Phenomenon of Gamma-Ray Bursts as Relativistic Detonation of Scalar Fields

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Abstract

In the modern Universe the existence of various forms of scalar fields is supposed. On the one hand these fields can explain recently discovered positive Λ-term (see e.g. Ref. [1]), on the other hand its form cluster systems creating gravitational wells for galaxies and their clusters. At that a natural hypothesis is the existence of compact configurations ("stars") from scalar fields with a large enough energy density and total mass. The hypothesis is that the energy of these fields can be converted in relativistic plasma by an explosive way. Such process can be initiated by collision of relativistic particles which form a relativistic microscopic fireball. Thus effective temperature can amount to value sufficient for change of phase for scalar fields. Then the wave of relativistic "detonation" similar to the same process in classical physics will be spread from this source. In this paper the parameters of such field star and process of detonation are estimated. If the effect of the indicated change of phase (or something similar to one) exists, it is possible to get the parameters of relativistic plasma (macroscopic fireball) which could generate gamma - bursts. If in the modern Universe there is such unique form of a matter as fields of high density it would be strange for Nature not to take advantage of the possibility to convert their energy to radiation by an explosive way.

1 Introduction

Now there is no conventional mechanism of origin of gamma-ray bursts (GRB). Also the accumulation of all required energy in initial small volume is rather doubtful. At the same time there are theoretical models in the theory of the early Universe when the beginnings of large volume of relativistic plasma occurs fast enough with expansion of front of a spherical wave (see e.g. an expansion of the bubble at decay of false vacuum (creation of the Universe from the bubble [4])). We are based on the following assumptions: now the candidate for a dark matter in the Universe are the scalar fields of a various type. The mass of these fields can essentially exceed a mass of luminous matter and then they first form the large-scale structure of the Universe. An apparent matter concentrates in their gravitational potential wells. It is possible that these fields can create and more dense ”star-like” configurations. Such relativistic models also were studied for a number of years [3, 4, 5]. Below will be shown that the similar

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star-like configurations with sufficiently large size and with big mass density are exist at weak gravitation when the configuration can be described in Newtonian approximation.

Let’s imagine that as a result of collision of relativistic particles some critical size of a fireball is formed (note that last one is present in other models of GRB also). It is that seed mechanism which effectively transfers scalar fields in creating pairs of unstable elementary particles. Such mechanism can be imagined as a beginning of fast oscillation of a field on exterior boundary of a fireball. Such process is equivalent to a relativistic detonation. The role of a chemical energy turning into relativistic plasma at the front of a detonation wave will be played by the energy of a scalar field which intensively passes in pairs of creating particles - antiparticles. Now such fireball, expanding with a relativistic velocity, will not depend on weak gravitational fields of Newtonian configuration and it can be considered in special relativity.

2 Relativistic Detonation

Let’s show the self-similar solution for a spherical relativistic detonation which transfer in the well known solution of Ya. B. Zeldovich in case of small velocities. The set of equations of relativistic hydrodynamics is convenient to present in a spherical frame with use of usual three-dimensional radial velocity of plasma $v$. Thus the equation of motion looks like:

$$
\frac{1}{\theta^2} \left( \frac{\partial v}{\partial \tau} + v \frac{\partial v}{\partial r} \right) + \frac{1}{w} \left( \frac{\partial p}{\partial r} + v \frac{\partial p}{\partial \tau} \right) = 0
$$  (1)

and the law of conservation of energy:

$$
\frac{1}{w} \left[ \frac{\partial \varepsilon}{\partial \tau} + v \frac{\partial \varepsilon}{\partial r} \right] + \frac{1}{\theta^2} \left( \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial \tau} \right) + \frac{2v}{r} = 0,
$$  (2)

here $\theta^2 = 1 - v^2$, $w = \varepsilon + p$ and $c = 1$. As well as in a nonrelativistic case the motion of plasma behind the front of the detonation wave is considered as isentropic and the relevant solution is described only by two equations referred above. The pairs of relativistic particles which are creating in area behind the front of wave generate high-temperature plasma with the equation of state:

$$
p = \omega^2 \varepsilon; \quad \omega^2 = \left( \frac{\partial p}{\partial \varepsilon} \right)_S = 1/3,
$$  (3)

where $\omega$ is the sound velocity. Similarly to the problem about a spherical detonation we shall search for a solution depending on the self-similar variable

$$
\xi = r/\tau.
$$  (4)

Thus the set of Eqns. (1), (2) passes in the system of ordinary differential equations and supposes the obtaining of one equation on $v$:

$$
\frac{dv}{d\xi} \left[ \frac{1}{\omega^2} \left( \frac{v - \xi}{1 - v \xi} \right)^2 - 1 \right] = \frac{2v}{\xi} \frac{\theta^2}{1 - v \xi}.
$$  (5)

In a nonrelativistic case ($v(\xi), \xi \ll 1$) the last equation passes in classical one. The qualitative analysis of this equation is similar to the known mentioned result. The solutions for $v$ and $\varepsilon$ have the infinite derivative at the front of wave ($\xi = D$ is the velocity of the detonation wave). It follows from the known fact of the detonation theory: the velocity of plasma, outgoing from the wave front, is equal to the sound velocity $\omega$. The expression in the parenthesis in the
Figure 1: The dependence of the energy density $\varepsilon$ and velocity $v$ of plasma on the self-similar variable $\xi$ behind the front of detonation wave.

$l.h.s.$ of Eqn. (5) corresponds to the relativistic law of a velocity addition and at $\xi = D$ it is equal to $\omega^2$. The last one means that at tending of argument $\xi$ to the wave front the whole expression in brackets aspires to zero from above. The $r.h.s.$ of Eqn. (5) remains finite that means tending of the derivative to infinity. The examination of a transformation of the velocity of plasma in a zero for Eqn. (5) is completely similar to the analysis of Ref. [7] as the motion becomes nonrelativistic. The single unknown parameter in this problem is the velocity of the detonation wave $D$. In case of classical detonation it is determined by an internal energy of explosive. For the considered hypothesis it will be defined by the energy flux density and by momenta of a scalar field entering the wave front.

The discussion of the possible mechanism of ”recycling” of the field behind the wave front in relativistic plasma is considered below. Let’s specify here the following estimation of value of $D$ and energy density behind the detonation wave. Let’s consider that the scalar field is set in the simplest variant:

$$T_i^k = \varphi_i \varphi^k - \delta_i^k \left( \frac{1}{2} \varphi_{\mu} \varphi^{\mu} - V(\varphi) \right), \quad V(\varphi) = m^2 \varphi^2 / 2$$  \hspace{1cm} (6)

and is in scalaron regime (the fast oscillations with frequency $m$): $\varphi(r,t) = a(r) \sin mt$. The spatial changing of the field is considered small. Thus the energy density of such field (in a laboratory frame) is determined by:

$$\varepsilon_f = m^2 a^2 / 2.$$  \hspace{1cm} (7)

The expression for $D$ and energy density of plasma behind the wave front is determined from conservation laws $T_0^0(field) = T_0^0(plasma)$ and $T_1^1(field) = T_1^1(plasma)$ for the observer which
is in the rest at the wave front. (Remind that the plasma goes away the wave front with the velocity $\omega$.) Hence

$$D = \frac{2\omega}{1 + \omega^2}; \quad \varepsilon_p = \frac{2}{1 - \omega^2}\varepsilon_f.$$  \hspace{1cm} (8)

In case of relativistic plasma $\omega = 1/\sqrt{3}$ and $D = \sqrt{3}/2$, $\varepsilon_p = 3\varepsilon_f$. The self-similar solutions for this case are presented in Fig. 1.

### 3 About possible mechanism of transition field - plasma

The most complicated are the processes at the front of detonation wave - transition of the field in plasma. Let’s note that for modern space fields (cluster component of the field in the terminology of Ref. [1]) the most different masses of quantums of a scalar field are choose. Let’s specify also that explicitly enough the relativistic models of boson stars are studied in different variants [5]. The most beautiful mechanism of the transition field - plasma can be the change of phase at penetration of the field in temperature bath with temperature $T$ close to critical at which there is a catastrophic decreasing of a mass of quantums of scalar fields [9]. The strong increasing of the oscillation amplitude behind the wave front realizes in multiple creation of pairs of elementary particles and filling of the next layer by hot plasma. (Other mechanisms of such transition are not excluded also.)

The most simple explanation of duration of radiation of the GRB would be the existence of extended enough area filled by scalar field with energy density and size about 1-10 light second acceptable to the given mechanism that corresponds to duration of complete radiation of the GRB. In considered variant it is close to time of "burning" of the field by the detonation wave. As the known examples of the field stars correspond to relativistic configurations we think that it is interested to specify a possibility of existence of scalaron Newtonian stars which together with high energy (mass) density would have a large enough expansion commensurable with the mentioned above typical size.

### 4 Newtonian Scalaron Star

The Newtonian gravitational configuration filled by scalar field with Lagrangian density is considered

$$L = \frac{1}{2}\dot{\varphi}^2 - m^2\varphi^2/2$$ \hspace{1cm} (9)

and equation for the field is

$$\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^i} \left( \sqrt{-g} g^{ij} \frac{\partial \varphi}{\partial x^j} \right) = -m^2 \varphi,$$ \hspace{1cm} (10)

where $m$ is the mass of the field quantum. In Newtonian approximation

$$g_{00} = 1 + 2\Phi/c^2; \quad g_{11} = -1; \quad g_{22} = -r^2; \quad g_{33} = -r^2\sin^2\theta.$$ \hspace{1cm} (11)

Consider further the stationary configuration in which the field $\varphi(r, t) = a(r)\sin mt$ and the gravitational potential $\Phi/c^2 = -\Psi(r)$, $\Psi > 0$ depends only on $r$. Thus the field equation will has the form:

$$\frac{1}{r} \frac{d^2}{dr^2}(ra) + 2m^2\Psi a = 0.$$ \hspace{1cm} (12)
The amplitude of the field also has spatial oscillations but by virtue of smallness of $\Psi$ the spatial derivatives are much less temporal one. For this reason the mass density of the field $\varphi$ is determined by the formula:

$$\rho = \varepsilon/c^2 = \left[\dot{\varphi}/2 + m^2\varphi^2/2\right] / c^2 = m^2a^2/2c^2. \quad (13)$$

It gives the basic contribution to gravitation. The spatial derivatives on $a(r)$ create an effective pressure counterweighting the forces of gravitation. The potential $\Psi(r)$ has found from the Poisson equation:

$$\Delta \Psi = -\frac{4\pi G \rho}{c^2} = -\frac{2\pi G}{c^4} m^2 a^2. \quad (14)$$

The set of Eqns. (12), (14) determines the structure of scalaron "star". The solutions of the system are convenient for investigation in dimensionless form. Thus the typical quantities used at undimensionality give the possible estimations of values for parameters of such "star":

$$r = \ell \xi; \quad \Psi = \Psi_0 U; \quad a = a_0 x, \quad (15)$$

$$\ell^2 \sim 10^9 \frac{n}{m_e V} \sqrt{\rho_0} \text{ cm}^2; \quad \Psi_0 \sim 10^{-18} \frac{n}{m_e V} \sqrt{\rho_0}, \quad a_0 \sim 10^6 \frac{\sqrt{2 \rho_0}}{m_e V} \left(\text{erg cm}^3\right)^{1/2},$$

here $\rho_0$ is the central field density in g/cm$^3$, $m_e$ is the mass of a field quantum in eV, $n \gg 1$ is the dimensionless number.

We take e.g. $m_e = 0.5 \times 10^{-8}$eV and central mass density $\rho_0 = 10^{16}$g/cm$^3$. Then at $n = 5$ the typical size of the configuration will be $\ell \sim 10^5$cm and total mass in the order of $M = 10^{31}$g. Thus the potential $\Psi_0 \sim 0.1$ that is evidence of applicability of Newtonian gravitation theory in this case. If the mechanism of transition of the field in plasma is realized in the front region then for this rough estimate we have the following:

According to the formulas (8) for the detonation wave going from centre on the initial stage we have temperature about 1 GeV. The more strict analysis of the structure of scalaron configurations presented below shows that the mass density of the scalar field is proportional to $r^{-2}$. At the indicated central density $\rho_0$ the yield of the detonation wave on boundary of configuration will give effective temperature behind the wave front about 1 MeV. Further the dispersion of such inhomogeneous macroscopic fireball is realized. This problem requires independent research as well as the problem of a relativistic detonation with energy density decreasing on the indicated law. But the rough estimate of average temperature of the whole fireball with the indicated energy $E = Mc^2$ shows that it achieves temperatures about 1 MeV at the size about 0.1 light second. Then the electron - positron pairs which "locked" by radiation disappear and the free dispersion of photons begins. The reorganization of distribution of the density during the dispersion can give an increasing of Doppler frequency of radiation of photons in the head part of the fireball and leading up it up to temperature about GeV again.

Now set of equations in the dimensionless form will be:

$$\frac{1}{\xi} \frac{d^2}{d\xi^2}(\xi U) = -x^2; \quad \frac{1}{\xi} \frac{d^2}{d\xi^2}(\xi x) + n^2 U x = 0. \quad (16)$$

Then $n$ will be proportional to number of half-waves of the field $\varphi$ on the typical size of configuration. The numerical solution of Eqns. (10) is presented in Fig. 2.

In the equation on $x$ there is the big parameter $n$ that allows to search for solution on $x$ as

$$x = f(\xi) \sin \Omega; \quad \Omega = n \int_0^\xi \sqrt{U} d\zeta. \quad (17)$$
The argument at a sine is the fast varying function in comparison with the potential $U$. Then the solution of the second equation from (16) is possible to present as

$$x = \frac{1}{\xi U^{1/4}} \sin \Omega + \left( \frac{1}{n^2} \right).$$

(18)

The obtained formula shows that according to expression (13) it corresponds to $\rho \sim r^{-2}$ as was used in estimations mentioned above. The substitution of Eqn. (18) in the equation for potential gives

$$\frac{1}{\xi} \frac{d^2}{d\xi^2} (\xi U) = -\frac{1}{2\xi^2 \sqrt{U}} \left[ 1 - \cos 2\Omega \right].$$

(19)

Hence the gravitational potential consists of slowly varying part described by the equation

$$\frac{1}{\xi} \frac{d^2}{d\xi^2} (\xi U) = -\frac{1}{2\xi^2 \sqrt{U}}$$

(20)

and fast varying one $\tilde{U}$

$$\frac{d^2}{d\xi^2} \left( \xi \frac{d\tilde{U}}{d\xi} \right) = \frac{1}{2\sqrt{U}} \cos 2\Omega,$$

(21)

which in $1/n^2$ times less then $U$ as follows from Eqn. (21). For this reason it is not taken into account in the whole formulas with $\sqrt{U}$. Note that expression on the r.h.s. in Eqn. (20) is valid at $\xi \gg \xi_0 \approx 1/n$. 

Figure 2: The diagrams of dependence of dimensionless gravitational potential $U$, potential of the scalar field $x$ and total mass of configuration $M$ on dimensionless radius $\xi$. 
5 Conclusion

The authors realize that the considered hypothesis requires an detailed examination in many items. The mechanism of creation of particles behind the front of the detonation wave is not clear in details, though in a series of models there are indication on a strong increasing of a mass of a field quantum at an approaching to critical temperature \[\beta\] that inevitably should result in strong increasing of an oscillation amplitude and creation of particles. The question with values of a mass of quantums of scalar fields existing in the modern Universe which generate dense cluster systems (”stars”) is not clear \[\beta\]. The desire to obtain the time of existence of the detonation wave commensurable with observable duration of bursts of GRB has forced to consider lengthy Newtonian scalaron configurations. The problem of their existence and stability is also requires original research. But if to refuse this hypothesis it is possible to consider the ”detonation” of relativistic configurations. Then the finite fireball will be small and the subsequent phenomenon of GRB will require considering its expansion either in vacuum or in an exterior medium. Thus according to available results there will be no problem with insufficiency of an energy for an explanation of the whole observable phenomenon. Anyway, if in the modern Universe there is such unique form of a matter as fields of high density it would be strange for Nature not to take advantage of a possibility to convert their energy to radiation by an explosive way.

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