and found that at high metallicities (O/H ∼ solar), the observed N/O ratio increases with O/H in a fashion consistent with the predictions of simple chemical evolution models. This indicates that secondary production of N dominates primary production at high metallicities. However, at low metallicities (O/H ≤ 0.3 solar), the N/O ratio becomes roughly independent of O/H, indicating that primary N production dominates. There is also significant scatter (roughly a factor of 2) in the N/O ratio at low metallicities, which cannot be attributed entirely to measurement errors (Garnett 1990; Pagel et al. 1992). The scatter can instead be understood as the result of time delay between the injection of primary N from intermediate-mass stars and that of O from shorter lived massive stars (see Vila-Costa & Edmunds 1993). The trend of constant N/O (i.e., independent of O/H) in low-metallicity H II regions has been confirmed by more recent
observations of blue compact and dwarf irregular galaxies, some with even lower metallicities (Garnett 1990; Pagel et al. 1992; Skillman & Kennicutt 1993; Thuan, Izotov, & Lipovetsky 1995). However, the expected increase in the scatter of the N/O ratios toward decreasing metallicity is not observed (see Fig. 1). In particular, Thuan et al. (1995) called attention to the remarkably small scatter (0.08 dex) in the N/O ratios for the 15 blue compact galaxies in their sample with 1/30 solar < O/H < 1/6 solar. Thuan et al. argued that such a smaller scatter in N/O is inconsistent with the standard time-delay model, in which the release of primary N from intermediate-mass stars is delayed relative to that of O from short-lived massive stars. Consequently, they argued, it must be possible to synthesize primary N in massive stars (M > 10 M☉). However, no clear mechanism for synthesizing primary N in massive stars has been identified in the course of theoretical investigations (Woosley & Weaver 1982; Maeder 1983).

The nearby blue compact and dwarf irregular galaxies exhibit a range of heavy-element abundances because of their different chemical enrichment histories. There is a rough correlation between the heavy-element abundance and luminosity of a system—a fact that has been exploited in searches for dwarf star-forming galaxies of very low metallicity. However, for hitherto unexplained reasons, no nearby galaxy has been discovered with a lower heavy-element abundance than that found in I Zw 18, namely, O/H ~ 0.02 solar.

A new approach to the problem of the origin of N was pioneered by Pettini, Lipman, & Hunstead (1995) and by Lipman, Pettini, & Hunstead (1995), who examined the behavior of the N abundance at large redshifts in three damped Lyα (DLA) absorption systems in quasar spectra. DLA systems are believed to be the high-redshift counterparts of present-day galaxies (see § 2 for more descriptions of their basic properties, and for references); some of them exhibit heavy-element abundances as low as 0.005 solar at redshifts z > 2 (see Lu et al. 1996a). Consequently, they offer an opportunity to examine the behavior of N in a hitherto unexplored metallicity region, and in stellar systems whose chemical enrichment history may be simpler than that of nearby galaxies (note that the age of the universe at z = 2 is only ~ 3 Gyr). Unfortunately, the only accessible O I line, λ1302, is practically always saturated, even at the lowest abundance levels found in DLA systems. Accordingly, it is only possible to derive lower limits to O/H and upper limits to N/O for DLA systems, so that a direct comparison with the N/O ratios measured in local metal-poor galaxies is not possible. For this reason, Pettini et al. and Lipman et al. used N/Si or N/S in place of N/O, on the grounds that the O/Si and O/S ratios are found to be the same as solar in Galactic disk and halo stars and in H II regions of nearby galaxies. While the small number of damped Lyα galaxies studied by these authors did not allow them to make any firm conclusions regarding the origin of N, these studies did illustrate the potential of the approach.

We describe measurements of N abundances in 15 damped Lyα galaxies at z > 2, based largely on high-resolution, high signal-to-noise ratio observations obtained using the High Resolution Spectrometer (HIRES; see Vogt 1992) on the 10 m Keck I Telescope. We demonstrate that the N/Si ratios in the most metal-poor ([Si/H] ~ 0.01 solar) damped Lyα galaxies do exhibit a very large scatter (~ 1 dex), consistent with the prediction from the time-delay model of primary N production. In § 2, we describe the abundance measurements for N, O, Si, and S obtained for DLA systems. The analysis and discussion of the damped Lyα abundance data in connection with the origin of N are presented in § 3. We give a brief summary of the results in § 4.

2. ABUNDANCE DATA FOR DAMPED Lyα GALAXIES

We recall that DLA galaxies are the objects responsible for producing neutral hydrogen absorption lines in the spectra of quasars with H I column densities N(H I) > 10²⁰ cm⁻² (Wolfe 1988). The exact nature of DLA galaxies remains unclear. They could be spirals, dwarfs, or, at high redshifts, collapsing protogalaxies in the process of being assembled from smaller subunits. Since the DLA clouds are very optically thick at the Lyman limit, the fraction of ionized gas should be small. DLA systems can currently be studied over the redshift range 0.0 < z < 5, and accurate abundances can be derived for many elements with minimal uncertainty in the ionization corrections. Accordingly, they provide the best opportunity to directly probe the chemical evolution history of galaxies from very early epochs. General reviews of the properties of DLA absorption systems can be found in Wolfe (1988, 1993). Extensive discussions of elemental abundances in DLAs are provided by Lauroesch et al. (1996), Pettini et al. (1994, 1997a, 1997b), and Lu et al. (1996a).

The abundance of N has been measured for DLA galaxies only recently, mostly based on HIRES echelle observations obtained with the 10 m Keck I Telescope. A compilation of such measurements appears in Table 1, where we give the quasar name and its emission redshift, the redshift and H I column density of the DLA galaxy, and the abundances of O, N, Si, and S, as well as references to the
original sources of measurements. All abundances are given relative to the solar values of Anders & Grevesse (1989) in the notation [M/H] = \log (M/H)_{\odot} - \log (M/H)_{\odot}. A few of the DLAs studied by Lu et al. (1996a) did not have reported N abundances because the N I lines were all contaminated by unrelated Ly\alpha forest absorption lines.\(^3\) However, it turns out that useful limits on the N abundance can be obtained for these systems despite the contamination. We provide the N abundance estimates for these systems in the Appendix and include the results in Table 1. Below we make some general remarks on the abundance measurements.

The abundances of N are usually determined from the N I triplet absorption lines near 1200 Å and/or the triplet near 1154 Å (especially when the stronger triplet lines near 1200 Å are saturated). Even though these N I lines occur in the Ly\alpha forest, it is still often possible to reliably identify and measure the column density of these lines because (1) there are three or more N I lines to work with, and (2) the N I lines are generally much narrower than the Ly\alpha forest lines as a consequence of the larger mass of N and, perhaps, of a lower temperature in the gas. However, there are many cases in which the N I lines are so weak and the contamination from Ly\alpha forest absorption is so strong that no obvious N I absorption is discernible at any of the N I line positions (e.g., the systems toward Q1055+4611, Q1202−0725, Q2212−1626, Q2233+1310, Q2237−0608, and Q2348−1444). In such cases, only upper limits to the N abundance are derived by treating the contaminating Ly\alpha forest absorption as upper limits to the true N abundances are likely to be significantly lower than the upper limits provided in Table 1. There is also one case (the system toward Q1425+6039) in which the N I lines are strongly saturated, so that only a lower limit to the N abundance can be derived.

The abundances of O are generally not measurable in DLA systems because the accessible O I 1\alpha3202 absorption line is always saturated. Consequently, only lower limits to O/H can be deduced. In some cases, the O I absorption line occurs in the Ly\alpha forest and is severely affected by forest absorption lines, making it impossible to derive even a lower limit to O/H. In general, the O/H lower limits listed in Table 1 are not tight enough to be of much use. The true O abundances are probably much higher in all cases than the lower limits listed in Table 1, given the heavy saturation of the O I lines in these systems.

The abundances of Si are generally derived from unsaturated absorption lines of Si II in the spectral region long-
ward of the Lyα emission lines. Hence they are not subjected to the contamination from Lyα forest lines. When the Si II lines are saturated (seven cases in Table 1), only lower limits to the abundances of Si are provided by assuming effectively the lines are not saturated. Component fitting analyses suggest that the true Si abundances for six of the seven lower limits given in Table 1 (Q1425 + 6039 being the exception) are likely to be no more than a factor of 2–3 (0.3–0.5 dex) higher than the lower limits provided.

The abundances of S are derived, where possible, from unsaturated absorption lines of the Si i λλ1250, 1253, 1259 triplet. These lines usually occur in the Lyα forest and are often contaminated by forest absorption lines. However, since there are three lines to work with, it is often possible to reliably identify and measure the column density of the lines. There are several cases in which either the Si i lines are too weak or the contamination from the Lyα forest absorption is too strong, so that no obvious Si i absorption is discernible; only upper limits on the S abundance are provided in these cases. Of the four upper limits listed in Table 1, the one for Q2344 + 1228 is a 2 σ upper limit, and those for Q1055 + 4611 and Q1946 + 7658 are based on measurements of the contaminating Lyα absorption at the positions of the Si i lines in a way similar to that described in the Appendix.

3. ANALYSIS AND DISCUSSION

3.1. Evidence for a Large Scatter in the N/Si Ratio

The most useful way to discuss the origin of N production is to examine the distribution of N/O as a function of O/H, as is normally done in such studies (see, e.g., Vila-Costas & Edmunds 1993). Constructing such a distribution for DLA systems is not literally possible since only lower limits to O/H are available and, in general, the O/H limits are not tight enough to provide significant constraints. However, we note that the abundance of O has been found to trace that of other α-capture elements (e.g., Si, S) in both Galactic disk and halo stars (see Wheeler, Sneden, & Truran 1989) and in Galactic and extragalactic H II regions (see Thuan et al. 1995 and references therein), in the sense that [O/α] ≃ 0 (i.e., O/α ≃ solar). Assuming that the same holds true for DLA systems, we can substitute Si/H in place of O/H and replace N/O with N/Si. The results of this exercise are shown in Figure 1, where the filled circles are [N/Si] versus [Si/H] for DLA systems and the other data points are the actual [N/O] versus [O/H] measurements from H II regions in nearby spiral, dwarf irregular, and blue compact galaxies (Garnett 1990; Pagel et al. 1992; Vila-Costas & Edmunds 1993; Skillman & Kennicutt 1993; Thuan et al. 1995). We also show the curves derived by Vila-Costas & Edmunds (1993), indicating the contributions from primary and secondary N production.

First, we note that the N/Si ratios in DLAs occupy the same general region delineated by the “secondary” and “primary + secondary” curves that Vila-Costas & Edmunds (1993) found to describe the N/O distribution of H II region measurements. However, at the low-metallicity end of the distribution ([Si/H] ≃ −2), the N/Si ratio in DLAs shows a considerably larger scatter (~1 dex) than that exhibited by nearby dwarf and blue compact galaxies of similar metallicities. We emphasize that the scatter is real. For example, of the six DLA systems at [Si/H] ≤ −1.8, the highest measured value of [N/Si] is −0.88, while the lowest is −1.70. In addition, if we assume [Si/H] ≃ [S/H], we find [N/Si] ≃ −0.79 for the Q1946 + 7658 DLA system. The large scatter in the N/Si ratios at very low metallicities provides strong evidence that primary N production in DLA galaxies does not coincide with that of Si. Rather, the large scatter is consistent with the behavior long predicted by the standard time-delay model of primary N production, assuming O/Si ≃ solar in DLA systems. As we discuss in the next section, it is not possible to attribute the large N/Si scatter in DLA systems to measurement uncertainties or possible systematic biases.

3.2. Uncertainties

There are a number of factors that could potentially affect the DLA abundance measurements and the interpretation of Figure 1, including systematic biases due to line saturation effects, ionization effects, dust depletion effects, and the assumption that O/Si ≃ solar in DLAs. We discuss each of these here, but note that the latter two are likely to be the dominant sources of uncertainty:

1. Most of the measurements given in Table 1 are based on high-quality Keck HIRES observations obtained by the present authors. We have tried to avoid using saturated absorption lines to derive ion column densities. Other measurements quoted in Table 1 were derived similarly. Consequently, we do not believe line saturation problems have significantly affected the abundance measurements presented in Table 1.

2. The abundances presented in Table 1 were derived from the observed N I/H I, O I/H I, Si II/H I, and S II/H I column density ratios under the assumptions that the hydrogen gas in the DLA systems is mostly neutral, and that N I, O I, Si II, and S II are the dominant ionization stages of these elements in the gas. The rationale for making these assumptions is that the DLA systems have Lyman limit optical depth greater than 10^{3}; hence, most of the elements should be in the ionization stages that require more than 13.60 eV to ionize, namely, N I (14.53 eV), O I (13.61 eV), Si II (16.34 eV), and S II (23.33 eV). Simple photoionization calculations (Viegas 1995; Lu et al. 1995; Prochaska & Wolfe 1996) support this conclusion.

3. In order to compare the abundance measurements in DLAs with local H II region measurements, it was assumed that O/Si ≃ solar in DLA systems. The rationale for making this assumption was discussed in § 3.1. It will be important to verify this assumption observationally.

4. The gas-phase abundance of heavy elements obtained from absorption-line measurements may or may not reflect the total abundance of the elements in a galaxy, depending on whether a significant fraction of the elements is locked up in dust grains. There has been some debate about the extent to which the DLA abundances are significantly affected by dust depletion (Pettini et al. 1994, 1997a; Lu et al. 1996a; Lauroesch et al. 1996; Prochaska & Wolfe 1996; Kulkarni, Fall, & Truran 1997; Welty et al. 1997; Vladilo 1998). The generally supersolar Zn/Fe and Zn/Cr ratios observed in DLA systems have been interpreted to indicate a small amount of depletion of Fe and Cr (see Pettini et al. 1997a). On the other hand, the near-solar Si/S ratios found...
in DLAs (Table 1) seem to suggest that Si is not significantly affected by dust depletion (Lu et al. 1996a), because S is not readily incorporated into dust grains in the Galactic interstellar medium (ISM) (Jenkins 1987). We could have used S rather than Si in the analysis to avoid the issue of dust depletion altogether; however, doing so would have substantially reduced the sample size suitable for this study. Interested readers are referred to the above cited papers for detailed discussions. We merely note here that the effects of dust depletion believed to exist in DLA systems are not large enough to significantly alter the conclusions obtained in this study. For example, the typical [Zn/Cr] and [Zn/Fe] values in DLAs at z > 2 are about 0.4 dex, with a range of 0 to 0.65 dex (Lu et al. 1996a; Pettini et al. 1997a). Zinc is largely unaffected by dust depletion effects in the Galactic ISM, while Cr and Fe are among the most refractory elements known (Jenkins 1987). Given that the relative abundances of Zn, Cr, and Fe remain close to solar in Galactic stars with [Fe/H] > −2.5 (see Wheeler et al. 1989), the DLA results suggest that Cr and Fe are depleted by about 0.4 dex (on average) in these systems. The depletion of Si in DLAs is expected to be less, since Si is only moderately affected by dust in the Galactic ISM (Jenkins 1987). For example, in ISM clouds where the depletion level of Fe and Cr is similar to that inferred for DLA systems, Si is depleted by only ~0.26 dex (see Table 7 of Sembach & Savage 1996). The abundances of N in DLAs should be largely unaffected by dust depletion, since in the Galactic ISM N is not readily incorporated into dust grains (see Savage & Sembach 1996). In summary, we expect dust depletion to shift the DLA measurements given in Figure 1 downward and to the right by an average of at most 0.3 dex. Such a shift should not affect the main conclusions of our analysis. In particular, the shift should not change appreciably the spread in N/Si.

3.3. Comparisons with Measurements in Nearby Galaxies

The finding that DLAs show considerably larger scatter in their N/Si ratio than local galaxies with similar metallicities appears to have at least two possible explanations:

1. It may be an unlucky consequence of small number statistics. Based on the limited DLA measurements available (see Fig. 1), it appears that the scatter in the N/Si ratio does not become appreciably larger than that displayed by local H II region measurements until [O/H] or [Si/H] < −1.6 or so. It may be significant that only one local galaxy (I Zw 18) has a metallicity this low. Possibly, observations of more local galaxies with such low metallicities will reveal a larger scatter in their N/O ratio.

2. The DLAs may follow an intrinsically different evolutionary track from blue compact and dwarf irregular galaxies. In order to reproduce simultaneously the observed abundances of He, N, and O in H II regions of blue compact and dwarf irregular galaxies, several authors (e.g., Pilyugin 1993; Marconi et al. 1994) found it necessary to include in their chemical evolution calculations the effects of galactic winds powered by Type II supernovae, which remove some of the Type II supernova ejecta, rich in O and z-elements, from the galaxies but leave the abundance of N unaffected. Variations in the efficiency of the galactic winds, coupled with the delayed release of N, then create the scatter in observed N/O ratios. The very low N/Si ratios of some DLA galaxies may result, if the effects of galactic winds are less important for some reason (e.g., differences in galaxy masses or intensity of starbursts). Given the large number of parameters that go into chemical evolution models (e.g., the number, duration, and intensity of star bursts, the mass of the galaxy, the form of the stellar initial mass function, galactic winds, stellar yields), it will be necessary to perform detailed calculations in order to see whether the above suggestion is tenable.

4. SUMMARY

It is currently believed that primary N is produced by intermediate-mass (3–8 M⊙) stars during the asymptotic giant branch phase, which dominates secondary N production at low metallicities. Calculations derived from Galactic chemical evolution models indicate that, if the above idea is correct, there should be considerable scatter in the observed N/O ratio at a fixed metallicity (O/H) for galaxies with low metallicities. The scatter stems from the delayed release of primary N from intermediate-mass stars relative to that of O from short-lived massive stars. In addition, the scatter should increase progressively as metallicity decreases. Such expected behaviors have not been convincingly demonstrated by observations of H II regions in nearby metal-poor galaxies. Consequently, several authors have suggested that massive stars may dominate primary N production at low metallicities, which is difficult to understand theoretically. We present observations of heavy-element abundances in 15 high-redshift (z > 2) damped Lyα galaxies, many of which have metallicities comparable to or lower than the lowest metallicity galaxy known locally (I Zw 18, with [O/H] = −1.7). We find that the N/Si ratio in our sample of damped Lyα galaxies exhibits a very large scatter (~1 dex) at [Si/H] ~ −2. Consideration of various sources of uncertainty suggests that the large scatter is real. These results provide strong support for the time-delay model of primary N production in intermediate-mass stars, if O/Si ~ solar in DLA galaxies. In particular, primary N production in massive stars is not required. However, it will be important to obtain accurate measures of O abundance in DLAs to verify the assumption that O/Si ~ solar in DLA galaxies.

The authors thank an anonymous referee for several insightful comments and suggestions. L. L. gratefully acknowledges support from NASA through grant HF 1062.01-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555. W. L. W. S. acknowledges support from NSF grant AST 95-29073.

APPENDIX

Three of the DLA systems listed in Table 1 (the z = 4.3829 system toward Q1202 − 0725, the z = 3.6617 system toward Q2212 − 1626, and the z = 4.0803 system toward Q2237 − 0608) were included in the analysis of Lu et al. (1996a, 1996b), who
did not provide measurements of the N abundance in these systems, because the spectral regions where the N I lines occur were badly contaminated by Lyα forest absorption lines. However, it turns out that useful upper limits on the N abundance for these systems can be derived despite the contaminations. We describe these estimates below. All data presented here are based on Keck I HIRES observations at 6.6 km s$^{-1}$ resolution and have been described in detail elsewhere (see Lu et al. 1996a, 1996b).

Figure 2 shows the spectral regions near the N I $\lambda\lambda1199.55, 1200.22,$ and 1200.71 lines in the $z = 4.3829$ DLA system toward Q1202$-$0725, plotted in velocity space in the rest frame of the DLA galaxy. Also shown is the well-observed absorption profile of the Si II $\lambda1304$ line in the same system to help define the region where N I absorption may be expected to occur. The contamination from the Lyα forest absorption lines is sufficiently strong, and the N I lines sufficiently weak, that no discernible evidence of N I absorption is present. Direct integrations of the apparent column density profiles $[N_\alpha(v);$ see Lu et al. 1996a for a detailed description] of the three N I lines over the velocity interval $[-30, 160]$ km s$^{-1}$, where most of the N I absorption is expected to occur based on the Si II $\lambda1304$ absorption, yield the following column densities: $>14.96 \ (1199.55),$ 14.22 (1200.22), and 14.96 (1200.71). The value for $\lambda1199.55$ is a lower limit because the absorption is saturated. These values should be considered strictly as upper limits to the actual N I column density since most or all of the absorption included in the integration regions is due to Lyα forest absorption. Taking the upper limit from the $\lambda1200.22$ line, we find $\log N$(N I) $< 14.22$ and $[N/H] < -2.35$, adopting the $N$(H I) from Lu et al. (1996b).

Figure 3 shows similar plots for the $z = 3.6617$ DLA system toward Q2212$-1626$. Again, the regions near the N I triplet lines are contaminated by Lyα forest absorption lines, and there is no obvious evidence that N I absorption is present. The best upper limit on $N$(N I) is provided by the intrinsically strongest 1199.55 Å absorption line, which yields $\log N$(N I) $< 13.64$ over the velocity range $[-50, 50]$ km s$^{-1}$. We thus find $[N/H] < -2.67$ for this system, adopting the $N$(H I) from Lu et al. (1996a).

Figure 4 shows similar plots for the $z = 4.0803$ DLA system toward Q2237$-0608$. Again, no evidence for the presence of N I absorption is evident. In this case, the best upper limit on $N$(N I) is obtained by combining the $N_\alpha(v)$ integration from N I $\lambda1200.22$ over $[-90, 60]$ km s$^{-1}$ with that from the $\lambda1200.71$ line over $[-130, -90]$ km s$^{-1}$. We find $\log N$(N I) $< 14.28$ and $[N/H] < -2.29$, adopting the $N$(H I) from Lu et al. (1996a).

![Fig. 2](image-url) Spectral regions near N I absorption lines in the $z = 4.3829$ DLA system toward Q1202$-$0725, plotted in velocity space in the rest frame of the DLA galaxy. These spectral regions are contaminated by Lyα forest absorption lines. The absorption profile of Si II $\lambda1304$ in the same system is shown for comparison.
Fig. 3.—Same as Fig. 2, but for the $z = 3.6617$ DLA system toward Q2212–1626.

Fig. 4.—Spectral regions near N I absorption lines in the $z = 4.0803$ DLA system toward Q2237–0608, plotted in velocity space in the rest frame of the DLA galaxy. These spectral regions are contaminated by Lyα forest absorption lines. The absorption profile of Si II $λ$1526 in the same system is shown for comparison.

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