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THE IMPORTANCE OF SEED IONIZATION IN CIV SPACE EXPERIMENTS

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ABSTRACT

A remarkable aspect of Alfvén's critical ionization velocity (CIV) is the ease with which one can observe its symptoms in laboratory experiments and the great difficulty in observing its presence in space experiments. The object of this paper is to compare and to contrast laboratory and space CIV experiments, focusing on one potentially important difference: the creation of an initial ion beam. In the laboratory experiments, the magnetic field is at rest along with the neutral gas while the plasma moves across it. In space, on the other hand, both ambient plasma and magnetic field are at rest while the neutral gas moves relative to the two. Plasma instability cannot occur until the neutral beam has obtained an ionized component. In space, the neutral cloud expands rapidly and the ultimate extent of ionization depends strongly on the time it takes to develop an ion beam capable of producing super-thermal electrons. Photoionization, charge exchange, associative ionization and stripping are possible mechanisms for seeding of the neutral cloud. However, because these produce ions yet are not CIV related, their presence confounds the experiment. Thus the presence of CIV-like symptoms, such as electron heating and lower hybrid waves, may give false evidence as to the occurrence of CIV. In this work, we suggest that the CIV interaction may be delayed in space experiments and that this delay, coupled with the rapid expansion of the neutral cloud, may explain the observed low yields.

I. INTRODUCTION

The concept of critical ionization velocity (CIV) [1,2] is remarkably simple: when a neutral gas and a magnetized plasma travel relative to each other with a velocity perpendicular to the magnetic field $V_\perp$ and exceeding a critical value V_*, rapid ionization of the neutral gas takes place. The value of V_* is given by

$$V_* = \sqrt{2e\phi/M} \tag{1}$$

CIV is a cyclic process. Crossing the magnetic field lines, the plasma creates an instability in the lower hybrid range, perhaps the modified two stream instability. The ions transfer their energy to the electrons through this interaction. According the quasi-linear theory [3,4], the electrons form a plateau tail distribution with a substantial fraction, perhaps 10%, exceeding the energy of the original ions. These electrons are energetic enough to ionize the accompanying neutrals. Newly generated ions feed further energy into the electron population, allowing the process to continue cyclically. This process results in the ionization of the neutral gas at the expense of its own kinetic energy.

II. THE CIV CONTROVERSY

The CIV interaction has received considerable attention in recent years. Apart from its potential importance in cosmology, the effect could have important ramifications in spacecraft interactions. In particular, the CIV interaction would affect the interaction of exhaust plumes with the space environment, modifying optical emission signatures of space vehicles.

The question of the importance of the CIV effect in space seems somewhat controversial at present. The facile occurrence of CIV in laboratory experiments [2,5,6] has repeatedly demonstrated the existence of the CIV interaction within well defined, and reasonably well understood, parametric bounds. On the other hand, space experiments [7,8] have shown mostly negative, inconsistent and puzzling results.

III. LABORATORY CIV EXPERIMENTS

The first laboratory experiment to test CIV used the homopolar device [2,9]. In this device, a neutral gas and a plasma fill the space between two concentric cylinders. In the experiment, crossed electric and magnetic fields drive the plasma around the space between two cylinders through the neutral gas, which remains at rest. Alfvén [10] described the homopolar experiment as follows: "When the fed-in energy increased gradually, the degree of ionization jumped suddenly from 0.1% to 100% in a time scale of a few μs".

Following this epoch experiment, many laboratory experiments using the homopolar device or the coaxial plasma gun have been conducted to test CIV [5,6, 11,12,13]. In a plasma gun (Fig.1), the magnetic field is parallel to the tube axis near the plasma source and perpendicular to the axis in the interaction region. In the experiment, a neutral gas is injected into the region, again at rest, and a puff of plasma is injected with an initial velocity well above V_c. As the plasma puff traverses the neutral gas, rapid ionization occurs. After passage through the gas, the plasma slows down to a final velocity V_f. Interestingly, V_f is near but above V_c.

Significantly, in both these arrangements, there exists from the outset a dense plasma which is moving relative to the neutral gas *and* the magnetic field.

Also significantly, laboratory experiments universally fail at high neutral density. This effect has been attributed in part to inelastic collisions of superheated electrons with the neutrals [14].

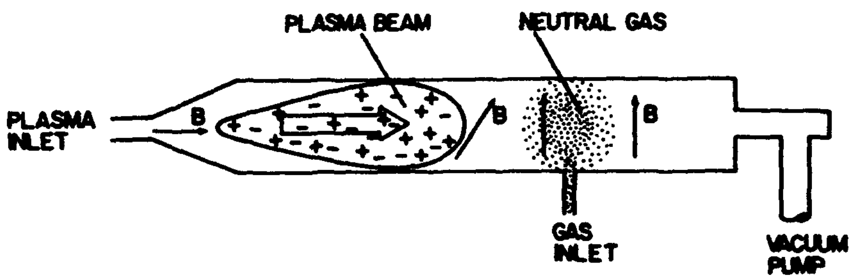

Figure 1. The coaxial plasma gun [5].

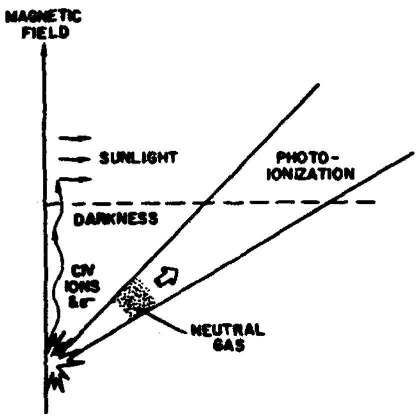

Figure 2. A schematic diagram of barium injection in a CIV space experiment.

IV. SPACE CIV EXPERIMENTS

In space experiments, a neutral gas is injected into the ambient plasma (Fig.2). Of the many such dedicated experiments, only three reported positive results. The three are Porcupine [15], CRIT II [16], and CRRES [17]. The rest, including King Crab [18], Bubble Machine I [19], Bubble Machine II [20], Star of Lima [21], Star of Condor [22], George Orwell [23], CRIT I [24], and the ten rocket releases of Hallinan [25], all failed to obtain positive results. In addition, the early rocket releases [26] of barium gas (not dedicated to tests of CIV) in the 1970s also failed to yield any evidence of CIV.

The ionization yields in the three positive experiments [15,16,17] are low (at 20%, 2%, and 1% approximately). Furthermore, it is questionable whether all of the ions observed were CIV generated. It has been pointed out that charge exchange [27], stripping ionization [15,28], and associative ionization [28,29] may have occurred under the conditions of the three experiments. These non-CIV processes may be easily mistaken as CIV.

Thus, it remains to be explained why the yield in space CIV experiments is uniformly low.

V. DIFFICULTY OF CIV IN SPACE

There may be several reasons why CIV acts so efficiently in the laboratory but leads to low yields in space. The laboratory and space CIV experimental conditions are very different. In the laboratory, the neutral and plasma densities are substantially higher than in space [30]. In the laboratory, a plasma is injected into a neutral gas; in space, a neutral gas is injected into the ambient plasma. In space, the magnetic field is much weaker than in the laboratory. Wall effects may play a part in the success of laboratory experiments. The use of barium in space experiments, although suitable for its diagnostic properties, may be a poor choice due to heavy electron energy loss through line excitation [31]. We focus here on one possible explanation, that initial conditions are not appropriate for the CIV interaction at the outset of the experiment and that, later, the rapid expansion of the neutral cloud leads to yields that are necessarily low.

In a homopolar device or a plasma gun, the plasma is established prior to interaction with neutrals. In the plasma gun experiments, instability and hot electrons are produced even before neutral contact. Thus, it is not too surprising that rapid ionization takes place. In space, on the other hand, there coexists a dense neutral cloud, a stationary ambient plasma of considerable density and a tenuous beam made up of seed ions created from the neutrals. In this case, the dispersion of the modified two stream instability becomes

$$\sin^2\theta \frac{\omega_e^2}{\omega^2} + \cos^2\theta \frac{\omega_e^2}{(\omega^2 - \Omega_e^2)} + \frac{\omega_i^2(Ba)}{(\omega - k \cdot V)^2} + \frac{\omega_i^2(O)}{\omega^2} = 1 \qquad (2)$$

where ω_e and Ω_e are the electron plasma and gyrofrequencies, ω_i(Ba) and ω_i(O) are the ion plasma frequencies for the barium beam and oxygen background respectively, **k** is the wave vector and θ is the angle between the wave vector and the ion beam velocity **V**.

The nature and extent of the wave heating of the electrons depends strongly on the relative density of beam and ambient ions. Also, when the neutral beam is very dense, electron/neutral elastic collisions can thwart the electron heating altogether [32]. To be considered as well is the energy drain arising from electron excitation of the neutrals, which is preclusive to the CIV discharge when the excitation time is smaller than the heating time [33]. This effect is especially severe for barium, the element used for the vast majority of space CIV experiments.

We propose that these factors, and perhaps others, create a situation in which the neutrals are not properly seeded in the early portion of space experiments. Improper seeding would result from any process which restricts the free and efficient flow of ion kinetic energy to the creation of superthermal electrons. These restrictions can be thought of as creating a delay time t_d between the release of the gas and the initiation of the cyclic energy transfer process that is the critical ionization velocity discharge. We show next that if t_d is too long, a simple model of the expansion predicts that the ultimate yield will be low.

VI. A CIV YIELD MODEL

We assume that the CIV discharge has been delayed by t_d. We can express the number of electrons e_i created by ionization through simple kinetics.

$$\frac{de_i}{dt} = k\alpha \frac{N-(e_s+e_i)}{V}(e_s+e_i)\Theta(t-t_d) \tag{3}$$

where e_s is the number of electrons created through seeding, N the number of neutrals of the beam, k = <vσ> the reaction rate constant with v the electron velocity and σ the ionization cross section, α the fraction of electrons energetic enough to ionize, V the volume of the neutral cloud, t is the time from release, and Θ the Heaviside function. For spherical expansion, which approximates many of the releases quite well, V can be modeled as

$$V = \frac{4}{3}\pi v_r^3 t^3 \tag{4}$$

where v_r is the radial expansion velocity.

If we neglect the contribution of seeding after t_d, we can divide by N on both sides, giving yield Y as a function of time

$$\frac{dY}{dt} = \left[\frac{3Nk\alpha}{4\pi v_r^3}\right]\frac{(1-Y)Y}{t^3}\Theta(t-t_d) \tag{5}$$

where we have defined the yield Y as

$$Y = \frac{e_s+e_i}{N} \tag{6}$$

Solving the differential eq(5), one obtains

$$Y(t) = \left[1 + \left(\frac{1}{Y_0} - 1\right) \exp\left(-\frac{\beta}{2}\left(\frac{1}{t_d^2} - \frac{1}{t^2}\right)\right)\right]^{-1} \tag{7}$$

for $t \geq t_d$ and where β is a constant:

$$\beta = \frac{3Nk\alpha}{4\pi v_r^3} \tag{8}$$

The yield Y(t) in eq(7) increases with the initial yield Y_0 at $t=t_d$. If we assume that the seeding mechanism does not substantially deplete the initial number of barium atoms, and if we further assume that the process is linear, we find that before the discharge begins,

$$\frac{dY}{dt} = \nu_s \tag{9}$$

where ν_s is the seeding rate. This means that

$$Y_0 = \nu_s t_d \tag{10}$$

At $t=\infty$, the yield Y from the experiment becomes

$$Y = \left[1 + \left(\frac{1}{\nu_s t_d} - 1\right) \exp\left(-\frac{3Nk\alpha}{8\pi v_r^3 t_d^2}\right)\right]^{-1} \tag{11}$$

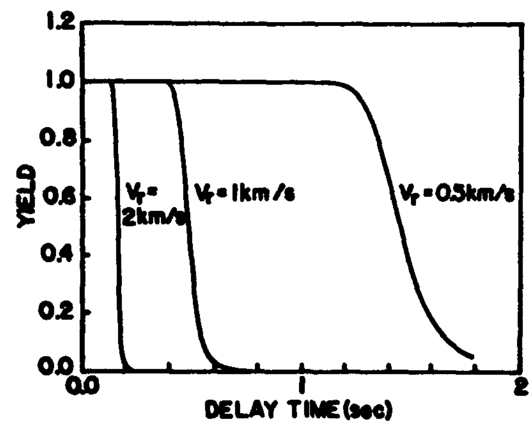

Figure 3. Yield as a function of delay time and radial expansion velocity.

It is remarkable that the yield $Y(t_d, v_r)$ (eq.11) depends crucially on the delay time t_d and on the expansion velocity v_r (Fig.3). This result has an important implication. If electron impact ionization is not initiated quickly in the barium injection CIV experiments in space, the ultimate yield will be compromised, even if the experiment last a very long time and if the energy transfer efficiency is 100%.

V. THE CONCEPT OF DELAY TIME

In this model, we treated the delay time t_d as an absolute prohibition to electron impact ionization and we assumed that the boundary between no CIV ionization and CIV ionization was sharp. Although the boundary may not in fact be a step function, there are factors which prohibit the energy cycle from taking place early in the expansion of the cloud.

Townsend's criterion [34] requires that the beam transit time τ_T across a magnetic field line exceeds the electron heating time τ_H. Physically, this limits the energy cycle because electrons are essentially tied to the plane of the field lines and EXB; the electrons cannot ionize if the neutral cloud passes them by before they are heated. This requires t_d to equal or exceed the critical transit time τ_T. In a typical space experiment model, the cloud velocity is 8 km/s, the radial expansion velocity 1 km/s, and the heating time [35] is about 30 ms. In this case, τ_T would exceed τ_H after 118 ms.

For an expanding beam starting from a singularity, the neutral density N is extremely high initially. This has two effects. First, line excitation will prohibit electron impact ionization [33] if the time for excitation of an allowed state of barium τ_{ex} is shorter than the heating time τ_H. Barium has an unusually large excitation cross section of the order of 2(-15) cm^2. With the expansion model, we find that τ_{ex} is shorter than 1 ms up to about 400 ms into the release and does not equal τ_H until about 1 second. Line excitation, then, appears to be a likely factor responsible for large t_d.

High neutral density also leads to electron/neutral elastic collisions. It has been suggested [15,32] that these collisions effectively suppress the modified two stream instability until such time as the elastic collision time τ_{el}, equals the lower hybrid time ω_{LH}^{-1} approximately. Evaluating this condition with the model above and an elastic collision cross section of 3(-15) cm^2 results in a delay time t_d value of about 500 ms, so that electron/neutral elastic collisions appear as a likely factor as well.

The above factors together impose restrictions on the experiment which can be imagined to result in a sharp boundary between no ionization and ionization at t_d. In addition, there is another factor due to the finite beam width $L_\parallel$. When $L_\parallel$ is much less than the lower hybrid wavelength λ, the growth rate is reduced [36]. In laboratory CIV experiment, this is not a problem because $L_\parallel > \lambda$. But, in space CIV experiments, λ is of the order of km; λ exceeds $L_\parallel$ by a factor of 10 in the first 100 ms. This factor does not have any sharp transition time at all.

V. CIV SYMPTOMS BY NON-CIV PROCESSES

A CIV discharge requires seed ionization to initiate. In CIV space experiments, seed ionization must be generated by non-CIV processes. For example, associative ionization [29], charge exchange [27], and stripping ionization [15,28] are non-CIV processes that may occur in barium jet injections in the ionosphere.

$$A + O \rightarrow AO^+ + e^- \qquad \text{(Associative Ionization)}$$

$$A + O^+ \rightarrow A^+ + O \qquad \text{(Charge Exchange)}$$

$$A + O \rightarrow A^+ + O + e^- \qquad \text{(Stripping Ionization)}$$

The product ions of these processes may be mistaken as evidence of the CIV interaction. Therefore, if barium ions are observed, it does not necessarily follow that the CIV interaction has contributed significantly to their production. Adding to this uncertainty is the fact that the magnitude of the reaction cross sections for the above processes are subjects for considerable dispute among researchers.

With the high velocities of neutral gas used in the CIV space experiments, the ions produced by the above non-CIV processes are probably beam-like [29]. The beam created by the chemical processes may energize electrons just as does the CIV interaction, thereby producing associated symptoms such as plasma instability waves, energetic electrons, electron impact ionization, electric field fluctuations and Alfvén waves, *etc.* It seems, then, that chemical reactions may mimic the CIV interaction almost completely, making accurate diagnosis of a space experiment extremely difficult.

VII. CONCLUSIONS AND DISCUSSIONS

The conflicting evidence for CIV from the laboratory experiments and from the space experiments has led us to to the explanations presented in this paper: In the laboratory, a plasma beam is readily available. In space CIV experiments, the ambient plasma is not beam like. It takes a delay time t_d for the neutral beam to form an ion beam and to initiate electron impact ionization. There are factors which prohibit the CIV cyclic process from taking place early in the beam expansion. The yield obtained in a simple model shows strong dependence on the delay time t_d and the expansion velocity v_r. If t_d is too long, the yield drops off dramatically. The result is even more remarkable when one considers that the model includes no loss mechanisms for electrons and ions. The loss of electron energy to line excitation [31], for example, could make the critical t_d even lower.

Considering the many complications in the performance and diagnosis of space CIV experiments, it seems unlikely that a 100% yield can be achieved. Minimization of the cloud expansion, however, appears to be an important consideration in maximizing the yield.

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