

## Interpreting the Convergence of Lyman Series Absorption Lines

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### Abstract

A gas system at a redshift  $z$  with  $N(\text{H}) \gtrsim 10^{17} \text{ cm}^{-2}$  in front of a quasar absorbs light over a broad wavelength band near and well below the system's Lyman limit,  $\lambda \lesssim 912(1+z)\text{\AA}$ . In the region where the Lyman series is converging, one can learn much about the velocity dispersion of some of the gas in the system by measuring how abruptly the intensity terminates with wavelength. For 21 such gas complexes appearing in a recent survey of quasar spectra (Sargent, Steidel and Boksenberg 1989), the median wavelength where half of the light is transmitted is about  $918.5\text{\AA}$  in the respective rest frame of each system. This result implies that a typical Lyman limit system has either approximately  $10^{17} \text{ cm}^{-2}$  of hydrogen spread over  $\Delta v \gtrsim 300 \text{ km s}^{-1}$  or considerably more than this amount of gas spread over half as large a velocity interval.

### 1. Introduction

Spectra of quasars at high  $z$  often show absorption at the Lyman limit from intervening gas systems at intermediate  $z$  having  $N(\text{H}) \gtrsim 10^{17} \text{ cm}^{-2}$  (Tytler 1982, Bechtold, *et al.* 1984). In some circumstances,  $N(\text{H})$  can be determined by measuring the strength of the Lyman limit absorption or the damping wings of Lyman- $\alpha$ . With a spectrum taken at low wavelength resolution, say,  $\lambda/\Delta\lambda \sim 10^3$ , it is usually not possible to distinguish individual Lyman series lines near the limit, yet one can still discern how rapidly the average intensity drops off as the limit is approached from the long wavelength side. The purpose of this discussion is to point out the information which is available from measurements of this series convergence.

### 2. Merging of Lines near the Series Limit

When the intervals between adjacent lines near the Lyman series limit are much less than the characteristic width of each absorption feature, the blended lines form a continuous absorption with an optical depth  $\tau$  equal to that of the ionizing continuum just beyond the limit (Sugiura 1927). As the lines become well separated at longer wavelengths, there are large variations in  $\tau$  even though the average of  $\tau$  over wavelength remains constant. This transition from a smooth to fluctuating behavior can be easily registered in a high resolution spectrum. If the peaks and valleys from line to line vary substantially on either side of  $\tau \sim 1$ , a spectrum taken at a resolution which can not discern the features will still show a change, since the average, smoothed *intensity* of the spectrum will increase at progressively greater distances from the Lyman limit.

From the above discussion, it is clear that the dispersion of Doppler velocities is a fundamental parameter that governs the behavior of intensities of an atomic hydrogen spectrum seen in absorption near the series limit. At a relative wavelength displacement from the limit  $\delta = \Delta z/(1+z)$ , the equivalent velocity separation between adjacent lines in the series is given by

$$\Delta v = \frac{2c \delta^{3/2}}{(1-\delta)}. \quad (1)$$

A progression of strongly saturated absorption lines produced by gas whose velocity profile is a single, pure Gaussian should have an *average* intensity of 0.5 times the continuum level of the spectrum at a wavelength  $\lambda_{1/2}$  where the intensity profile widths are half their separation, i.e., when  $\tau = 1$  is found at a point  $\Delta v/4$  from each profile's center. In this simple case one could derive the velocity dispersion parameter  $b$  (equal to  $\sqrt{2}$  times the rms velocity) by measuring the spectrum's half-intensity point

$\delta_{1/2} = (\lambda_{1/2} - \lambda_{LL})/\lambda_{LL}$  and solving the equation

$$\exp(F^2/4) - AFN(H) = 0$$

with

$$F = \frac{c \delta_{1/2}^{3/2}}{b(1 - \delta_{1/2})} \quad (2)$$

and the constant  $A = 7.3 \times 10^{-18} \text{ cm}^2$ .

If the central optical depths of the lines are very large in the vicinity of  $\delta_{1/2}$ , it is probably inappropriate to invoke the traditional, practical assumption that the profile shape follows the wings of a Gaussian absorption, as with the classical Voigt profile. Rather, a small proportion of the gas may be in unrelated parcels at high velocities, as in the case where one may look through a galaxy and see fragments of halo gas with low column densities and high velocities supplementing a strong, narrow component from the galaxy's disk (see, e.g. Briggs, *et al.* 1985). In this context, at the wavelength where the transmission of light is about 0.5, the absorption by the high-velocity components strongly dominates that of the main component, as is illustrated in Figure 1. We can envision two regimes (or some intermediate combination thereof) which could apply near  $\delta_{1/2}$ : (a) a column density of hydrogen of about  $10^{17} \text{ cm}^{-2}$  is spread over a velocity at least  $\Delta v$  or (b)  $N(H) \gg 10^{17} \text{ cm}^{-2}$  spans a velocity  $\Delta v/2$ .

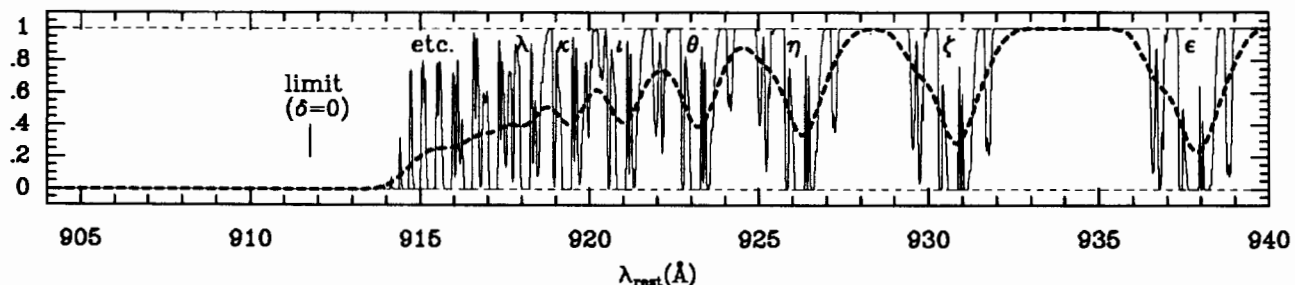


Fig. 1 -- Synthetic spectrum near the Lyman series limit of a gas complex containing  $10^{19}$  hydrogen atoms  $\text{cm}^{-2}$  in a narrow velocity range accompanied by small clumps of material intercepting about half of the radiation within an interval  $\pm 400 \text{ km s}^{-1}$ . The dashed line shows a smoothed version of this spectrum.  $\delta_{1/2} = 0.007$  (at  $918 \text{ \AA}$ ).

### 3. Application

For an illustration on how to implement the above interpretation of the Lyman series convergence for real absorption systems, we can examine examples from the recent survey by Sargent, Steidel and Boksenberg (1989) of QSO spectra recorded at a resolution  $\lambda/\Delta\lambda = 10^3$ . In most cases, the position of the Lyman limit  $\lambda_{LL}$  can be inferred from the wavelengths of identified metal lines. For 21 of the Lyman limit systems seen in these spectra<sup>1</sup>, the median  $\delta_{1/2}$  was 0.0074 (see Fig. 2). A similar result was obtained by Tytler (1982).

For pure Gaussian profiles, the above result implies that a typical  $b$  would be 40 or 53  $\text{km s}^{-1}$  for  $N(H) = 10^{19}$  or  $10^{18} \text{ cm}^{-2}$ , respectively (eq. 2). Alternatively, most of the hydrogen which produces the Lyman limit absorption could be contained within a very narrow profile, and this gas might be accompanied by  $N(H) \gtrsim \text{few} \times 10^{17} \text{ cm}^{-2}$  spanning  $\pm 75 \text{ km s}^{-1}$ . Neither of these choices seems too attractive,

<sup>1</sup>Sargent, Steidel and Boksenberg (1989) identified metal-line redshifts for 25 of their Lyman limit systems. The author of this paper identified one more, making a total of 26. Out of this collection, 3 systems were too noisy to analyze and 2 had very gentle, strange looking drops in intensity that seemed to be inconsistent with the interpretation offered here. From the average number of systems with intermediate  $r$  ( $16.75 \leq \log N(H) \leq 17.5$ ) per unit  $z$ , in this sample one would expect about 1 system which, by chance, might confound the interpretation of another because it produced some intermediate absorption in the interval  $0 < \delta < 0.05$ . A coincidence of this sort could explain the strange looking cases.

because the spacing of Lyman lines at around  $\delta \sim 0.01$  is sufficient that the strong contrasts in absorption could be resolved if the profiles were monolithic. Generally, a regular pattern of oscillating intensities near  $\delta = 0.01$  is not evident in the data. Thus, one would favor an interpretation closer to case (a) discussed in the above paragraph, namely, that there is approximately  $10^{17} \text{ cm}^{-2}$  of hydrogen scattered over at least  $\pm 150 \text{ km s}^{-1}$ .

#### 4. Conclusions

The Lyman series of atomic hydrogen offers a coherent replication template for absorption lines, with a smoothly varying interval between adjacent members. We can use this property to investigate the velocity spread of the absorbing gas, even as we examine a spectrum which was recorded at nowhere near the resolution needed to explicitly resolve even the broadest structures of each profile. The change in transmission created by the transition from a smooth absorption to well separated features occurs gradually. This property helps us to overcome the confusion created by noise in the spectrum or other, randomly placed absorption lines, such as those associated with the Lyman- $\alpha$  forest.

By measuring Lyman limit systems in a collection of low resolution quasar spectra, we have learned that the objects which are responsible for the absorption may contain material moving at velocities well over  $100 \text{ km s}^{-1}$ . Indeed, we have witnessed a similar phenomenon in a more familiar context: any line of sight through our own galaxy has a good chance of intercepting an isolated, high velocity cloud in the halo (Oort 1966) or a coherent stream of gas, such as the Magellanic Stream (Mathewson, Cleary and Murray 1974). Also, we know that some distant, highly ionized systems which show C IV and Si IV absorption lines in quasar spectra likewise show multiple components distributed over a span of many hundred  $\text{km s}^{-1}$  (e.g. Pettini, *et al.* 1983).

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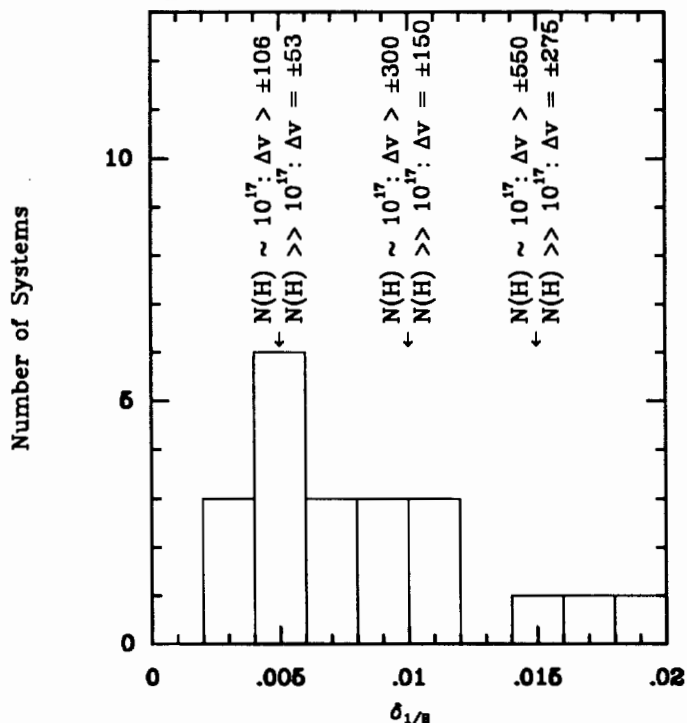


Fig. 2 - A histogram showing the frequency of measured half-intensity displacements  $\delta_{1/8} = (\lambda_{1/2} - \lambda_{LL})/\lambda_{LL}$  in the survey of QSO spectra recorded by Sargent, Steidel and Boksenberg (1989).

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## APPENDIX

### A Theorem on Optical Depths

The energy of an electronic level above the ground state of atomic hydrogen

$$E = R(1 - \frac{1}{n^2}) \quad (1)$$

may be rewritten as

$$E = R(1 - \delta), \quad (1a)$$

where  $R$  is one Rydberg. The quantity  $\delta$  represents a relative energy (or wavelength) shift from the Lyman limit, and for a large quantum number  $n$  the energy difference between adjacent upper levels is given by

$$\frac{dE}{dn} = 2R\delta^{3/2} \quad (2)$$

For any individual high order Lyman line, eq. (2) may be reformulated in terms of a Doppler velocity shift

$$\Delta v = \frac{2c\delta^{3/2}}{(1 - \delta)} \quad (3)$$

to the next higher (or lower) order line in the series.

For any single absorption line, the optical depth  $\tau(v)$  is given by

$$\tau(v) = 2.65 \times 10^{-15} N(v) f \lambda \quad (4)$$

where  $N(v)$  is the column density of hydrogen per unit velocity [expressed in the units  $\text{cm}^{-2} (\text{km s}^{-1})^{-1}$ ],  $f$  is the transition's  $f$  value, and  $\lambda$  is the wavelength in Å. For high-order Lyman lines, the  $f$  values follow the relation

$$f = 1.56n^{-3} = 1.56\delta^{3/2}. \quad (5)$$

In a regime where  $\Delta v$  is much less than the characteristic velocity spread of the hydrogen, the optical depths for an ensemble of Lyman lines

$$\sum \tau = 3.78 \times 10^{-12} \frac{\delta^{3/2} \int N(v) dv}{(1 - \delta) \Delta v} = 6.30 \times 10^{-18} \text{cm}^2 N(\text{H}) \quad (6)$$

is equal to the continuum optical depth at wavelengths just below the Lyman limit. Thus the true Lyman limit absorption will be indistinguishable from the combined absorption by the higher order Lyman lines. When  $\Delta v$  becomes comparable to or larger than the scale over which  $N(v)$  shows significant structure,  $\tau$  will no longer be uniform, but the average of  $\tau(v)$  over wavelength will nevertheless equal the amount shown in eq. (6) provided that  $n$  is not so low that either the differential approximation in eq. (2) or the formula for  $f$  values [eq. (5)] is no longer valid.