GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 6, PAGES 499-502, MARCH 19, 1993

CIV EXPERIMENTS ON ATLAS-1

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Abstract. A test of the Critical Ionization Velocity (CIV) theory was made with neutral xenon releases from the Space Experiments with Particle Accelerators (SEPAC) hollow cathode plasma contactor onboard the Shuttle Orbiter Atlantis during the ATLAS-1 mission. The gas velocity perpendicular to the Earth's magnetic field was essentially the orbital velocity (7.5 km/s), and thus it exceeded the CIV for xenon. The releases were observed with onboard instrumentation. A factor of 60 enhancement was seen in the Langmuir probe current. Calculations confirmed that release conditions generally satisfied criteria for CIV and predicted a maximum factor of 20 increase in plasma density. Thus, CIV effects were likely to have occurred during the ATLAS-1 experiments.

Introduction

Space Experiments with Particle Accelerators (SEPAC) was the only active experiment in the ATLAS-1 payload, which was carried into a 57°, 290 km orbit by the Shuttle Orbiter Atlantis on March 24, 1992. Although SEPAC was primarily a series of experiments with a 7.6 kW electron beam, in particular aimed at the creation of an artificial aurora, the second SEPAC accelerator, a plasma contactor (PC), was used to perform several tests of the Alfvén Critical Ionization Velocity theory. The CIV theory, first postulated by Alfvén [1954], states that neutral gas travelling perpendicular to a magnetic field will suddenly become ionized when its velocity in the rest frame of the magnetic field reaches a threshold value such that the kinetic energy of the gas in that frame is equal to its ionization potential (ϕ_{ion}): $v_{crit} = (2e\phi_{ion}/M)^{1/2}$.

The CIV phenomenon has been suspected to play an important role in various plasma dynamics situations ranging from cometary comas and astrophysical problems to spacecraft environment interactions and ionization in magnetoplasmadynamic (MPD) thrusters. A recent review of the significance of CIV has been made by Biasca [1992]. While CIV has been observed in many laboratory experiments (see Piel [1990] for a review), a definitive and unambiguous observation of this phenomenon in space has proven elusive. Torbert [1990] reviews attempts to observe CIV in the ionosphere, and Brenning [1992] gives a thorough review of all aspects of CIV.

A CIV study using a xenon gas release from Spacelab was proposed by the AMPS Science Working Group in 1975 (see Möbius [1979]). This method takes advantage of the fact that the Shuttle orbital velocity of >7 km/s exceeds the 4.2 km/s critical ionization velocity for xenon. It has several advantages over sounding rocket experiments, including better control of the magnetic field configuration, and the possibility of repeating the experiment many times in one mission while varying release parameters. Further, it avoids difficulties with ground based optical observations [Wescott et al., 1992] by using optical diagnostics on the Shuttle, and has a much higher mass flow rate than other satellite experiments, e.g. the APEX xenon releases.

The first Spacelab CIV experiment was performed by ejecting argon plasma at supersonic speeds (near 20 km/s) from a SEPAC plasma accelerator on Spacelab 1. Ionization of the ambient neutrals was reported by Sasaki [1986]. For ATLAS-1, the argon plasma accelerator was replaced by the xenon PC, making it possible to perform the CIV experiment as originally proposed for AMPS.

Hardware

The SEPAC PC is a 25 cm hollow cathode plasma source capable of ejecting 1.6 A of xenon plasma in a continuous mode and/or .15 mole of neutral xenon in 100-ms pulses, and was intended to aid in neutralizing the Orbiter during electron beam firings. In addition to the PC and the electron beam, the SEPAC hardware also included a diagnostics package. Details of the diagnostic instruments are given in Burch et al. [1992]. Figure 1 shows the layout of the SEPAC experiment on the ATLAS-1 pallet. The plasma contactor orifices are approximately 1.5 m from the diagnostics package probes.

The CIV Experiments

The SEPAC CIV experiments, designated Functional Objective 8 (FO8), consisted of a series of 100-ms neutral xenon releases, one every five seconds for five minutes. The release velocity of the xenon from the PC at the 245

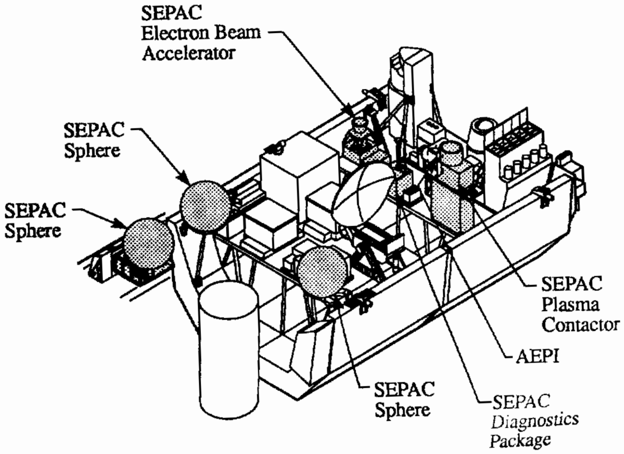

Fig. 1. ATLAS-1 pallet configuration. SEPAC equipment is shaded.

Paper number 93GL00593
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psi nominal plenum tank pressure is only ~30.5 m/s, and therefore the neutral xenon will have essentially the orbital velocity of 7.5 km/s when released from the PC regardless of the orientation of the release with respect to the velocity vector. In order to satisfy the CIV criterion, the velocity perpendicular to the magnetic field must exceed the critical value; we therefore planned to perform FO8 at high latitudes, where the angle between the orbital velocity and the field line is nearly 90°.

Figure 2a shows the planned orientation of the Orbiter for the CIV experiment, with xenon released into the wake. FO8 was performed twice during ATLAS-1: once with the payload bay in the wake (Figure 2a) and once with the payload bay toward the Earth (Figure 2b). The latter is not optimum for the CIV experiment because the gas is released perpendicular to the velocity vector, i.e., not into the ram or wake where the plasma environment is more easily modeled; however, we chose to take advantage of available experiment time with the Orbiter in this attitude.

Results from SEPAC Diagnostics

The SEPAC diagnostics package included a Langmuir probe, a floating probe with three vertically spaced sensors, high and low frequency wave receivers and a vacuum gauge. In addition to these diagnostics, the Atmospheric Emissions Photometric Imager (AEPI) was used to obtain images of the neutral gas releases. We plan to report on the optical measurements, as well as the wave data, in a later paper.

Figure 3 shows diagnostics package data from the 16:07:39 to 16:07:40 UT on March 27 (Day 87), 1992, the beginning of the first ATLAS-1 CIV experiment; Universal Time is plotted on the x axis. The payload bay was toward Earth at that time (Figure 2b). All data are plotted with maximum resolution (1 msec, except in the case of the valve status, which is 2 msec). The top plot shows the neutral gas fast acting valve status as "on" when the valve is open; the valve stays open for approximately 100 ms every 5 sec.

The second plot is the Langmuir probe current (top) and voltage (bottom). Before the beginning of the FO, the probe voltage was swept in order to obtain the ambient electron temperature and density. Once the neutral gas releases began, we held the voltage constant at +9 V (the maximum applied voltage) in order to record density fluctuations. Unfortunately, voltage sweeps immediately before the start of the releases show that the probe does not reach the electron saturation limit at this voltage. During the release shown the current does saturate the probe electronics, increasing by a factor of at least 60 as compared to the background level. Although the exact increase in plasma density cannot be calculated because +9 V does not represent the electron saturation limit, this does indicate a substantial amount.

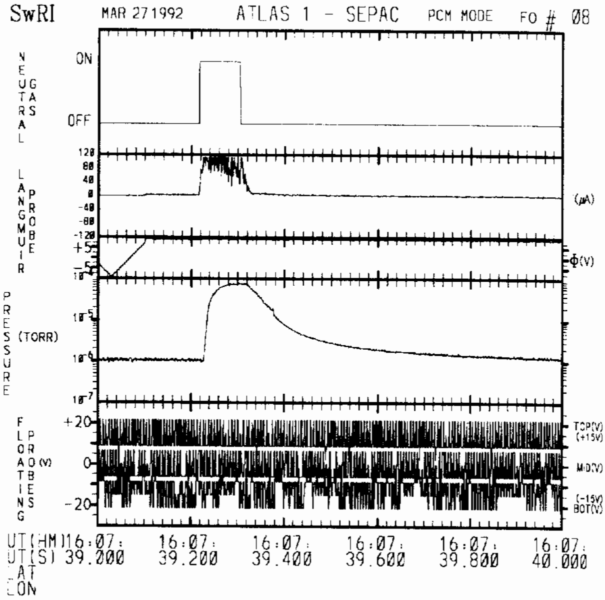

Fig. 3. Data from the SEPAC diagnostics package plotted against universal time from 16:07:39 to 16:07:40 on Day 87 (March 27), 1992.

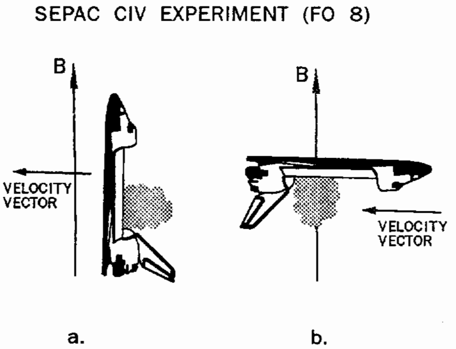

Fig. 2. (a) Orbiter orientation planned for SEPAC CIV experiment and used for FO8-2. (b) Orbiter configuration for FO8-1.

The third panel shows data from the vacuum ionization gauge, located at the base of the Langmuir probe. The increase in Langmuir probe current shown above precedes the increase in neutral pressure shown here by 14 msec. This lag may occur because the vacuum gauge is farther from the release point than is the Langmuir probe sensor, or it may reflect the response time of the gauge.

The bottom panel shows the voltages on the floating probe top, middle and bottom sensors, each spaced 25 cm apart vertically. The voltages on the top and bottom sensors have been offset by +15 V and -15V, respectively, so that the traces can be distinguished. The data are extremely noisy; however, there is no discernible increase on any sensor during the gas releases, indicating that the Langmuir probe current spikes are due to increases in density and not merely the result of a shift in vehicle potential.

Figure 4 shows a summary plot of the peak Langmuir probe current (solid line) and the peak ambient neutral pressure (dashed line) for each gas release in FO8-1, indicating that the plasma density during neutral xenon pulses is proportional to the amount of xenon released, which declines over the five minute extent of the experiment. Similar data from the second performance of FO8 (FO8-2) show that the level of ionization in that experiment, which was performed with the payload bay in the wake (Figure 2a), was not qualitatively different from that in the first FO8. (Recall that FO8-1 was performed with the payload bay toward the Earth.) Table 1 summarizes the two CIV experiments from ATLAS-1.

Evaluation of CIV Test Criteria

In addition to the relative velocity requirement, there is a set of necessary conditions or criteria that a neutral gas-plasma release in space must satisfy in order for a CIV interaction to be possible. Most of these criteria have been discussed by Lai and Murad [1992]. To compare with the

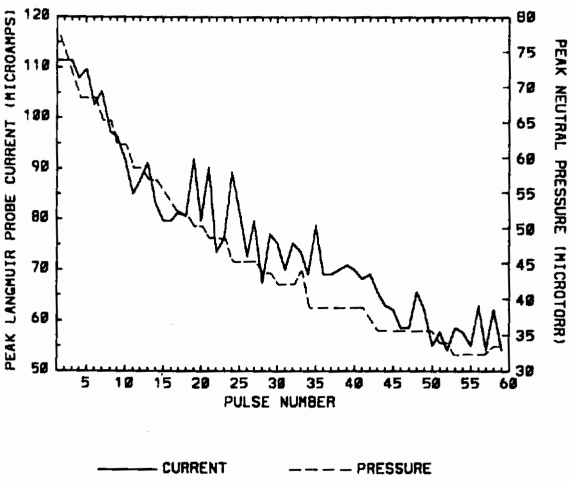

Fig. 4. Summary plot of peak Langmuir probe current (solid line) and peak ambient neutral pressure (dashed line) for each neutral xenon release in the first performance of the SEPAC CIV experiment.

CIV test criteria, we selected a typical 100-ms xenon gas release at 131 g/s from the FO8-1 series. This particular release happened at 16:11:19 UT on Day 87 (March 27) with a spacecraft orbital velocity of 7.5 km/s. The Langmuir probe current-voltage characteristic from immediately before the FO started yielded a density of at least 5 x 10^4 cm^{-3}, but was too noisy to determine accurately the electron temperature. We selected an electron density of 5 x 10^4 cm^{-3} and an electron temperature of .1 eV for use in the calculations.

CIV Criteria

CIV-prone Region. Lai and Murad [1992] define a CIV-prone region bounded by distances x_1 and x_2 from the spacecraft. The distance x_1 is the upper bound for the CIV-prone region and is obtained by requiring the ionization time scale to be shorter than the residence time scale of electrons in the spirit of a Townsend criterion for the initiation of a self-sustained discharge. For the above conditions, this distance was calculated to be x_1 = 134 m from the spacecraft. At the end of the 100-ms pulse the released gas cloud would have a dimension of 6 m. Since this dimension is smaller than x_1 the release cannot be considered as a steady-state conical beam but rather as a symmetrically expanding cloud.

The distance x_2 is the lower bound for the CIV-prone region and is obtained by requiring the time it takes a magnetic field line to move across the cloud to be shorter than the time needed for the electrons to be heated by the instability fueling the CIV interaction. Assuming that the latter time scale is $30/\omega_{LH}$, as suggested in Tanaka and Papadopoulos [1983], we get x_2 = 12 m. CIV is therefore restricted to happen between 12 and 134 m from the release point.

Table 1. Summary of CIV experiments from ATLAS-1

FO	Attitude	Max LP Current (μA)	Vperp	Pitch Angle
8-1	Payload bay to Earth	>111.4	7.36 km/s	81°
8-2	Payload bay in wake	>111.4	7.46 km/s	90°

Release Velocity Criteria. Alfvén's original criterion for CIV $v_{rel} \geq v_{ci}$ was satisfied for xenon, whose v_{ci} is only 4.2 km/sec. Another inequality that must be satisfied by the relative velocity, as pointed out by Papadopoulos [1984], states that the v_{rel} must not exceed $(1 + \beta_e)^{1/2} v_A$ (where v_A is the Alfvén velocity and β_e is the electron beta) lest electromagnetic modes decrease the heating efficiency of the instability. This yields an upper limit for v_{rel} of 460 km/sec at x_1 and 400 m/s at x_2, implying that this criterion is initially violated near the spacecraft where the density is relatively high (n_e = 1.7 x 10^{12} cm^{-3} at x_2 assuming an ionization fraction of 10^{-8}) but quickly becomes satisfied as the cloud recedes from the spacecraft (n_e drops to 2.6 x 10^4 cm^{-3} at x_1.)

Magnetic Field Strength Criterion. The inequality $\omega_{pe}/\omega_{ce} > (m_e/M)^{1/2}$ was proposed by Brenning and Axnäs [1981, 1990] to set an upper limit on the magnetic field. The smallest value for this upper limit in our particular experiment is calculated to be 0.04 Tesla, which is well above the strength of the local magnetic field, implying that the criterion is satisfied (at both x_1 and x_2).

Pitch Angle Criterion. Lai and Murad [1992], using electron escape arguments, stated that the release pitch angle θ must satisfy the inequality $L\sigma n_e > sin\theta > v_{ci}/v_{rel}$, where L is the dimension of the cloud and σ is the effective cross-section for electron impact ionization of xenon neutrals. This yields 33° < θ < 90° (at both x_1 and x_2) for our case, a condition well satisfied by the release.

Collisionality Criteria. Choueiri et al. [1985] derived from a model of the rate kinetics a condition that must be satisfied by the level of collisionality of the newly produced ions in order for collisions not to disrupt the energization process. This criterion, cast in terms of a condition on the maximum allowable effective Hall parameter for the newly produced ions, Ω_{Hi}, is $\Omega_{Hi} > 1/(v^2_{rel}/v^2_{ci} - 1)$. This sets an upper limit on the allowable effective collision frequency for the new xenon ions, which is calculated to be about 18 Hz. This criterion is clearly violated at x_2 where the neutral gas density is very high (n_n = 1.7 x 10^{20} cm^{-3}) but becomes more tenable toward the outer boundary of the CIV-prone region (the effective collision frequency of the new xenon ions drops to 96 Hz near x_1).

Criterion for Metastable Enhancement. The ionization time from the $(6s[3/2]_2)$ metastable state of xenon is calculated to be 70 s for the conditions at x_1 and 3 μs for the conditions at x_2. Both values are lower than the metastable lifetime for that state. This implies that the likelihood of sustaining a CIV discharge for this particular release may be enhanced because of ionization from metastable states [Lai et al., 1988; 1989].

Mass Loading. The mass loading effect may reduce the effective relative velocity through strong momentum coupling between the ions produced in the beam and the ionospheric ions [Haerendel, 1983; Lai and Murad, 1992]. This effect sets an upper limit on the plasma density in the beam, n_b, given by Lai and Murad [1992] as $n_b = 0.8 n_a M_a v_A / M_b v_{rel}$. For the conditions of our particular release this translates into a ion density yield of 10^6 cm^{-3}, which is about a factor of 20 increase in the ambient density. The number is of the same order as the factor by which the Langmuir probe current increased during the release.

Prospect for a CIV Interaction. The prospect for a CIV type interaction for this particular release is good judging from the application of the above criteria. The criteria are mostly (and at worst marginally) met at distances close to x_1 from the spacecraft. One criterion not considered stipulates that the dimension of the cloud must exceed the wavelength of the unstable mode responsible for electron energization. The evaluation of this criterion must await the study of the wave data for this particular release. Finally, criteria for disqualifying the possible role of other ionization mechanisms in these releases (such as charge-exchange and the entrainment of collisionally ionized neutrals to the probe as discussed by Sasaki [1985]) have not yet been addressed quantitatively.

Discussion and Conclusions

Model calculations indicate that the release under study is a good candidate for CIV effects, and predicts a maximum density enhancement in qualitative agreement with the factor of 60 increase seen in the Langmuir probe current. Data taken with the release in the ram compared with data taken from a release perpendicular to the ram show no qualitative difference in the Langmuir probe current. The calculations, however, predict CIV-enhanced ionization to occur between 12 and 134 m from the release point, and it is difficult to determine how the plasma, which should be tied to the magnetic field, could have been transported to the vicinity of the Langmuir probe.

There are possible explanations other than CIV effects for the high probe current. Recalling the probe was not at the electron saturation voltage, it is possible that the density increase may be overestimated compared with the ambient. Alternatively, the density may be due to plasma resulting from collisional interactions between the injected gas molecules and the ambient plasma that is then channeled to the probe by the magnetic field. This effect was observed on Spacelab 1, as described by Sasaki [1985]. The ionization in the two cases studied here does not vary with attitude, however, as was the case in Spacelab 1.

We plan to model releases in other attitudes, hoping to find a case for which the model does not predict substantial CIV density enhancement. Comparison with the current increases in such a case should shed light on the likelihood that the enhancement is due to CIV effects. Optical data, when they are available, will also help to confirm that there was indeed enhanced ionization in the region predicted by our calculations.

Acknowledgements. The authors gratefully acknowledge the work of the entire SEPAC team and the ATLAS-1 POCC Cadre and crew. We also thank Amy Cotton for her painstaking work on the SEPAC data analysis software and Gerry Murphy for a very helpful discussion. This work was supported by NASA contract NAS8-32488 and Air Force contract AFOSR-91-0162.

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(Received 24 August 1992;
revised 19 November 1992;
accepted 7 January 1993.)