Observation of the CIV Effect in Interstellar Clouds: A Speculation on the Physical Mechanism for Their Existence

Anthony L. Peratt, *Fellow, IEEE,* and Gerrit L. Verschuur

***Abstract*—Observations of neutral hydrogen (HI) emission profiles produced by gas in the local interstellar medium are found to be characterized by four linewidth regimes. Dominant and pervasive features have widths on average of 5.2, 13, and 31 km/s, and a very broad component approximately 50 km/s wide. A striking coincidence exists between these linewidths and the magnitudes of the critical ionization velocities of the most abundant atomic species in interstellar space: 6 km/s for sodium and calcium; 13 km/s for carbon, oxygen, and nitrogen; 34 km/s for helium; and 51 km/s for hydrogen. The data relate to observations near neutral hydrogen structures that are filamentary.**

***Index Terms*—CIV, electric space, interstellar clouds, plasma universe.**

I. INTRODUCTION

THE concept of a critical ionization velocity (CIV) was first introduced by Alfvén [1], [2] for the study of plasma phenomena in the solar system. If a neutral gas and magnetized plasma are in relative motion, a rapid ionization of the neutrals takes place if the kinetic energy of the neutrals relative to the plasma exceeds the ionization potential eV_i of the neutrals. This then defines a critical velocity for the neutral mass M

$$V_{cr} = (2eV_i/M)^{1/2} \tag{1}$$

above which the CIV ionization will take place. This concept was used by Alfvén to suggest that plasma and electromagnetic phenomena play a crucial role in the evolution of the solar system.

II. CIV PROCESS IN LABORATORY EXPERIMENTS

The ionization of neutral gas in laboratory experiments [3] verified that CIV exists and occurs at a threshold near or slightly above that predicted by (1). However, it was discovered that the efficiency of the ionization derives often not from the direct collision of ions with neutrals nor with electrons with neutrals, but rather from a plasma instability leading to the transfer of energy from fast ions to background electrons. The resultant distribution function is pseudo-Maxwellian at low energies with a high-energy tail containing electrons of energy that exceeds that of the initial ion energy. It is the high-energy electrons within the tail $E > eV_i$ which then ionize the neutrals. The instability found in the laboratory requires a magnetic field strength above a threshold, approximately requiring that the flow be sub-alfvénic.

The process for generating an ionizing source of fast electrons begins with one of the most common instabilities in plasma, the two stream instability. The modified two-stream instability for cold ions and electrons in the linear approximation is an efficient mechanism leading to fast seed ions in a counterstreaming flow of electrons and ions. The modified two-stream instability is driven by relative ion-electron drift across B. For cold ions and electrons, the linear dispersion relation is [5]

$$\omega_e^2 \sin^2\Theta\omega^2 + \omega_e^2 \cos^2\Theta(\omega^2 - \Omega_e^2) + \omega_i^2(\omega - kV\cos\Theta)^2 = 1 \tag{2}$$

where

ω_e and ω_i	electron and ion plasma frequencies, respectively;
Ω_e	electron gyrofrequency;
k	wave vector;
V	beam ion velocity;
Θ	angle between the wave vector and beam ion velocity.

The relevant angle is between the k and the magnetic field B. We have studied the linear–nonlinear evolution of the two-stream instability with the 2 1/2 dimensional, fully electromagnetic particle-in-cell (PIC) code ISIS [6], even for high-electron/ion mass ratios, e.g., Argon [7]. A maximum in the growth rate is consistent with the theoretical prediction $\Theta \approx (m/M)^{1/2}$ and the electrons respond quite rapidly to the electric fields generated by the two-stream instability, with the heating time of the electrons occurring generally in several tens of inverse plasma frequency periods. The interplay of collisional versus collective processes in the ionization of neutrals, including charge exchange and line excitation, has been studied in depth [8]. Three-dimensional (3-D) electromagnetic Monte Carlo PIC simulations of CIV experiments in space have been studied by Wang *et al.* [9].

The randomization and heating of the electrons due to CIV has been reported by Sherman [10], [11] in laboratory experiments involving cross field $\mathbf{E} \times \mathbf{B}$ plasma sheath acceleration through a neutral gas background such as found in rail guns and plasma thrusters [12]. Here, the CIV effect limits the deuterium,

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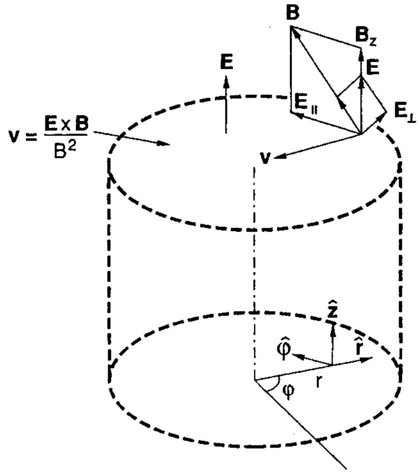


Fig. 1. When the pressure is negligible, the plasma acquires a drift velocity v such that the electric field in the moving plasma is parallel to B. Therefore, current flows only along the magnetic lines of force.

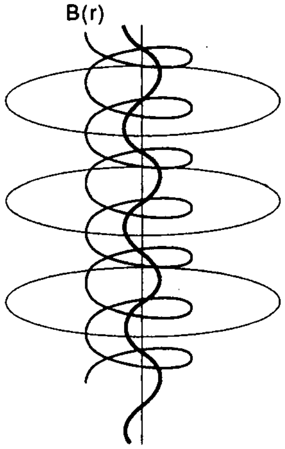


Fig. 2. Magnetic rope with magnetic field lines shown at three different radii.

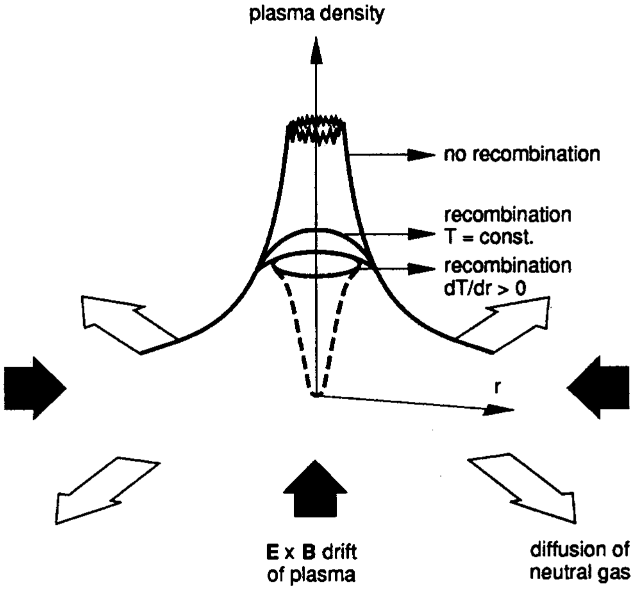


Fig. 3. Plasma density profile as a function of radius sketched qualitatively for three cases: No recombination, recombination with T = constant, and recombination with a lower central temperature.

helium, and argon propellant velocities while the heating adversely affects the electrode lifetimes.

III. CIV PROCESS IN INTERSTELLAR SPACE

If laboratory-like coaxial plasma discharges existed in space, explanation of the observed data would be straightforward in terms of CIV. However, no agreement has been reached as to whether CIV exists in the natural space environment, primarily based on the study of ionospheric barium releases [13]. However, an effective means for producing CIV in interstellar space involves the cross-field equivalent in space called the Marklund convection mechanism (for a review, see [14]). When an electric field is present in a plasma and has a component perpendicular to a magnetic field, radial inward convection of the charged particles is possible. Under the influence of the $\mathbf{E} \times \mathbf{B}$ force, both the electrons and ions drift with the velocity

$$v = \mathbf{E} \times \mathbf{B}/B^2 \tag{3}$$

so that a portion of the plasma moves radially inward (Fig. 1). This mechanism provides a very efficient convection process for the accumulation of matter from plasma. The material should form as a filamentary structure about the twisted flux tubes, the lines of which are commonly referred to as "magnetic ropes" because of their qualitative pattern (Fig. 2). Magnetic ropes should tend to coincide with material filaments that have a higher density than the surroundings.

A stationary state occurs when the inward convection of ions and electrons toward the axis of a filament is matched by recombination and outward diffusion of neutralized plasma. The equilibrium density of the ionized component normally has a maximum at the axis (Fig. 3). However, because of the following mechanism, hollow cylinders, or modifications of hollow cylinders of matter, form about the flux tubes.

Because of the radiated loss of energy, the filaments cool and a temperature gradient is associated with the plasma. As the radial transport depends on the ionization potential of the element, elements with the lowest ionization potentials are brought closest to axis. The most abundant elements of cosmical plasma can be divided into groups of roughly equal ionization potentials as follows: He (24 eV); H, O, N (13 eV); C, S (11 eV); and Fe, Si, Mg, Na, Ca (5–8 eV). These elements can be expected to form hollow cylinders whose radii increase with ionization potential. Helium will make up the most widely distributed outer layer; hydrogen, oxygen, and nitrogen should make up the middle layers, while iron, silicon, and magnesium will make up the inner layers. In the classical Marklund picture, the production and diffusion of neutral gas is outwards from the plasma filament.

While the magnetic flux tubes themselves are not directly observable, relics of their existence in the interstellar medium would require both the existence of filamentary structures and a signature of the CIV process.

Hydrogen is the most pervasive atom in the universe and neutral hydrogen emission at 21-cm wavelength is easy to observe using radio telescopes. It is seen in all directions in the Milky

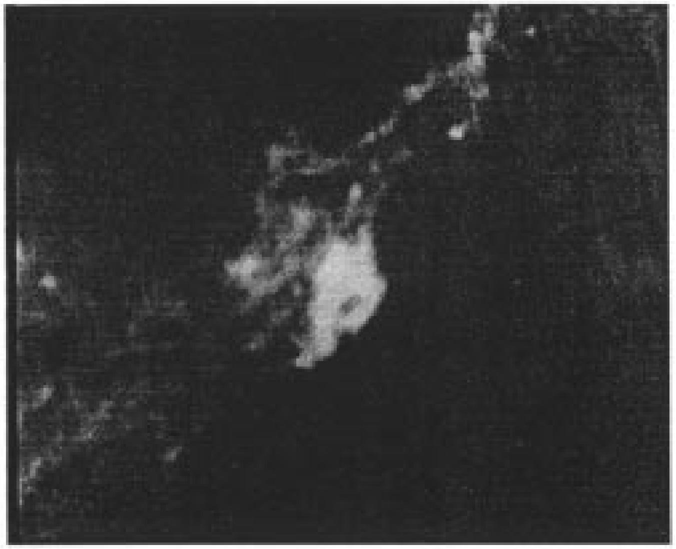


Fig. 4. The 100-μ emission from cool dust associated with the HI filamentary feature H0287 + 10. The image size is $4^\circ \times 5^\circ$ centered on right ascension 8 h 27 m, declination $+9^\circ 48'$.

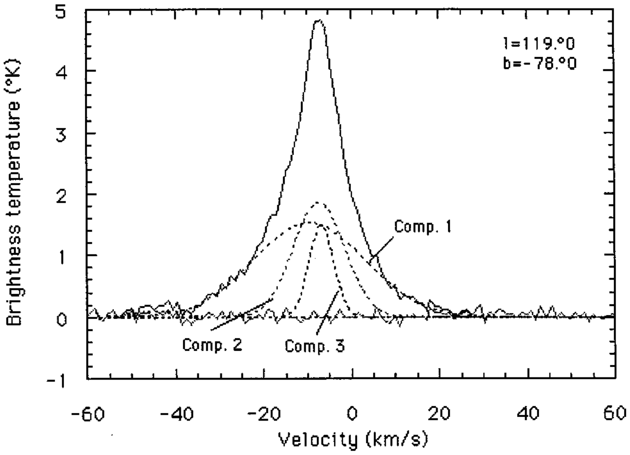


Fig. 5. Gaussian fit to the L-D Survey profile at $l = 119^\circ$, $b = -78^\circ$. The three components are each represented just once, and at about the same amplitude. The residual left after subtracting the three components from three data is also indicated.

Way galaxy. The other elements that are referred to in discussions of the CIV are also found in interstellar space but are less pervasive and can only be seen in absorption toward suitably bright stars.

The first criteria, that the interstellar medium show a filamentary morphology, was satisfied with the discovery of interstellar neutral hydrogen filaments from high resolution data from radiotelescope observations at high latitude (Fig. 4). The 100-μ emission from interstellar dust shown in Fig. 4 follows the pattern of HI data but allows greater resolution. Application of the Carlqvist relation for Bennett pinched cosmic currents inferred that the data originated from electrical currents $I_z \approx 1.4 \times 10^{13}$ A with circumferential magnetic fields B_ϕ of the order five microgauss [15]. The Carlqvist relation is applicable to a range of plasma configurations, from force free to gravitationally balanced.

The second criteria, that CIV phenomena be associated with interstellar space, is the hypothesis of this paper. The cross-field Marklund convection of electrons in the vicinity of a filament, both in the presence of the background plasma and neutral gas, initiates the two stream instability as the electrons flow through the background ions at velocity $|v_r| = E_z/B_\phi$, where E_z is the (longitudinal) component of the electric field within a filament. Collective ion acceleration [16], [17] is caused by the electrons pull on the ions in the convection flow, thus producing the fast ion beam that imparts its energy on the braking electrons in collisional and collective action.

The ions, as do the neutrals, flow unimpeded by the presence of $\mathbf{B}$. However, the electrons, deriving both from the background plasma as well as those newly formed from the neutral gas heated by the high-energy tail of the electron distribution function, tend to spiral about $\mathbf{B}$. This imparts a thermal plasma distribution with velocity components in all three spatial directions to the neutral gas.

The basic picture, albeit without the 3-D electron motion explicitly included in the simulation, is the case studied numerically by Machida and Goertz [18] who investigated via a one-dimensional (1-D) electrostatic PIC code the CIV process in high and low neutral particle densities. In their simulation, both ions and neutrals were assumed to cross the magnetic flux lines transversely while the electrons spiraled around the lines. Included in their formulation was charge exchange, ion and electron elastic collisions, momentum coupling, electron impact neutral excitation and ionization, cross-field ion beam dynamics, electrostatic wave excitation, and finally, electron heating. Machida and Goertz found that ionization of the neutrals by the fast electrons proceeds effectively by forming a positive feedback loop until thermal saturation limited by the nonlinear energy budget occurs. It is this thermal signature which manifests itself in HI linewidth spectra.

Proof or disproof of the hypothesis awaits the completion of a fully electromagnetic, fully 3-D PIC code that includes neutral elements, electron impact neutral excitation and ionization, charge exchange, ion and electron elastic collisions, and momentum coupling for the purpose of demonstrating the selective electron heating. One attribute, not studied, is the inclusion of magetized ions. In this way, a qualitative study of the CIV phenomena can be quantitatively established with particle gyrofrequencies, ionization rates, Alfvén velocity, neutral drift speeds and mean free paths, neutral and plasma densities, self-consistently matched to the inferred currents and fields estimated from the radiotelescope and satellite observations.

The most ubiquitous elements in the CIV process in the interstellar medium are H and He. The former, designated band 1a in Table I [4], is that of the lightest element, hydrogen, and corresponds to the base state in the CIV process with a critical ionization velocity V_{cr} of 50.9 km/s. This value infers a longitudinal electric field E_z of about 25 mV/M when the interstellar filament current derived by Verschuur is used. Most of space, being either fully or partially ionized hydrogenic plasma, is susceptible to the CIV process at this velocity, provided a magnetic field is present, such as that produced by a field-aligned current or magnetic rope. When detectable in HI measurements, the major and most widespread

TABLE I
PARAMETERS ASSOCIATED WITH THE CRITICAL IONIZATION VELOCITY

Element[a]	Ionization potential volts	Average atomic mass amu	Atomic abundance[b] Si= 10^6	Critical velocity (10^5 cm/sec) (km/sec) (mm/μsec)	Band	Equivalent HI component
H	13.5	1.0	2×10^{10}	50.9	I	1a
He	24.5	4.0	2×10^{9}	34.3	I	1b
Ne	21.5	20.2	2×10^{6}	14.3	II	2
N	14.5	14.0	2×10^{6}	14.1	II	2
C	11.2	12.0	1×10^{7}	13.4	II	2
O	13.5	16.0	2×10^{7}	12.7	II	2
(F)	17.42	19.0	4×10^{3}	13.3	II	2
(B)	8.3	10.8	1×10^{2}	12.1	II	2
[Be]	9.32	9.0	8×10^{-1}	14.1	II	2
[Li]	5.39	6.9	5×10^{1}	12.2	II	2
Ar	15.8	40.0	1×10^{5}	8.7	III	3
P	10.5	31.0	1×10^{4}	8.1	III	3
S	10.3	32.1	5×10^{5}	7.8	III	3
Mg	7.6	24.3	1×10^{6}	7.7	III	3
Si	8.1	28.1	1×10^{6}	7.4	III	3
Na	5.12	23.0	6×10^{4}	6.5	III	3
Al	5.97	27.0	8×10^{4}	6.5	III	3
Ca	6.09	40.1	7×10^{4}	5.4	III	3
Fe	7.8	55.8	9×10^{5}	5.2	III	3
Mn	7.4	54.9	1×10^{4}	5.1	III	3
Cr	6.8	52.1	1×10^{4}	5.0	III	3
Ni	7.6	58.7	5×10^{4}	5.0	III	3
(Cl)	13.0	35.5	2×10^{3}	8.4	III	3
(K)	4.3	39.1	2×10^{3}	4.6	III	3

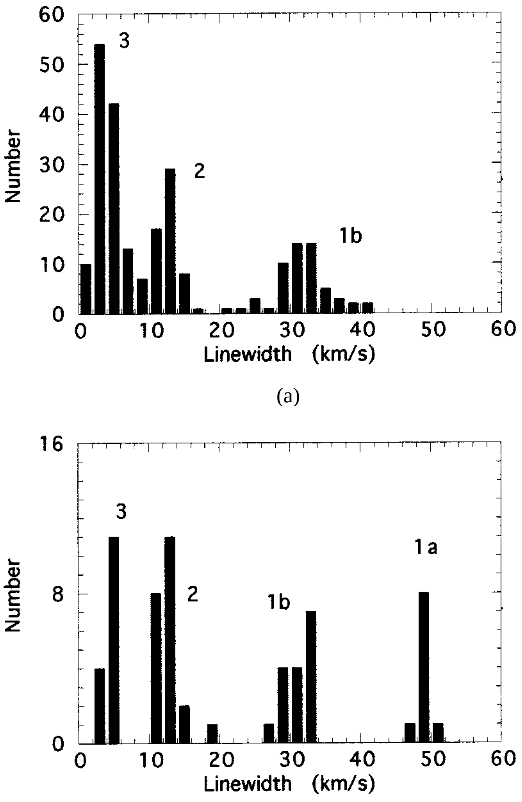
CIV component is that of hydrogen with CIV band I (HI component 1a) (Fig. 5). However, He should be nearly as equally spatially distributed at CIV band I (HI component 1b) corresponding to $V_{cr} \approx 34.4$ km/s.

After the two CIV band I components, the CIV process then cascades toward ionizing increasingly heavier elements in the neutral background, if these heavy elements are present. As discussed above, these must be progressively closer to the filamentary flux tube. After CIV band I comes CIV band II with a mean critical velocity of 13.5 km/s. Finally, CIV band III should be observable at a mean critical velocity of 6 km/s for heavy elements. As noted by Alfvén, overlap between the individual layers should occur and these can be expected to crowd the individual thermal lines. Additionally, because of the ordering, the HI linewidth spectra must show CIV band I, then band II, followed by band III. It is important to note from Table I that all of the elements fall in one of three CIV bands with four delineable HI thermal bandwidths, 1a, 1b, 2, and 3, from the thermal saturation mechanism discussed above (Fig. 5). Band III (HI component 3) is unique in that its region of occurrence must start to coincide with the Marklund pump action close in to a filament and should then be associated with the dusty plasma forming there. This is precisely what is seen in the HI emission measurements from interstellar filaments.

Neutral hydrogen emission line data can be presented in a variety of ways, each of which reveals some specific aspect of the physical processes that give rise to the emission. In the early days of HI studies (the 1950s and early 1960s) it was common to report emission profile shapes (spectra) which were then discussed in broad terms, at best. When contour mapping hardware and software came available in the late 1960s and early 1970s, a new trend emerged. Maps of HI brightness as a function of velocity and position were published in large numbers. That, in turn, led to the production of area maps of HI brightness or column density as a function of two spatial coordinates being published in catalog form. Such area maps of HI properties are readily compared to photographs or other area representations of astronomical data, such as the brightness of infrared 100-μ or 60-μ emission from interstellar cirrus dust. These allow extensive qualitative comparison between, for example, HI column density and 100-μ brightness in order to learn about the underlying physics of the regions in which HI and cirrus dust coexist.

Today, many data bases containing HI survey profiles are stored as data cubes. Slices across such cubes are extracted to plot brightness as a function of two spatial coordinates or one of space and one of velocity to suit a given project. Alternatively, a profile at any given point in the cube may be displayed.

Previously, it was shown that the two broad linewidth components are widespread [19]. A more extensive study has confirmed this [20] which reports that Component 1a has a linewidth around 51 km/s while a second broad component 1b is typically 31 km/s wide [Fig. 3(a)]. Component 2 has a velocity approximately 13 km/s wide and is also widespread over the sky. Component 3 includes narrow features from 2–6 km/s wide, with a mean around 5.2 km/s, and these are invariably superimposed on Component 2.



(a)

(b)

Fig. 6. (a) Histogram of linewidths of 179 Gaussians fit to 140-ft radio telescope data for the region of the thin filament. The three dominant component categories are clearly evident in the area of sky in which relatively small column densities of HI are observed. (b) Linewidth histogram for the Gaussian fits to the 12 profiles in directions of very low HI column density. Here, four linewidth regimes are evident, the fourth around 50 km/s.

Component 1 has linewidths ranging from 25 to 40 km/s and it occurs in every direction observed [Fig. 6(a)]. Component 2 has a velocity approximately 12 km/s wide is also widespread over the sky. Many directions were identified where these were the only two components in an emission profile. Component 3 includes narrow features from 2 to 6 km/s wide and these are invariably superimposed on Component 2. The narrow components are never found as isolated profiles away from the velocity of the broader features. In general, Component 3 appears associated with dust and sometimes molecular structures, but even this is not always so. Fig. 6(b) pertains to a sample of HI profiles for low-column densities in 12 directions [21]. A review of the emission between cool HI and dust is given in [15], [22], and [23].

The data show that in directions of the sky where very little HI is seen a further distinction between a group of Gaussians with linewidths around 50 km/s (Component 1a) and those with linewidths around 30 km/s (Component 1b) may be made. In most cases, Component 1a is very difficult to identify, largely because its width is so great and its brightness temperature so low ($\approx$0.3 K).

IV. CONCLUSION

In conclusion, a striking coincidence has been discovered between radiotelescope measurements of neutral hydrogen (HI) emission linewidths in the vicinity of interstellar neutral hydrogen filaments at high galactic latitudes and the critical ionization velocities of the most abundant atomic species in interstellar space, thereby revealing nature's signature of CIV.

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REFERENCES

[1] H. Alfvén, "On the cosmogony of the solar system," *Stockholms Observatoriums Annaler*, vol. 1, p. 14, 1942.
[2] ——, *On the Origin of the Solar System*. Cambridge, U.K.: Cambridge Univ. Press, 1954.
[3] N. Brenning, "Review of the CIV phenomenon," *Space Sci. Rev.*, vol. 59, p. 209, 1992.
[4] A. L. Peratt, *Physics of the Plasma Universe* Springer-Verlag, New York, 1992.
[5] O. Buneman, "A beam instability," *J. Nucl. Energy*, vol. 4, p. 111, 1962.
[6] A. L. Peratt, *Advanced Topics in Astrophysical and Space Plasmas*, E. M. de Gouveia Dal Pino, A. Peratt, G. A. Medina Tanco, and A. C.-L. Chian, Eds. Norwell, MA: Kluwer, 1995.
[7] A. Peratt and M. Jones, "Particle-in-cell simulations of heavy ion plasma double layers," in *IEEE Int. Conf. Plasma Science*, Saskatoon, SK., Canada, 1986.
[8] W. J. McNeil, S. T. Lai, and E. Murad, "Interplay between collective and collisional processes in critical velocity ionization," *J. Geophys. Res.*, vol. 95, p. 10 345, 1990.
[9] private communication, 1994.
[10] J. C. Sherman, "Review of the critical velocity of gas-plasma interaction—II: Theory," *Astrophys. Space Sci.*, vol. 24, p. 487, 1973.
[11] ——, "Critical ionization velocity," *J. Phys. B.*, vol. 7, p. 244, 1974.
[12] J. T. Scheuer, K. F. Schoenberg, R. A. Gerwin, R. P. Hoyt, I. Henins, D. C. Black, R. M. Mayo, and R. W. Moses, Jr., "A magnetically-nozzled, quasisteady, multimegawatt coaxial plasma thruster," *IEEE Trans. Plasma Sci.*, vol. 22, p. 1015, Aug. 1994.
[13] N. Brenning, "A comparison between laboratory and space experiments on Alfvén's CIV effect," *IEEE Trans. Plasma Sci.*, vol. 20, p. 778, June 1992.
[14] G. T. Marklund, "Plasma convection in force-free magnetic fields as a mechanism for chemical separation in cosmical plasmas," *Nature*, vol. 277, p. 370, 1979.
[15] G. L. Verschuur, "Interstellar neutral hydrogen filaments at high galactic latitudes and the Bennett pinch," in *Plasma Astrophysics and Cosmology*. Norwell, MA: Kluwer, 1995.
[16] H. Alfvén and U. Wernholm, "A new type of accelerator," *Ark. för Fys.*, vol. 15, p. 175, 1952.
[17] R. J. Faehl and B. B. Godfrey, "Collective ion acceleration through temporal modulation of relativistic-electron beam energy," *Phys. Rev. Lett.*, vol. 40, p. 1137, 1978.
[18] S. Machida and C. K. Goertz, "A simulation study of the critical ionization velocity process," *J. Geophys. Res.*, vol. 91, p. 11 965, 1986.
[19] G. L. Verschuur and L. Magnani, "On the nature of 21 cm emission profile structure at high galactic lattitude: Implications for the warm neutral medium," *Astrophys. J.*, vol. 107, p. 287, 1994.
[20] G. L. Verschuur and A. L. Peratt, "Galactic neutral hydrogen emission profile structure," *Astro. J.*, vol. 118, pp. 1252–1267, 1999.
[21] J. Lockman, K. Jahoda, and D. McCammon, "The structure of galactic HI in directions of low total column density," *Astrophys. J.*, vol. 302, p. 432, 1986.
[22] G. L. Verschuur, *Infrared Cirrus Diffuse Interstellar Clouds*, vol. 58, p. 184, 1994.
[23] ——, "Interstellar neutral hydrogen filaments at high galactic latitudes and the Bennett pinch," *Astrophys. Space Sci.*, vol. 227, p. 187, 1995.

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