AN ALUMINUM-ENHANCED CLOUD IN A C IV ABSORBER AT z = 1.94

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ABSTRACT

In the z = 1.94 C iv absorption-line system in the spectrum of quasar Q1222+228 (z_{em} = 2.04), we find two clouds that have contrasting physical conditions, although they are only at a 17 km s^{-1} velocity separation. In the first cloud, Si ii, Si iv, and C ii are detected, and Al ii and Al iii column density limits in conjunction with photoionization models allow us to infer that this cloud has a large Si abundance and a small Al abundance relative to a solar abundance pattern. This pattern resembles that of Galactic metal-poor halo stars, which must have formed from such high-redshift gas. The second cloud, in contrast, has detected Al ii and Al iii (also Si iv and C ii) but no detected Si ii. We demonstrate, using photoionization models, that Al/Si must be greater than (Al/Si)$_\odot$ in this unusual cloud. Such a ratio is not found in absorption profiles looking through Milky Way gas. It cannot be explained by dust depletion since Al depletes more severely than Si. Comparing this cloud with other Al-rich environments, we speculate about the processes and conditions that could give rise to this abundance pattern.

Subject headings: galaxies: evolution — galaxies: structure — quasars: absorption lines

1. INTRODUCTION

One of the motives for studying quasar (QSO) absorption-line systems is to document the photoionization structure, chemical composition, and kinematics of the interstellar matter (ISM) and halos of high-redshift galaxies at a level of detail on par with studies of the Milky Way ISM and halo. QSO lines of sight that pass through high-redshift galaxies sample multiple gaseous structures having a variety of physical conditions such as those found in Galactic H i and H ii regions, supershells, infalling halo gas, and material being processed at the Galaxy/halo interface. Recognizing the abundance patterns, photoionization conditions, and kinematics associated with these various types of structures is a prerequisite for a detailed understanding of the evolution of galactic gas.

Based on low-resolution spectra, early QSO absorption-line efforts have been limited to simple curve-of-growth analyses of equivalent widths, providing only a weighted average of the absorbing gas properties in each system. A great deal has been learned from these studies, and a global (statistically based) picture of chemical and ionization evolution has been suggested (see Steidel 1993 and references therein). The next logical step is to examine variations in the chemical and ionization conditions within single galaxies and to incorporate kinematic information. Using high-resolution UV spectra, several researchers studied the Milky Way disk and halo at a detailed level (Welty et al. 1997; Savage & Sembach 1996; Snow et al. 1996; Spitzer & Fitzpatrick 1993, 1995; Fitzpatrick & Spitzer 1994). Some recent efforts have focused on the cloud-by-cloud conditions in high-redshift galaxies (see Tripp, Lu, & Savage 1997; Petitjean, Rauch, & Carswell 1994). It is hoped that, ultimately, a statistical picture of the processes that give rise to the observed absorbing gas properties will improve our understanding of the present-epoch Milky Way and galactic evolution. In this Letter, we study the cloud-to-cloud properties in a C iv system at z ~ 1.94 along the line of sight toward the quasar Q1222+228 in order to (1) demonstrate a large variation in ionization and/or abundance conditions between two kinematically adjacent clouds in the same absorber and (2) present an unusual cloud that has an Al/Si abundance ratio enhanced by a factor of several relative to the solar ratio.

2. THE DATA

Our spectrum of Q1222+228, which has a resolution $\Delta v_{\text{FWHM}} = 6.6$ km s^{-1} with 3 pixels per resolution element, is a 3600 s exposure obtained with the HIRES spectrograph on the Keck I telescope (Vogt et al. 1994) on 1995 January 23. The wavelength coverage is 3810.5–6304.9 Å, with breaks redward of 5100 Å. The spectrum was obtained as part of a large study of intermediate-redshift Mg ii absorbers (Churchill 1997), and thus the captured wavelength coverage did not include certain desirable transitions of the z ~ 1.94 C iv system. The reduction and analysis of the data are described elsewhere (Churchill 1997; Churchill, Vogt, & Charlton 1998a; Schneider et al. 1993; Churchill et al. 1998b). In Figure 1, we present the detected transitions (5 σ) aligned in the line-of-sight velocity.

We focus on the Si ii λ1527, Al ii λ1671, and Al iii λ1863 transitions in two absorbing clouds centered at $v \sim 0$ and $v \sim 17$ km s^{-1}. The C iv λ1548, 1550 profiles are saturated across this velocity interval, but the Si iv and C iv profiles clearly show two distinct clouds. In cloud A, at $v \sim 0$ km s^{-1}, we have detected Si ii λ1527 and obtained upper limits on both Al ii λ1671 and Al iii λ1863. In cloud B, at $v \sim 17$ km s^{-1}, the converse is true; we have detected Al ii λ1671 and Al iii λ1863 and obtained an upper limit on Si ii λ1527. The Al iii λ1855 transition, the doublet counterpart of Al iii λ1863, was not covered.

The cloud velocities, column densities, and Doppler b parameters were obtained from a Voigt profile (VP) decomposition of the spectra using the program MINFIT (Churchill 1997), which minimizes $\chi^2$ between the model and the data. All detected transitions were fitted simultaneously, with the exception of the C iv λ1550 transition, which is blended with an un-
of growth and therefore is well constrained despite the large fractional error in \( b \langle \text{S II} \rangle \).

Constraints are available for the total neutral hydrogen column density of the absorber, which can be interpreted as an upper limit on \( N(\text{H I}) \) of any single cloud in the system. In the \textit{Hubble Space Telescope} Faint Object Spectrograph (\textit{HST}/FOS) spectrum of Impey et al. (1996), there is no indication of a break at the expected location of the Lyman limit. They report detections of Ly\( \beta \) and Ly\( \gamma \) that are members of complex blends that suffer from a pre-COSTAR point-spread function. Fernández-Soto et al. (1995) performed a profile fit to a saturated, multicomponent Ly\( \alpha \) feature at \( \sim 3571 \) Å in a spectrum with a resolution of \( \sim 30 \text{ km s}^{-1} \).

However, the number of components and their \( b \) parameters and column densities are too uncertain to provide a constraint more useful than that provided by the lack of a Lyman limit break. We have conservatively adopted an upper limit of log \( N(\text{H I}) \) \( \sim 16.5 \text{ cm}^{-2} \).

3. PHOTONIZATION MODELING OF THE CLOUDS

We inferred the clouds’ physical conditions using CLOUDY (Ferland 1996). We have assumed a \( z = 2 \) extragalactic UV-ionizing background, given by Haardt & Madau (1996) (log \( F_\gamma = -20.35 \text{ ergs s}^{-1} \text{ Hz}^{-1} \)); column density, \( N(\text{H I}) \); the metallicity, \( Z \); and the total number density of hydrogen, \( n_\text{H} \). CLOUDY assumes that photons are incident on one side of a plane-parallel slab of gas with a constant \( n_\text{H} \) and integrates the equations of radiative transfer along an optical path through the slab until it reaches a specified \( N(\text{H I}) \). For a fixed spectrum, there is a relationship between \( n_\text{H} \) and the ionization parameter \( U \) (the number density of hydrogen-ionizing photons over the number density of electrons). For simplicity, we adjusted the two ratios \(^3 \lvert \text{Si/H} \rangle \) and \( \lvert \text{Al/H} \rangle \), keeping \( \lvert \text{C/H} \rangle = 0 \). An important assumption is that the modeled transitions arise in a single-phase environment. The broad, saturated, C iv profile may arise in a physically distinct, higher ionization phase from the C ii and other lower ionization species. We argue that the precise velocity alignment of the lower ionization species and the fact that their \( b \) parameters are consistent (see Table 1) justify the assumption.

For cloud A, we measured \( N(\text{Si ii}) \), \( N(\text{Si iv}) \), \( N(\text{C ii}) \), and upper limits on \( N(\text{Al ii}) \) and \( N(\text{Al iii}) \). Without precise information on the neutral hydrogen distribution in the system, we modeled the cloud for a range of \( N(\text{H I}) \). For a given \( N(\text{H I}) \), we ran CLOUDY in its “optimized” mode, allowing \( Z \), \( n_\text{H} \), and \( \lvert \text{Si/H} \rangle \) to vary until the cloud model was consistent with the observed \( N(\text{Si ii}) \), \( N(\text{Si iv}) \), and \( N(\text{C ii}) \). The ratio \( N(\text{Si ii})/N(\text{Si iv}) \) constrained both the ionization parameter and the metallicity. For models with log \( N(\text{H I}) \) \( > 15.4 \text{ cm}^{-2} \), \( N(\text{Al ii}) \) was greater than the upper limit. We therefore set all other parameters equal to those given by the optimized solution and then solved for the model cloud by varying \( \lvert \text{Al/H} \rangle \) and optimizing on the measured upper limits on \( N(\text{Al ii}) \) and \( N(\text{Al iii}) \). In the upper panel of Figure 2, we illustrate how the \( \lvert \text{Si/H} \rangle \) and \( \lvert \text{Al/H} \rangle \) ratios, \( U \), and \( Z \) must be scaled for the models to be consistent with the data. For log \( N(\text{H I}) \) \( \geq 15.5 \text{ cm}^{-2} \), a factor of 2–3 enhancement of \( \lvert \text{Si/H} \rangle \) and an underabundance of \( \lvert \text{Al/H} \rangle \) are obtained, nearly independent of metallicity. The lack of a Lyman limit break in the \textit{HST}/FOS spectrum of Impey et al. (1996) precludes a large \( N(\text{H I}) \). This cloud could be consistent with \( \lvert \text{Si/H} \rangle \) and \( \lvert \text{Al/H} \rangle \sim 0 \) (solar values) only if the

\(^3\) We use the notation \( \lvert X/H \rangle = \log (X/H) - \log (X/H)_{\odot} \).
metallicity is supersolar [for log N(H i) \sim 15 cm^{-2}]. We conclude that [Si/H] is enhanced and [Al/H] is underabundant by a factor of a few for the more plausible range of metallicities, \( -1.4 \leq [Z/Z_{\odot}] \leq -0.3 \). This pattern is similar to that seen in Galactic halo stars of comparable metallicities (Lauroesch et al. 1996; Savage & Sembach 1996).

For cloud B, we have measured \( N(\text{Al} \ ii), N(\text{Al} \ iii), N(\text{C} \ ii), N(\text{Si} \ iv), \) and an upper limit on \( N(\text{Si} \ ii) \). As with cloud A, the Lyman limit break provides the constraint of \( \log N(\text{H} \ i) \leq 16.5 \text{ cm}^{-2} \). Al is unusual in that its high-temperature dielectronic recombination rates are high and the ratio \( N(\text{Al} \ ii)/N(\text{Al} \ iii) \) can increase with increasing \( U \) for \( \log N(\text{H} \ i) \geq 17 \text{ cm}^{-2} \) (Petitjean et al. 1994). For smaller \( N(\text{H} \ i) \), this is not the case; a decreasing \( U \) yields an increasing \( N(\text{Al} \ ii) \), as naively expected. Nonetheless, because of the unusual nature of reactions involving Al, we approached the modeling of cloud B with caution.

First, we considered the constraints that can be placed on the model cloud without considering the Al column densities (i.e., using only the C ii and Si iv detections and the Si ii limit, we allowed \( Z, n_{\text{H}}, \) and [Si/H] to vary). We found the models to be consistent with the data for \( N(\text{Al} \ iii) \leq 15.5 \leq \log N(\text{H} \ i) \leq 16.75 \text{ cm}^{-2} \). Smaller \( N(\text{H} \ i) \) values were unable to produce enough Si iv relative to C ii. For larger \( N(\text{H} \ i) \) values, \( U \) must be larger, corresponding to a smaller \( n_{\text{H}} \), and the model cloud was unrealistically large and Jeans unstable. For the acceptable range of \( N(\text{H} \ i) \), we found \(-0.3 \leq [\text{Si/H}] \leq -0.5 \). The metallicity ranged from \([Z/Z_{\odot}] = 0.2 \) for \( N(\text{H} \ i) = 15.5 \text{ cm}^{-2} \) to \([Z/Z_{\odot}] = -1.5 \) for \( N(\text{H} \ i) = 16.75 \text{ cm}^{-2} \). Next we considered what model clouds were consistent with the constraints provided by only the Al ii and Al iii column densities while allowing \( Z \) and \( n_{\text{H}} \) to vary. Again, a consistent model cloud could be achieved for \( 15.0 \leq \log N(\text{H} \ i) \leq 16.75 \text{ cm}^{-2} \). Systematically, the required metallicities were 0.5–1 dex larger than those required by the C and Si constraints alone. Naively, these two experiments imply [Al/Si] > 0, consistent with the striking strength of the Al profiles for cloud B.

When we ran CLOUDY in optimize mode, using all Si, C, and Al constraints and allowing \( Z, n_{\text{H}}, [\text{Si/H}], \) and [Al/H] to vary, we found that [Si/H] < 0 and [Al/H] > 0 were required for all possible \( N(\text{H} \ i) \). Only the narrow range \( 15.9 \leq \log N(\text{H} \ i) \leq 16.25 \text{ cm}^{-2} \) yielded acceptable cloud models. For smaller values of \( N(\text{H} \ i) \), the ratios \( N(\text{Si} \ iv)/N(\text{Si} \ ii) \) and \( N(\text{Al} \ iii)/N(\text{Al} \ ii) \) could not be made consistent with the data (for the same \( U \)). The model results are illustrated in the lower panel of Figure 2. Over the permittable range of \( N(\text{H} \ i) \), we have \(-0.55 \leq [Z/Z_{\odot}] \leq -0.32, -2.5 \leq \log U \leq -2, [\text{Al/H}] \sim 0.3, \) and \(-0.6 \leq [\text{Si/H}] \leq -0.2 \).

Given the unusual conclusion we have reached that the Al in cloud B is enhanced by a factor of 2 relative to the solar value, we now consider the validity of our assumption of photoionization equilibrium. Trapero et al. (1996) found the ratio of \( N(\text{Al} \ iii)/N(\text{Al} \ ii) \) to be out of equilibrium in the interstellar cloud toward the B1 V star 23 Ori. In that case, excited carbon implied a high density, so that collisional ionization was applicable; the ratio of \( N(\text{Al} \ iii)/N(\text{Al} \ ii) \) implied a higher temperature than that measured from Doppler parameters, indicating that the gas had cooled faster than it could recombine. We obtained an unrestricted upper limit on the density in cloud B from an upper limit on \( N(\text{C}^\ast \ ii) \). However, we have no reason to believe that cloud B suffers from such a nonequilibrium situation. Cloud B is consistent with photoionization in that the

TABLE 1

| Transition       | Cloud A | Cloud B |
|------------------|---------|---------|
|                  | log N  | b       | log N  | b       |
|                  | (cm^{-2}) | (km s^{-1}) | (cm^{-2}) | (km s^{-1}) |
| Al ii 1670.787   | <11.13  | ...     | 11.85  | 0.04     |
| Al iii 1862.790  | <11.79  | ...     | 12.06  | 0.10     |
| C ii 1334.532    | 13.11   | 0.11    | 13.45  | 0.07     |
| Si ii 1526.707   | 12.42   | 0.11    | 1.84   | 1.88     |
| Si iv 1393.755   | 12.72   | 0.04    | 4.70   | 0.74     |
| Si iv 1402.770   | 12.72   | 0.04    | 4.70   | 0.74     |

a Upper limit for assumed \( b = 5 \text{ km s}^{-1} \), based on the C ii \( \lambda 1334 \) transition.

b Upper limit for assumed \( b = 5 \text{ km s}^{-1} \), based on the Al ii \( \lambda 1670 \) transition.

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Fig. 2.—The [Al/H] and [Si/H] abundance ratios (relative to solar) as a function of \( \log N(\text{H} \ i) \) for clouds A (upper panel) and B (lower panel). The corresponding metallicities, \([Z/Z_{\odot}]\), are given by the upper horizontal axes. The unshaded regions give the range of models that are consistent with the observed data (see text). The long-dashed curves are the ionization parameters, \( \log U \), which are given by the right-hand vertical axes. The \( \log N(\text{H} \ i) \) at which the model cloud sizes exceed 10 kpc and become Jeans unstable are marked by the vertical short-dashed lines.
Cloudy models are found to have kinetic temperatures consistent with those inferred from the Doppler parameters under the assumption of thermal broadening (which was not the case for the models of Trapero et al. 1996).

Since the clouds are likely to be in a galaxy, it is possible that stellar sources could affect the shape of the ionizing radiation spectrum. However, the following basic argument applies. Both Al II and Si II have similar ionization potentials (6.0 and 8.2 eV, respectively) as do Al II and Si II (18.8 and 16.3 eV, respectively). Unless the spectrum of ionizing radiation has a very abrupt feature in these energy ranges, Al II and Si II will be similarly affected by a change in spectral shape. We ran tests models and confirmed this with a star-forming galaxy spectrum (Bruzual & Charlot 1993).

4. SUMMARY AND SPECULATIONS

Two kinematically adjacent, absorbing clouds in the same galaxy at $v_1 = 0$ and $v_2 = 17$ km s$^{-1}$ have very different abundance patterns, if they are in photoionization equilibrium. Based on CLOUDY models, cloud A is inferred to have Si that is enhanced relative to a solar abundance pattern and Al that is underabundant relative to solar. This abundance pattern is characteristic of Milky Way halo stars (Lauroesch et al. 1996; Savage & Sembach 1996), which could have formed from gas like that observed in this $z = 1.94$ galaxy. We would expect such a pattern for many clouds in high-redshift galaxies. Independent of the details, cloud B has Al that is at several times enhanced relative to Si (compared with the solar abundance pattern). This Al enhancement is highly unusual. If depletion onto dust grains is important, we would expect a smaller Al/Si since Al depletes more readily than Si. To date, such an Al-enhanced pattern has not been seen in absorption profiles looking through Milky Way interstellar gas (Savage & Sembach 1996; Snow et al. 1996; Spitzer & Fitzpatrick 1993, 1995; Fitzpatrick & Spitzer 1994).

How could an enhancement of Al originate in a $z = 1.94$ cloud? In an attempt to find clues, we note three astrophysical environments in which Al enhancement is observed: (1) in the stellar photospheres of the most metal poor globular clusters (Shetrone 1996; Smith & Kraft 1996), (2) in the broad-line regions of some active galactic nuclei (Shields 1997), and (3) in the photospheres of Milky Way bulge stars (McWilliam & Rich 1994). The common theme for the enhancement of Al in these three seemingly different environments is novae. The novae could produce the Al either directly in their ejecta (Smith & Kraft 1996) or indirectly by providing magnesium isotopes to the ISM that later deposit onto stellar photospheres (Walker & Hoffman 1995). The $^{25}Mg$ and $^{27}Mg$ isotopes would then be converted to Al through proton capture in deep CNO convective mixing layers in metal-poor stars (Langer & Hoffman 1995). More generally, does this suggest that a concentration of novae contributed to the enhancement of the Al in this cloud? In the globular cluster environment, one key is to have a large number of stars that were formed coevally. Another key, which may apply to all three environments, is to have a potential well large enough to retain the gas. These may be prerequisites in our case also. Another possibility for excess Al production is a particular class of supernova for progenitors over a narrow mass range. The predicted amount of enhancement relative to other elements depends on the specific supernovae model adopted (Nomoto et al. 1997); however, only a small subclass of models would give Al/Si in agreement with that inferred for this cloud.

Just how unusual is this cloud with a large Al/Si ratio? Such a pattern has not been seen in absorption along dozens of lines of sight toward Milky Way disk and halo stars. Most high-redshift clouds do not have large Al II and Al II (relative to Si II). However, in the $z = 2.14$ damped Ly$\alpha$ absorber in Q0528–251 (Lu et al. 1996), we have identified a single outlying cloud (at approximately $-100$ km s$^{-1}$) for which the equivalent width of the Al II $\lambda$1671 transition is larger than that of the Si II $\lambda$1527 transition. The other clouds in the same system clearly have the opposite ratio. Finding more examples and establishing similarities between Al-rich environments are logical next steps in diagnosing the origin of the abundance pattern at high redshift and perhaps understanding the anomalous enhancements seen in metal-poor globular cluster and bulge stars.

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\* We note that the absorber lies 30,000 km s$^{-1}$ from the emission redshift of the QSO, which is not a broad absorption line active galactic nucleus.

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