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Comment on “NO_x production in laboratory discharges simulating blue jets and red sprites” by Harold Peterson et al.

J. de Urquijo[1] and F. J. Gordillo-Vázquez[2]

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[1] After a careful reading of the paper by *Peterson et al.* [2009], we have found a number of misinterpretations, both on the experimental technique used, and in the measured current through the spark gap, from which important conclusions are drawn regarding the production of NO_x. In particular, we have found inaccuracies in the method to evaluate the energy dissipated in the discharge gap, with a rather unclear description. The authors introduce some correction factors to evaluate the NO_x concentration even though these lack a sound, necessary explanation. In our view, the experimental technique deserves revision and serious improvement, since we regard this work as one of the very few attempts up to now to study and quantify in laboratory experiments the complex chemical phenomena related to TLEs and, in particular, with NO_x production during sprite and blue jet events in the upper atmosphere.

[2] The research activities on experiments and simulations leading to a better understanding of transient luminous events (TLE) like sprites and blue jets is an emerging field within the geophysical community. The work by *Peterson et al.* [2009] represents an attempt to correlate the energy dissipated in the discharge plasma of a spark gap with simultaneous measurements of NO_x concentrations. This work has been commented on previously by *Nijdam et al.* [2010], different lines than those presented in this comment. We concur with most of the comments and criticisms made by *Nijdam et al.* [2010], regarding some conceptual errors and erroneous calculations in the paper of *Peterson et al.* [2009]. Here, we are concerned with some misunderstandings and errors of interpretation of the experimental techniques, and its consequences in the accurate derivation of the amount of NO_x that is actually produced in the discharge spark gap.

[3] Figure 4 of *Peterson et al.* [2009] describes the electrical setup. Capacitor C is charged via the series combination of the 2 MΩ resistor plus the CVR (current viewing resistor), the value of which is not given in the text. Assuming that CVR $\ll$ 2 MΩ (which is shown below), then the RC time constant for charging the capacitor is 0.3 s, which is congruent with the minimum reported charging time of 1 s, that is, between three and four time constants.

[4] By the time the high-voltage discharge switch is pressed, the spark gap becomes conducting and forms a series circuit with the inductance L (1.255 mH), the charging capacitor C (0.15 μF), the CVR (unknown value or, at least, not given in the paper), and the spark gap. Nothing is said about the plasma impedance in the spark gap. Let us call R_m the value of the CVR, and assume that the discharge plasma is predominantly resistive, and designate this property by R_{SG}. Thus, the total resistance (R_t) in the series circuit is

$$R_t = R_m + R_{SG} \tag{1}$$

[5] The current in the RLC series circuit of Figure 4 is correctly expressed by equation (3) of *Peterson et al.* [2009], although the natural frequency of oscillation, ω_0, is wrongly typed, since $\omega_0 = (LC)^{-1/2}$. Notwithstanding that the discharge gap should be represented by an impedance with inductive, capacitive and resistive components, and that these are time dependent, we shall only consider the resistive part, since this is the most relevant during discharge development other than the initiation and extinction stages.

[6] The fourth paragraph of section 2.1 of *Peterson et al.* [2009] is particularly confusing and unclear. We would like to raise the following comments.

[7] 1. In equation (1) of *Peterson et al.* [2009], the magnitude E is defined only as the energy, without identifying it with any of the components of the electrical circuit.

[8] 2. Equation (1) of *Peterson et al.* [2009] aims at describing an energy balance during the discharge regime, but it is incorrect. The correct energy balance equation reads as

$$\frac{1}{2}CV_0^2 = \int R_m i^2 dt + \int R_{SG} i^2 dt + \frac{1}{2}Li^2 + \frac{1}{2C}\left[V_0 C + \int i dt\right]^2 \tag{2}$$

where i = i(t) is the time-dependent current in the circuit, and V_0 is the charging voltage of the capacitor. The term on the left-hand side of this equation is the energy stored in capacitor C prior to the discharge. The third and fourth terms on the right-hand side of equation (2) correspond to the

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[1] Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Cuernavaca, Mexico.

[2] IAA-CSIC, Granada, Spain.

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energies stored in the inductance and capacitor, respectively, and these are nondissipative.

[9] 3. In equation (3) of *Peterson et al.* [2009], the current depends inversely on R, as it should be, but this R is identified by them as that of the measuring resistor (R_m), according to the last sentence in section 2.1. Thus, if R_{SG} is ignored, that would mean that the spark gap plasma has zero resistance; this, in turn, would imply that there is no energy dissipation in the discharge, thereby hindering any further estimate of NO_x production from it. Thus, it would appear that the authors assume that the discharge plasma behaves as a perfect short circuit, even though this is not the case. It is perhaps more illustrative to write equation (3) of *Peterson et al.* [2009] for the temporal evolution of the current in the circuit as

$$i(t) = \frac{V_0}{Z_0}\frac{\exp(-t/2\tau)}{\sqrt{1-(R_t/2Z_0)^2}}\sin\left(\omega_0 t\sqrt{1-(R_t/2Z_0)^2}\right) \quad (3)$$

where the angular frequency of oscillation is $\omega_0 = (LC)^{-1/2}$, the characteristic impedance is $Z_0 = (L/C)^{1/2}$, the decay time constant is $\tau = L/R_t$, and V_0 is the charging voltage of the capacitor. Thus, the peak current depends strongly on the characteristic impedance which, for the values of L and C given, is $Z_0 = 91.5\ \Omega$, and $\omega_0 = 72.9$ krad s^{-1}, from which the period of oscillation is 86 μs, which is consistent with that estimated from the current transients shown in Figure 5 of *Peterson et al.* [2009]. This current is also dependent on the term in the denominator containing the ratio $(R_t/2Z_0)^2$, from which the condition $R_t < 2Z_0$ should be fulfilled for the circuit to oscillate. Thus, in the absence of any value in the text for R_t, we infer from the above that $R_t = R_m + R_{SG} < 183\ \Omega$.

[10] The two overdamped transients on the left-hand side of Figure 5 suggest that the discharge plasma resistance was higher than that present in the transients on the right-hand side. It is very unfortunate that no experimental conditions at all were attached to Figure 5 in its caption, since such information would have been very valuable to gain a better understanding both of the experiment and its analytical method.

[11] The authors state at the last sentence of section 2.1 that the measured currents were squared over the "apparent decay times", and that this yielded the energy dissipated in the external circuit. Then, with R multiplying in their equation (1) the square of the current, and the same R dividing the charging voltage in their equation (3), it appears that the authors have neglected the contribution of the spark gap plasma resistance, that is, $R_{SG} = 0$ for them, since the same value of R ($=R_m$) appears in both expressions. Moreover, the spark gap plasma would behave as a perfect, nondissipative conductor, and hence the analysis of NO_x production by the measurement of the energy dissipated in the discharge gap would be impossible. Formally, the analytical formulation of *Peterson et al.* [2009] regarding the energy balance is incorrect and incomplete.

[12] Equation (1) of *Peterson et al.* [2009] appears to be an energy balance equation, even though the "E (joule)" term is poorly defined as "energy", only. The correct energy balance equation was written above in equation (2) of this comment. The paper by *Peterson et al.* [2009] states that the inductance also dissipates the energy, and this is also incorrect. In fact, one can easily demonstrate that in a lossless circuit, the sum of the energies stored in the capacitor and the inductance equals that in the originally charged capacitor. With this in mind, the energy dissipated in the spark gap discharge plasma is

$$E_{SG} = \int R_{SG} i^2 dt = \frac{1}{2}CV^2 - \int R_m i^2 dt \quad (4)$$

[13] Certainly, a better measuring setup is that of, for instance, *Briels et al.* [2008b, 2008a], in whose work the spark gap voltage and current are measured unambiguously, thereby making it possible to evaluate E_{SG}. The procedure described by *Peterson et al.* [2009], leading to the obtention of E_{SG} is not clearly defined and leads to erroneous interpretations.

[14] In spite of the efforts made by the authors in measuring E_{SG}, the second paragraph on section 4.1 (energy method) appears to discard all this work with the sentence: "Discharge energy is equal to energy stored in the capacitor prior to discharge divided by the appropriate correction factor". This is very confusing, since the authors do not explain the origin of such correction factors. Furthermore, if the energy dissipated in the discharge had already been measured, then we see no reason to apply correction factors, nor the authors explain why.

[15] It appears to us that any comparison of the NO_x yields would only proceed if every yield were normalized to the energy dissipated in the spark gap, namely E_{SG}, and not to the initial energy stored in the capacitor, such as the authors describe in paragraph 4.1. It is totally unclear the origin and way of reasoning to determine the correction factors for stratospheric pressures, derived from the peak discharge current and *ringdown* time. In Table 1, t^2 is not defined, neither is it on the text, hence it is left to the reader to wonder about its meaning. If one assumes that this is the square of the *ringdown* time, then these particular times turn out to be much longer than those read off the transients in Figure 5 shown by *Peterson et al.* [2009]. Throughout, the footnote of Table 1 is, in our view, completely unclear. It appears to us that it would have been preferable to calculate the total charge flowing across the discharge gap, and to use it to normalize the NO_x yield, rather than estimating the energy dissipated in the gap, which, in this case, is erroneous and even subjected to rather arbitrary correction factors.

[16] It is stated in the footnote of Table 1 of *Peterson et al.* [2009] that the chamber air will have a higher capacitance at higher pressures; however, the permittivity of air is nearly that of vacuum. Certainly, the capacitance of the discharge gap would not change from vacuum to air at 500 mbar, which is close to atmospheric pressure at ground level. Nevertheless, *Peterson et al.* [2009] go even further by stating that ".. the correction factor will be higher at higher pressures, for equal voltage, current, and ringdown time". Finally, correction factors are provided only in the range 0.36–10 mbar. Maybe the higher pressures are those between 10 and 500 mbar, for which no table is even presented.

[17] In summary, we are of the opinion that the method presented for the analysis of measured transients from the

experimental setup of *Peterson et al.* [2009] is incorrect, its description is confusing and misleading, and its application may lead to erroneous results. On the other hand, it might well be that some modifications to the driving circuit would provide useful and interesting results when correlated to NO_x production, even if the discharges are not equivalent nor properly scaled with respect to those associated to sprites and blue jets in the upper atmosphere. In its present form, the setup used by *Peterson et al.* [2009] is inappropriate for the simulation of lightning or sprite discharges driven by an oscillatory circuit. Perhaps a better setup to infer the value of the spark gap resistance, R_{SG}, and the energy dissipated in the discharge would be that using the same RLC circuit, crowbarred [*Lee et al.*, 2002] with a diode connected between the spark gap and earth (or a diode chain, depending on the initial voltage), so that the resultant current waveform would bear an initial rise due to the first quarter of the oscillation period followed by an exponential decay with a time constant given by $\tau = (R_D + R_{SG})\,C$, where R_D is the crowbar diode resistance. The measuring resistor could be eliminated by substituting it with a Rogowski coil [*Hutchinson*, 2002]. Thus, with previous knowledge of R_D, then R_{SG} can be duly estimated. Of course, the condition $R_D \ll R_{SG}$ should always be met.

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J. de Urquijo, Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, PO Box 48-3, 62151 Cuernavaca, Mexico. (jdu@fis.unam.mx)

F. J. Gordillo-Vázquez, Instituto de Astrofísica de Andalucía, CSIC, PO Box 3004, E-18080 Granada, Spain. (vazquez@iaa.es)