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D. P. Sheehan
University of San Diego, dsheehan@sandiego.edu

C. A. Casey
University of California, Irvine

L. T. Volz
University of California, Irvine

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Interaction of an expanding plasma cloud with a simple antenna: Application to anomalous voltage signals observed by Voyager 1, Voyager 2, ICE, and Vega spacecraft

D. P. Sheehan, C. A. Casey, and L. T. Volz

Department of Physics, University of San Diego, San Diego, California
Department of Physics, University of California, Irvine

Abstract. High-velocity impacts of interplanetary dust grains with spacecraft can give rise to transient plasma clouds from the spacecraft bodies. It is believed these plasma clouds can affect spacecraft instruments. Laboratory results are presented demonstrating the interaction of small expanding plasma clouds with a simple antenna. Results corroborate the hypothesized origin of anomalous impulsive voltage signals recorded by Voyager 1 and 2 spacecraft during flybys of Saturn, Uranus, and Neptune, the International Cometary Explorer (ICE) during its flyby of comet Giacobini-Zinner, and Vega during its flyby of comet Halley. Results suggest that preflight calibration of antenna-plasma interactions may extend the range of spacecraft diagnostics.

1. Introduction

During equatorial flybys of Saturn, Uranus, and Neptune the Voyager 2 spacecraft registered many impulsive voltage spikes on its plasma wave and radio astronomy instruments consistent with high-velocity impacts by micron-sized dust or ice grains on the spacecraft body [*Gurnett et al.*, 1983, 1986a, 1987, 1989, 1991; *Aubier*, 1983; *Meyer-Vernet et al.*, 1986; *Scarf et al.*, 1982; *Warwick et al.*, 1982, 1986, 1989; *Pederson et al.*, 1991; *Tsintikidis et al.*, 1994]. Voyager 1 recorded similar events during its flyby of Saturn in 1980. These purported impacts are believed to have resulted in brief, expanding plasma clouds which intercepted the spacecraft's antennae, producing voltage spikes on the spacecraft's instruments. Similar spikes were recorded by the International Cometary Explorer (ICE) during its flyby of the comet Giacobini-Zinner [*Gurnett et al.*, 1986b; *Scarf et al.*, 1986] and by Vega on its flyby of comet Halley [*Oberc and Parzydlo*, 1992].

In this brief communication we report on a laboratory study of the interaction of expanding plasma clouds of varied composition with a simple antenna. The aim of this experiment was to test the hypothesis that expanding plasma clouds can produce the characteristic voltage signatures observed by the above-mentioned spacecraft. In fact, voltage signatures from the laboratory antenna closely resembled in shape and magnitude those obtained by the Voyager spacecraft, thus supporting previous interpretions of flyby data.

2. Theory

The physics of the impact of a hypervelocity grain with a spacecraft body and the subsequent interaction of its expanding plasma cloud with a spacecraft antenna is complex and not amenable to exact solution. However, the component phenomena, impact ionization, plasma expansion, and charge coupling to a conductor, may be discussed separately with some confidence.

Impact ionization of a projectile on a target surface is conceivable when the kinetic energy of the projectile relative to the target is comparable to or exceeds the molecular and atomic dissociation energy of the projectile's matter. For impacts between the high-velocity Voyager or ICE spacecraft and a quasi-stationary grain (typical relative velocity of 10–20 km/s) one expects partial ionization of the grain and some spacecraft surface material [*Adams and Smith*, 1971; *Auer and Sitte*, 1968; *Dietzel et al.*, 1973; *Fechtig et al.*, 1978; *Frichtenicht et al.*, 1964; *Grün*, 1984; *McDonnell*, 1978]. Spacecraft surface materials are mostly plastics and to a lesser part metals (e.g., gold and aluminum), while grain compositions are likely metal silicates or oxides, water ice, or other simple compounds. Grain sizes encountered by the spacecraft in question were estimated to be 0.1–10 μm. Plasma temperatures have been estimated to be between 10^4 and 10^5 K at the impact site [*Hornung and Drapatz*, 1981]. The ratio of ionized to neutral matter should be of the order of 10^{-4}.

Once ionized, the grain/surface plasma should expand away from the impact site, sweeping past the antenna. Plasma expansion into a vacuum has been studied experimentally and theoretically by a number of investigators (see review by *Gurevich and Pitaevsky* [1975]). Consider a temporally brief point source of unmagnetized isothermal plasma expanding hemispherically into a vacuum away from a surface. Electrons, by virtue of their higher thermal velocity, preceed the ions into the vacuum, and so one expects the floating potential of the expanding plasma front to be negative. A conductor in the path of this plasma front should acquire an initial negative charge. For this geometry one expects particle flux densities to decrease as $1/r^2$ from the source.

The magnitude of the voltage pulse V measured on the antenna can be estimated by the method used by *Gurnett et al.* [1983]. The voltage registered should be

$$V = \alpha \frac{Q}{C_a} \qquad (1)$$

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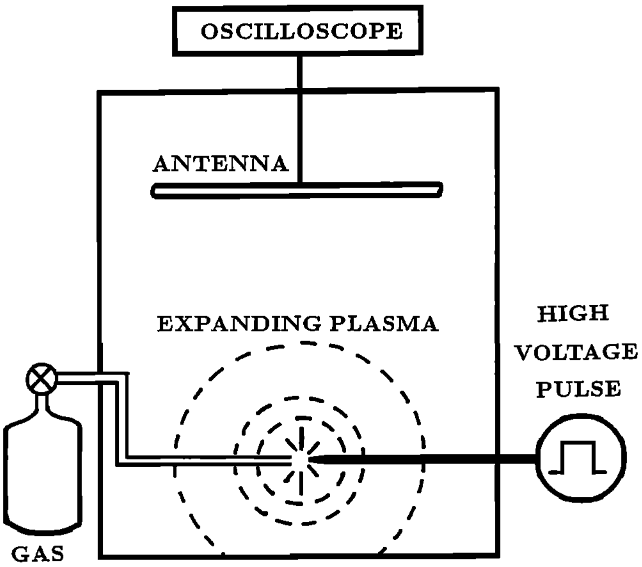

Figure 1. Schematic of experimental apparatus.

where Q is the magnitude of the charge released by impact ionization, C_a is the antenna capacitance, and α is an empirical dimensionless coupling coefficient for the plasma and antenna which accounts for the geometry and relative positions of the antenna and plasma cloud, induced charge on the antenna, and perhaps other factors.

3. Experimental

The present experiments were carried out at the University of California, Irvine, and the University of San Diego. The apparatus consisted of a cylindrical vacuum vessel, a pulsed plasma source, a simple antenna, and a high-impedance digital storage oscilloscope (see Figure 1). The vacuum vessel (length = 35.5 cm, diameter = 12.7 cm) was maintained at a base pressure of 2×10^{-6} torr. Pulsed plasma clouds were initiated at the bottom of the vessel by a low duty cycle ($f \sim 5$ Hz; $\tau_{on} \sim 20\ \mu s$; $\tau_{off} \sim 200$ ms), high-voltage (10–30 kV) electrical spark acting upon a small, localized region of dense gas ($P \sim 10^2$–10^3 mtorr). The arc supply provided an intense, brief, high-voltage spark between a pointed tungsten electrode and an electrically grounded, small-bore (diameter ~ 2 mm) stainless steel tube through which the gas to be ionized was fed continuously. The plasma cloud was initiated in the small volume ($V \sim 10^{-2}$ cm^3) between the tungsten electrode and the gas feed tube where neutral gas density was substantial. The neutral gas density in the discharge region was estimated to be $n \sim 10^{15}$–10^{16} cm^{-3}. Although the local gas pressure near the electrodes was relatively high, the overall background vacuum vessel pressure was typically about 10^{-5}–10^{-4} torr such that the mean free path for plasma and neutrals was of the order of the vessel length ($\lambda_{mean} \sim 20$ cm) and legitimate plasma effects could be observed. The pulsed plasma duty cycle and repetition rate were sufficiently low to allow complete clearance of residual plasma from the chamber between discharges.

Several gases were used independently: H_2, He, Ar, N_2, CO_2, and air. The plasma cloud, once formed, expanded to fill the vessel. The plasma density in the region between the electrodes was estimated to be of the order of 10^{12} cm^{-3} at a local temperature of several eV ($T \sim 10^5$ K). The plasma was collisional very near the discharge (mean free path, $d \sim 1$ cm), so some plasma cooling probably occurred. In fact, the plasma environment between the electrodes was perhaps similar to the hypothesized environment nearby a grain impact region on a spacecraft, namely, a high-temperature plasma ($T \sim 10^5$ K) composed of light elemental and molecular ions immersed in a much denser neutral background gas.

The laboratory antenna, inserted from the top of the vacuum vessel on a vertically mobile, electrically shielded shaft, consisted of a solid copper rod (length = 8 cm, diameter = 0.14 cm) oriented such that its length would intercept the maximum possible plasma flux. The antenna was electrically attached at its midpoint to the central conductor of a 1.5-m strand of RG-58 coaxial cable. The calculated free-space capacitance of the antenna was about 1 pF, that of the coax cable about 70 pF. The coaxial cable was connected to a high-impedance amplifier (digital storage oscilloscope: 1 MΩ input impedance, 20 pF input capacitance). The separation between the plasma discharge and the antenna could be varied between 2 and 18 cm.

In comparison, the Voyager 2 antenna system consisted of two 10-m-long 1.3-cm diameter antennae, mounted in a V formation [*Gurnett et al.*, 1983]. When operating as a plasma wave instrument, the antennae are operated as electric dipoles, responding to voltage differences between the two antennae; for the radio astronomy instrument, on the other hand, they operate as monopoles, detecting voltage differences between themselves and the spacecraft body. The antennae were monitored by a high-impedance amplifier (impedance of the order of 1 MΩ). The total capacitance of the instrument was roughly 90 pF, a value comparable to the laboratory antenna-detector circuit.

4. Results and Discussion

Pulsed plasma-antenna interactions were studied for the following ionized gases: H_2, He, N_2, Ar, CO_2, and O_2/N_2 (air). Antenna voltage signatures for each of the laboratory gases were qualitatively and quantitatively similar to each other and also closely resembled those registered by the Voyager 1 and 2.

In Figure 2 a typical voltage signature is shown as registered by the laboratory antenna/detector circuit for an argon pulsed discharge. This trace represents an average over about 40 individual discharges. The signature has three distinct features: a sharp positive spike, followed by a broader negative spike, followed by another broad positive spike. The first positive spike was determined to be an electrical transient from the discharge electrical circuit, rather than a genuine plasma phenomena; hence in the following discussion it will be ignored. The negative flux spike broadens temporally and decreases in absolute magnitude with increased antenna-discharge separation as might be expected for a thermal plasma pulse; the positive flux spike decreases in magnitude with antenna-discharge separation. Voltage amplitudes increased roughly linearly with increased feed gas pressure, arc voltage, and arc current.

The laboratory voltage signatures (sans the initial positive transients) are similar in shape and magnitude to those observed by the Voyager spacecraft which were attributed to plasma clouds interacting with spacecraft antennae. For instance, compare the laboratory data to the following spacecraft data: Voyager 2 in Figure 5 of *Gurnett et al.* [1991], Voyager 1 in Figure 4 of *Gurnett et al.* [1987], and Voyager 1 in Figure 3

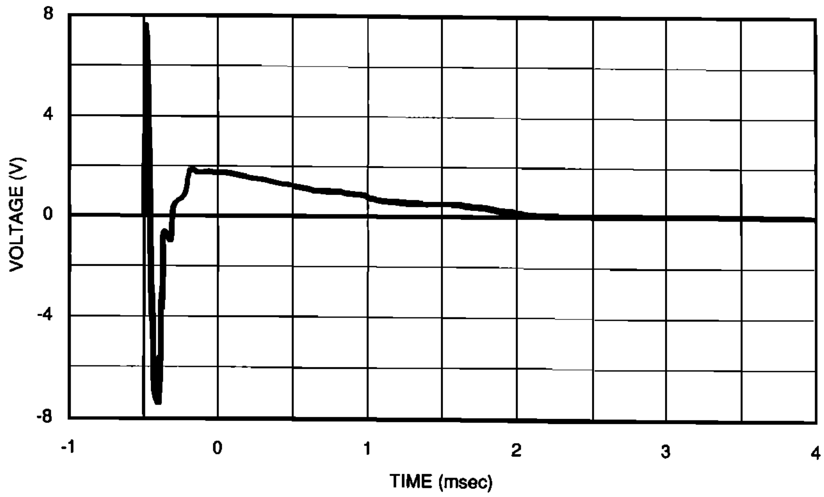

Figure 2. Voltage versus time signature measured on the laboratory antenna intercepting expanding argon plasma cloud. Antenna-discharge separation $z = 4.3$ cm.

of *Gurnett et al.* [1983]. For both space and laboratory plasmas the rise time for the initial spike is of the order of tens of microseconds, the breadth of the initial spike is less than the secondary spike, and the timescale for the entire voltage signal is of the order of a few milliseconds.

The laboratory antenna was moved with respect to the plasma discharge. In Figure 3 the time-integrated positive argon flux signal is plotted versus the antenna-discharge separation. The flux collected decreased roughly with the inverse square of the antenna-discharge separation, as expected for a spherically expanding plasma. As the antenna is separated from the discharge, one would also expect an increasing delay time between plasma initiation and plasma reception by the antenna. In Figure 4 the delay time between plasma initiation and reception τ_d is plotted versus antenna-discharge separation z. The delay time is taken to be from plasma initiation to the maximum of the negative spike. As expected, the delay time increased roughly linearly with antenna-discharge separation. The slope of the data curve should be the average expansion velocity of the plasma. Here it is calculated to be $v = z/\tau_d \simeq 1.5 \times 10^3$ m/s. It was not determined whether this represents a thermal speed or a radial drift velocity; however, if one equates this to the thermal velocity for argon ions, one infers a plasma temperature of roughly 4000 K. This is reasonable if one assumes cooling of the hot discharge plasma by neutral collisions near the discharge. The laboratory and space plasmas are produced by different mechanisms so some of their characteristics may be different, in particular, their expansion velocities. Their initial plasma temperatures are similar (10^5 K); however, their neutral gas temperatures are quite different. The laboratory neutrals are cold (~300 K) and so can cool the plasma, reducing its expansion velocity. The dust-impact neutrals, on the other hand, should retain a significant fraction of their initial kinetic energy and can carry the plasma outward at high speed. In fact, laboratory expansion velocities are roughly 10–20 times smaller than those found for impact-produced plasmas [*Hornung and Drapatz*, 1981].

In all, the hypothesis that the anomalous impulsive voltage spikes observed by Voyager 1 and Voyager 2 spacecraft can be attributed to grain impact ionization is corroborated by these laboratory findings. Further corroboration might be sought by repeating this experiment, replacing the arc plasma source with the plasma from impact-ionized hypervelocity grains as investigated by *Grün* [1984] and *Eichhorn and Grün* [1993].

These results hint that the "anomalous voltage spikes" observed during planetary flybys may contain quantitative information about the nature of the plasma clouds and grains which probably cause them. Perhaps preflight plasma cloud experi-

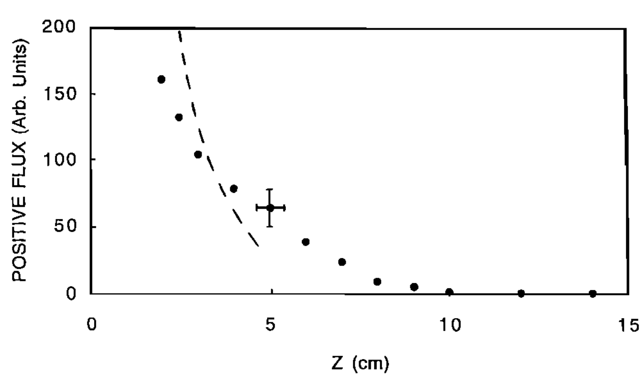

Figure 3. Positive argon ion flux intercepted by antenna versus antenna-discharge separation. Theoretical $1/r^2$ fit given by dashed line.

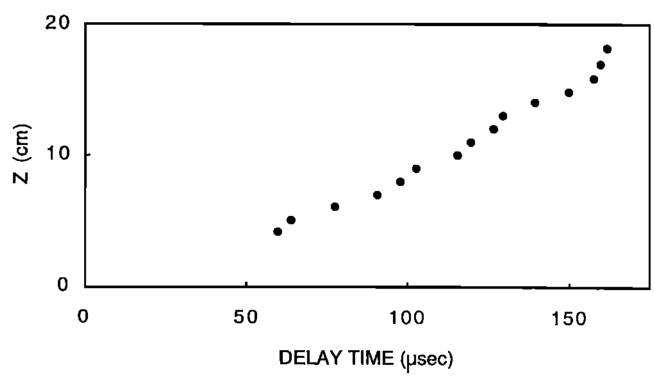

Figure 4. Argon plasma reception delay time versus antenna-discharge separation. Slope corresponds to average plasma expansion velocity $v \simeq 1.5 \times 10^3$ m/s.

ments with the spacecraft may allow calibration of existing diagnostics, thus offering another data line without substantial additional effort.

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C. A. Casey, D. P. Sheehan, and L. T. Volz, Department of Physics, University of San Diego, 5998 Alcala Park, San Diego, CA 92110. (e-mail: dsheehan@acusd.edu)

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