On electromagnetic models of ball lightning with topological structure

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Abstract

It has been long admitted that a consequence of the virial theorem is that there can be no equilibrium configurations of a system of charges in electromagnetic interaction in the absence of external forces. However, recent results have shown that the virial theorem can not preclude the existence of certain nontrivial equilibrium configurations. Although some of these new results are based on an effective microscopic field theory, they are important for a theory of ball lightning that has been developed by the authors of the present work. Other theoretical results relative to magnetic force-free fields with field aligned currents and self-organized filamentary structures are also found to be relevant for this model.
1 Introduction

Ball lightning is one of the oldest open problems of physics. It consists in flaming balls or fireballs, usually bright white, red, orange or yellow, which appear unexpectedly sometimes either near ground, following the discharge of a lightning flash, or at midair coming from a cloud.

Most of them are associated with thunderstorms, their shape is usually spherical or spheroidal and they tend to move horizontally. Typically, their diameter is between 10 and 50 cm. The observed distribution of their lifetime has a maximum between 2 and 5 s and an average value of about 10 s or higher, some cases of more than 1 minute having been reported. They are bright enough to be clearly seen in daylight, the visible output being in the range 10 to 150 W, similar to that of a home electric bulb (for a detailed description of their properties see [1, 2, 3]). Some balls have appeared within aircraft, traveling inside the fuselage along the aisle from front to rear. There are reports of odors, similar to those of ozone, burning sulfur or nitric oxide, or of sounds, mainly hisses, buzzes or flutters. The majority decay silently, others with an explosion. They have killed or injured people and animals and damaged trees, buildings, cars or electric equipment, fires having been produced also. This shows that there is something hot inside. In such events the released energy has been estimated between 10 kJ and more than 1 MJ. They have never been produced in laboratories, in spite of many attempts and some interesting results, which have produced thus far some luminous objects that decay too quickly. Consequently, their properties are investigated on the basis of reports by witnesses, who are usually very impressed and excited by the phenomenon and have no scientific training.

A probably related phenomenon has been observed sometimes in submarines, after a short circuit of the batteries: balls of plasma have appeared at the electrodes and floated in air for several seconds. In these occasions, the current was about 150 kA and the energy was estimated between 200 and 400 kJ.

The most surprising property of a ball lightning is its great stability and long lifetime, two related features which are very difficult to explain. Indeed, nobody less than Faraday himself stated in his *Experimental Researches in Electromagnetism* that ball lightning cannot be an electromagnetic phenomenon since it would decay then instantaneously.

The previous features of the fireballs strongly suggest an electromagnetic
nature of the phenomenon. Note however that this is compatible with the necessity of considering the chemical aspects of plasmas, for instance in the determination of transport coefficients such as the electric and thermal conductivities or the viscosity.

There are two kinds of models of ball lightning, depending on whether the energy source is external or internal. There has been a tendency towards the internal energy models since the experimental verification, at the beginning of the nineties of the existence of stable filamentary structures in a great variety of plasmas, form laboratory to astrophysics. These observations suggests that plasmas may have a self-organization ability that could lead to long lifetime configurations. Electromagnetic models with plasmas and magnetic fields since therefore to be most promising candidates to build a theory of BL.

However the fact remains that, in spite of many attempts, there is not an accepted theory of the energy confinement in fireballs, specially of their long lifetime and great stability. It must be added that some researchers interpret the magnetic virial theorem as a serious obstacle to electromagnetic model since, according to them, this theorem shows that the magnetic pressure would be so strong that nothing could stand to avert an almost instantaneous explosion [4]. This could be considered as a modern formulation of Faraday’s argument.

As a consequence, there has been a certain shift of the interest of the researchers from purely or mainly electromagnetic to chemical models. Aerosol model, for instance, have received recently much attention. In one of them [5], the authors argue that a lightning discharge can vaporize silicon dioxide in the soil which, after interacting with carbon compounds, is transformed in pure silicon droplets of nanometer scale. These droplets become coated with an insulating coat of oxides and are polarized, after which they become aligned with electric fields and form networks of filaments, in a loose structure that has been called “fluff balls”. In another model [6], the discharges pick up organic material from the soil and transform it in a kind of “spongy ball” that can confine electric charges. It seems difficult, however, to understand how these models could explain the observed fact that some fireballs do appear near clouds or in midair, where there is neither silicon nor organic nor any other similar material.

We present in this paper some arguments, inspired both in experimental and theoretical recent findings, which suggests that this shift away from electromagnetic models may has been excessive and that more emphasis must
be put in them, even acknowledging the necessity of paying due attention to the chemical properties of the plasmas.

2 Plasma model with a topological filamentary structure

2.1 The topological model

In 1996, Rañada and Trueba proposed a model with a topological structure of magnetic lines and currents (“the topological model” from now on), in which the fireballs are spheres of plasma coupled to a magnetic field with non-vanishing magnetic helicity or, equivalently, with linked magnetic lines and plasma streamlines [7]. Although that model is very simple, it was useful to show that the lifetime of such spheres increases with the linking number of the lines. In other words tangled structures are more stable. However, the plasma filled all the interior of the ball, so that the radiation output was too high. A more elaborated model was proposed by Rañada, Soler and Trueba in 1998 [8] and developed in 2000 [10], in which the plasma is contained in streamers, i.e. filamentary structures along which the current flows, so that it fills only a small fraction of the ball, of the order of one ppm of the volume. Moreover, the streamers and the magnetic field are parallel. Such a configuration is the result of the so called Taylor relaxation of the plasma [9], a very rapid process in which the magnetic helicity is conserved, its value characterizing the final relaxed state. Again a non-vanishing value of the linking number gives stability to the system. What is important here is that the ball decays rapidly to a quasi-force-free (FF) state, with finite radius, and begins thereafter a slow expansion (termed almost quiescent in [10]) which approaches asymptotically to a force-free state. Such tangled structures are particular cases of “electromagnetic knots”, as were called in [12] the fields with linked magnetic and electric lines.

In 2000, Faddeev and Niemi (FN) [11] presented an effective microscopic field theory to give results on electrically neutral plasmas with an equal number of negative and positive charge carriers, which in their own words “challenge certain widely held views on plasma behavior”. As already said before, it is frequently admitted that the virial theorem implies that there can be no equilibrium configurations of a system of charges in electromagnetic interac-
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...tion in the absence of external forces. However, Faddeev and Niemi showed that this is not necessarily the case, that simple arguments based on the virial theorem can not preclude the existence of nontrivial, non-dissipative equilibrium configurations, which are “topologically stable solitons that describe knotted and linked flux tubes of helical magnetic fields” with “self-confining plasma filaments”. This results is clearly very important. It gives support to the topological model by Rañada, Soler and Trueba, which has precisely a structure of linked currents and magnetic lines.

2.2 The magnetic virial theorem

Let us consider a plasma or gas cloud inside a volume \( V \) bordered by a surface \( S \), with pressure \( p \), density \( \rho \), fluid velocity \( \mathbf{v} \) and magnetic field \( \mathbf{B} \). The momentum equation can be written as

\[
\frac{\partial}{\partial t}(\rho v_i) + \frac{\partial}{\partial x_k}(\rho v_i v_k) = -\frac{\partial p}{\partial x_i} - \rho \frac{\partial \Phi}{\partial x_i} + \frac{1}{\mu_0} \frac{\partial}{\partial x_k} \left[ B_i B_k - \frac{B^2}{2} \delta_{ik} \right], \tag{1}
\]

where \( \Phi \) is the self-gravitating potential, the last term being the Lorentz force \( \mathbf{j} \times \mathbf{B} \), with \( \mathbf{j} = \nabla \times \mathbf{B} / \mu_0 \). Note that \( B^2/2\mu_0 \) acts as a pressure, usually called “the magnetic pressure”. It plays a similar role as \( p \): if it has a great gradient it gives a large contribution to the force density. In many cases, it causes explosive expansions.

The magnetic virial theorem is the result of taking the first momentum of this equation, i.e. of multiplying by \( x_i \) and integrating over the volume \( V \) (more precisely this is the “second order magnetic virial theorem”. The “first order theorem” is just the integral of the Euler equation over the volume \( V \). It simply expresses the uniform motion of the center of mass.) There is also a tensorial form of the theorem but it is not relevant here. If we do that and assume that no fluid goes out of the volume, i.e. that \( \mathbf{v} \cdot \mathbf{n} = 0 \) if \( \mathbf{n} \) is a unit vector normal to the border \( S \), we obtain the equation

\[
\frac{1}{2} \frac{d^2 I}{dt^2} - 2T = -\int_S x_i \rho n_i dS + 2U + W + U_B + \frac{1}{\mu_0} \int_S x_i M_{ik} n_k dS. \tag{2}
\]

where

\[
I = \int_V \rho r^2 d^3 x / 2,
\]
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\[
T = \int_V \rho v^2 d^3 x / 2,
\]

\[
U = 3 \int_V p d^3 x / 2,
\]

\[
U_B = \int_V B^2 d^3 x / 2\mu_0,
\]

\[
W = -\int_V \frac{G\rho(r)\rho(r')}{|r-r'|} d^3 x d^3 x',
\]

\[
M_{ik} = B_i B_k - B^2 \delta_{ik} / 2.
\]

\( I \) is called the moment of inertia, \( T \) is the kinetic energy, \( U \) the internal energy, \( U_B \) the magnetic energy, \( W \) the gravitational self-energy. If the pressure is constant in \( S \), \( p = p_{ext} \), the first integral in the RHS of (2) is equal to \(-3p_{ext}V\). The gravitational self-energy is important for astrophysical plasmas but can be neglected in the case of ball lightning.

A frequent argument states that the term \( U_B \) in (2) would produce a very rapid increase of \( I \), \( i.e. \) an explosion, since nothing would balance the large magnetic pressure \( B^2 / 2\mu_0 \) (according to the witnesses reports, the magnetic energy of a BL must be of tens of kJ, even reaching several MJ). The calculations indicate that this would happen in a small fraction of a second, so that the virial theorem would exclude indeed any electromagnetic model of BL.

### 2.3 Force-free magnetic knots and a model of ball lightning

However, Chandrasekhar and Woltjer showed in 1958 [15] that plasmas relax to minimum energy stable states, so called force-free fields (FFF), in which the electric current and the magnetic field are parallel,

\[
\mathbf{B} \times (\nabla \times \mathbf{B}) = 0,
\]

so that the Lorentz force vanishes. They concluded that such states can confine large amounts of magnetic energy. If the force-free condition is verified, the sum of the two last terms in (2) is zero. In these cases, the magnetic virial theorem reduces to

\[
\frac{1}{2} \frac{d^2 I}{dt^2} = 2T - 3 \int_V \delta p dV,
\]
where \( \delta p = p_{\text{ext}} - p \) is the depression inside the ball, i.e. the difference between the exterior and interior pressures. As a consequence, the argument for an instantaneous explosion fails (as happens in the topological model [10] its solution being dubbed “force-free magnetic knots”).

2.4 On filamentary BL plasma formation and dissipative processes

In this section, we try to justify the existence of a filamentary plasma structure by means of a more realistic inspection into plasma formation processes beyond the minimum energy relaxation (under helicity conservation) arguments provided by Taylor. Otherwise, we are interested in investigate how dissipative processes in a real plasma can be modified in a magnetically dominated plasma regime to increase the lifetime of a set of linked filaments. In the following, we shall refer to the streamers, or a longitudinal section of one them, as a subsystem inside the global plasma ball structure (the system itself).

First of all, one has to be aware of our BL model assumes an anisotropic plasma with linked streamers coupled to the magnetic field in air. For this reason, we provide here some arguments related to the achievement of such filamentary structures that have been actually observed in natural plasmas. We are also concerned in looking for possible mechanisms to reduce transport processes in a magnetically dominated plasma regime since such processes would reduce plasma lifetime due to energy dissipation and charged particles diffusion. We think that both problems, filamentary linked plasma structure and dissipative processes reduction are directly related to plasma dynamics driven by the magnetic field itself.

It is well known that filamentary and localized current-plasma structures have been observed experimentally in a wide range of plasma scenarios. From simple electrical discharges to Tokamaks and astrophysical plasma jets, filamentation phenomena drastically lead the dynamics of plasma system, providing both positive and negative effects on the global stability. Otherwise, due to plasma ability to self-organize, one can expect the existence of a metastable system if some conditions are really fulfilled.

For instance, large stable filamentary currents in plasma may last in a larger time scale compared to plasma energy confinement time. Since this
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property has been experimentally tested in several plasma regimes, as predicted theoretically by Faddeev and Niemi in [11], a plasma system mainly composed of such filamentary long-living structures could last a long time. Note that in the atmosphere, the fireball may be also surrounded by a partially ionized plasma air, at last in the first stages before reaching a stable structure. We mean here, that it would be possible to combine a fully ionized plasma regime inside each streamer with a surrounding partially ionized cold plasma in our model. This property could be very important if one deals with eventual energy sources in each current channel.

In treating on filamentary plasma formation, let us assume that in an ordinary lightning a vortex type structure of plasma can be reached in atmospheric conditions. Thus, a toroidal like plasma could exist encircling the straight discharge channel of an ordinary lightning following the strong magnetic field associated with the lightning current. This primary toroidal plasma could also be surrounded by secondary current channels and all of then could be filled increasingly by charge injection coming from the main stroke that branches, and returns, through partially ionized channels. There are some photographic evidences of such lightning formations where it can be seen a tangled structure, sometimes not a single one, along lightning path. Moreover, this tangled lightnings have been also seen associated to a ball lightning\(^1\).

At this stage, it can be assumed that the strong lightning current source suddenly disappears along the vortex axis so that large pressure gradient can induce a plasma compression. The confining magnetic field disappears also and secondary currents channels start to self-organize into a new system. Note that due to the different mobilities of electron and (massive) ions, charge separation occurs after the lightning decay. This happens in a time scale shorter than the one required to destroy completely the secondary configuration, so that the current has time enough to collapse before the vortex destruction into a set of thin channels having relatively large energy densities. This collapse may be achieved by attraction of laminar currents carrying opposite charges. A simpler explanation for the streamer linked structure can also be given by just considering self-cutting (by pinch effect in both incoming and outgoing extremes) and separation of the ordinary lightning tangled

\(^1\) http://www.ernmphotography.com/Pages/BallLightning/BallLightningEmM.html
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formation followed by current collapse and compression.

Note that this mechanism would explain the existence of closed streamers created by simple charge collapse, not by the usual single sign charge avalanche in ordinary arc discharges. Otherwise, the plasma can also rotate as well as it can modify its structure due to air whirlwind enhancing the tangled or eddy for of the new plasma regime while magnetic reconnection starts. We mention here that recent laboratory experiments show that a plasma ball with loop formations can be ejected from a burning metallic wire.

As said before, toroidal like fluid flow rotating tube structures in the initial vortex will be compressed by simple collapse, providing twisting and filamentation in the charge distribution currents in an almost instantaneous magnetic reconnection process. The role played by finite thermal conductivity and Lorentz forces are relevant to energy conversion into the new self-organized state. The result may be a set of relatively high density linked streamers or filaments strongly coupled to the structure of the new magnetic field.

Up to now we have argued in favor of a meta-stable self-organized system of charged particles coupled to a magnetic force-free field, but concentrated only on the standard Taylor relaxation processes. However it has been recently shown that a plasma can relax to a Taylor force-free state under more general assumptions than helicity conservation constraints. In this sense, Zhu et al [16] have shown that a magnetohydrodynamic plasma can self-organize to a force-free or quasi-force-free state if finite thermal conductivity is taken into account during magnetic reconnection, while a non-Taylor state with electric current perpendicular to magnetic field is reached without thermal conduction. The enhanced heat conduction tends to smooth nonuniformity of both peaked pressure and perpendicular electric current component during driven magnetic reconnection. In this way, the Taylor force-free state under no pressure gradients is approximately realized in a short time (microseconds). The role played by magnetic reconnection combined with heat conduction could be very important to explain field-aligned currents and magnetic energy conversion into kinetic energy. As shown in [13], the effect of magnetic reconnection, enhanced by heat conduction along field lines, can explain the loop structures in solar chromosphere. Note that our ball lightning model ([8, 10]) could share some traits with astrophysical phenomena, because of the MHD scale invariance.

From our point of view, the above argument is relevant to the formation of
almost relaxed states, which are very close to force-free configurations in air. Furthermore, it explains the direct relation of the current plasma alignment and the subsequent current-field coupling, as well as the direct heating of the particles and the high deposition of energy into the system. Otherwise, it should be noted that magnetic reconnection plays also an important role in redistributing total magnetic helicity, globally conserved, providing locally twisting of currents filaments and contributing to global plasma stability after a self-organized state is reached.

Moreover, it is well-known that the magnetic reconnection generates charge acceleration and system heating, because of this, the current $J$ and magnetic field strength $B$ inside each filament can be very large. This is an important feature because of large magnetic field generation and current alignment may be very important to justify the long lifetime of a fireball.

It is remarkable that one can not reject the possibility of certain large number of suprathermal electrons or runaways, as experimentally found in upper atmosphere storms. Note that a nonvanishing suprathermal electrons population would increase the plasma electrical conductivity $\sigma$ providing a highly conductor fluid slowing down the magnetic helicity decay rate, $\eta \int J \cdot B d^3r$, keeping the field topology, if one assumes a real plasma with finite resistivity $\eta$.

These arguments lead us to treat with some non-ordinary plasma regimes inside each channel subsystem as well as inside the whole anisotropic plasma ball.

Roughly speaking, the magnetic field inside a streamer may be treated as a singularity in the global field, although its size (radius) may be much greater than the standard Debye length and typical plasma skin depth. Under such assumption, we have tested the evolution time of an isolated plasma column treated as a longitudinal cylindrical filament. Mechanical effects leading to energy losses can be neglected in a force-free state because of this energy decay is given by the volume integral

$$\epsilon_{\text{mech.}} = \int v \cdot (J \times B) d\mathbf{r}$$

which vanishes exactly inside any streamer. Otherwise, magnetic field diffusion, can be reduced if the new evolutionary plasma system departs from a
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force-free state with field-aligned fluid velocity since
\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu \sigma} \nabla^2 \mathbf{B}
\] (7)

the first term vanishes, and \( \nabla^2 \mathbf{B} = -\lambda^2 \mathbf{B} \) for a linear force-free field having \( \nabla \times \mathbf{B} = \lambda \mathbf{B} \). Thus, the magnetic field strength \( B \) would decay exponentially with a relaxation time \( \tau = \mu \sigma / \lambda^2 \) which increases linearly with conductivity \( \sigma \) and could be very large if we associate \( 1/\lambda \) to a system characteristic length \( L \) and we take for \( L \) the length of a streamer that may be several meters in length.

At this stage, the question relative to justify the stability and long lifetime of our system arises naturally. Since exploring quantitatively the stability of the configuration is still a subject for future works, we only treat here with the problem of ordinary dissipative processes. In an isolated simple plasma regime without energy sources, thermal transport will lead to an energy decay time for a plasma in a range \( 50 - 100 \mu m \) for streamer’s width of a fraction of second. In spite of local (streamer) and global (plasma ball) stability is a direct consequence of the strong linkage between the filaments, in this qualitative approach on for an isolated plasma column we must keep in mind that the severe anisotropic structure provided by the magnetic field can also contribute to increase the plasma lifetime, even for a relatively small subsystem which is a current filament.

Using the time evolution equation for the fluid enthalpy volume density \( h = \rho c_p T \) in an air plasma
\[
\rho \frac{dh}{dt} = -\nabla q + S
\] (8)

with mass density \( \rho \), mass specific heat at constant pressure \( c_p \) and heat flux \( q \) we deal with time dependence of kinetic temperature radial profile \( T(r) \). As the filament is supposed to be closed, above equation only takes into account perpendicular heat flux transversal to \( \mathbf{B} \) i.e., parallel heat conduction does not contribute effectively to dissipation processes because of the closed nature of the filament. Moreover, particles can flow almost freely along the field in a quasi collision-less regime. Note that the mechanical energy loss rate \( \int \mathbf{v} \cdot (\mathbf{J} \times \mathbf{B}) dV \) vanishes identically if a force-free configuration inside the column is assumed. The heat flux reads \( q = -\lambda_\perp \nabla_\perp T \), after dropping other energy
sinks or sources $S$. Here, $\lambda_\perp$ is the perpendicular component of the thermal conductivity tensor which has been modeled assuming classical behavior [17]: $\kappa_\perp \simeq \kappa_\parallel/\omega^2\tau^2 \sim 1/(B^2T^{1/2})$ for thermal conductivity coefficients. In this sense, the thermal isotropic conductivity $\lambda_0 = \kappa mc_p$ for a reacting plasma in air having mean molar mass $m = m(T)$, taken from the work of Capitelli et al in [18], is modified by a factor $\epsilon = 1/(1 + \omega^2\tau^2)$ providing $\lambda_\perp = \lambda_0\epsilon$. Here, $\omega = eB/m$ is the electron gyro-frequency and $\tau$ is the collision time, obtained from electrical standard conductivity in an air plasma. The simple force-free magnetic field $\mathbf{B}(r) = (0, B_\phi(r), B_z(r))$ in cylindrical polar coordinates is assumed to be constant in time with $B_\phi$ increasing from zero to a maximum value $B$ at $r = a$. The functional dependence on $r$ is not so longer relevant for our actual aims.

As a departure state we consider a smooth radial temperature profile decaying to ambient temperature (over 1,000$K$ in a surrounding partially ionized air). Since there is no physical nozzle enclosing the current, free boundary conditions are considered, choosing as streamer effective radius $a$ the distance at which plasma temperature is about 14,000$K$. Note that under these assumptions, the magnetic field may provide the subsystem by an effective confinement magnetic nozzle. In this sense, for instance, a similar kind of plasma regime has been recently investigated in [19]. In this work, the authors present a plasma regime that can be confined without a physical nozzle (magnetic nozzle system) if the plasma is collisionless only along the magnetic field.

As shown in figure 1, temperature diffusion implying filament destruction is clearly inhibited by a strong enough local magnetic field. This means that transversal heat transport due to electrons is reduced in a strongly magnetized media. Dissipative processes would take place in a larger temporal scale if it is compared to similar diffusive situations for the isotropic case (low or null magnetic field). Note that the temperature $T_c$ at $r = 0$ also decreases slowly when this value reaches approximately 1,600$K$, around this value, the air thermal conductivity also shows a minimum value leading the system to be in an almost stable state with low thermal dissipation.
3 Conclusions

It can be said that the main problem for the plausibility of an electromagnetic model of BL is to reconcile the interpretation of the classical virial theorem with the recent arguments on electrically neutral plasmas presented by Faddeev and Niemi [11]. In this work, we have related the FN results with a model of ball lightning [10, 8, 7] that uses the concept of force-free magnetic knot. The conclusion is that a frequent argument against electromagnetic models of ball lightning fails.

There are two other reasons why the FN result is interesting. One is that the power emitted by a plasma ball of the size of a BL is too high (one litre at 15,000-20,000 K emits about 5 MW), which is an indication that most of the ball is cold, only a fraction being concentrated in filamentary structures as hot current streamers as in reference [8]. Another: it is sometimes assumed as a matter of fact that the streamers can not last because they will be necked or cut in a very short time by the pinch effect (i.e. by the Lorentz force), contrary to the FN result. But this does not happen if the FFF holds, since there is no pinch effect, so that the streamers would be stable. In the case of almost FFF, the pinch effect would be small and would contribute only weakly the decay, which will be produced only after a certain much longer time, another stabilizing factor.

Force-free states can be reached not only under Taylor assumptions, such states may also appear in Nature as a consequence of the implication of dissipative processes as thermal conduction during (and after) magnetic reconnection that also plays a significant role in field-current aligned structure, charge acceleration and redistribution of global helicity to improve stability and self-organized quasi-force-free state. The ordinary dissipative processes are drastically reduced due to anisotropic structure in the system induced by the magnetic field. Thus, a self-organized plasma structure through charge and currents concentration in linked filaments can provide a stable long living plasma system with reduced dissipation.

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Figure 1: Kinetic Temperature profiles inside a filament
Radial temperature streamer profile in $10^4$ K. Under a strong magnetic field the free streamer radius tend to be constant and diffusion expansion is drastically reduced changing the characteristics temporal scale. Time evolution of central temperature $T_c(t)$, ($t$ in s) at $r = 0$ is also shown. Clearly, the system exhibits a large time scale evolution for magnetized filament.

The slope for almost linear decreasing $T_c(t)$ is greater under small or vanishing magnetic field.