The Role of the Critical Ionization Velocity Effect in Interstellar Space and the Derived Abundance of Helium

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Abstract—Gaussian analysis of new, high-angular-resolution interstellar 21-cm neutral hydrogen emission profile structure more clearly reveals the presence of the previously reported signature of the critical ionization velocity (CIV) of helium (34 km s$^{-1}$). The present analysis includes 1496 component line widths for 178 neutral hydrogen profiles in two areas of sky at galactic latitudes around $-50^\circ$, well away from the galactic plane. The new data considered here allow the interstellar abundance of helium to be calculated, and the derived value of 0.095 ± 0.020 agrees extremely well with the value of 0.085 for the cosmic abundance based on solar data. Although the precise mechanisms that give rise to the CIV effect in interstellar space are not yet understood, our results may provide additional motivation for further theoretical study of how the mechanism operates.

Index Terms—Cosmic abundances, critical ionization velocity, interstellar matter, Milky Way.

I. INTRODUCTION

VERSCHUUR and Peratt [1] and Peratt and Verschuur [2] noted that interstellar neutral hydrogen (HI) emission line profiles revealed the signatures of the critical ionization velocity (CIV) of the most abundant interstellar species; namely, helium (He) at 34.3 km s$^{-1}$, part of Band I [3], and the four elements carbon (C), nitrogen (N), oxygen (O), and neon (Ne) that cluster around 13–14 km s$^{-1}$, which make up Band II. Note that the CIV for hydrogen is 51 km s$^{-1}$, which makes it part of Band I, but because it becomes ionized it plays no role in creating a signature in 21-cm HI emission profiles. Verschuur and Schmelz [4] subsequently used a great deal of more data and argued strongly that the observed 34 km s$^{-1}$ wide HI emission line component found in their work as well as in the linewidth values published by nine other authors is related to the CIV of helium. It is difficult to observe helium directly in interstellar space, which means that the presence of 34 km s$^{-1}$ wide HI emission line component opens a new window into deriving the composition of interstellar matter.

II. ANALYSIS

The data used here are from the second data release of the Galactic Arcadio L-band Feed Array (GALFA) HI survey [5]. The channel bandwidth of the data is 0.7 km s$^{-1}$. The brightness temperature noise is 140 mK rms per 1 km s$^{-1}$. The survey included all the HI in and around the Milky Way galaxy in the $0^\circ$–$40^\circ$ declination (DEC) range.

The angular resolution of these data is a factor of 10 better than that of earlier 21-cm surveys used to investigate the relationship between HI emission line components and CIVs.

Gaussian decomposition provides information on the properties of each component including the peak brightness temperature, $T_B$, linewidth, $W$, center velocity, $V_c$, and the area of the Gaussian, which gives its total hydrogen column density along the line-of-sight, $N_H$. These parameters provide information on the physical conditions of the astrophysical environments producing the HI profiles in any given direction. For example, the line widths themselves are generally assumed to reveal the kinetic temperature of the gas, but we will argue here that this may not always be the case.

Table I lists details of the directions studied. Right ascension (RA) is shown in column 1, the DEC in column 2, and the corresponding galactic coordinates, longitude, and latitude, in columns 3 and 4. These are the central coordinates of each series of profiles separated by $0.5^\circ$ in DEC at the RA shown. The HI profiles over the full velocity range for these directions were decomposed into Gaussians. For each direction, the number of profiles listed in column 5 was decomposed into the number of Gaussians listed in column 6. The average reduced chi-squared values for the best-fit solution (discussed below) together with the standard deviation are shown in column 7. The first set of six entries in Table I includes cuts across a long filamentary feature of hydrogen gas in the southern galactic sky moving at $-60$ km s$^{-1}$ with respect to the observer, which has been fully mapped by Verschuur et al. [6]. A second set of 34 km s$^{-1}$ wide HI emission line component opens a new window into deriving the composition of interstellar matter.
involves cuts across an HI spheroidal feature just to the north of this filament. Previous detailed analysis of these regions [6] has shown that a broad underlying component is present in all directions, as revealed in low-level wings in the overall profile.

The analysis of the 21-cm emission profile shapes was carried out using the Solver algorithm (see, e.g., [7]). Solver is a Microsoft Excel application that uses the generalized reduced gradient (GRG2) nonlinear optimization code developed by L. Lasdon, University of Texas at Austin, and A. Waren, Cleveland State University. Details regarding this method may be found at http://www.optimalmethods.com where it is described as almost surely the most widely used general purpose optimization modeling system in industry and academia. Solver performs iterations in N-dimensional space, where N is the number of variables. For an HI profile three parameters define a Gaussian component—amplitude, center velocity, and linewidth. We set up Solver to consider up to ten components, which is seldom required. For an HI profile three parameters are present in all directions—a broad underlying component and the residual of the fit usually shows where a superfluous component is present. The superfluous component is removed, and the algorithm is again run again, often resulting in a solution with $\tilde{\chi}^2 \approx 1.0$. If, on the other hand, $\tilde{\chi}^2 > 1.2$, another component may be needed to produce a better fit. At this stage the residual usually indicates where such a component is likely to be located. The algorithm is then again run and the result for reduced chi-squared is usually close to unity.

The solution found for the first profile in any given data set is used as the starting point for the next adjacent profile, and so on. This technique, which was originally developed for simple profiles that could be fit with a few components, can readily be extended for more complex profiles such as those seen in Fig. 1. The panels highlight two spectral components that are present in all directions—a broad underlying component of order 34 km s$^{-1}$ wide (shown in red) that fits the profile wings, and a second component of order 14 km s$^{-1}$ wide (shown in green). Other narrower components, black lines, are superimposed on these two. The underlying Gaussian component for the negative velocity gas invariably has a linewidth of order 21 km s$^{-1}$ and which shows no hint of components of order 34 or 14 km s$^{-1}$ wide in this gas.

For the final analysis, components with peak brightness temperatures $<0.1$ K and/or line widths $<1.5$ km s$^{-1}$ are removed from further consideration since they are at the level of noise on the data so that the present study included Gaussian analysis of 178 individual HI profiles that netted 1496 components.

The histogram in Fig. 2 combines the linewidth results for all the components derived from the Gaussian fit to the HI profile data for the sample given in Table I. The peak around 34 km s$^{-1}$ is similar to the results from the literature as summarized by Verschuur and Schmelz [4].

The traditional interpretation of a Gaussian linewidth, $W$, is that it indicates the kinetic temperature, $T_k$ [8], [9] of the gas involved, which makes the component at 34 km s$^{-1}$ particularly intriguing. Using $T_k = 21.86$ W$^2$ K [10] implies a temperature of 25 000 K, high enough to ionize the hydrogen gas so the 21-cm HI emission spectral line should not be visible. This concern originally led to the speculation [11] that such a component might result from telescope

| RA (°) | DEC (°) | Longitude (°) | Latitude (°) | No. of profiles | No. of Gaussians | Average $\tilde{\chi}^2$ |
|--------|--------|--------------|-------------|----------------|-----------------|-----------------------|
| 357.0  | 10.6   | 98.6         | -49.3       | 14             | 118             | 1.12 ± 0.18          |
| 356.0  | 9.6    | 100.5        | -50.8       | 13             | 108             | 1.17 ± 0.23          |
| 358.0  | 10.3   | 99.9         | -49.9       | 22             | 107             | 1.10 ± 0.19          |
| 358.7  | 9.6    | 100.5        | -50.8       | 14             | 121             | 1.23 ± 0.37          |
| 359.0  | 9.5    | 93.8         | -49.1       | 15             | 131             | 1.06 ± 0.17          |
| 360.0  | 8.7    | 102          | -52.1       | 15             | 121             | 1.10 ± 0.15          |
| 0.1    | 12     | 103.7        | -49.0       | 22             | 211             | 1.05 ± 0.15          |
| 0.6    | 12     | 104.4        | -49.1       | 14             | 127             | 1.04 ± 0.19          |
| 1.1    | 12     | 105.2        | -49.2       | 13             | 125             | 1.10 ± 0.17          |
| 1.6    | 12     | 105.9        | -49.4       | 13             | 126             | 1.12 ± 0.18          |
| 2.1    | 12     | 106.6        | -49.5       | 13             | 118             | 1.12 ± 0.16          |
| 2.6    | 12     | 107.3        | -49.6       | 10             | 83              | 1.07 ± 0.08          |
Fig. 1. Examples of the Gaussian fits for four profiles showing the underlying broad component of order 34 km s$^{-1}$ wide in red. The green curves represent a pervasive component of order 14 km s$^{-1}$ wide. The black curves are other components required to fit the profile that are narrow enough to be explained by the traditional temperature method (see text). The residuals found after Gauss fitting are shown. The first two profiles pertain to the southern filamentary feature at $-60$ km s$^{-1}$, well separated from the low velocity peak, are (a) at RA 360.0, DEC 8.7 and (b) at 358.0, 9.9. Two profiles for the southern spheroidal feature are shown in (c) at RA 1.6, DEC 11.7 and (d) at 2.1 and 11.2. The peak around $-50$ km s$^{-1}$ pertains to the spheroidal feature, which is again separate from the low velocity peak. The brightness temperature scale on the vertical axis is chosen to detail the Gauss fitting rather than to display the full amplitude of the entire profile.

Fig. 2. Twenty-one-cm interstellar hydrogen line component linewidth distribution for 1496 Gaussians derived from 178 profiles in two areas of sky using GALFA HI survey data from the Arecibo 305-m diameter radio telescope. The clustering around 34 km s$^{-1}$ is related to the CIV of helium. The peak at around 14 km s$^{-1}$ may be related to the CIVs of C, N, O, and Ne although we cannot rule out that they indicate warm HI gas, which may also account for the peak around 21 km s$^{-1}$, see text. The large peak at around 4 km s$^{-1}$ includes contributions from cold (100–300 K) HI and possibly the CIV signatures of heavier elements such as Na, Ca, and Fe in the range 5–8 km s$^{-1}$. The broad distribution from 20 to 30 km s$^{-1}$ is produced solely by the HI peaks at negative velocities seen in Fig. 1.

sidelobe contamination. However, using sidelobe-corrected data [7], [1] from the Leiden/Dwingeloo HI survey [12], Gaussian analysis still revealed a pervasive, underlying, 34 km s$^{-1}$ wide component in all directions. Turbulence could explain a broad component, but there is no reason to expect that it should always have the same numerical value.

Our new data now confirm the presence of a pervasive broad Gaussian component with a linewidth of order 34 km s$^{-1}$, which may be explained by the CIV of helium.

There is one result in the refereed literature that disagrees in part with the histogram in Fig. 2. Although the distribution in Fig. 3(b) of Nidever et al. [9] contains a secondary peak at 34 km s$^{-1}$, it is not sharply peaked like ours shown in Fig. 2. Rather, it shows a long tail extending to higher velocities revealing a continuum of very broad line components, which would not be consistent with the CIV model.

Verschuur and Schmelz [13] were able to examine the Nidever et al. [9] Gaussian fits in detail and compare the results of their automated Interactive Data Language (IDL) technique with our profile-by-profile, semiautomated approach. Both methods use data from the Leiden/Argentina/Bonn all-sky HI survey. The comparisons led to the identification of four problems with the Nidever et al. analysis. The first involves different methods of calculating reduced chi-squared ($\tilde{\chi}^2$), a measure of goodness of fit. Verschuur and Schmelz limited the calculation of $\tilde{\chi}^2$ to the velocity range of the HI profile itself, usually from $-80$ to +20 km s$^{-1}$ (see Fig. 1), whereas Nidever et al. used the full range of velocities available to them, from $-400$ to +400 km s$^{-1}$, which does nothing to
improve a fit because the extra velocity range contributes only noise. In fact, that reduces the significance of the fit by producing deceptively low $\chi^2$ values, which therefore does not offer a measure of the quality of the Gaussian decomposition. The Nidever et al. analysis also finds an ultra-broad component bridging the gap between low- and intermediate-velocity gas in profiles such as shown in Fig. 1 as well as multiple, fundamentally different solutions for the profiles at both the north and south galactic poles, and a lack of spatial coherence, which allowed different components to appear and disappear in profiles separated by a fraction of a beamwidth. In contrast, Verschuur and Schmelz [13] show that the long tail in the distribution in Fig. 3(b) of Nidever et al., which did not reveal the 34 km s$^{-1}$ family of line widths, disappeared once these problems were recognized. The modified results then appear to be consistent with Fig. 2 and the CIV model.

III. On the Nature of the CIVs

The 34 km s$^{-1}$ component may be associated with the plasma phenomenon known as the CIV [1], which is defined as that velocity at which a neutral particle traveling through a plasma and normal to the magnetic field becomes ionized. That occurs when its kinetic energy is equal to its ionization potential. The phenomenon was first proposed by Alfvén [14], [15] and has since been extensively verified in terrestrial laboratory and near-Earth space-borne tests, as reported in a number of reviews [16]–[19].

The critical velocity, $V_{cr}$, is defined by

$$V_{cr} = (2eV/M)^{0.5}$$

where $M$ is the mass of the atom (or ion), and $V$ is its ionization potential.

As pointed out in these reviews, the precise mechanism that drives the CIV effect remains elusive. Peratt and Verschuur [2] invoked the plasma two-stream instability. A stream of energetic electrons passing through cold plasma excites ion waves, which will grow rapidly in magnitude at the expense of the kinetic energy of the electrons. A high energy tail of the electron distribution ionizes the neutrals. Brening and Axnäs [18] and Lai [19] emphasized the importance of lower hybrid instabilities in facilitating the ionization. Although researchers have not settled on a theoretical explanation that satisfies everyone, the observational evidence for the CIV effect occurring in nature seems to be beyond question.

The neutral gas masses and plasma observed within the beam of a radio telescope encompass large volumes of space and the subsequent CIV-induced motions will modulate the 21-cm hydrogen spectral lines whose widths are then determined by the CIV effect acting on a range of atomic species. For example, if the motions of the ionizing electrons (coupled to the magnetic field and the neutrals) extend between + and −34 km s$^{-1}$ along the line-of-sight, the Gaussian line widths we observe would appear to have a width at half maximum of order 34 km s$^{-1}$.

The outstanding thing about the 34 km s$^{-1}$ component is that it cannot be explained with the traditional kinetic temperature model. This is because the emission linewidth would imply a temperature high enough (25 000 K) to ionize the very gas that is producing the observed HI profile. The narrower peaks in Fig. 2 around 14 and 21 km s$^{-1}$ wide can be interpreted in terms of kinetic temperatures of 4300 and 9600 K, respectively, but they also happen to correspond to the CIV values for other astrophysically prominent atoms. The peak in Fig. 2 around 14 km s$^{-1}$ has a value corresponding to the CIV band of C, N, O, and Ne, the most abundant elements in the Galaxy after H and He. The 21 km s$^{-1}$ wide components have widths close to the CIVs of ionized C, N, O, and Ne. The significance of these relationships will be considered in a later article.

The CIV effect in interstellar space will not operate if it exceeds the Alfvén velocity in the medium. For the two areas discussed here, which are at large galactic latitudes (−50°), it is likely that the HI gas is located in the thick disk where interstellar electron densities are low, of order 0.01−0.03 cm$^{-3}$, certainly less than the value of 0.1 cm$^{-3}$ found in the so-called Local Interstellar Cloud [20]. More specifically, pulsar dispersion measure data give 0.01 cm$^{-3}$, Cordes and Lazio [21, Fig. 3]. Estimates of the ambient magnetic field strength are sparse though Verschuur et al. [6] estimated that the magnetic fields involved in controlling the stability of the southern filament lie in the range 5−18 μG. These values imply Alfvén velocities of order 100 km s$^{-1}$ or greater. Therefore, the CIV for helium, 34 km s$^{-1}$ is permitted.

The fact that the interstellar medium is permeated by distorted magnetic fields, which in some areas have a net preferred direction, has to be borne in mind. In general, however, it is reasonable to assume that there will be deviations in direction on all scales smaller than the beamwidth. This means that as seen from the point of view of neutral gas or plasma streams interacting throughout this medium, the velocity component of the motion normal to localized field segments will have a large range of values. Given that the CIV effect depends on the velocity of the neutrals with respect to the plasma (or vice versa) normal to the localized magnetic field direction, a wide range of CIVs will be triggered in the space enclosed within the beam of the radio telescope used to study the HI emission profile structure. A source of relative motion is required to trigger the CIV effect, and old supernova expanding shells and/or large-scale accretion of matter from the galactic halo onto the disk are obvious candidates. Thus, in any given direction the CIV signatures related to the entire range of atomic species may be expected.

Table II summarizes the Gaussian component linewidth data for the directions toward southern filamentary and spheroidal features. The RA label from Table I is listed in column 1 followed by the total hydrogen column density in units of 10$^{18}$ cm$^{-2}$ in column 2 for all the profiles in the sample, noted in Table I, column 5. Column 3 gives the total column density of the hydrogen in the 34 km s$^{-1}$ wide components seen in Fig. 2, that is, the hydrogen being affected by the He CIV, which gives a measure of the column density for the helium. The average linewidth for the 34 km s$^{-1}$ family of components and their standard deviation are listed in column 4. The weighted average linewidth for entire ensemble of 12 entries in Table II is 34.2 ± 0.3 km s$^{-1}$, which compares
to the CIV for helium of 34.3 km s\(^{-1}\). We regard this as more than just coincidence and therefore worthy of further consideration. Our next step is to use this result to derive the interstellar He abundance, which is obtained from the ratio of the data in columns 3 and 2 and listed in column 5.

### IV. Discussion

If we now assume that the CIV effect operates in interstellar space and determines the clustering of HI component line widths that we see in Fig. 2, we can use this result to investigate the abundance of helium. This can be done by comparing the column density of the helium signature seen in the 34 km s\(^{-1}\) wide component with respect to the total column density of the HI observed along the entire line of sight. We propose that this ratio is the interstellar helium abundance, which is listed in column 5 of Table II for each of the data samples. The weighted average helium abundance for all 12 entries in the table is 0.095 ± 0.020. This compares extremely well with a value of 0.085, the photospheric/cosmic abundances found in the literature: [22]–[24]. Although abundances may deviate from photospheric values in certain astrophysical environments such as the solar corona, solar wind, and solar energetic particles [25], and, on occasion, one element may deviate from the norm [26], [27], photospheric abundances are widely accepted to be good measures of their cosmic values. Thus, the helium abundance derived from the CIV data is within one sigma of the photospheric/cosmic value. It is difficult to observe helium directly in interstellar space, so the 34 km s\(^{-1}\) feature in the 21-cm spectrum opens a new window into investigating the composition of interstellar matter.

Note that at 51.0 km s\(^{-1}\), the CIV effect ionizes hydrogen atoms, but that signature is not revealed in the 21-cm data because the resulting protons and electrons do not contribute to the observed emission profiles. Similarly, the He\(^+\) produced by the CIV effect at 34 km s\(^{-1}\) discussed here has a CIV at 51.1 km s\(^{-1}\) so that the singly ionized helium loses its remaining electron to create an alpha particle and an additional electron. These particles are also lost to our observations. Both a certain amount of hydrogen and ionized helium effectively “disappear,” that is, they no longer contribute to the 21-cm emission profile, at 51 km s\(^{-1}\), and therefore the column densities of the remaining helium and hydrogen allow the He-to-H ratio to be derived as shown in Table II.

### V. Conclusion

Analysis of new, high-resolution observations of 21-cm interstellar HI emission profiles from the GALFA-HI survey confirm the results of Verschuur and Schmelz [4], who showed that a good fit generally required a broad component with a width of order 34 km s\(^{-1}\). Since this component could not be interpreted as the kinetic temperature or result from telescope beam side lobes, they suggested that the feature might be due to the CIV effect operating in interstellar space. By accepting this conclusion, the new data allow us to derive a value for the interstellar abundance of helium, 0.095 ± 0.020, which agrees to within half a standard deviation with the cosmic abundance value of 0.085 [22]–[24].

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