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Final Report

The Frequency and Distribution of High-Velocity Gas
in the Galaxy

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Joy S. Nichols

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1. Introduction

The purpose of this study was to estimate the frequency and distribution of high-velocity gas in the galaxy using UV absorption line measurements from archival high-dispersion IUE spectra and to identify particularly interesting regions for future study. Approximately 500 spectra have been examined. The study began with the creation of a database of all O and B stars with $b \leq 30^\circ$ observed with IUE at high dispersion over its 18 year lifetime. This original database of 2500 unique objects was reduced to 1200 objects which had optimal exposures available. Figure 1 shows the distribution of the stars in this group. Note that the coverage of the galactic plane is quite good. The next task was to determine the distances of these stars so the high-velocity structures could be mapped in the Galaxy. Spectroscopic distances were calculated for each star for which photometry was available. The photometry was acquired for each star using the SIMBAD database. Preference was given to the *ubvy* system where available; otherwise the *UBV* system was used.

Each high dispersion spectrum was examined for the presence of high velocity features in the lines of Si II, S II, C II, Fe II, Mn II, Mg II, Al II, Al III, Si III, Si IV, C IV, and N V. The radial velocity of each high-velocity feature was measured, along with the equivalent width. Because the IUE wavelength assignments are not always accurate, we measured the neutral lines of C I, Cl I, and Mg I, averaging these velocities to determine the zero-point for the measurements for each spectrum. The spectral were retrieved from the IUE archive and were not reprocessed for this project.

2. High Velocity Gas in the Line of Sight to the VELA SNR

2.1 Introduction

One of the best objects for study of the structure, kinematics, and evolutionary status of a middle-aged supernova remnant (SNR) is the VELA SNR, due to its proximity (500 pcs or less), extensive filamentary structure, and an abundance of hot background stars for absorption line research. The VELA remnant is 6° in diameter, based on recent x-ray

imagery with ROSAT, with the pulsar nearly centered in the remnant (Aschenbach et al. 1995). The western region of the remnant has much lower x-ray surface brightness than the remainder of the remnant and in fact escaped earlier detection with previous instrumentation. High-velocity absorption components to the interstellar lines in UV data, which can yield important information concerning gas kinematics, morphology, abundances and depletions, were first reported by Jenkins, Silk, & Wallerstein (1976), who studied 4 stars in the VELA line of sight using Copernicus data. They found velocities in the range of -90 km s^{-1} to $+180 \text{ km s}^{-1}$ with a possible component at -450 km s^{-1} . Jenkins, Wallerstein, & Silk (1984) studied absorption line profiles in IUE high dispersion data of 45 stars in the VELA line of sight, finding high velocity components in more than one third of the program stars, with velocities up to $+180 \text{ km s}^{-1}$. Their analysis of IUE data showed chaotic kinematics, no geometric effects of expansion, lower depletion than the normal interstellar medium (ISM), and some relatively strong lines of C I. Raymond, Wallerstein, & Balick (1991) found evidence of a thermally unstable shock wave behind a 150 km s^{-1} shock. Their calculations also indicate the shock is nearly face-on. An important result by Jenkins & Wallerstein (1995) revealed 6 distinct components to the interstellar C I lines for one star behind VELA, HD 72089. Their analysis was based on HST GHRS data. These authors conclude the $+121 \text{ km s}^{-1}$ component represents gas that has cooled and recombined behind the shock wave. They also find that the implied energy of the supernova is too large if a distance of 500 pc is accepted. They proposed instead a distance of 250 pc.

While IUE high resolution data do not have the resolution of GHRS, the large number of spectra available in the IUE archives provide an opportunity to map spatially the high-velocity components to the interstellar lines and compare the morphology of the hot gas to x-ray imagery.

2.2 Observations

We surveyed all high dispersion IUE data of hot stars near the galactic plane with the goal of cataloging high-velocity components in the interstellar absorption lines. The project includes high ionization (C IV, Si IV, and N V) and low ionization (Fe II, C II, Si II, Al II, and S II) lines present in either SWP or LWP/R spectra of O and B stars. The primary interest in our survey is the radial velocity of the interstellar components; equivalent widths are not presented here. The wavelengths of each high velocity feature was measured from the archived IUESIPS spectrum. These wavelengths were then corrected to heliocentric velocity using software available at the IUEDAC which uses contemporaneous orbital elements for the calculation. The heliocentric wavelengths in IUESIPS data use a single set of orbital elements from early in the IUE mission and can be in error by several km s^{-1} . Even after correction to heliocentric velocities, there are residual errors in each spectrum due to image distortion and spectra format motion. We would have preferred to add a correction to each radial velocity measurement which was determined from the mean of the neutral ion lines as has been done in previous studies, but as noted below, the neutral C I (the majority of the available neutral ions in SWP spectra) are variable and sometimes have high-velocity components of their own, making them unreliable fiducials in the VELA region. We therefore report heliocentric velocities as described above. There is one remaining important source of error in the radial velocities reported here. The long-wavelength spectrum of an object often has a velocity offset from the SWP spectrum of the

same object, based on the mean of the main interstellar components and in particular on the Fe II $\lambda 1608$ line radial velocity in the SWP spectrum compared to the Fe II $\lambda 2382$, 2585, 2599 lines in the LWR/P spectrum. This offset, which is generally about $+17 \text{ km s}^{-1}$ for the LWR/P spectra, has been previously reported (Nichols-Bohlin & Fesen 1986) but the source of the error remains unknown. Because the error is not always present, and SWP spectra analyzed here form a consistent group of main component velocities, we assume the error is in the long-wavelength assignments from IUESIPS, and have corrected these velocities such that the main components in the LWR/R spectrum match those in the corresponding SWP spectrum.

We have selected 60 stars in the region for study of the VELA SNR. While the sampling of the region is generally quite good, there are a few unsampled pockets evident in the figure, particularly about 1° west and 1° east of the VELA pulsar. The lack of data in these regions must be considered in the conclusions to this work.

It was not always possible to measure all of the lines in an image. For example, the C II line at $1334 \text{ \AA}$ is contaminated by a reseau mark in large aperture spectra, discounting valid measurements. Al II lies at the end of an echelle order and the ripple correction for this order was often unsatisfactory, producing spurious features. Al III has not been included in this study because it almost always includes a photospheric component. Although the Si II lines at $1190 \text{ \AA}$ and $1993 \text{ \AA}$ were always examined, this region of the IUE echellogram is almost always too noisy to make confident measurement. The spectra were smoothed with a three-point boxcar filter for analysis. The main component generally lies at $+20 - +30 \text{ km s}^{-1}$ in the VELA direction.

The high-velocity C I features presented here represent a serendipitous discovery which occurred while surveying the spectra of stars in the line of sight to the VELA SNR. Because the wavelength assignments in high dispersion data are not sufficiently reliable to be used directly for absolute velocity displacements of high-velocity features, we normally measure the radial velocity of a series of neutral features (C I, Cl I, Si I) in each SWP image and use the mean of these velocities to determine the heliocentric radial velocity of high-velocity features found in each spectrum. However, in making the C I measurements, we found that many stars had displaced C I lines with respect to the main components of the other interstellar lines in the spectrum, and eleven stars actually showed high-velocity features in the C I lines, with the high-velocity feature of similar strength to the main component. Because the intent of our investigation was to measure the low and high ionization lines for high-velocity features, and to use the C I lines as fiducials, no equivalent widths were measured. The number of stars showing high-velocity C I presented here must be considered a lower limit, because only the strongest component(s) were recorded in our log. Indeed, it was only at the conclusion of our study of the VELA region that the consistent pattern of high-velocity C I in this region was recognized.

2.3 C I Discussion

The 11 stars showing high-velocity C I are generally confined to a band extending from

the north edge (near Pup A) to the south edge of the x-ray image. This band is about 1° wide on the image. This clearly defined spatial morphology of this region of high-velocity C I implies the high-velocity gas arises from a single coherent structure. The structure is most likely associated with the VELA SNR because (1) there is a lack of such high-velocity C I gas outside the x-ray region except for 1 star slightly outside the south-west edge of the remnant and not associated with the "band" in the interior of the remnant, and (2) the velocity is consistent with the most pervasive high-velocity components in other species detected toward VELA. The fact that all of the high-velocity components have positive velocities is particularly helpful in determining the nature of the associated high-velocity gas. The band must be on the back side of the remnant only and confined to a small region, suggesting it is not pervasive in the supernova shell but perhaps a dense, pre-existing cloud in the ISM which is now interacting with the SNR. The band of high-velocity C I lies close to the sharp line in the ROSAT x-ray image separating the high surface brightness region (previously seen by EINSTEIN) and the low surface brightness region, newly revealed with ROSAT. However, the high-velocity C I structure lies inside the high surface brightness region.

2.4 Low Ionization Discussion

While it is clear from the detection of multiple high-velocity components to many of the interstellar lines that the lines of sight intersect multiple cooling regions, it is also clear that these regions are quite patchy and stars separated by as little as a few parsecs show different velocity structures.

Figure 2 is a histogram of the high velocity components measured in the sample of 60 stars. Each component was counted separately, even when 2 or more high velocity components appeared in the spectrum of a single star. The histogram makes use of the large number statistics available in the IUE archive and illustrates a concentration of components at -90 km s^{-1} and $+120 \text{ km s}^{-1}$. There are two stars with a component at $+400 \text{ km s}^{-1}$ and two stars with a component at $+500 \text{ km s}^{-1}$. There are also apparent component at $+150 \text{ km s}^{-1}$ and -140 km s^{-1} . The occurrence of these features appears to be random across the VELA SNR in the region sampled by the program stars and geometric effects are not clearly evident, although they may be present in the components with radial velocity $|v| \leq 100 \text{ km s}^{-1}$ seen in a number of the stars. However, these lower velocity components are not confined to the outer regions of the VELA remnant and cannot be exclusively attributed to the lower velocities expected when viewing the edge of a shell as opposed to the center. These lower velocities may indeed represent an additional structure to the obvious one at $|v| = 100\text{-}120 \text{ km s}^{-1}$ and $|v| = 400\text{-}500 \text{ km s}^{-1}$.

2.5 Si IV Discussion

There are far fewer high-velocity components to the Si IV lines (total of 19 in our sample) than are present in either the low ionization lines (39 in our sample) or in the C IV data (56 in our sample). The smaller number of components compared to the low ionization lines may be understandable since there are 7 low ionization lines normally measured in each spectrum as opposed to two Si IV lines (a doublet). The components at -100 km s^{-1} and $+120 \text{ km s}^{-1}$ are again the most common, with the $+150 \text{ km s}^{-1}$ components also well represented. In addition, two components are present at -225 to -250 km s^{-1} and two components at -800 km s^{-1} . There is one component at -420 km s^{-1} and one at -350 km s^{-1} . While components present in only one spectrum are viewed as questionable, these two components have counterparts in the low ionization data (-400 km s^{-1}) and in the C IV data (-350 km s^{-1}).

2.6 C IV Discussion

The C IV high-velocity features are remarkable for their high frequency of incidence, especially considering that only 2 lines per spectrum contribute to the statistics. Figure 3 is a histogram of the high-velocity C IV features detected in the program star spectra. As in the cases of the low ionization lines and the Si IV lines, the -100 km s^{-1} and $+120 \text{ km s}^{-1}$ components dominate the statistics, with the $+150 \text{ km s}^{-1}$ also well represented. Here we see the strongest evidence for additional high-velocity structures. The $v = +400 \text{ km s}^{-1}$ components are clearly identifiable as a distinct structure, with 4 stars showing this component. The component at -325 km s^{-1} to -350 km s^{-1} is also well defined, with 4 stars exhibiting these components. This set of components, like the $[-100, +120]$ set, indicate a shell of cooling material expanding in VELA about the systematic velocity of $+20$ to $+30 \text{ km s}^{-1}$, although, again, no geometric effects are clearly seen. There are also components at -230 km s^{-1} and $+350 \text{ km s}^{-1}$, which may be statistically significant.

2.7 General Discussion

Because IUE coverage of the VELA region is not complete, it is difficult to describe the morphology of the structures responsible for the high-velocity gas. We can certainly conclude that the structures are patchy because detection at IUE's resolution varies over distances as short as a few parsecs. The structures do not appear to be shells expanding uniformly from the center of VELA due to the lack of geometric effects, which leads us to conclude that these are preexisting clouds overrun by multiple shocks. The four C I lines examined in our analysis are each the ground state transition in multiplets of up to 5 transitions. Each group of lines is generally too complicated to measure any but the strongest component at the resolution of IUE. This situation also leads to lower reliability of measurements. However, each of the 4 multiplets has a different set of components transitions, so that strong features

verified in most of the multiplets can be considered reliable. Occasionally, the wavelength region of a multiplet was too confused to measure any component.

Jenkins & Wallerstein (1995) recently observed HD 72089 with HST, measuring the components of the C I lines 1656Å, 1329Å, and 1280Å. They find evidence of 6 high-velocity components in the line of sight to HD 72089, which lies only 25' from HD 72537, a star in our study, and also well within the band of stars showing high-velocity C I in our study. We did not detect high-velocity C I for HD 72089 in the IUE data because the high-velocity features are not as strong as the main component in the ground star C I and the high-velocity feature at $+121.5 \text{ km s}^{-1}$ is blended with other lines in the multiplet at IUE's resolution. As mentioned above, we were not looking specifically for high-velocity features in C I. This illustrates the fact that the number of stars showing high-velocity C I we detected is a lower limit.

Certainly, the clear detection of positive velocity C I in the HST spectrum of a star along nearly the same line of sight as many of the stars we studied validates the IUE results. The Jenkins & Wallerstein analysis of the high-velocity neutral and excited star C I indicates the gas producing the high-velocity C I absorption features in UV data is in a high density and high pressure zone behind the shock front that has cooled and recombined.

This study supports the proposal by Jenkins & Wallerstein (1995) that the distance to VELA should be revised. The distance of 400-500 pc has been accepted, primarily because of the presumed association between VELA and the Gum Nebula. Jenkins & Wallerstein suggested that VELA is at 250 pc due to energy considerations. Two of the stars in this study which show positive C I components have distance estimates of 375 and 360 pc, respectively. In addition to C I, these 2 stars show positive velocity components in both low and high ionization lines. Thus, a revised distance of 300-350 pc for VELA SNR would be consistent with our data.

The detailed analysis and conclusions of Jenkins in reference to the neutral and excited state C I gas in the VELA SNR appear to be generalizable to the band of high-velocity neutral gas described here. It is possible that the high pressure and density region is not a distinct cloud or structure in the SNR, but is global to the SNR in the sense that a shell of neutral recombined gas exists in the post shock material, with the column densities large enough to be detected with IUE only in the western limb. But in this case, some negative velocity components should probably have been detected. The data suggest we are viewing evidence of pre-supernova inhomogeneities in the ISM.

Considering the distances of the stars studied, we find the various high-velocity components may originate in spatially distinct regions. For stars with distance estimates less than 580 pc, only the -90 , $+120$, and $+150 \text{ km s}^{-1}$ components are seen in any ionization state. The $+400$ and $+500 \text{ km s}^{-1}$ components appear in stars with distance estimate $\geq 580 \text{ pc}$. This would imply that the higher velocity components are formed in a different, background structure to the lower velocity components. The Gum Nebula and the VELA SNR are at similar distances and it is conceivable that some of the high-velocity components arise in the Gum Nebula rather than the VELA SNR. However, we find no evidence for such high-velocity components in stars outside the VELA region. The distance differentiation could be fortuitous, because the higher velocity components are few in number. Assuming the -90 ,

+120, and +150 km s⁻¹ components are associated with the VELA SNR, we estimate the distance to the VELA SNR to be 300-350 pc, based on the positive velocity components in HD 70930 at 375 pc.

The distribution of high-velocity components suggests the most prevalent components (-90, +120, +150 km s⁻¹) are global in the VELA SNR and perhaps associated with the cooling interface behind the shock wave of the supernova. The higher velocity components (+400, +500 km s⁻¹) are less uniformly distributed but still cover the entire projected SNR. It is difficult to believe that these components arise at the conductive interface of several clouds embedded within the SNR because of the consistent velocities at several lines of sight to the SNR. Other components occurring in more localized regions could be interpreted as conductive cloud interfaces. Danks & Sembach (1995) suggest that some of the high-velocity gas in VELA may be accelerated by events other than the Vela SNR, based on the wealth of components seen in the spectra of member stars of IC 2395, situated in the line of sight to the southeastern edge of the VELA x-ray perimeter. This is a somewhat confusing result because if the high-velocity features arise in the cooling gas behind the supernova shock wave, the velocities in this region should be near zero, yet the velocities are consistent with those seen near the center of the remnant. The suggestion of Danks & Sembach is tempting, but is countered by the occurrence of similar velocities at other lines of sight to VELA. It seems unlikely that several independent explosive events would produce such similar high-velocity features.

3. High-Velocity Gas in the Line of Sight to Sco OB1

Sco OB1 has one of the highest concentrations of massive stars in the Galaxy, and not surprisingly, an optically detected superbubble. High-velocity gas has been detected in the line of sight to Sco OB1 in Ca II and Na I lines (Crawford, Barlow, & Blades 1989). Three groups of velocity components were identified in the spectra of Sco OB1 members: (1) strong absorptions between 0 and -20 km s⁻¹, (2) discrete, sharp absorptions up to -50 km s⁻¹, and (3) absorptions at positive velocities of approximately +20 km s⁻¹. In the first group N(Na)/N(Ca II) ratios were found to be from 4-200, implying the gas in this velocity range is due to diffuse clouds intercepted in the line of sight to the association. The components with larger negative velocities (group 2) showed smaller Na I/Ca II ratios, near unity. The gas around -50 km s⁻¹ was interpreted as arising in the swept-up shell of a superbubble surrounding Sco OB1. Finally, the positive velocity components with an even lower Na I/Ca II ratio may be due to the warm intercloud medium. The lower Na I/Ca II ratio in the gas associated with the superbubble may be due to the removal of calcium from grain surfaces by the 20-30 km s⁻¹ shock. Since the degree of depletion is density-dependent for calcium but not for sodium, we may conclude that the warm intercloud medium (group 3) has higher density than the superbubble shell.

While the diameter of the superbubble could not be directly determined by Crawford et al. (1989) because they were not able to observe any background stars outside of Sco OB1, evidence for the size of the superbubble is available from H α imagery and IRAS AllSky Survey data. The H α image of the Sco OB1 region in an emission line survey of the Milky Way by Parker et al. (1979) shows a clearly defined shell structure approximately 240° complete, extending from the galactic plane to the northwest and northeast, with Sco OB1 situated

near the projected center of the shell. On the $60\mu\text{m}$ IRAS image of this region a similar shell-like structure is seen, nearly coincident but outside of the $\text{H}\alpha$ structure. If we assume the shell seen in $\text{H}\alpha$ and $60\mu\text{m}$ represents the superbubble around Sco OB1, the radius of the superbubble is 1.5° (50 pc at a distance of 1900 pc). Using the relations of Weaver et al. (1977) and an expansion velocity of 30 km s^{-1} determined from the optical study of Crawford et al., we find an age of the superbubble of 1×10^6 yrs. This age is much larger than those determined for the Orion, Carina, and Cygnus superbubbles ($3\text{--}4 \times 10^5$ yrs). Yet the ages of the Orion, Carina, Cygnus, and Sco OB1 associations themselves are similar ($2\text{--}3 \times 10^6$ yrs) and Sco OB1 contains more O stars than any of the other three associations (Humphreys 1978). This implies the Sco OB1 superbubble has evolved without benefit of multiple supernovae and was produced perhaps entirely by the stellar winds of its many massive stars, consistent with the calculated energy budget for the superbubble. This makes the superbubble around Sco OB1 distinct in character from other superbubbles previously studied in the UV. The current wind power from the O stars in Sco OB1 is estimated to be 5.0×10^{37} ergs/s (Abbott 1982) and from the WR stars, 22.3×10^{37} ergs/s (Abbott et al. 1986). If the WR stars have been losing mass at their current rate for about 2×10^5 yrs, and the O stars for about 1×10^6 yrs, the total wind power available to form the superbubble is 9×10^{51} ergs. However, assuming an expansion velocity of 30 km s^{-1} , a radius of 50 pcs, and $n_0=1$, we find the total wind luminosity required to produce the superbubble is 8×10^{50} ergs, an order of magnitude less than what appears to be available in Sco OB1 from stellar winds alone. Of course, the more massive stars may have formed rather recently, reducing the estimate of the available energy to form the superbubble.

If we instead assume the superbubble is the result of supernovae, following Chevalier (1974), we find that the bubble could have been formed by one supernova, but in this scenario the massive stellar winds that are obviously present would make no contribution to the energetics, which is rather implausible. It is clear that the superbubble around Sco OB1 is much less energetic than those found in Orion, Carina, and Cygnus, in spite of the more generous membership of massive stars in Sco OB1. This region therefore provides a unique opportunity to study the properties of a superbubble produced from stellar winds alone.

While the analysis of high-velocity UV absorption line data could add a great deal to the study of the Sco OB1 superbubble, including ionization level and structure in the shocked material, abundances, depletions, and column densities, a previous attempt to detect high-velocity features in the IUE spectra of 6 stars in this region produced a null result (Crawford 1989). With our more complete survey, both in ionization species and in numbers of lines of sight, we were able to detect high-velocity components in the IUE spectra of 8 stars in the Sco OB1 region, most of them members of the association. While the -30 km s^{-1} component detected in the visual by Crawford et al. is apparent in the low ionization lines of these 8 spectra, and is in fact as strong as the zero velocity component, the high ionization lines of Al III, Si IV, and C IV have even higher velocity components, near -50 km s^{-1} . Two of the stars also exhibit a positive component at $+50 \text{ km s}^{-1}$, presumably due to the receding side of the superbubble.

4. Carina Region

While high-velocity gas was identified in several stars in the Carina Nebula region from IUE spectra in 1982 (Walborn & Hesser) and 1984 (Walborn, Heckathorn, & Hesser), we have found in this study that the high-velocity gas has a much greater spatial extent than previously thought. High-velocity gas is detected well outside the optical emission region and covers a 15° region along the galactic plane. This discovery changes the energy budget for the Carina Nebula considerably.

5. General Galactic Plane

In the region $295^\circ \geq l \leq 320^\circ$, the lines of sight to 68 stars were studied. We present this region as an example of the results in regions of the galactic plane where no high-velocity gas has previously been detected. Fourteen of the 68 stars showed evidence of high-velocity components in their spectra. None of these lines of sight intersect known supernova remnants and only one is a member of or background to an OB association. The most obvious conclusion is that these 15 lines of sight intersect previously undetected supernova remnants. In future work we will evaluate these lines of sight in detail, attempting to parameterize the supernova remnants and calculate their energy budgets.

But the overwhelming conclusion of this work is that high-velocity gas is quite rare in the galactic plane, outside of known superbubbles and supernova remnants. We have sampled a significant portion of the galactic plane to distances of 3 kpc, and find only a few instances of isolated high-velocity gas. If the hot component of the interstellar medium is dominant and supernovae and superbubbles continue to expand until they interconnect, we would expect to find high-velocity gas along most lines of sight. Perhaps the column densities are too small to be detected with IUE, but the fact that we do detect known supernova remnants and superbubbles would argue otherwise.

Conclusions

We have found that high-velocity gas is rare in the galactic plane, other than in regions of known supernova remnants and superbubbles. Interstellar bubbles produced by individual hot stars do not have column densities, as a rule, sufficient to be detected with IUE. We have found that the structure of supernova remnants and superbubbles is much more complex than previously thought, with multiple components to the interstellar lines more the norm than the exception. In the VELA supernova remnant, for example, we have found the largest velocity range yet reported in galactic studies. Geometric effects from a uniformly expanding shell are not usually apparent. The velocity structure of supernova remnants and superbubbles is complicated, probably due to preexisting inhomogeneities in the interstellar medium, and the densities are quite patchy.

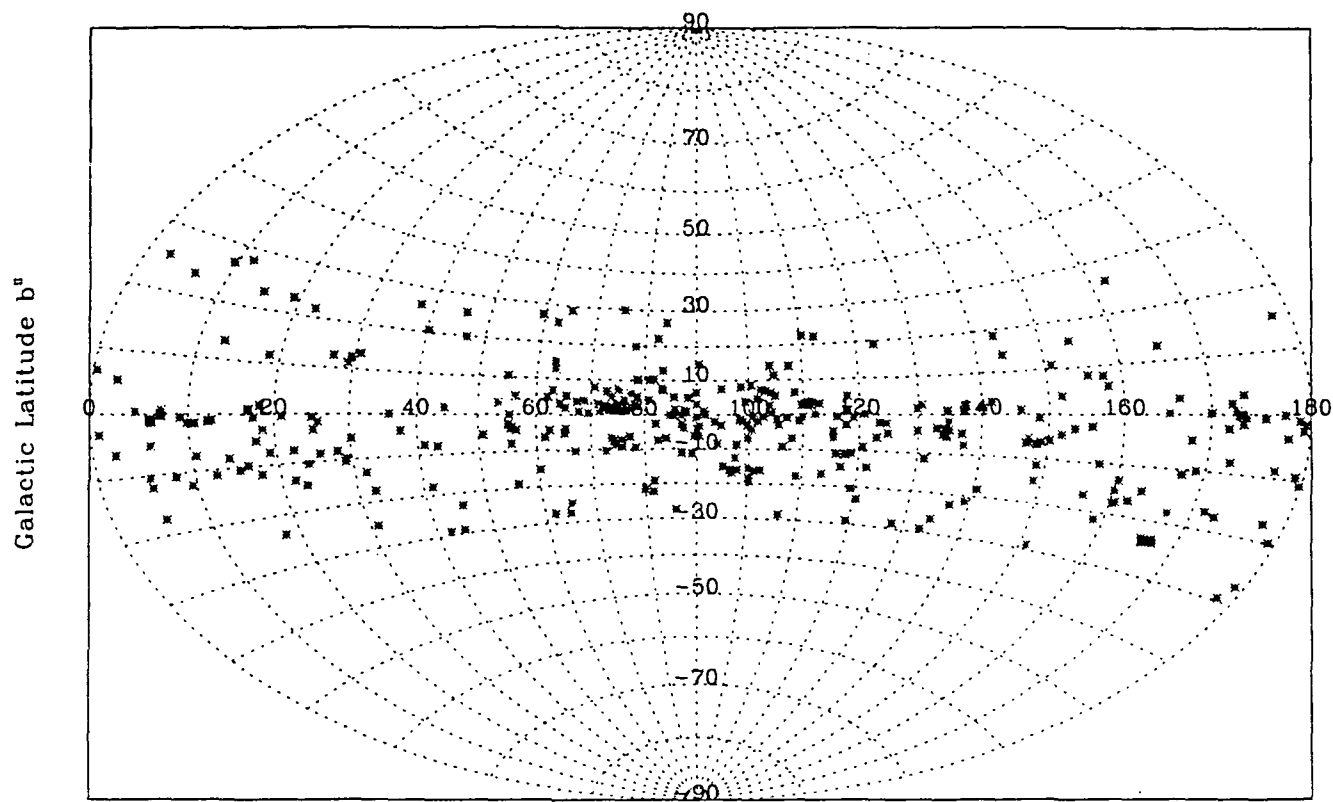
The IUE archive has proved extremely useful for studying interstellar structures, in spite of the relatively low resolution, because of the large number of lines of sight available.

The data from this program, including distance estimates and velocity displacements of high-velocity absorption components have been saved in IRAF tables for distribution to the community.

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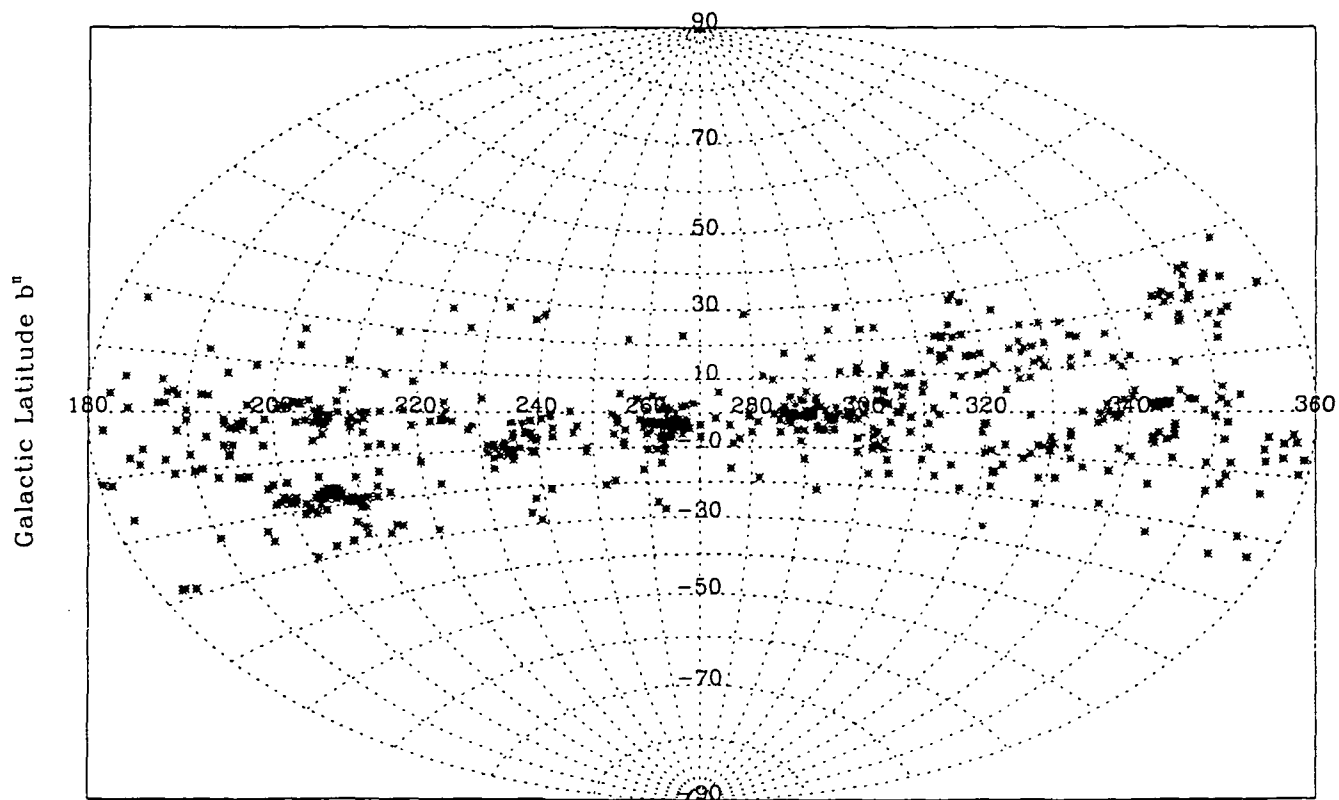
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Hemisphere Centered on $l^{\circ}=90^{\circ}$



Galactic Longitude l°

Hemisphere Centered on $l^{\circ}=270^{\circ}$



Galactic Longitude l°

FIGURE 1

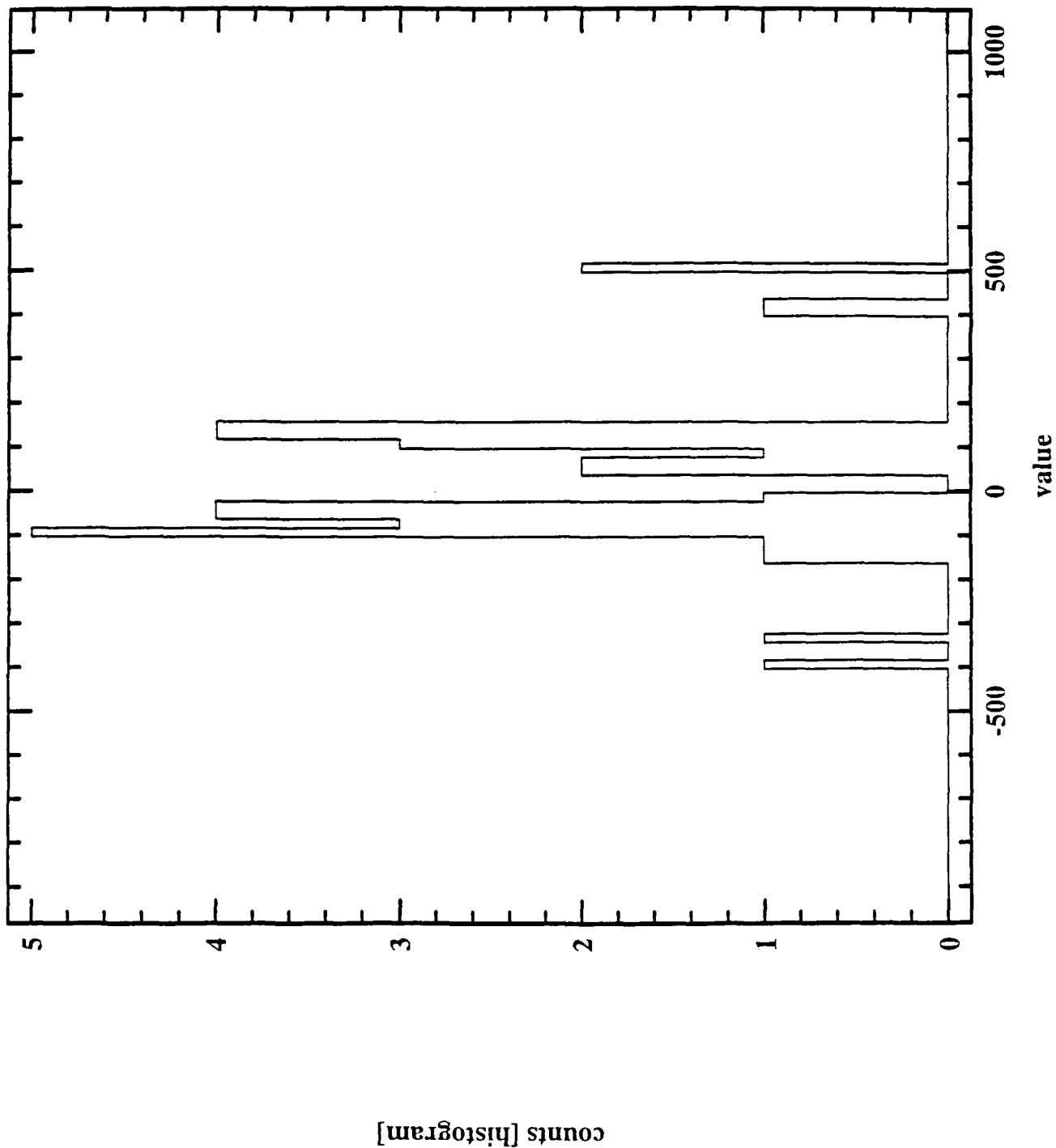


FIGURE 2

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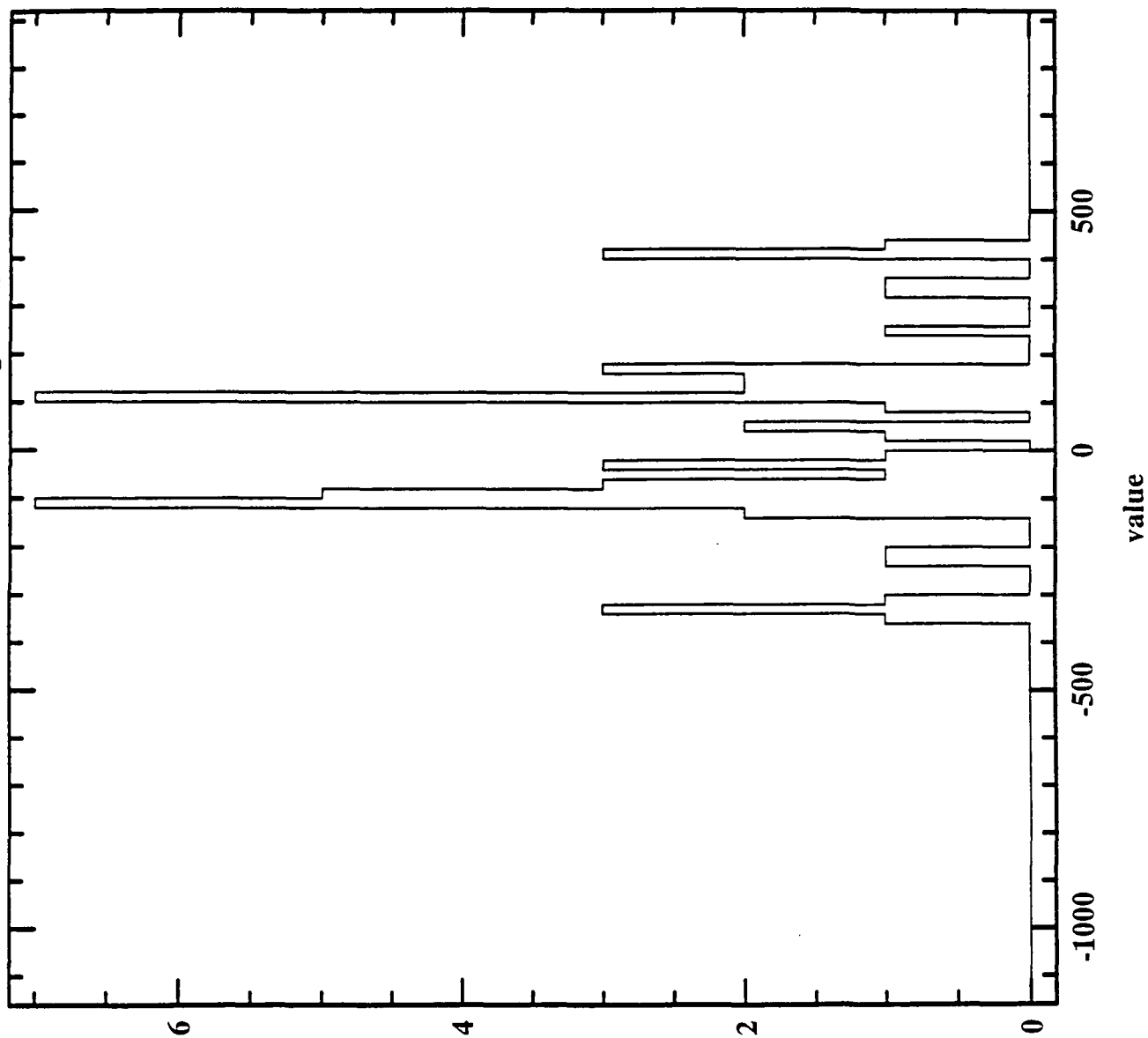


FIGURE 3

bin = 20

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