OBSERVATIONS OF THE INTERSTELLAR MEDIUM WITH IUE

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IUE'S POTENTIAL FOR INTERSTELLAR MATTER RESEARCH

Over nearly eight years of operation, the Copernicus satellite has brought forth far-reaching conclusions on the composition and physical state of the interstellar medium. The many milestones of research from this orbiting telescope and spectrometer have demonstrated the unique value of ultraviolet absorption lines, far beyond some early, enthusiastic projections (e.g. ref. 1), since this region of the spectrum is especially rich in strong transitions from the lowest electronic levels of astrophysically important substances. In a complementary way, the IUE instrument has continued the tradition of disclosing new insights on the properties of low density regions in space.

In reviewing IUE's promise for exploring new frontiers, it is helpful to examine the strengths and weaknesses of this instrument relative to its predecessor, the one on board Copernicus. Since IUE records a spectrum with an image sensor instead of a scanning photomultiplier, it can integrate the signals from all spectral elements simultaneously and obtain information from stellar sources about 6 magnitudes fainter than those recorded by Copernicus (in spite of the latter's much larger collecting area). This increase in sensitivity means much to astronomers who wish to study the intrinsic properties of sources in the sky which emit UV radiation, since the classes of objects open to examination has broadened enormously, as this IUE symposium will attest. However, the observer dealing with the interstellar medium also realizes a gain, inasmuch as he or she can see to considerably greater distances or probe denser clouds where the absorption by grains is substantial.

On the other hand, we must acknowledge some important limitations of IUE for analyzing interstellar lines. Because there are small-scale photometric irregularities, it is generally conceded that the minimum detectable equivalent width is about 20 mÅ (Copernicus often registered lines at the 1 mÅ level). For a line to have a measurement of acceptable accuracy, it must have a strength of several times this threshold. However, the saturation of this line must be small, say less than a factor of 2, for a column density derivation to have even modest reliability. This condition is satisfied only if the velocity dispersion b for the gas is greater than about 8 km s^{-1}, which is often not the case for the more common interstellar species in individual absorbing regions. While saturated lines and the resulting uncertainties in their interpretation are a universal problem for astronomers, we must not be too harsh and categorically deny that useful work can be done in such instances. For example, one may compare the abundances of several species if their absorption lines are seen to have comparable strength and there is good reason to believe their velocity profiles are nearly identical. In this circumstance, we acknowledge that we have no information about what is happening in the saturated cores of the lines, but we do have the opportunity to compare abundances of material in the outer wings of the velocity profile. Also, quite apart from equivalent widths, valuable information on the kinematics of interstellar gases in specially interesting contexts can be derived from ordinary measurements of the lines' radial velocity centroids.

HIGHLY IONIZED GAS

The appearance of sharp Si IV and C IV doublet absorptions in the IUE high dispersion stellar spectra of distant stars has attracted much attention. Initially, these lines were seen in the spectrum of the X-ray binary system HD153919 (4U1700-37) during the satellite's commissioning phase (refs. 2 and 3). At the time, it was suggested that X-rays from the binary system were responsible for ionizing the atoms in the ambient medium, since the Si IV and C IV absorption lines seemed extraordinarily strong. Now that a large number of stars have been observed with IUE, we realize that the highly ionized atoms in front of this source are not at all unusual; many of the ordinary O and B type stars show lines of comparable strength.

Throughout the history of high dispersion stellar spectroscopy, a recurrent controversy about the appearance of narrow absorption lines is whether they arise from some circumstellar accumulation of material or, alternatively, from the general medium between the stars. We can trace questions of this sort even back to the period following Hartmann's pioneering discovery of the stationary Ca II lines in the spectroscopic binary δ Ori in 1904 (ref. 4). It was not until about five years later that enough evidence from many binaries (ref. 5) could convince the skeptics that the Ca II lines indeed arose from the general reaches of space. Challenges on the general interstellar origin of some absorption lines also occurred during the era of the Copernicus satellite (refs. 6 and 7), to be answered by detailed case analyses (e.g., ref. 8) or by extensive statistical conclusions (refs. 9 and 10). The issue remains alive today, as we can see from the divergent viewpoints expressed by research groups interpreting their IUE recordings of the narrow Si IV and C IV lines. These features are found within their broader stellar counterparts and in most instances are well distinguished. Black et al. (ref. 11) have argued that the line widths are in accord with the expected values from material within an H II region which is photoionized by relatively energetic photons from the hot star. In contrast, from the perspective of Bruhweiler et al. (ref. 12) such lines may be produced in a hot phase of collisionally ionized interstellar material, which they labeled as "semitorrid" to differentiate it from the much hotter interstellar gas responsible for O VI absorption (refs. 13 and 14) and diffuse soft X-ray emission (ref. 15). Convincing evidence that Si IV and C IV lines can originate from general regions of space was presented by Savage and deBoer (ref. 16), who observed absorptions near zero velocity against a star in the LMC — a system with a radial velocity of approximately +250 km s^{-1}.

Neither of the conflicting interpretations seem to have serious flaws, and indeed both viewpoints may be correct. To support their respective conclusions, however, Black et al. and Bruhweiler et al. have had to rely on circumstantial relationships seen within fairly limited data bases. In this review, we will try to resolve the question by gathering all of the Si IV and

C IV data available at present and explore their relationships with various relevant parameters. We are no longer hampered by an insufficiency of independent observations, but we should be prepared to deal with spurious correlations arising from biased target star selections and the inclusion of data which are near the threshold of measurement. Our problems may be compounded when we commit the sin of mixing the data from different investigators, each of whom had categorically different types of coverage (stellar types and distance) and may have measured their lines in slightly different ways. Fortunately, the difficulties arising from selection effects and marginal detections are ameliorated by considering the complementary outputs from both the Copernicus and IUE satellites. The former is sensitive to very weak absorptions in nearby stars, while the latter can register the spectra of much fainter and more distant stars with their correspondingly higher column densities.

Table 1 summarizes the principal sources of Si IV and C IV data which are utilized for the studies which follow below. It must be emphasized that there are probably significant errors in some of the results. Many values are from preliminary analyses, others from reductions with a defective IUE intensity transfer function (ITF), while still others refer to target stars whose distances (or intrinsic characteristics) are poorly known. While individual points in the plots which follow may not be very trustworthy, the overall trends should, with some qualifications, be reasonably fair representations. To avoid inconsistencies and questionable assumptions, all of the column densities were rederived using the doublet-ratio method on the original measurements, rather than using the authors' quoted values for N(Si IV) or N(C IV). For doublet ratios less than 1.3, a lower limit corresponding to a factor of two saturation for the weaker line was assigned.

Support for the hypothesis that the observed Si IV and C IV arise primarily from the star's ionizing photons might be seen in a positive (but decidedly nonlinear) correlation of column density versus the star's effective temperature T_{e*}. Figure 1 shows these relationships for Si IV and C IV; one would be hard pressed to say that there is a convincing trend here. The column densities are adjusted by each star's radius to the 2/3 power to compensate for different sizes of the respective radiation-bounded Stromgren spheres of a given internal density. We might argue that the scatter could be blamed on wide variations of the density of the ambient gas in the different cases. Another test, which should be less sensitive to changes in density, is to determine if the ratio of C IV to Si IV varies with T_{e*}. We would expect this ratio to increase with T_{e*} since C III has a higher ionization potential than that of Si III. Figure 2, however, seems not to be at all encouraging in this regard.

Before we abandon the notion that photoionization from stars may be important sources of Si IV and C IV, we should remember that a good fraction of the chosen stars reside within OB associations. In such cases, the radiation field may be dominated by stars other than the target, such as possibly hotter but less conspicuous members of the group. Perhaps one could see more meaningful correlations if one classified the results according to association's distribution of stellar types or the conspicuousness of its H II region, rather than just the properties of the target stars.

We now turn to the hypothesis that the high stages of ionization arise primarily from widely distributed material at a high temperature. There are strong observational precedents (refs. 14 and 15) and sound theoretical reasons (ref. 21) which support the existence of very hot phases. Figure 3 shows how the column densities relate with the stars' distances. The wide dynamic range for distances and column densities for the Si IV plot results from our combining the Copernicus and IUE data. The lines of C IV were not measured in most of the Copernicus data base because the corrections for scattered light were too uncertain. Over the limited range of parameters for the C IV data, there seems to be no convincing dependence of column density with distance, but the Si IV results show an embarassingly strong relationship, with a best-fitting slope greater than unity, albeit the scatter at any given distance is large. It seems reasonable to suggest that Si IV is widely distributed but in a very irregular manner. Perhaps within 500 pc of the sun the density is significantly less than normal.

Figure 4 allows us to explore whether or not there is a relationship between the equivalent column density perpendicular to the galactic plane $N|\sin b|$ and the star's distance from the plane z. There is a hint of a turnover above 200 pc for the Si IV data. A deficiency of C IV at high z is less apparent, but the points above 1 kpc fall below a line of unit slope which passes through the middle of the low z points.

Further insight on the behavior of Si IV and C IV away from the galactic plane has been given by Savage and deBoer (refs. 16 and 22). They ranged the distance of the gas by assuming its radial velocity was dominated by corotation with the material in the plane of the galaxy. Their derived scale heights for C IV and Si IV absorption of approximately 2 and 4 kpc toward HD38282 and HD36402, respectively, seem generally consistent with what one would expect for hot gas in hydrostatic equilibrium above the plane. Of course, if a galactic wind or fountain of the type proposed by Shapiro and Field (ref. 23) is operating, the theoretical situation becomes more complicated and the distance cues from radial velocities become invalid (e.g. see ref. 24). The results of Bromage, Gabriel and Sciama (private communication via last-minute telex) for high latitude stars give a scale height for C IV of approximately 3 kpc, in accord with determinations toward the LMC.

If we proceed on the assumption that nearly all of the Si IV and C IV outline the presence of collisionally ionized interstellar gases, it is clear from the calculations of ionization equilibria (ref. 25) that the peaks in the relative fractions of 3-times ionized silicon and carbon occur at temperatures well below that of O VI ($\log T \sim 5.5$) or the characteristic temperatures for the observed diffuse X-ray emission ($\log T \sim 6$). We should not be surprised to find that the hot phases of interstellar gases exist over a broad range of temperatures. Indeed, we would be hard pressed to express why any particular temperature would be favored, since there are no abrupt changes in atomic properties (e.g. cooling functions) as there are, for instance, in an ordinary H II region near 10^4K (ref. 25). Viewed superficially, the relative absence of NV in the IUE spectra might indicate a lack of material near $\log T = 5.3$, between the O VI peak and those of Si IV or C IV. However, as the following discussion will demonstrate, the lower abundance of N V is consistent with plausible physical explanations.

If interstellar gases are shock heated to a very high temperature by randomly arriving blast waves from supernovae (ref. 21) and allowed to cool radiatively, we would expect to find an overall temperature distribution for the material dn_e/dT which is proportional to the inverse of the cooling function Λ, if the cooling is isochoric. The relative ion abundances would then be evaluated by integrating over temperature the product of this distribution function, the appropriate ionization fraction curve and the element's overall abundance (assumed to be cosmic). For Λ and the ion fractions, we must use time dependent calculations which recognize that as a gas cools radiatively, there is a significant lag in the recombination from higher to lower stages of ionization.

Table 2 gives the relative fractions of Si IV, C IV and N V for the radiative cooling case, normalized to that of O VI. As it cools, the gas spends most of the time at $\log T > 5.5$, and then it plunges fairly rapidly below this temperature. While the material spends relatively little time at the Si IV and C IV temperatures, the abundances of these ions are enhanced by a pronounced shoulder on the low temperature side of the time-dependent curves caused by dielectric recombination from higher stages. An interesting speculation is that the large variations in recorded densities of Si IV and C IV seen in Figure 3, significantly greater than those of O VI (ref. 10), are caused by the highly transitory aspect of the lower temperature cooling, making our ability to see the gas much more chancy. For isobaric cooling the decrease is slower at higher temperatures, and the low temperature plunge is more abrupt. This effect, coupled with time-dependent ion fraction curves which are closer to the steady-state ones, would result in significantly lower Si IV and C IV abundances.

An alternative to consider is that evaporation of cool clouds (ref. 26) is more important than radiative cooling, and that the ions we observe reside within the interface between the cloud's cool interior and the surrounding hot medium. In a different context (interstellar bubbles around stars losing mass), Weaver et al. (ref. 27) have calculated the time-dependent ion fractions for gas which is being heated within such an interface. These ratios are very close to those for the radiative cooling (see Table 2).

To arrive at a global value for the average densities of Si IV and C IV from the data sources listed in Table 1 is not a straightforward task, because over half of the data consist of upper or lower limits. One solution, however, is to assume that the actual distribution of column densities is fairly well-behaved and that a distance-weighted median is a good measure to adopt. Table 2 lists these medians for the Si IV and C IV data sources in Table 1. Put differently, over the total path length covered by all observations, half of the distance had lower densities and half had larger. Because most of the upper and lower limits are below and above these densities, respectively, the results would be virtually unchanged if we had actual measured values instead. One aspect of these determinations which is probably unfair is that there may be over-representation of the anomalously low-density volume within several hundred pc. of the sun. The N V density listed in the table is based on the fact that, except for the survey by Black et al.(ref.11), the absorption lines are usually not detected and in a few cases only marginally seen. The O VI densities are from the summary by Jenkins (ref. 10).

The observed relative abundances of O VI, N V and C IV seem to fit the expected ratios rather well. On the other hand, the amount of Si IV present seems to be well above the expectations. Perhaps starlight ionization is an important contributor of additional Si IV. An alternative explanation may be that the ion fraction computed by Shapiro and Moore (ref. 25) on the low temperature side of the Si IV peak is significantly underestimated. Baulinas and Butler (ref. 28) have shown that charge exchanges with ionized helium atoms can be an important additional source of ionization for Si III (their calculations, however, depict only the steady-state solutions).

VENTURES OUT OF THE GALACTIC PLANE

A significant triumph of the IUE mission has been the instrument's ability to record spectra of sources fainter than those indicated by prelaunch projections for limiting magnitudes. Observers of the interstellar medium have been able to capitalize on this advantage by bridging the vast regions of space between the plane of our galaxy and the two Magellanic Clouds. At present count, thirteen early-type stars having V magnitudes between 10.5 and 12.5 have been observed at high resolution by IUE (refs. 22 and 29). As mentioned earlier, these observations gave us the most straightforward proof that Si IV and C IV exist in general regions of space and not just in the vicinity of very hot stars. If one is willing to accept the assumptions on how radial velocities scale with distance, the distribution of gas along the line of sight is mapped by the extension of absorption from zero to moderately high positive velocities, an effect which shows qualitative differences over the different ranges of ionization (and inherent line strengths).

In their spectra of stars in the Large Magellanic Cloud (LMC), Gondhalekar et al. (ref. 29) and Savage and deBoer (ref. 22) have identified discrete absorbing regions having radial velocities of about 80 km s^{-1} and 130 km s^{-1}, midway between the gas in the plane and that associated with the LMC. For their best example, HD36402, Savage and deBoer were able to measure the column density of Fe II in the material at intermediate velocity, because this ion had many transitions with widely different f-values and the velocity dispersion was large. They could also assign lower limits for the abundances of O I, Mg II, Al II and Si II. From an upper limit for N(HI) based on a lack of 21-cm emission in the same direction, Savage and deBoer concluded that these heavy elements are no less than a factor of ten below solar abundances. They were quick to add, however, that this conclusion may be invalid if the ions are associated primarily with ionized, rather than neutral hydrogen. One point does seem clear: material processed through stellar interiors may be found at large distances from the plane provided, of course, that we are not being fooled by the presence of high velocity clouds which are relatively local.

A group of observers analyzing the low resolution spectra of 3C273 (ref. 30) confirmed that along a direction quite different from that of the LMC the absorption by C IV in our halo is also quite strong. Using 21 cm profiles in the same direction to model the velocity structure of neutral halo material, they too found that the heavy element abundances were not far below the cosmic ratios. Once again, the validity of this conclusion rests upon there not being much ionized hydrogen present (or extended wings of high velocity H I below the 21-cm detection threshold). Interstellar lines at low resolution for a supernova in M100 (ref. 30) were used to derive a velocity dispersion of about 20 km s^{-1} for neutral and once ionized atoms in our (and M100's) disk and halo material and 50 km s^{-1} for the highly ionized species. Because these lines were very strongly saturated, no abundances could be derived.

Material in the general vicinity of stars rapidly losing mass in the 30 Doradus complex (in the LMC) has been investigated by deBoer, et al. (ref. 32). They find absorption lines associated with H I regions at a velocity of +290 km s^{-1}. This neutral material is presumably part of a large, quiescent complex of gas surrounding the system. Lines from dense H II region material, such as those from O I, C II and Si II in states of fine structure excitation, are shifted by -40 km s^{-1} with respect to the neutral gas (i.e. they appear at +250 km s^{-1}). Such an outflow from the stellar system could result from either the rapidly moving stellar winds, an ionization front, or disturbances generated by past supernova activity. Even larger velocity shifts are seen for the highly ionized material, which is likely to be part of a hot corona around the LMC system (ref. 33). The relative abundances of Si II and O I in the H I gas near the LMC seem consistent with that in our galaxy, but the uncertainties are large. From their low resolution recording of Lα absorption, deBoer et al. estimated a ratio of gas to reddening of 1.9 x 10^{22} atoms cm^{-2} mag^{-1} for the material near 30 Doradus, after subtracting off estimates for the amount of foreground H I and reddening in the galactic plane. This figure is about 4 times that found toward stars in the plane surveyed by the *Copernicus* satellite (ref. 34).

HIGH VELOCITY GAS

New observations and theoretical treatments over the past decade have expanded our awareness of the widespread propagation through the interstellar medium of mechanical disturbances created by supernova explosions and high speed mass-loss winds from early-type stars (ref. 35). Rapidly moving gases which collide with the quiescent material form shocks which in turn cause significant heating and ionization. When interstellar absorption lines are shifted by at least 50 km s^{-1}, they are well enough separated from the strong lines of undisturbed gas to be studied with the IUE spectrograph. The velocity dispersion of the post-shock material is usually rather large, which helps to reduce the difficulties arising from curves of growth which are too flat.

Gondhalekar and Phillips (ref. 36) have investigated the high velocity material seen in front of one star behind the supernova remnant IC443 and another behind Shajn 147. From their column density measurements and an upper limit for the 21-cm emission they claim the depletions of Fe, Mg, Al, Si and Ca to be no more than a factor of 10 below the cosmic values. Actually, this conclusion would be invalid if these lines arose from ionized material, but the *uniformity* of their formal numbers from element to element suggests that the depletions are indeed rather modest. This conclusion is in accord with an earlier study of the Vela remnant using the Copernicus satellite (ref. 37).

Giaretta et al. (ref. 38) have measured abundances and derived physical conditions in high velocity clouds in front of four stars not near any particular known supernova remnant. A study of emission lines from the Cygnus Loop by Raymond et al. (ref. 39) gives results which are consistent with a shock velocity of about 130 km s^{-1}, but with a deficiency of recombined material indicated by a higher than expected ratio of [O III] to Hβ emission. They suggest that either they are viewing a recently shocked cloud which has not yet had time to recombine or the shock is just beginning to enter the snowplow phase. By studying the strengths of C IV, C III and C II emission lines relative to those of other elements in the Cygnus Loop, Benvenuti et al. (ref. 40) concluded that the depletion of carbon is largest in the immediate post-shock region containing C IV and becomes progressively smaller when the gas works its way downstream, presumably because graphite grains are evaporating in the hot material. Corrections for the effects of line saturation and the departures from steady flow, however, may modify this conclusion (ref. 39).

OTHER AREAS OF INVESTIGATION

We must not overlook IUE's value in contributing to our understanding of non-atomic species in the interstellar medium. Unfortunately, the short end of the wavelength coverage of IUE just misses the molecular hydrogen electronic transitions (the Lyman bands, and at shorter wavelengths still, the Werner system). But another important molecule, carbon monoxide, has its fourth positive system situated right in the middle of the short wavelength camera's coverage. This system is ideal for study, since the different vibrational members give us a very wide range of line strengths to observe. Black has reported on the CO column densities toward 12 stars (ref. 41), and much like the early Copernicus observations (ref. 42), finds no easily identifiable lines from other molecules. Tarafdar et al. (ref. 43) have tentatively identified the presence of circumstellar CO toward the star 9 Cep.

The behavior of the interstellar extinction in the ultraviolet by dust is an important diagnostic for studying the size and composition of the particles. Often there are large differences in the shape of the extinction curve from one region to the next (ref. 44). Results for eight reddened stars in the LMC seem to indicate that, with the exception of one star, the extinction curves turn up more rapidly at the short wavelength end than for stars in our part of the galaxy (ref. 45). This behavior is consistent with the notion that there are greater numbers of small particles in the dust mixture near the LMC stars.

Finally, we should not lose our awareness of IUE's potential for studying the very local regions of space. "Reversals" caused by interstellar gases can be seen in the chromospheric emission of cool stars at Lα (ref. 46) or Mg II (ref. 47), and if studied systematically, could help us to better understand the distribution of material within a few tens of parsecs.

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TABLE 1

Source	No. of stars	Remarks
Bruhweiler, et al. (ref. 17)	17	All targets were binary systems. Flawed ITF used.
Black, et al. (ref. 11)	12	Distances typically 1 kpc. Flawed ITF used.
Taylor and York (private communication of preliminary results)	46	Distances typically somewhat greater than 1 kpc, mostly in the galactic plane. Good ITF used.
Jenkins (special workup for this review)	22	High latitude, distant stars. Good ITF used.
	40	From Copernicus archives. Most stars are closer than 1 kpc.
Miscellaneous sources of Copernicus data (refs. 18, 19, 20, and 8)	3	ζ Oph, γ Ara, ζ Pup, and γ Vel.

TABLE 2 -RELATIVE ION ABUNDANCES

	Si IV	C IV	N V	O VI
Prediction for Isochoric Radiative Cooling	0.018	0.28	0.078	1.00*
Prediction for Evaporation Interfaces	0.010	0.16	0.063	1.00*
Observed representative densities (cm^{-3}):				
a) near the galactic plane (from data sources in Table 1)	$3.6 x 10^{-9}$	$6.9 x 10^{-9}$	$\lesssim 1.2 x 10^{-9}$	$2.0 x 10^{-8}$†
b) away from the galactic plane (ref. 22)	1×10^{-9}	3×10^{-9}	$\lesssim 1 \times 10^{-9}$	---

* O VI set to 1.00; other ions are expressed relative to O VI.

† from ref. 10, corrected to $z = 100$ pc.

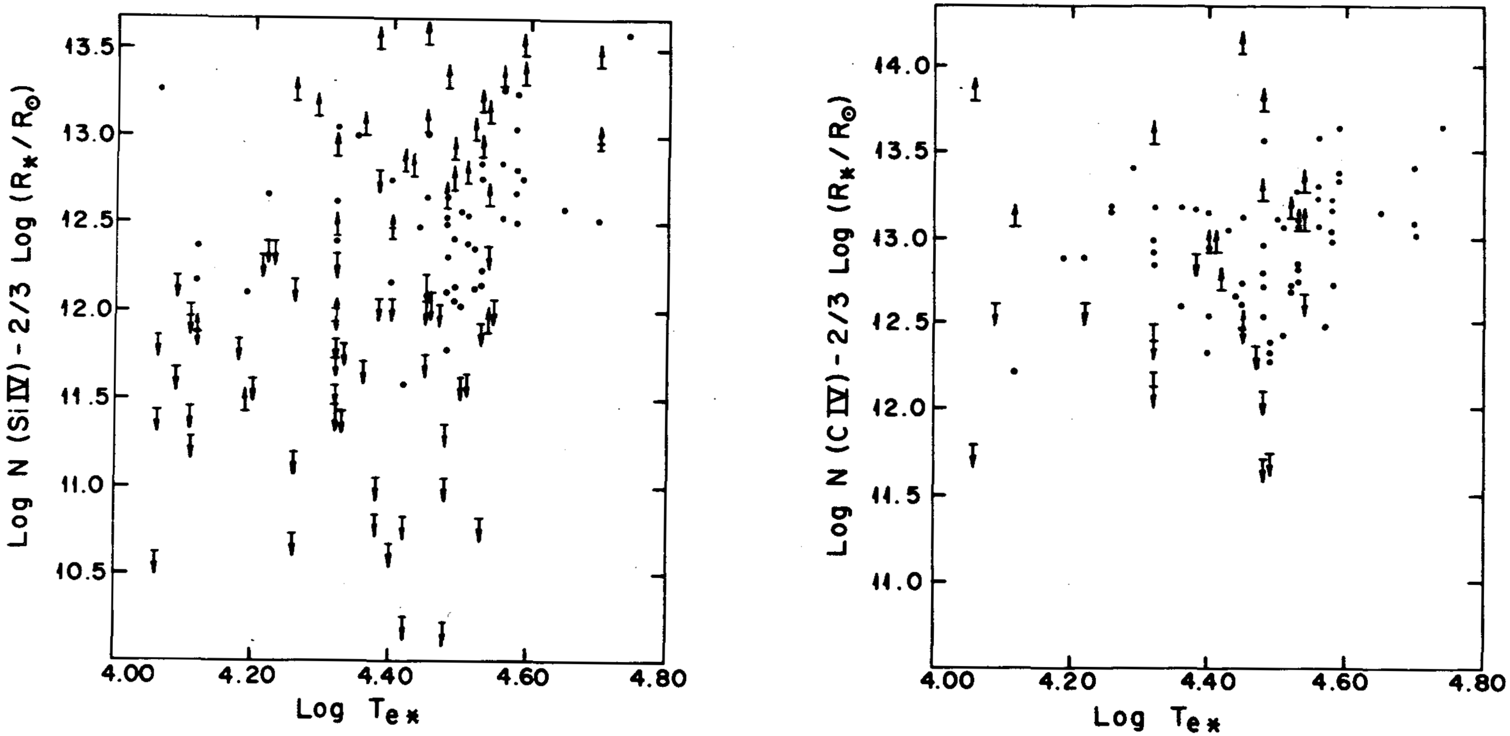

Figure 1. Logarithmic plots of column densities, adjusted for varying Stromgren Sphere sizes, versus the effective temperatures of the target stars.

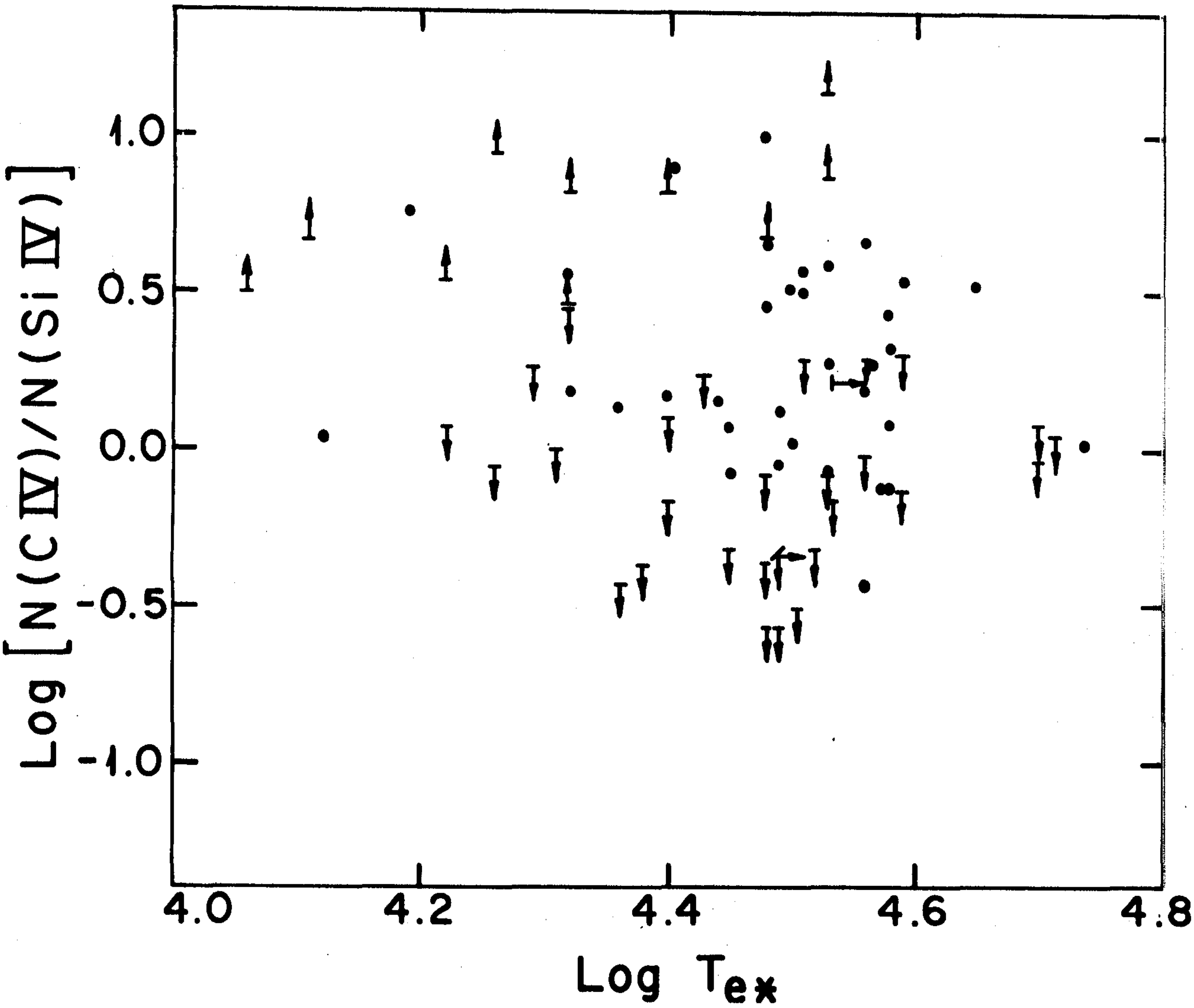

Figure 2. Logarithmic plot of the ratio of C IV to Si IV column densities versus the effective temperatures of the target stars.

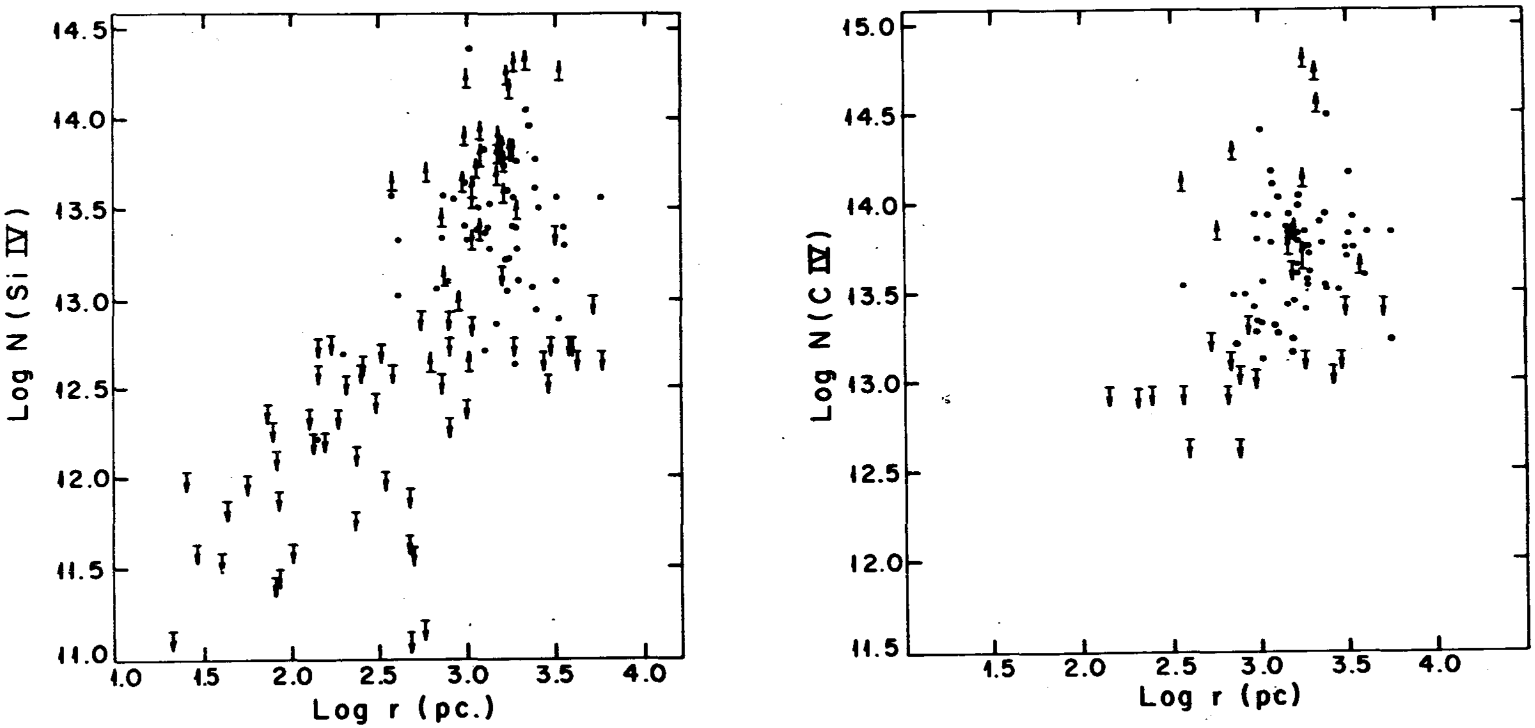

Figure 3. Logarithmic plots of column densities versus distances to the stars.

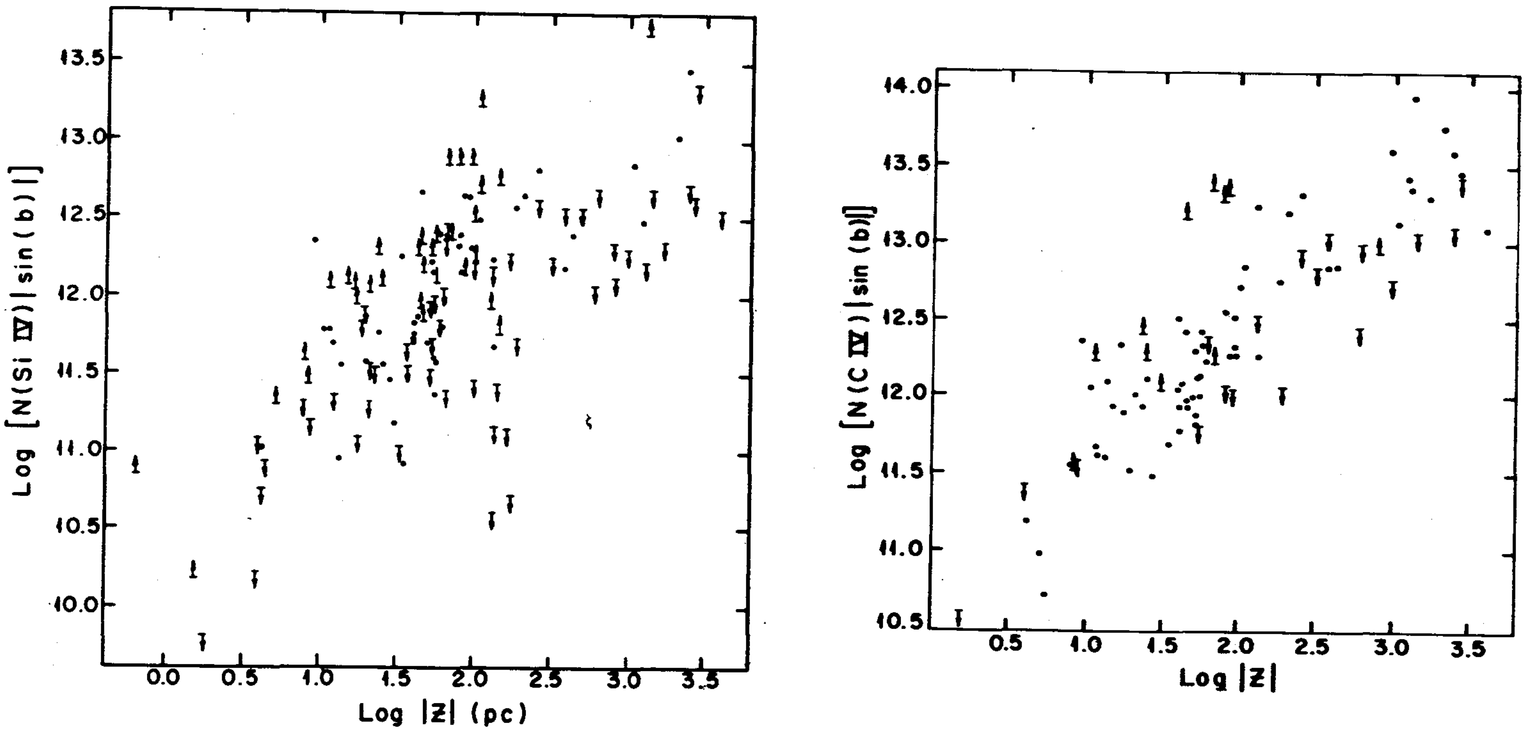

Figure 4. Logarithmic plots of equivalent column densities perpendicular to the galactic plane versus distance of the stars from the plane.