BALL LIGHTNING DISCHARGE FED BY AN ATMOSPHERIC MASER

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ABSTRACT: The present paper describes the interaction of the maser with the soliton, finally deriving the fundamental ball lightning (BL) equation for the linear heat diffusion case. This equation is a rough first approximation based on many drastic simplifications. It assumes stationarity and neglects the field emission of carriers caused by the maser. Our calculations prove for the first time that the instantaneous feedback present in the atmospheric maser allows the discharge to remain stable in the so far always unstable, much colder, discharge branch at atmospheric pressure, even without field emission processes. In fact, according to the basic Maser-caviton theory, natural BL is too cold for electrons to be present and allow it to exist in the stationary state, so it continually extinguishes and is reignited by very fast maser feedback. These are in fact maser spiking oscillations.

The life of the dynamically stabilized BL soliton consists therefore from a continual succession of deaths and rebirths.

INTRODUCTION

When lightning strikes on flat terrain, a strong homogeneous electric field pulse is present simultaneously in a large volume of moist air, of the order of cubic miles. As shown earlier [*Handel* 1988, 1989], this pulse can lead to homogeneous population inversion in the rotational energy levels of the H_2O molecule. Close to mountain tops, the electric field and the ensuing population inversion is limited to a cone-shaped volume, so this pulse does not lead to maser action without cavity walls. On flat terrain this field pulse will sometimes lead to maser action for a period of the order of seconds, due to the low rate of forbidden transitions between closely spaced pairs of rotational energy levels of the water molecule. The condition for this maser action to take place is that the gain G exceeds the loss L in the number of photons per time unit

$$dn/dt = G-L > 0, \qquad (1)$$

resulting in a net increase in the number of photons n first in a certain, well defined standing wave mode of oscillation of the decimetric electromagnetic spectrum, or in small number of modes of the same frequency. The loss term can always be represented in terms of an effective cavity lifetime τ_c, and in terms of an effective load lifetime τ_b, the load being represented by the caviton, i.e., by the visible ball lightning (BL). In the open air case there are no cavity walls, at best some reflecting objects, such as the trees lining an opening in the forest. In the absence of any cavity walls and reflecting objects or boundaries, τ_c assumes the lowest value, of the order of L/c, where L is the diameter or characteristic size of the inverted volume which can be of the order of several miles. With L = 3 km we get τ_c = 3 km /(3 10^5 km/s) = 10^{-5} s, better than for resonant cavities with copper walls. On the other hand, on a high peak, such as K. Berger's observatory on Mount San Salvatore in Lugano (Switzerland) we have l≈10m and $\tau_c \approx 3\ 10^{-8}$ s, which precludes maser action. This explains why Berger never saw ball lightning.

Collisional deexcitation of molecules is in competition with stimulated emission. The latter wins sometimes because it is faster when it happens to go into a high-gain field mode.

MASER DYNAMICS

The gain G is from stimulated emission, being proportional to the number N_2 of molecules present in the upper maser level E_2, and to n+1, i.e., roughly to the number of photons already present in the mode under consideration

$$dn/dt = K(n+1)N_2 - n/\tau_c - n/\tau_b \qquad (2)$$

$$dN_2/dt = -KnN_2 - N_2/\tau_2 + R_e, \qquad (3)$$

where we added also the rate equation for the upper maser level population N_2 in terms of the relaxation time τ_2 ($>>\tau_c$) of the upper maser level, a time which can be as long as a second or a minute, because the transition is, in fact, one of the many well-known strongly forbidden transitions between pairs of nearly coincident rotational energy levels of the H_2O molecule and is becoming only weakly allowed under the influence of perturbing fields. We also included an effective pumping rate R_e describing the rate by which in some cases the population inversion is replenished by various processes (such as, e.g., a circulation of inverted air through a barn, or recuperation of a hole burned into an inhomogeneously widened gain profile in the frequency domain).

In the quasi-stationary regime the time-derivatives are zero in equations (2)-(3). We can then eliminate N_2 and solve the resulting quadratic equation for n, with the result

$$n = (p/2)\{ r-1 + [(r-1)^2 + 4r/p]^{1/2}\} \approx p|r-1|\{\theta(r-1) + r/p(r-1)^2\}, \qquad (4)$$

where $p = 1/K\tau_2$, $r = R_e/R_t$ is the reduced pump rate close to 1, $R_t = 1/\tau_2 K\tau$ is the threshold pump rate, and $\tau^{-1}=\tau_c^{-1}+\tau_b^{-1}$. We have introduced $\theta(x)$ which is 1 for x>0 and 0 for x<0. Here p is close to the number of field modes within the width of the maser line. This width is very large in our case. Therefore, p is a very large number of the order of 10^{20} and equation (4) describes an explosive growth of the number of photons n as a function of r, whenever r exceeds unity even by very little. Indeed, from the last form of Eq. (4) obtained for $p >> 4r/(r-1)^2$, we see that for r>1 but close to 1, we get $n \approx p(r-1)$ which is an enormously large number of the order of 10^{20}, for r<1 we get $n \approx r/1-r$ which may be a number from 1 to 1,000 for example, and for r=1 we have $n=\sqrt{p}$.

Precisely this explosive growth as a function of r (and also in time) is what happens at the start and also at the demise of a BL discharge. The demise causes τ_b to become suddenly infinite and therefore r to exceed unity considerably. A similar spike exists also at the creation of the BL discharge when the original population inversion is established by the initial field pulse.

BALL LIGHTNING IN INTERACTION WITH THE ATMOSPHERIC MASER

To Eqs. (2)-(3) an effective heat diffusion equation describing the BL must be added. The simplest form considered is

$$P = \alpha(T-T_o), \qquad (5)$$

where α is a heat exchange coefficient and T_o is the ambient temperature of about 300K. Here we have introduced the power P absorbed by the BL from the standing wave of the main maser mode. This power is assumed to be ohmic as in previous experiments of Ohtsuki & Ofuruton (1991) as well as Zhil'tsov et al. (1995), although other forms of absorption such as multiphoton field-ionization of neutral atoms in the BL will also be present:

$$P = v\sigma_T n\hbar\omega/V = v\sigma_o(n/V)\hbar\omega e^{-I/2kT} = v\sigma_o(n/V)\hbar\omega e^{-I/2k(P/\alpha + T_o)}. \qquad (6)$$

Here we have used the relation $E^2 = 8\pi n\hbar\omega/V$ connecting the squared electric field amplitude with the photon concentration n/V. Here V is the volume of the atmospheric maser divided by a factor larger than 1 describing the solitonic localized electric field enhancement in the BL, and v is the BL volume. I is the ionization energy and k is Boltzmann's constant. We have assumed thermal ionization equilibrium at the temperature T in calculating the conductivity σ_T, although this is not likely to be exact for the cold (orange-colored) form of BL. Nevertheless, this approximation will give us already an approximate basis for developing the BL theory. The curve

$$n = [VP/v\sigma_o\hbar\omega]e^{I/2k(P/\alpha + T_o)}. \qquad (7)$$

has a maximum, a minimum and a linear asymptote as shown in Fig 1. Indeed, setting dn/dP=0 we obtain

$$kP^2 + (2kT_o - I/2)\alpha P + k(\alpha T_o)^2 = 0 \qquad (8)$$

with the discriminant

$$\Delta = I(I/4 - 2kT_o) > 0. \qquad (9)$$

This inequality is applicable, since I is of the order of 10 eV, much larger then kT_o which is 0.025 eV. Therefore we get the roots

$$P_1 \approx \alpha I/2k \quad \text{and} \quad P_2 \approx (\alpha T_o)^2/[\alpha I/2k] = 2k\alpha T_o^2/I. \qquad (10)$$

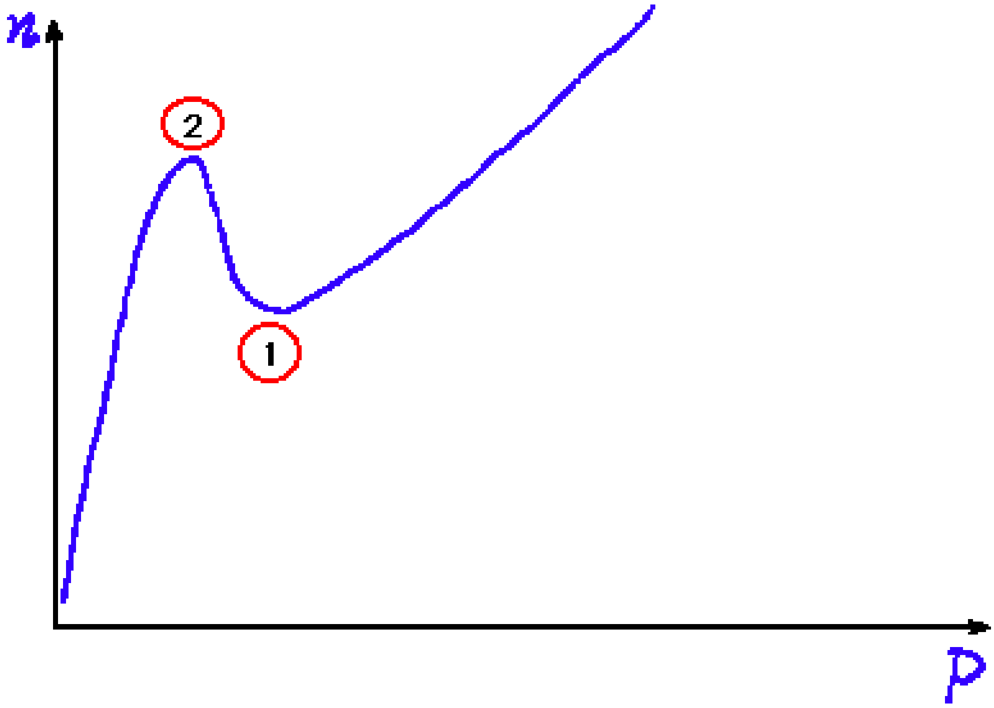

Fig. 1: Photon number n of the maser as a function of the power P absorbed in the BL.

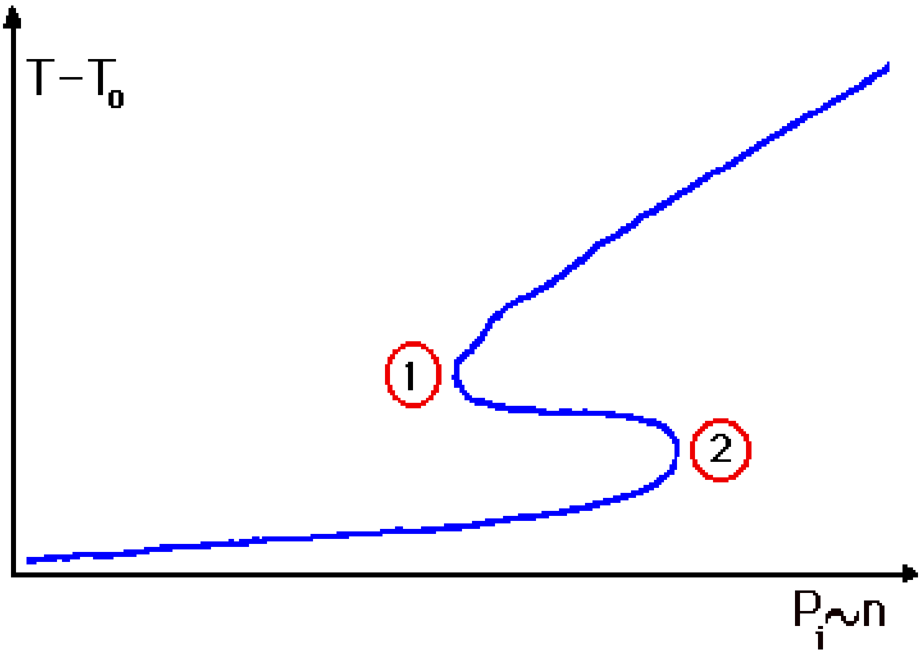

Fig. 2: Relative temperature of BL discharge as a function of incident power or maser photon #

These roots define two branches of the curve in Fig. 1, corresponding to the two forms of BL.

Note that in our model, P is related to T through a simple linear transformation and can be considered an equivalent variable with T. On the other hand, n is equivalent to the external power incident on the BL, P_i. Switching the axes, we obtain the T versus P_i diagram shown in Fig. 2.

Note also that replacing Eq. (5) with the other extreme case, energy transfer by radiation with $\beta(T^4-T_0^4)$, does not change the situation qualitatively, although the maximum and minimum are less pronounced and less separated.

Let us assume now that we have r just slightly larger than 1 with a BL present as a load. Then n=(r-1)p. Since $\hbar\omega n/\tau_b$ is the load $P = v\sigma_o(n/V)\hbar\omega e^{-I/2k(P/\alpha+T_o)}$, we can identify τ_b as

$$1/\tau_b = \sigma_o(v/V)e^{-I/2k(P/\alpha+T_o)}. \qquad (11)$$

This result is substituted into the expression of R_t present in the definition of r, yielding

$$n = (r-1)p = p[r_o/(1+v\tau_c\sigma_T/V) - 1], \qquad (12)$$

where we introduced $r_o = R_e K\tau_2\tau_c$ as the reduced rate corresponding to a given pumping rate R_e in the absence of the BL load (for $\tau_b=\infty$).

Equating the two expressions of n in Eqs. (7) and (12), we obtain the fundamental stationary BL equation

$$p[r_o/(1+v\tau_c\sigma_T/V) - 1] = VP/v\sigma_T\hbar\omega, \qquad (13)$$

or, for the linear heat diffusion case,

$$p[r_o/(1+vV^{-1}\tau_c\sigma_o e^{-I/2k(P/\alpha+T_o)}) - 1] = [VP/v\sigma_o\hbar\omega]e^{I/2k(P/\alpha+T_o)}. \qquad (14)$$

This equation determines the reduced equivalent pumping rate $r_o = R_e K\tau_2\tau_c$ that an atmospheric maser must have in order to sustain a stationary BL discharge with power dissipation P, heat convection coefficient α and volume v at an ambient temperature T_o. Substituting the roots defined in Eq. (10), we obtain two limiting values of r_o, one for white and one for orange BL. These are the values corresponding to the end points of the hot (white or "1"-type) and cold (orange or "2"-type) BL state-branches, present in both Figs. 1 and 2. More details are found in the appended recent paper of the author with Timofeev and Zvonkov, proving for the first time that the “forbidden” branch can be stabilized with feedback, as from masers. Available also online at http://ojps.aip.org/journal_cgi/dbt?KEY=PPHREM&Volume=26&Issue=9

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