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AUTOMATED CALIBRATION OF A FLIGHT PARTICLE SPECTROMETER

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ABSTRACT

During the first year of this fellowship, an automated calibration system was designed for use in the vacuum facility at the Space Science Laboratory of the Marshall Space Flight Center. That system was developed and used in the intervening winter to calibrate the ion spectrometer that eventually flew in May 1986 aboard the NASA project, CRIT I. During this summer, we planned to implement the calibration of both an ion and electron spectrometer of a new design whose basic elements were conceived during the winter of 1985-1986. This spectrometer was completed in the summer and successfully mounted in the vacuum tank for calibration, as described the report for 1985. However, the source gate valve malfunctioned, and, at the end of the summer, we were still waiting for a replacement. Once again, we will finish the calibration of this instrument in the fall. During the inevitable delays in any experimental research, I completed the numerical model of the Critical Velocity effect and presented these results to my colleagues at MSFC. The remainder of this report is a description of that effort.

INTRODUCTION

The critical velocity effect, as first proposed by Alfven (1954), has a long controversial history. Nevertheless, it is frequently evoked in many astrophysical situations where neutral gas if found flowing through a plasma. Basically, Alfven proposed that when such a flow reaches a velocity, perpendicular to the ambient magnetic field, of Vcr,

$$Vcr = \sqrt{2e\theta_i/M} \qquad (1)$$

(where M and θ_i are, respectively, the mass and the ionization potential of the neutrals), then the neutrals would be anomalously ionized. Since this process has been shown to involve the transfer of the energy of the recently ionized neutrals to a heated electron population, the above velocity must be increased to Vcr*

$$Vcr^* = Vcr / \sqrt{\eta} \qquad (2)$$

where η (less than 1) is the efficiency of this energy transfer (Haerendel, 1982).

Besides the original applications to the formation of the early solar system, they include light emission around the space shuttle (Papadopoulus, 1984), cometary coma ionization (Formisano, et. al. 1982 and Galeev, 1985). The recent experiments around both artificial and natural comets has further excited scientific effort on this problem. During the last ten or so years, active experiments using the fast plasma jets created in alkali-metal shaped-charge releases have attempted to test the validity of this effect in the ionosphere. For a review, see Newell (1985). In this paper, we review the critical items of two such experiments: Porcupine, which reported an ionization yield of nearly 30 percent of those neutrals whose perpendicular velocity exceeded Vcr, and Star of Lima, with a yield of only 0.1 percent. To try to understand this discrepancy, a numerical model of such releases was developed. Although the problem remains unexplained, it does become clear that the total yield depends critically on the macroscopic limits of time and energy in these shaped-charge releases. In fact, I suggest that the total ionization yield is a poor indicator of a nonlinear discharge of this type and one should instead determine the value of η, discussed above. If this factor is of order 10 percent or greater (even taking into account electron number and energy losses out of finite beam regions), then the effect can be said to be present.

Experimental Results

Previous ionospheric critical velocity experiments have been conducted using barium or strontium shape charge releases which produce a fast jet of neutral gas with a velocity distribution similar to that shown in Figure 1. This particular distribution was measured optically in the Star of Lima experiment from Peru (Wescott, et. al., 1986). A recent list of several such experiments is given in Table 1. The striking feature of this table is that all but one, project Porcupine, produced very little ionization. The other feature of this table is that the radial shape charges have been particularly inefficient in producing prompt ionization. To those five listed one should add also the Star of Condor, which was a radial shape charge producing less than 3*10**-5. We would like to treat in detail two of these, namely Project Porcupine and the Star of Lima, as representative of high yield and low yield experiments.

The experimental condition of Project Porcupine is summarized in Figure 2, where the fast barium jet is shown propagating from the explosion point at an angle of approximately 28 degrees with respect to the local magnetic field. As in nearly all such experiments, the intention is to explode the barium below the solar terminator at 320 nm, where barium will not photoionize. If ionization is produced close to the explosion point, so called "prompt" ionization, then those ions will propagate up the magnetic field line and be seen spatially separated from those neutrals that have then become ionized in sunlight as some further distance away from the explosion point.

Now in Project Porcupine there were no diagnostics actually in the electron beam; however, from optical observations, Haerendel reported 30 percent of those neutrals with perpendicular velocities greater than the critical velocity, were in fact ionized. Furthermore, there was a diagnostic payload on a magnetic field line which went near or through the interaction region of the beam. Large electric fields consistent with the emission of Alfven waves were detected (Haerendel, 1982). Superthermal electrons with a flux somewhat less than an auroral flux were seen. This flux is in fact 3 to 4 orders of magnitude less than what must have existed in the beam. Haerendel also estimated that the ionization rate was not so large that the cloud would have polarized due to the burning current (i.e. the discharge was not 'mass limited', as described later.)

Although the collective plasma instability that is responsible for the transfer of ion energy to electron energy was not directly measured in Porcupine, considerable consensus exists in the theoretical community that this must be the lower hybrid instability (Piel, 1980). The most efficient version is the linear ion beam, which Galeev (1981) estimates may give an (referred to above) of as much as two-thirds. However, this only occurs when the ionization is rapid enough to make the distribution look like a beam, and not like a ring. That is, η is order 2/3 if

$$\dot{n}_i/n_i \geq \Omega_i \qquad (3)$$

where Ω_i is the ion gyrofrequency. If $\dot{n}_i$ is much less than this, then η approaches 0.025.

Haerendel estimates that the fast limit existed in Porcupine. Furthermore, he estimates that the density in the beam remained sufficiently high out to 15 km that the Townsend condition, as used in similar work on Beam Plasma Discharge, was satisfied (see Brenning, 1982). This states that the probability that an electron, which is created in an ionizing collision, is accelerated and makes a subsequent ionizing collision is sufficiently near 1, so that the effect has a positive feedback and can grow upon itself.

Porcupine remains the single outstanding successful experiment conducted with shape charge releases. With this promising result, an experiment was designed to maximize these results and also to place diagnostics in the barium beam for the first time. The intended configuration of Project Condor, conducted near the earth's equator, is given in Figure 3. The idea here was to inject vertically the barium jet, which is thus perpendicular to the magnetic field. The diagnostic payload was below the explosion point by approximately 2 kilometers. Due to financial constraints, diagnostics were limited. Again the UV determinator was intended to be above the explosion point and as the sun rose, one could make a complete inventory of ions that were produced promptly. However, the rocket over-performed and in fact some solar UV illuminated the injection point. Data from particle and field instrumentation on board the Lima probe is summarized in Figure 4, which gives about 2 seconds of data from the explosion point (from Torbert and Newell, 1986). One can see that large ionization was produced in the electron channels, so large that in fact one sweeping electron detector was saturated for some good fraction of the first second and an electric field pulse of about 400 mv/meter was created.

Note in this figure the very rapid time scale on which the entire effect occurs at the rocket location. The total electron flux of electrons greater than about 5 eV, shown in the middle panel, is such that superthermal electrons of substantial flux were created, 4 to 5 times a typical aurora. Data in the second panel, from a detector that was sweeping out approximately 20 degrees of pitch angle, shows that these electrons definitely were pitch angle modulated after the first quarter second of the burst. An expanded interval at about a half second around this burst time is seen in the next figure where we have both electron and ion data along with that of the single axis electric field. Unfortunately, a great deal of ambiguity exists in this experiment because the electric field is measured only along an axis which is perpendicular to the beam direction and therefore had varying angles in respect to the magnetic field as the experiment progressed. In fact, the ambiguity is such that the large electric field pulse seen between a 100 and 160 milliseconds is still somewhat unexplained (Kelley, et. al., 1986). Our best guess right now is that the pulse is the manifestation of a fast neutral oxygen jet produced by collisions with the initial barium in the very first moments of the explosion. This is supported by the fact that V x B at this time is consistent with a velocity of 22 kilometers a second, much faster than any barium in Figure 1. Furthermore the time events associated with that pulse are such that whatever produced it could have only been traveling at that velocity from the injection point. Barium did not really appear at the injection point until around 160 milliseconds at which time there is a slight dc electric field along with very large AC component, hundreds of millivolts per meter, seen between 160 and 230 milliseconds in the electric field. At the same time, the particles increased by over an order in magnitude and a large peak at around 10 electron volts in the fast electron sweeper that was very soon saturated. The electric field fluxuations were in fact at a frequency consistent with the lower hybrid for barium.

Using the electron data, we can address the vital question of electron trapping in the interation region. Electrons must remain sufficiently long to satisfy the Townsend condition described above. In Figure 6, the electrons at three fixed energies are plotted as a function of time along with the corresponding pitch angle. During the 400 ms interval or so of the interaction time, these electrons are not heavily modulated with pitch angle. There is only a slight dip in each one of them at pitch angles off of 90 degrees. However, after the barium has passed over the payload, a large reduction of 90 degrees pitch angle appears, implying at least that during the interaction time, a large number of electrons were contained in the interaction region and did not escape.

Estimates have been made for this experiment, like those of Porcupine, for both the time scale and the Townsend condition, with similar conclusions. Table II summarizes the details of the two experiments and points out the large discrepancy between the final results. All the electrons were observed in Lima. They were consistent with the optical observations. The electric field magnitude is reasonably consistent with a saturated lower hybrid instability and yet only about 10**-3 of those neutrals perpendicular to the magnetic field were actually promptly ionized by the plasma physics operating after the explosion.

Numerical Model

To resolve this large discrepancy. I undertook to create a model to answer the following specific question. What is the absolute maximum yield I could expect for the given value of the efficiency parameter, η, consistent with the macroscopic constraints of time and energy. This is essentially just a bookkeeping problem. We describe first, the source of free energy: the neutral beam as given in Figure 1, the actual velocity distribution that was measured in Star of Lima. Next, we must calculate the neutral density that appears at a given position and time in the beam. The coordinate system we use is given in the Figure 7, where X is the distance, perpendicular from the magnetic field, from the injection point. Since we wish to consider the maximum yield, we will draw a box at a fixed X containing the neutral beam and consider any electron density in that box is constant and that no electrons are allowed to escape from that box if they are created there. At any given radial distance, angle and time, the neutral density can be computed from the velocity distribution, as given in the equation in the figure, where the angular distribution is taken to be a Gaussain in one direction, constant in the azimuthal direction, and is properly normalized. The angular width, θ_w, is taken in these simulations to be 15 degrees, consistent with experiment. Note several implications of this equation. First of all, the density falls off as R**-3; and, since the neutral density is the driver, our free energy is rapidly diminished the further away from the injection point. Furthermore, this neutral density, as a function of time at any given place, will evolve on a time scale that will be larger, the further out from the injection point. These effects can be seen in Figure 8, where the neutral density is plotted as a function of time for six different fixed positions for the case of the Star of Lima.

Next, we compute the electron production rate. Qe, as a sum of three terms, each proportional to the neutral barium density: one, due to collisional ionization, proportional here to the electron density times the average over the hot electron population of the cross-section times the velocity; second, charge stripping from the collision of barium onto oxygen; and finally, ions produced by solar UV with a time constant, if fully illuminated, of 28 seconds.

$$Q_e \equiv \dot{n}_e = N_{Ba} \left(n_e \langle\sigma v\rangle_{ion} + Q_{ST} + Q_{uv}\right) \qquad (4)$$

The ion production rate, Q_i, is Q_e plus charge exchange rate of barium onto ionized oxygen with a fixed cross-section of 5*10**-17 cm**2. Furthermore, an initial, thermally created ionization yield of 10**-4 was also assumed in this model. The ionization cross-section average was computed using a Born cross-section model with a maximum at 10.4 electron volts of 1.2*10**-15 cm**2. The resulting rate is somewhat more rapid than if a simple Error function of θ_i/T_e is incorrectly used.

The energy requirements can be computed as follows:

$$\frac{d}{dt}\left(\frac{3}{2} n_e T_e\right) = \eta \left[\frac{1}{2}M (\Delta V)_{\perp}^{2} Q_i\right] - \phi_i N_{BA} n_e \langle\sigma v\rangle_{ion} - \phi_b N_{BA} n_e \langle\sigma v\rangle_{exc} \qquad (5)$$
$$- \phi_{oxy} N_{oxy} n_e \langle\sigma v\rangle_{exc,oxy}$$

The positive contribution is that given by the total energy of the neutrals that have just been ionized at the rate, Q_i, in the plasma frame (with relative velocity, ΔV) times the parameter, η, the efficiency with which the energy can be transferred to the electrons. Note that we are assuming that this energy goes immediately into the electron population, consistent with the philosophy of computing the maximum possible production. This is however not a bad approximation because, for the case of lower hybrid waves acting here somewhat as a catalyst, the growth rates and resonance times are far more rapid than the time scales that are considered here. In equation (5), there is energy lost for each ionizing collision and also from hot electron excitation of the barium and the ambient oxygen. Values of these cross-sections were taken from Newell and Torbert (1985). To have a complete closed system of equations, only the relative velocity of the neutrals with respect to the plasma, ΔV, remains to be determined. These set of equations can now be integrated over time and horizontal distance, X, to computer our total yield. Interestingly, the critical velocity nowhere appears explicitly in this model. However, the rate of energy production would not be positive unless ΔV is greater than the critical velocity (correctly by η), just as was postulated by Alfven, provided that the secondary losses from electron excitation are ignored.

Calculating ΔV can become complicated, but it can be estimated using current conservation as illustrated in Figure 9. Assume the reference frame of the fast neutral barium. In this frame a newly ionized atom is initially at rest. Outside of a box containing the neutral beam, the background plasma experiences an electric field which is V_{BA} cross B, as shown. As ionization occurs, an electric current results from the displacement of ions by one gyro-radius due to whatever electric field exists within the cloud, which would then tend to polarize. However, charge can be bled away by Alfven waves which carry away a known parallel current, determined by the change in the electric field across the boundary of this box. Equating the Alfven current to the polarization current, one easily derives the electric field inside the cloud as a function of the electric field outside the cloud, as shown in the figure. This interesting relation is called the mass limiting condition and is identical to that derived by Haerendel (1982) in a different way. Note that this electric field (crossed into B) within the box is precisely the relative perpendicular velocity of the plasma with respect to the neutral barium frame, the final quantity that we seek. In the earlier, simpler sense, this relative velocity (i.e. electric field) must be greater than Vcr* for the effect to grow. Since V depends on dNi/dt, this mass loading condition limits the maximum burning rate so that

$$\dot{n}_i \lesssim 2\rho_A U_A / M\ell_Z \qquad (6)$$

Any faster rate will polarize the cloud and shut off the source of free energy. Now, this does not necessarily limit the total ion production, because the hot electrons will convect along with the neutrals all the time ionizing at or near the limited rate (provided the electrons can be contained, of course). In fact, all the above equations are total derivatives and the model must be run with convective terms whose velocities are given by the equation in Figure 9. These complicated interdependences were the motivating factors in designing the present model. However, we have found that, for the events simulated, outside of about one kilometer from the explosion, the mass loading condition was never satisfied and the reaction was granted the full energy of the neutral beam. This is consistent with the earlier statement that, in both Porcupine and Lima, the mass loading factor was not limiting the process.

Only the ambient neutral oxygen density remains unspecified. Figure 10 shows these densities for both Lima and Porcupine, as well as the recent CRIT flight, as determined by a model run of the MSIS neutral model of A. Hedin. The ambient ionized oxygen density was about 2*10**4 in Lima and 2*10**5 in Porcupine.

The model is then run at successfully farther perpendicular distances away from the injection point and for all times where there is appreciable ionization due to hot electrons. As an example of the results, we choose to show the evolution of parameters for the Star of Lima experiment at a radial distance of 2 km. Since the beam was perpendicular to the magnetic field, this is equivalent to a horizontal distance of 2 km. In figure 11 are plotted four quantities as a function of time at this distance. The barium neutral density is reproduced with a peak density of about 2*10**8 per cc. As the neutral density rises, the electron temperature begins to increase, reaching a peak of around 5 eV, nearly the ionization potential, but, just as significant burning begins to occur, the electron temperature falls off for several reasons. First, energy is consumed in the ionization process; second, as more electrons are created, they must in turn be heated; and third, as time progresses at any one location, both the density and the velocity of neutrals that are driving the process becomes less and less, and, likewise, the available free energy. The hot electrons cause the production of electrons consistent with our equations. However, the electron density (which is very nearly the ion density) increases only about an order of magnitude. In effect, just at the time of maximum rate of electron production, the free energy goes away. This can clearly be seen in the final curve showing the ionization time,

$$\tau_{ion} = 1/(N_{Ba}\sigma v) \tag{7}$$

This is the effective time for any one electron to produce an ion-electron pair. From a very large value, it reaches a minimum of about 0.1 seconds, which is the same time scale as the variation in the barium neutral density. Thus, a few e-folding factors is the maximum increase in electron density that we could expect. At further distances out, the time scales increase, but the decrease of maximum barium density, and the resulting fall in electron temperature, increase the ionization time even faster.

The model is now run, for several values of η, to compute the total number of ions created as a fraction of those neutrals whose perpendicular velocity is greater than Vcr (see Figure 12). As a check of the background, the curve $\eta = 0$ shows the total contribution due to all sources but electrons. The initial value of 10**-4 for explosive thermal ionization is apparent. The experiment was assumed to be illuminated with 2.5 percent full solar UV, as reported in Wescott, et. al. (1986). The remarkable feature of this figure is that, with $\eta = 0.3$, only 10**-3 yield (the same as reported by Wescott) is produced in the Lima experiment. This assumes no electron loss from interaction regions and still is within a factor of 3 of the theoretical limit of Galeev cited above! If the value of η is any indication, the critical velocity effect occurred in the Star of Lima, only the macroscopic limits of time and a limited energy budget prevented a larger yield. In other words, given the experimental conditions, one should never expect any greater yield, no matter what plasma process is operating.

The larger yields of Project Porcupine nevertheless disagree substantially with these results. Figure 13 shows the yield plot for the same model for the experimental parameters of Porcupine. Almost no yields could be expected. The difference from Lima is primarily the result of the small pitch angle of the jet in Porcupine. Since the free energy is a function of the perpendicular velocity, it is greatly reduced in this case. Model runs of Porcupine for pitch angles varying from 28 to 90 degrees show a continuous transition back to yields similar to those of Lima.

It can be argued that one should not distribute the ion energy over the entire electron distribution, since only a fraction resonate with the lower hybrid wave and, even then, they are accelerated primarily along the magnetic field and not isotropically. A so-called "hot" model was created and will be discussed in a later paper. This model gains about a factor of two in yield over the "cold" model presented here for the same values of η. If these electrons are formed into a "beam" with only one degree of freedom, this gains us about another factor of two (maybe three) so that a maximum of about 10**-3 could be expected in Porcupine from these models.

Summary

The above results indicate that there must have been some other source of ionization in Porcupine other than those considered here. Nevertheless, the agreement with the Star of Lima experiment implies that the Critical Velocity effect was operating in that case and that a very high energy transfer efficiency, about 30 to 50 percent, was obtained. Only the experimental conditions limited the total yield. It should be noted that, in nearly all astrophysical cases, the limiting factor of short time scale is not present. However, longer scales could also allow for more electron loss along field lines out of the interaction region. There are cases (the early formation of the solar system with a very slow spiral to the magnetic field) where this concern is not so great. Further experimentation, along with new results from the recent CRIT experiment, is needed to resolve many of these issues.

REFERENCES

1. Alfven, H., "On the Origin of the Solar System," Oxford University Press, New York, 1954.

2. Brenning, N., "Comment on the Townsend condition," paper presented at Workshop on Alfven's Critical Velocity Effect, Max-Plank-Inst. fur extraterr. Phys., Garching, Munchen, Federal Republic of Germany, October 11-13, 1982.

3. Formisano, V., A. A. Galeev, and R. Z. Sagdeev, "The role of the Critical Ionization Velocity Phenomena in the production of inner Coma Cometary Plasma," Planet. Space Sci., 30, 491-497, 1982.

4. Galeev, A. A., and I. Ch. Chabibrachmanov, "Origin and Energetics of the Io plasma Torus," Adv. Space Res., 3, 71-75, 1983.

5. Haerendel, G., Alfven's critical velocity effect tested in space, Z. Naturforsch. A, 37, 728-735, 1982.

6. Kelley, M. C., R. F. Pfaff, and G. Haerendel, "Electric field measurements during the Condor critical velocity experiment," J. Geophys, Res., 1986 (in press).

7. Newell, P. T., "Review of the critical ionization velocity effect in space," Rev. of Geophys, 23, 93-104, 1985.

8. Newell, P.T., and R. B. Torbert, "Competing Atomic Processes in Ba and Sr Injection Critical Velocity Experiments," Geophys. Res. Let., 12, 835, 1985.

9. Piel, A., E. Mobius, and G. Himmel, "The influence of the plasma inhomogeneity on the critical velocity phenomenon," Astrophys. Space Sci., 72, 211-221, 1980.

10. Torbert, R. B., and P. T. Newell, "A magnetospheric critical velocity Experiment: Particle Results," J. Geophys. Res., 1986 (in press).

11. Wescott, E. M., H. C. Stenbaek-Nielsen, T. Hallinan, H. Foppl, and A. Valenzuela, "Star of Lima: Overview and optical diagnostics of a critical velocity experiment," J. Geophys. Res., 1986 (in press).