ULTRAVIOLET OBSERVATIONS OF HALO CLOUDS

Laura Danly and Chris Blades
Space Telescope Science Institute
3700 San Martin Drive, Baltimore MD 21218

I. Introduction

Since the earliest optical absorption line studies of Munch and Zirin (1961) identified clouds of gas located at large distances from the galactic plane, considerable effort has gone into trying to understand the origin and nature of Milky Way halo gas. Subsequent high resolution optical absorption studies (Albert 1981; Blades et al 1989) have expanded on the early results, demonstrating clearly that (1) halo clouds are more likely to have velocities outside the range allowed by galactic rotation and (2) halo clouds show smaller depletion of refractory elements compared to their disk counterparts (i.e. the Spitzer-Routley effect).

Further insight into the nature of halo gas has been provided by absorption studies in the near ultraviolet region of the spectrum (Savage and deBoer 1979, 1981; Pettini and West 1983; Savage and Massa 1987; Danly 1987, 1989). Despite the lower (25 km/s) resolution, the wider range of ionization states available for study in the ultraviolet and the greater sensitivity provided by higher f-value lines of more abundant species have permitted several additional pieces of observational information to be uncovered. These include: (1) the nearly ubiquitous presence of C IV and Si IV in the halo, (2) the higher scale height of the high ionization species, (3) the very low column density, low ionization gas that pervades the halo, (4) the strong bias toward infall of gas in the northern galactic hemisphere and (5) the strong asymmetry in the characteristics of halo gas toward the NGP vs that toward the SGP.

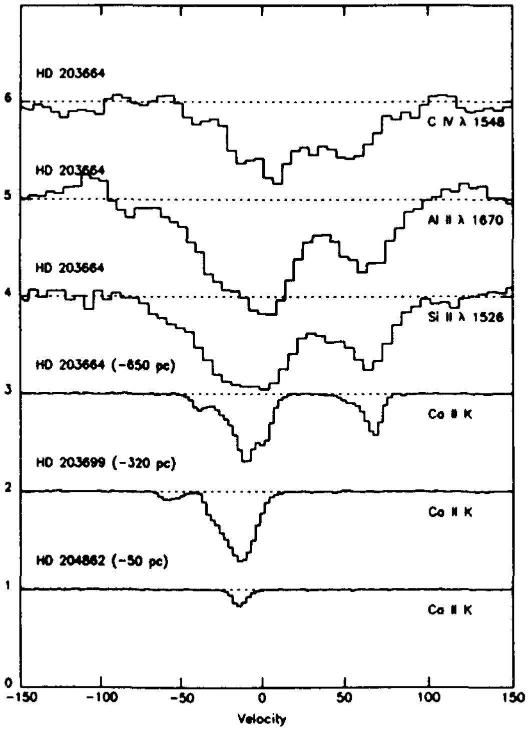
Comprehensive absorption line and 21-cm surveys have provided insight into the gross characteristics of halo gas and have lead to several plausible theoretical explanations for its origin. However, no definitive conclusions have been reached as to the nature of its support or ionization, or to the origin of diffuse halo gas or of the high velocity clouds (HVCs). Differentiation between competing theories for halo gas will only be achieved by in-depth studies of physical characteristics on a component-by-component basis. This is the hope and expectation for GHRS (the Goddard High Resolution Spectrometer on HST): to observe and analyze ultraviolet species at ground based resolution.

In order to make the most efficient use of data available in advance of the launch of HST, we have been combining high-resolution, ground based optical data with lower resolution IUE data on several important species observed toward high latitude halo stars. The selected lines of sight are those known from previous work to have complex, multi-component spectra where at least one cloud lies outside the bulk of the HI layer (e.g. z>250 pc). Here we present results toward one of our stars, HD 203664.

II. The line of sight toward HD 203664 -- Qualitative Description

HD 203664 lies in the direction of l=61°, b=-28° at z=-650 pc. Within four degrees lie two nearer stars, HD 203699 (z=-320 pc) and HD 204862 (z=-50 pc). All three of these stars were observed at Ca II by Blades et al (1989, which provided the data in advance of publication; see also Albert et al, this volume). Only HD 203664 has been observed with IUE; time has been allocated to observe the other stars in the ultraviolet during the coming (13th) IUE episode. The data are discussed below.

optical: The bottom three spectra in Figure 1 show the Ca II profiles toward the three stars in order of increasing distance from the plane. The data have a resolution of 5 km/s. The data clearly show an increase in the complexity of the interstellar spectra with increasing distance from the plane. The interstellar spectrum toward HD 204862 (-50 pc) reveals only a single, weak primary component with broadened wings suggestive of additional component structure. At -320 pc, HD 203699 shows a broadening of the primary component out to -35 km/s, and an additional component at roughly -60 km/s. Between -320 pc and -650 pc one finds in the spectrum of HD 203664 the onset of a strong feature at +70 km/s. Interestingly, the *negative* velocity absorption shows its central minimum at about -40 km/s, compared to the -60 km/s for the *nearer* HD 203699. The lack of -60 km/s absorption in the more distant HD 203664 is very likely due to structure in the intermediate velocity gas at scales < 4°.



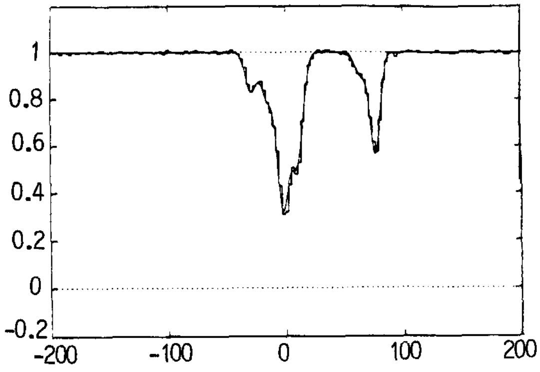
ultraviolet: The top three spectra (nos. 4-6) in Figure 1 show the absorption profiles of Si II λ1526, Al II λ1670, and C IV λ1548, respectively, *all in the direction of HD 203664*. The data have a resolution of 25 km/s. The Si II and Al II profiles are very similar in overall shape to the Ca II K profile, although the UV lines are stronger. Note the strongest UV line does show absorption beyond -60 km/s, suggesting that the -60 km/s cloud in front of HD 203699 does extend in front of HD 203664, but perhaps has too little column density to be detected at Ca II K.

The C IV profile reveals a markedly different structure from the low ionization profiles. The most noticeable difference is the continuity in the absorption between the 0 km/s and the +70 km/s features. While the low ionization species show very weak (or non-existent in the case of Ca II) absorption near 40 km/s, the C IV absorption is strong at these velocities -- nearly as strong as the 0 km/s and +70 km/s features. The data suggest that the gas near 40 km/s range is in a higher ionization state than the strong 0 km/s and +70 km/s components. The data also suggest that the component structure in the high ionization gas may be *different* from that in the low ionization gas. For example, the C IV profile does not show the strong feature at +70 km/s seen in the low ions. Instead the C IV shows a local minimum near ~50 km/s, and the line has nearly returned to the continuum by +70 km/s.

III. Quantitative Discussion -- the Method for Determining Column Densities

In order to accurately model the cloud structure along any line of sight through the interstellar medium one must know the number of components, their central velocities, their b-values, and their column densities. The lower the resolution, the more difficult it is to determine any of these quantities. For those species with the doublet transitions of $2s\,^2S$--$2p\,^2P^0$ or $3s\,^2S$--$3p\,^2P^0$, such as N V, C IV, and Si IV, limits on the column densities can be set using the doublet ratio method. But generally speaking, cloud b-values and column densities are found simultaneously using a curve-of-growth (c.-o.-g.) analysis by fitting the measured equivalent widths of several lines of the same species to theoretical curves. Frequently, interstellar column densities are determined from the *total* measured equivalent width which is independent of component structure. Results from such a "single-component c.-o.-g." analysis can have large uncertainties and give little insight into the physical conditions of gas along lines of sight with complex structure.

For example, in their IUE survey of 261 lines of sight, Van Steenberg and Shull (1988) found a column density for Si II toward HD 203664 based on a single-component c.-o.-g. analysis of $14.87 < \log N_{Si\,II} < 17.86$ and a range in b-values of 0.05 km/s $< b < 60$ km/s! Although their best fit gives a total $\log N_{Si\,II} = 15.37$ and $b=15.23$ for the entire line, the values still provide no information on the relative abundance, depletion or ionization state of different clouds along the line of sight. An examination of the profile shape for Si II in Figure 1 immediately shows that a one-component model is not an accurate representation of the physical conditions of the gas toward this star. The higher resolution optical data reveal that *at least* six components are needed to account for the Ca II K profile shape toward this star (Figure 2).



Six component fit to Ca II K line

Cloud Model:

1	4.0000	−29.000	3.00000E+11
2	5.0000	−15.000	4.00000E+11
3	4.0000	−2.0000	2.00000E+12
4	5.0000	10.000	1.20000E+12
5	5.0000	65.000	2.00000E+11
6	3.0000	77.000	9.60000E+11

The velocity model provided by the high resolution optical data fixes most of the free parameters of the fit to a much greater accuracy than on the basis of the lower resolution UV data alone, and can be applied to other species along the sightline. For each of the six observed Ca II clouds, the central velocity and b-value is determined and the values remain fixed for any species (such as Si II, Al II, Fe II, etc.) that also arise under the same interstellar conditions as Ca II. The only remaining free parameter is the column density for each component which can be adjusted until the best fit to the observed profile is found. The most accurate fits are achieved for those species (such as Si II; see Figure 3) where two or more lines are observable with IUE, spanning a wide range in f-value.

IV. Limitations

There are several limitations to this method of determining column densities, including:

- *Ca II cannot detect weakest components.* There may be components along the line of sight which are not detected at Ca II. We have already shown that toward HD 203664, the Si II and Al II profiles show absorption at -60 km/s and +40 km/s while the Ca II profile does not. Therefore at least two additional (bringing the total to eight) components are required to model the interstellar gas along the line of sight to HD 203664.

There is very little that can be done to get around this problem. However, with the bulk of the ultraviolet absorption accounted for by the "known" components, the range of possible values for the column densities and b-values of the weak lines are more restricted than they would be without the benefit of the optical data. Furthermore, the non-detection of Ca II puts an upper limit on how much of any given ion, X, can be present, by assuming "reasonable" values for the Ca II/X ratio.

- *Ca II velocity model is not (necessarily) applicable to the high ionization species.* As discussed in §II, the profiles of the high ionization lines suggest different velocity structure than that seen in the Ca II and other low ionization species. As C IV and Si IV arise under different physical condition than the low ions, this is not unexpected. Indeed, one of the aims of this study is to investigate how well (or how poorly) the velocity structure seen in the low ion lines relates to that seen in the high ions.

- *The Ca II lines are probably not fully resolved.* Even at 5 km/s resolution, the optical data probably does not adequately resolve the true component structure along the line of sight. The apparent components in Figure 2 may actually be made up of several narrower components. Observations by Hobbs (1969a,b) at a resolution of ~1 km/s show that clouds have b-values that are typically 1.5 - 2.5 km/s. Even lower velocity dispersion clouds may exist, though they would have to be *extremely* narrow (<0.2 km/s) or very weak to be undetected in Hobbs' data.

Fortunately, the signal-to-noise ratio in the Ca II data is so high that even components with b-values ~1 km/s would be detected if they contain comparable or greater column density than the 5 km/s component. Therefore, we claim that our Ca II column densities are good to a factor of 2, and that there are no hidden narrow components of significant additional column density. The only exception to this result is for the very core of the near-zero velocity component where even the Ca II components are fairly heavily saturated. The determination of the column density near 0 km/s is therefore only a lower limit. We return to this in the next section.

The applicability of the 5 km/s components is supported by the work of Jenkins (1986) who showed analytically that if, for a given ensemble of lines, the range of b-values and optical depths are smoothly distributed (i.e. not bi-modal), a single component analysis provides a remarkably accurate determination of the column density. The result holds for a wide range of b-values and/or optical depths, though it breaks down at levels of high saturation.

As a final comment, we note that *any* work done with GHRS on the abundances, ionization and depletion of interstellar clouds will necessarily be limited by these same assumptions. Although the resolution is improved over the optical data (3 km/s vs. 5 km/s), the detection limit for narrow components will likely be comparable because of a reduction in signal-to-noise ratio.

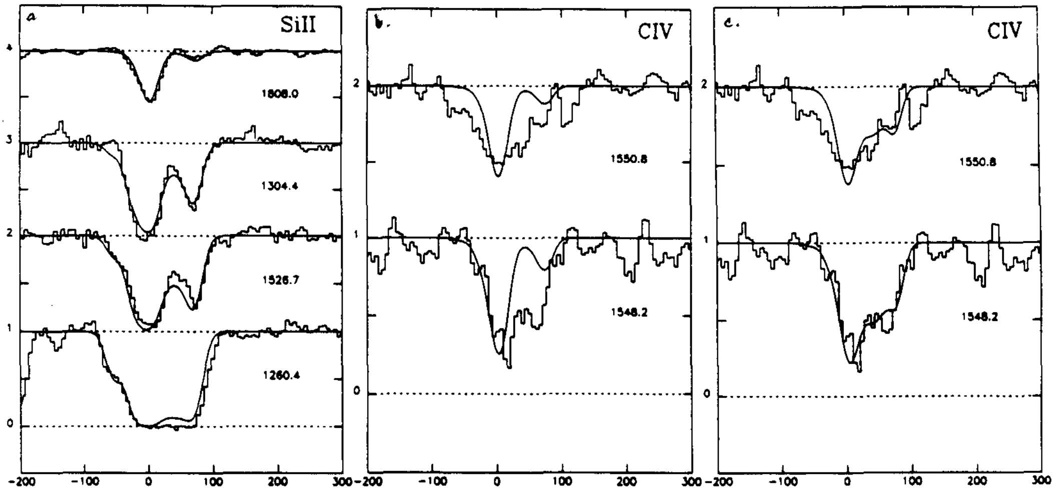
V. Results for HD 203664

In this section we illustrate our method by showing profile fits of two species, Si II and C IV, along the line of sight to HD 203664. Si II is an ideal species for study since it has several lines observable with IUE which span 2.5 orders of magnitude in f-value (values taken from Morton and Smith, 1973). Of the high ionization lines, the C IV lines are the strongest and the best exposed. Figure 3a shows the "best fit" to the Si II data. The listed column densities are good to a factor of two for all but the components near 0 km/s which are lower limits. An upper limit to the amount of column density that could be hidden in a ≤ 1 km/s wide component near 0 km/s is set by the absence of radiation damping wings which would become evident at column densities on the order of 10^{16} cm^{-2}. Interestingly, the *total* column density of Si II along this line of sight is about 1.6×10^{15} cm^{-2}, within a factor of two of the best estimate given by Van Steenberg and Shull (1988) for the sightline. The reasonable agreement between the two different methods supports Jenkins' (1986) view that a one component c.-o.-g. gives a reasonably reliable estimate of total column density.

Comparing to the fit of the Ca II K line in Figure 2, one sees that the Ca II/Si II ratio varies from component to component. Even more significant variations among components are seen in the Si II/H I ratio, though this may be due to beam size effects in the 21-cm data (the profile and discussion of beam effects can be found in Danly et al. 1989). In particular, the +70 km/s component is very weak, or even non-existent in the HI data. Interferometric observations of the HI in this direction will be made in September, 1989, in the hope of answering this question in greater detail.

By far the most difficult data to fit is in the region of the +40 km/s gas. While the fit appears a bit too strong in the $\lambda1304$ and $\lambda1526$ lines, it is a bit too weak for the $\lambda1260$

line. Some of the error may be due to uncertainties in the f-values, though errors in the atomic parameters should be uniform over the entire profile. Our best fit is achieved with a component having a significantly larger b-value of 20 km/s. Components with smaller b-values result in λ1304 and λ1526 lines which are even stronger and a λ1260 line that is even weaker! This can be understood in view of the fact that narrower lines saturate "quicker" (i.e. at lower column density) and thus there is *less* of a difference between the resulting λ1304 and λ1526 profiles and the λ1260 profile. A single narrow component does not have a large enough equivalent width to make the λ1260 line uniformly black, while adding additional narrow components makes the λ1304 and λ1526 lines unreasonably strong.



Cloud Model:

#	b	v	N
1	7.00	−55.00	8.00E+12
2	4.00	−29.00	4.00E+13
3	5.00	−15.00	8.00E+13
4	4.00	−2.00	8.00E+14
5	5.00	10.00	4.80E+14
6	20.00	40.00	3.00E+13
7	5.00	65.00	4.00E+13
8	3.00	77.00	9.00E+13

Cloud Model:

#	b	v	N
1	7.00	−55.00	6.40E+11
2	4.00	−29.00	3.20E+12
3	5.00	−15.00	6.40E+12
4	4.00	−2.00	6.40E+13
5	5.00	10.00	3.84E+13
6	20.00	40.00	2.40E+12
7	5.00	65.00	3.20E+12
8	3.00	77.00	7.20E+12

Cloud Model:

#	b	v	N
1	7.00	−55.00	6.40E+11
2	4.00	−29.00	3.20E+12
3	5.00	−15.00	6.40E+12
4	4.00	−2.00	6.40E+13
5	5.00	10.00	3.84E+13
6	20.00	40.00	4.00E+13
7	5.00	65.00	3.20E+12
8	3.00	77.00	3.00E+13

Figure 3b shows the C IV λ1548 profile, along with the best Si II model which has been scaled in order to bring the central optical depth of the 0 km/s gas into the best agreement possible with the data. The C IV/Si II scaling is a factor of 0.08. In this figure one clearly sees that a uniform scaling of all the components is not appropriate: significant component-to-component variations are found in the C IV/Si II ratio. A better fit is seen in Figure 3c, where the appropriate scaling for the +70 km/s gas is more like 0.33, while the +40 km/s feature has *more* column density in C IV than in Si II! There is *at least* a factor of 170 increase in the C IV/Si II ratio in the +40 km/s gas compared to the 0 km/s gas. The difference in the ratio could be even greater since the Si II column density in the 0 km/s gas is a lower limit.

VI. Discussion

From the models shown in §V and even from the profiles in Figure 1 it is evident that significant variations in physical conditions are likely to exist from one component to the next in gas along the line of sight toward halo stars. The data indicate moderate differences in the ion ratios between the +70 km/s halo cloud and disk gas, and even more extreme variations in the +40 km/s gas. Lack of space prevents more data from being shown, but this trend is seen in other species as well: both the O I (which is found only in H I regions) and the C II* (indicative of higher density) lines show strong 0 km/s and +70 km/s absorption features while they are very weak or non-existent near +40 km/s. The gas in this region shows higher ionization, lower column density, lower number density and higher velocity dispersion than the gas in the stronger "cloud" components. These are just the characteristics that one might expect to see in an inter-cloud medium and it is tempting to speculate that we are detecting such inter-cloud gas in our observations.

In addition to providing a comparison of conditions among various components, the method shown here has reduced the uncertainty in column density by two orders of magnitude and has placed more meaningful limits on b-values than those provided by a one component analysis. Further improvements can be made through better signal-to-noise in the UV data and better atomic data. The uncertainties introduced by possibile hidden narrow components can be reduced by studying this line of sight at very high (~ 1 km/s) resolution from the ground and/or by observing very weak lines that are probably not saturated (e.g. Cr II and Zn II) using HST. Finally, only GHRS observations of the UV species can provide the final word on whether such a cloud model is appropriate. Similarly, only GHRS can reveal the differences in velocity structure between the high ionization species and the low ionization species which are suggested in our data.

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Discussion:

MÜNCH (Comment): The difficulties you find in fitting the observed profiles (strong components) are only a consequence of the known fact (W.S. Adams, G. Münch, L. Hobbs) that as the resolving power of the spectrograph is increased the strong components unfold into a number of weaker partially overlapping components. Even with the highest resolving power - say 500000 - there is no hope of resolving all of them. Now, it is also known that the velocity distribution, macroscopically observable as line multiplicity and microscopically as line with, depends on the optical depth of the cloud. The net result is that the strongest lines in abundant ions have apparently larger Doppler parameters than the same lines in less abundant ions.

DANLY: By all means, uncertainties in obtaining column densities from unresolved lines are well documented. As described in our paper, we investigated the magnitude of the uncertainty in our analysis by attempting to "hide" both narrow and very broad components in the model, and them evaluate their contribution to the resultant profile. We claim our column densities are accurate to a factor of two, with the exception of the core of the gas near 0 km s^{-1} for which our analysis gives a lower limit (and then only if the hidden gas is in a component narrower than $\sim$ 1 km s^{-1}).

PECKER (Comment): I found your data very impresive and rich. But don't you take too much out of them? I observed CIV, SiII, UV lines, etc. in the solar UV spectrum: they are definitely formed in different regions. Then what is the meaning of their ratios? Secondly, in order to obtain, from line intensities, the column density, you insisted (correctly) that one important source of error is the uncertainty in the f-values. True! But not less worrying is the bad knowledge of all radiative and collisional transitions are involved in ionization and excitation of the atomic -ionic species you have observed; therefore I would take your column densities with extreme caution!

DANLY: I agree that the Si II and CIV lines are probably produced in different regions. Indeed the velocity structure differences between these lines suggest different component structure along the lines of sight. The "meaning" of our ion ratios is to suggest that differences in physical conditions exist in different regions along the line of sight. For example, gas near +40 km s^{-1} toward HD 203664 is almost certainly more highly ionized and lower density than the +70 km s^{-1} or 0 km s^{-1} gas.

Regarding your second point, a lack of complete knowledge of transition rates, non-LTE effects, etc., introduces uncertainties not in the derived column densities, but in their interpretation. One of our aims in embarking on this observational study in the pre-HST era is to challenge the theorists: are current models sufficiently detailed and sufficiently predictive to make use of the wealth of data of this sort which will become available with HST?