Terminal Velocity Infall in QSO Absorption Line Halos

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Abstract.
We explore the hypothesis that clouds detected in quasar absorption line systems are falling at a terminal velocity toward the center of high redshift gaseous galactic halos. Since both the ionization level and terminal velocity of halo clouds increase with increasing distance from the central galaxy, velocity resolved profiles of highly ionized gas are predicted to have a greater width than low ionization gas. A line of sight passing through the center of gaseous halo (an idealized damped Ly alpha system), yields low ionization absorption at the velocity of the galaxy, flanked by high ionization on either side. Reasonable halo parameters yield total velocity extents for C IV of $\Delta v_{CIV} = 100 - 200$ km s$^{-1}$, in agreement with several observed systems. The remaining systems may better described by the rotating disk model of Prochaska & Wolfe (1998). Finally, observational tests are suggested for verifying or falsifying the terminal velocity hypothesis for these systems.

1. Do Quasar Absorption Line Clouds Fall at Terminal Velocity?

The spectra of distant quasars typically exhibit numerous absorption lines which arise in discrete intervening gas clouds. Many of these clouds, particularly those producing metal absorption lines, are thought to be embedded in the gaseous disks and halos of “normal” high redshift galaxies (Bahcall & Spitzer 1969). In a previous paper, it has been argued that drag may dominate the motions of neutral clouds observed in the gaseous “halo” of our Galaxy, and that these clouds fall at or near terminal velocity toward the Galactic plane (Benjamin & Danly 1997, BD97). Generalizing these results to a spherical system using reasonable profiles for enclosed mass and gas density, the terminal velocity is

$$v_T(r) = 25.3 \text{ km s}^{-1} \ C_D^{-1/2} \ v_{r,100} \ n_f^{-1/2} \ N_{19}^{1/2} \ r_{10}^{(n-1)/2} , \quad (1)$$

where $C_D \approx 1$ is the drag coefficient, $N_{19}$ is cloud total hydrogen column density integrated along the direction of cloud motion in units of $10^{19}$ cm$^{-2}$. The mass enclosed by radius $r_{10} = r/10$ kpc in units of $10^{10} M_\odot$ is $M_{10}(r) = 2.3 v_{r,100}^2 r_{10}$, where $v_{r,100} = v_r/(100 \text{ km s}^{-1})$ is the rotational velocity associated

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with this mass distribution. The gas density exterior to some fiducial radius, \( r_f \), is 
\[ n_h(r) = n_{f,-2}(r/r_f)^{-n}, \]
where \( n_{f,-2} \) is the halo density at \( r_f = 10 \) kpc in units of \( 10^{-2} \) cm\(^{-3} \). Here we use \( n=2 \) (c.f., Mo & Miralda-Escude 1996).

We implicitly assume the absorption arises due to a collection of discrete clouds intervening along a line of sight passing through a more tenuous gaseous halo. This is consistent with the tendency for absorption lines to break into multiple components when observed with higher resolution. For simplicity the halo is assumed to be spherical and steady-state and the clouds falling radially inward. For a line of sight passing through the halo with impact parameter, \( r_{imp} \), the velocity spread of absorption is 
\[ \Delta v = 2v_T(R_i)[1 - (r_{imp}/R_i)^2]^{1/2}, \]
where \( R_i \) is the maximum radius at which absorption due to an ion \( i \) occurs. Allowing for a reasonable range of input parameters, i.e. \( 0.5 < v_{r,100} < 2.5 \) (c.f., Casertano & van Gorkom 1991), \( 0.01 < n_{f,-2} < 10 \) (c.f., Mo & Miralda-Escude 1996), \( 0.1 < N_{19} < 10 \) (c.f., Dickey & Lockman 1990), and \( 3h^{-1} < R_{i,10} < 10h^{-1} \) (Lanzetta 1993), equation (2) satisfies the observed velocity spread of \( 100 < \Delta v < 200 \) km s\(^{-1} \) (c.f., Lanzetta & Bowen 1992; Churchill, Steidel, & Vogt 1996; Lu, Sargent, & Barlow 1996).

2. First Test: Is There a Correlation Between Ionization and Velocity?

Given the latitude in the above parameters, one can say that observed velocities spreads are consistent with, but not conclusive evidence for, terminal velocity infall. Consideration of the velocity profile as a function of ion may provide additional support for the terminal velocity model in some systems. Statistics of quasar absorption line systems indicate that at a given redshift, the absorption cross section increases with level of ionization of absorber ion. At \( z \gtrsim 1.5 \), \( R_{Mg\,II} \gtrsim 66h^{-1} \) kpc, while \( R_{C\,IV} = 98h^{-1} \) kpc. Although the cross section depends on the geometry of absorber and cosmological model (c.f. Lanzetta 1993, Steidel 1993), the general result that \( R_{C\,IV} > R_{Mg\,II} > R_{DLA} \) (DLA="Damped Lyman Alpha") is robust.

The simplest (but not only) explanation of this correlation is that it indicates an increase in the ionization parameter of the absorbing clouds with radius. Bergeron & Stasinska (1986) have shown that the ionization parameter, \( \Gamma = \phi/cn_c \), inferred from comparison of photoionization models to observational data is consistent with constraints on the extragalactic ionizing radiation field, \( \phi \approx (0.9 \pm 0.5) \times 10^6 \) H ionizing photons s\(^{-1} \) cm\(^{-2} \) for \( z = 2 - 4 \) (Cooke, Espey, & Carswell 1996), and reasonable cloud densities, \( n_c \). But regardless of the origin of this correlation, if the terminal velocity model is appropriate, there should be a second correlation between ionization level and velocity. Highly ionized clouds in the diffuse outer halo fall faster, while more neutral clouds in the inner halo fall more slowly.

Quantifying these expectations requires adapting a model for the ionization mechanism and structure of the clouds. Using version 84.12a of CLOUDY (Ferland 1993), we model the clouds as constant density slab photo-ionized by the intergalactic radiation field of Madau (1992) with total hydrogen column density log \( N_H = 19 \) and metallicity log\((Z/Z_\odot) = -2 \), assuming a uniform radiation field everywhere in the halo. In order to link the cloud ionization, which
depends on $n_c$, to the cloud dynamics, which depends on $n_h$, we assume initially that clouds maintain a constant ratio $\chi = n_c/n_h$. We calculate the absorption column making no correction for the inclination of the absorbing cloud relative to the line of sight. Such a correction could be important but depends on the detailed geometry, morphology, and internal density structure of falling clouds which is poorly understood (BD97).

In Figure 1, we illustrate a few examples of absorption depth for C IV 1549 Å and Fe II 1608 Å as a function of velocity. We assume a “base” case with the following parameters: $\phi_6/\chi_2 = 1.0$, $n_{f,-2} = 1$, $n = 2$, $v_{r,100} = 2.0$, $r_{imp} = 0$, $N_{19} = 1$, and $\log(Z/Z_{\odot}) = -2$. The parameter varied is noted in each panel. In each case, the spatial integration is restricted to $R_{\text{max}} = 300$ kpc, and the absorption envelope is artificially truncated at that point. The photoionization models were carried out with a resolution of only 0.25 dex in ionization parameter, the resulting profiles of Fe II have an unphysical cusp at low velocities. Since we have not specified a model for the location of individual absorbers, nor how the density of absorbers depend upon radius, these are not bona fide synthetic absorption line profiles, but rather define an absorption “envelope” into which more detailed models will fit.

As expected, the absorption envelopes show a neutral low-velocity core, and two high ionization wings. If the halo density structure flattens interior to some radius (as suggested by Mo & Miralda-Escude 1996) the velocity width of the neutral core will decrease. The envelopes here are comparable to the data taken for selected systems: $z_{\text{abs}} = 2.8268$ in Q 1425+6039 (Lu et al 1996) and $z_{\text{abs}} = 2.8443$ in HS 1946+7658 (Tripp et al ) are two examples.

3. Second Test: Is There a Correlation Between Component Column Density and Velocity Spread?

The three principal classes of motions expected to occur in gaseous halos which have been compared with various subsets of data are radial infall (Lanzetta & Bowen 1992), rotation (Prochaska & Wolfe 1997), and velocity dispersion (Charlton & Churchill 1996 ; McDonald & Miralda-Escude 1998). The principal difference between our proposed dynamical model and these other models is that drag-dominated motions depend upon the column density of the cloud, whereas the other classes of motion have been assumed to be independent of cloud parameters. We expect that the more an absorption component is offset in velocity from the assumed centroid velocity, the higher the column density of the cloud or the greater the distance from the kinematic center or both. From equation (1), the velocity spread of components should go as $\Delta v \propto \sqrt{N}$, assuming that the gaseous halo is uniformly filled with clouds of varying column density. It should be emphasized that the relevant parameter is the total column density of the feature; this can only be obtained from the data by applying a ionization model to convert column density of individual ions into the total column. Quantitative predictions are currently being prepared.
Figure 1. Calculated “absorption envelopes” for a line of sight with impact parameter $r_{imp} = 0$. The fiducial parameters are listed in the text; the four panels show the effect of varying the halo-to-cloud density conversion factor, $\phi_6/\chi_2$ [top panel], the overall density level, $n_f$ [second panel], the slope of the density profile, $n_0$ [third panel], and the overall galaxy mass, characterized by $v_r$ [bottom panel]. Comparison of these profiles to observations could constrain the physical parameters of QSO absorption line halos.

4. Deciding on a model

All models of quasar absorption line systems must necessarily make a large number of assumptions in order to make predictions that can be directly be compared with observations. Many of these assumptions are not directly related to the kinematics of individual components, but will affect the prediction for observations. Variations in metallicity, radiation density, filling factor, or mean absorber column density are all assumed here to be constant with radius, since we lack firm theoretical prejudices or observational guidance to tell us exactly how such quantities should vary. But such variations probably do occur, and will affect our ability to observationally discriminate between the primary classes of motion.

Another difficulty is that depending upon the orientation and history of the absorption system, rotation, infall, and velocity dispersion may all be occurring simultaneous, and matching the profile requires tuning the parameters of all three types of motions simultaneously. Nearly edge-on disks will have profiles dominated by rotation while face-on disks or spheres will have profiles more dominated by vertical or radial infall, and the structure of the profiles as a function of ion will depend upon the impact parameters.
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Given the large number of parameters that are necessary to compare models of QSO absorption line systems to the data, final adoption of any model will ultimately be motivated by a combination of satisfactory agreement with data and physical plausibility. Building a model of high redshift halos requires constructing the interstellar medium of galaxies from first principles, so one test of the physical plausibility of a model is whether it is agrees with behavior in our own Galaxy. Rotation and velocity dispersion have been characterized in our own Galaxy for a long time. Drag-dominated infall has only recently been proposed for our Galaxy (BD97), and the status of this proposal is summarized in Benjamin (1999). Since it has only been mentioned in passing for QSO absorption line halos (Mo 1995), it seems worthwhile to consider the potential importance of this type of motion. After all, at the time galaxies were first formed, gaseous infall, terminal velocity or otherwise, must have been the predominant type of motion.

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