Hidden Source of High-Energy Neutrinos in Collapsing Galactic Nucleus

V. S. Berezinsky\textit{a,b}, V. I. Dokuchaev\textit{b}

\textit{a}Laboratori Nazionali del Gran Sasso, INFN, Italy
\textit{b}Institute for Nuclear Research, Russian Academy of Sciences, Moscow

Abstract

We propose the model of a short-lived very powerful source of high energy neutrinos. It is formed as a result of the dynamical evolution of a galactic nucleus prior to its collapse into a massive black hole and formation of high-luminosity AGN. This stage can be referred to as “pre-AGN”. A dense central stellar cluster in the galactic nucleus on the late stage of evolution consists of compact stars (neutron stars and stellar mass black holes). This cluster is sunk deep into massive gas envelope produced by destructive collisions of a primary stellar population. Frequent collisions of neutron stars in a central stellar cluster are accompanied by the generation of ultrarelativistic fireballs and shock waves. These repeating fireballs result in a formation of the expanding rarefied cavity inside the envelope. The charged particles are effectively accelerated in the cavity and, due to $pp$-collisions in the gas envelope, they produce high energy neutrinos. All high energy particles, except neutrinos, are absorbed in the thick envelope. Duration of this pre-AGN phase is \(\sim 10\) yr, the number of the sources can be \(\sim 10\) per cosmological horizon. High energy neutrino signal can be detected by underground neutrino telescope with effective area $S \sim 1\ km^2$.

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1 Introduction: Hidden Sources

High energy (HE) neutrino radiation from astrophysical sources is accompanied by other types of radiation, most notably by the HE gamma-radiation. These HE gamma-radiation can be used to put upper limit on the neutrino flux emitted from a source. For example, if neutrinos are produced due to interaction of HE protons with low energy photons in extragalactic space or in the sources transparent for gamma-radiation, the upper limit on diffuse neutrino flux $I_\nu(E)$ can be derived from e-m cascade radiation. This radiation is produced due to collisions with photons of microwave radiation $\gamma_{bb}$, such as $\gamma + \gamma_{bb} \rightarrow e^+ + e^-$, $e + \gamma_{bb} \rightarrow e' + \gamma'$ etc. These cascade processes transfer the energy density released in high energy photons $\omega_\gamma$ into energy density of the remnant cascade photons $\omega_{cas}$. These photons get into the observed energy range 100 MeV–10 GeV and their energy density is limited by recent EGRET observations [1] as $\omega_{cas} \leq 2 \cdot 10^{-6}$ eV/cm$^3$. Introducing the energy density for neutrinos with individual energies higher than $E$, $\omega_\nu(> E)$, it is easy to obtain the following chain of inequalities (reading from left to write)

$$\omega_{cas} > \omega_\nu(> E) = \frac{4\pi}{c} \int_E^\infty EI_\nu(E)dE > \frac{4\pi}{c} E \int_E^\infty I_\nu(E)dE = \frac{4\pi}{c} EI_\nu(> E).$$ \hspace{1cm} (1)

Now the upper limit on the integral HE neutrino flux can be written down as

$$I_\nu(> E) < \frac{4\pi \omega_{cas}}{c} E = 4.8 \cdot 10^3 E^{-1} \text{eV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.$$ \hspace{1cm} (2)

However, there can be sources, where accompanying electromagnetic radiation, such as gamma and X-rays, are absorbed. They are called “hidden sources” [2]. Several models of hidden sources were discussed in the literature.

- **Young SN Shell** [3] during time $t_\nu \sim 10^3 - 10^4$ s are opaque for all radiation, but neutrinos.
- **Thorne-Zytkow Star** [4], the binary with a pulsar submerged into a red giant, can emit HE neutrinos while all kinds of e-m radiation are absorbed by the red giant component.
- **Cocooned Massive Black Hole** (MBH) in AGN [5] is an example of AGN as hidden source: e-m radiation is absorbed in a cocoon around the massive black hole.
AGN with Standing Shock in the vicinity of a MBH can produce large flux of HE neutrinos with relatively weak X-ray radiation.

In this paper we propose a new model of the hidden source which can operate in a galactic nucleus at pre-AGN phase, i.e. prior to MBH formation in it. The MBH in AGN is formed through the dynamical evolution of a central stellar cluster resulting in a secular contraction of the cluster and its final collapse. The first stage of this evolution is accompanied by collisions and destruction of normal stars in the evolving cluster, when virial velocities of constituent stars become high enough. The compact stars (neutron stars and black holes) survive this stage and their population continue to contract, being surrounded by the massive envelope composed of the gas from destroyed normal stars. Pre-AGN phase corresponds to a near collapsing central cluster of compact stars in the galactic nucleus. Repeating fireballs after continuous collisions of compact stars in this very dense cluster result in the formation of a rarefied cavity in the massive gas envelope. Particles accelerated in this cavity interact with the gas in the envelope and produce HE neutrinos. Accompanying gamma-radiation can be fully absorbed in the case of thick envelope (matter depth \( X_{\text{env}} \sim 10^4 \text{ g/cm}^2 \)). The proposed source is short-lived (lifetime \( t_s \sim 10 \) years) and very powerful: neutrino luminosity exceeds the Eddington limit for e-m radiation.

2 The Model

We consider in the following the basic features of the formation of a short-lived extremely powerful hidden source of HE neutrinos in the process of dynamical evolution of the central stellar cluster in a typical galactic nucleus.

2.1 Dynamical Evolution of Galactic Nucleus

The dynamical evolution of dense central stellar clusters in the galactic nuclei is accompanied by a secular growth of the velocity dispersion of constituent stars \( v_0 \) or, equivalently, by the growth of the central gravitational potential. This process is terminated by the formation of the MBH when the velocity dispersion of stars grows up to the light speed (see for a review e.g. \cite{8} and references therein). On its way to a MBH formation the dense galactic nuclei inevitably proceed through the stellar collision phase of evolution \cite{9–13},

\( \frac{1}{2} \text{AGN with Standing Shock in the vicinity of a MBH can produce large flux of HE neutrinos with relatively weak X-ray radiation.} \)
when most normal stars in the cluster are disrupted in mutual collisions. The necessary condition for the collisional destruction of normal stars with mass $m_\ast$ and radius $r_\ast$ in the cluster of identical stars with a velocity dispersion $v$ is

$$v > v_p,$$  \hspace{1cm} (3)

where

$$v_p = \left(\frac{2Gm_\ast}{r_\ast^2}\right)^{1/2} \simeq 6.2 \cdot 10^2 \left(\frac{m_\ast}{M_\odot}\right)^{1/2} \left(\frac{r_\ast}{R_\odot}\right)^{-1/2} \text{ km s}^{-1}. \hspace{1cm} (4)$$

is an escape (parabolic) velocity from the surface of a constituent normal star. The kinetic energy of colliding star is greater in general than its gravitational bound energy under the inequality (3). If $v > v_p$, the normal stars are eventually disrupted in mutual collisions or in collisions with the extremely compact stellar remnants, i.e. with neutron stars (NSs) or stellar mass black holes. Only these compact stellar remnants will survive through the stellar-destruction phase of evolution ($v = v_p$) and form the self-gravitating core. We shall refer for simplicity to this core as to the NS cluster. Meanwhile the remnants of disrupted normal stars form a gravitationally bound massive gas envelope in which the NS cluster is submerged. The virial radius of this envelope is

$$R_{\text{env}} = \frac{GM_{\text{env}}}{2v_p^2} = \frac{1}{4} \frac{M_{\text{env}}}{m_\ast} r_\ast \simeq 0.56 M_8 \left(\frac{m_\ast}{M_\odot}\right)^{-1} \left(\frac{r_\ast}{R_\odot}\right) \text{ pc}, \hspace{1cm} (5)$$

where $M_{\text{env}} = 10^8 M_8 M_\odot$ is a corresponding mass of the envelope. The gas from disrupted normal stars composes the major part of the progenitor central stellar cluster in the galactic nucleus. So the natural range for the total mass of the envelope is the same as the typical range for the mass of a central stellar cluster in the galactic nucleus, $M_{\text{env}} = 10^7 - 10^8 M_\odot$. The envelope radius $R_{\text{env}}$ is given by the virial radius of a central cluster in the galactic nucleus at the moment of evolution corresponding to normal stars destructions, i.e., $v = v_p$. The mean number density of gas in the envelope is

$$n_{\text{env}} = \frac{3}{4\pi} \frac{1}{R_{\text{env}}^3} \frac{M_{\text{env}}}{m_p} \simeq 5.4 \cdot 10^9 M_8^{-2} \left(\frac{m_\ast}{M_\odot}\right)^3 \left(\frac{r_\ast}{R_\odot}\right)^{-3} \text{ cm}^{-3}, \hspace{1cm} (6)$$

where $m_p$ is a proton mass. A column density of the envelope is

$$X_{\text{env}} = m_p n_{\text{env}} R_{\text{env}} \simeq 1.6 \cdot 10^4 M_8^{-1} \left(\frac{m_\ast}{M_\odot}\right)^2 \left(\frac{r_\ast}{R_\odot}\right)^{-2} \text{ g cm}^{-2}. \hspace{1cm} (7)$$
Such an envelope completely absorbs electromagnetic radiation and HE particles outgoing from the interior, except neutrinos and gravitational waves. A column density becomes less for more massive envelopes.

We assume that energy release due to star collisions supports the gas in the cluster in (quasi-)dynamical equilibrium. It implies the equilibrium temperature $T_{eq}$ of the gas,

$$T_{eq} \sim \frac{m_p G M_{env}}{6k R_{env}} \sim 1.6 \cdot 10^7 \text{ K.} \tag{8}$$

The thermal velocity of gas particles at the equilibrium temperature is of order of an escape velocity from the surface of a normal star. If $T \gg T_{eq}$ the gas outflows from the cluster with the sound speed

$$v_s = \left(2\gamma \frac{kT}{m_p}\right)^{1/2} \approx 600 \left(\frac{T}{T_{eq}}\right)^{1/2} \text{ km/s,} \tag{9}$$

where $\gamma$ is adiabatic index ($\gamma = 5/3$ for hydrogen). If $T \ll T_{eq}$ gas collapses to the core.

### 2.2 Dense Cluster of Stellar Remnants

As was discussed above, the dense NS cluster survives inside the massive envelope of the post-stellar-destruction galactic nucleus. The total mass of this cluster is $\sim 1 - 10\%$ of the total mass of a progenitor galactic nucleus [9]–[12] and so of the massive envelope, i.e. $M \sim 0.01 - 0.1 M_{env}$. We will use the term ‘evolved galactic nucleus’ for this cluster of NSs assuming that (i) $v > v_p$ and (ii) the (two-body) relaxation time in the cluster is much less than the age of the host galaxy. Under the last condition the cluster has enough time for an essential dynamical evolution. For example the relaxation time of stars inside a central parsec of the Milky Way galaxy is $t_r \sim 10^7 - 10^8$ years. A further dynamical evolution of the evolved cluster is terminated by the dynamical collapse to a MBH.

We consider in the following an evolved central cluster of NSs with identical masses $m = 1.4 M_\odot$. This evolved cluster of NSs is sunk deep into the massive gas envelope remaining after the previous evolution epoch of a typical normal galactic nucleus. Let $N = M/m = 10^6 N_6$ is a total number of NSs stars in the cluster. The virial radius of this cluster is:

$$R = \frac{GN m}{2v^2} = \frac{1}{4} \left(\frac{c}{v}\right)^2 N r_g \simeq 1.0 \cdot 10^{13} N_6 (v/0.1 c)^{-2} \text{ cm,} \tag{10}$$


where \( r_g = 2Gm/c^2 \) is a gravitational radius of NS. For \( N \sim 10^6 \) and \( v \sim 0.1c \) one has nearly collapsing cluster with the virial size of \( \sim 1 \) AU. The characteristic times are (i) the dynamical time \( t_{dyn} = R/v = (1/4)N(c/v)^3r_g/c \simeq 0.95N_6(v/0.1c)^{-3} \) hour and (ii) the evolution (two-body relaxation) time of the NS cluster \( t_{rel} \simeq 0.1(N/\ln N)t_{dyn} \simeq 19N_6^2(v/0.1c)^{-3} \) years. In general \( t_{rel} \gg t_{dyn} \), if \( N \gg 1 \). This evolution time determines the duration of an active phase for the considered below hidden source, as \( t_s \sim t_{rel} \sim 10 \) years.

### 2.3 Fireballs in Cluster

The most important feature of our model is a secular growing rate of accidental NS collisions in the evolving cluster, accompanied by large energy release. The corresponding rate of NS collisions in the cluster (with the gravitational radiation losses taken into account) is

\[
\dot{N}_c = 9\sqrt{2}\left(\frac{v}{c}\right)^{17/7}\frac{c}{R} = 36\sqrt{2}\left(\frac{v}{c}\right)^{31/7}N_6\frac{1}{N r_g} \simeq 4.4 \cdot 10^3N_6^{-1}(v/0.1c)^{31/7} \text{ yr}^{-1}.
\]  

(11)

The time between two successive NS collisions is

\[
t_c = \frac{1}{\dot{N}_c} = \frac{1}{9\sqrt{2}\left(\frac{c}{v}\right)^{10/7} t_{dyn} = \frac{1}{36\sqrt{2}\left(\frac{c}{v}\right)^{31/7} N r_g}} \simeq 7.3 \cdot 10^3N_6(v/0.1c)^{-31/7} \text{ s}.
\]  

(12)

Note that a number of NS collisions, given by \( \dot{N}_ct_s \), comprises only a small fraction, about 1%, of a total number of NSs in the cluster to the time of the onset of dynamical collapse of the whole cluster into a MBH.

Merging of two NSs in collision is similar to the process of a tight binary merging: the NSs are approaching to each other by spiralling down due to the gravitational waves radiation and then coalesce by producing an ultrarelativistic photon-lepton fireball \([17]–[21]\), which we assume to be spherically symmetric.

The energy of one fireball is \( E_0 = E_{52}10^{52} \) ergs, and the total energy release in the form of fireballs during lifetime of the hidden source \( t_s \sim 10 \) yr is

\[
E_{tot} \sim \dot{N}_cE_0t_s \sim 4 \cdot 10^{56} \text{ ergs},
\]  

(13)

where \( \dot{N}_c \) is the NS collision rate.
The physics of fireballs is extensively elaborated especially in recent years for the modeling of cosmological gamma-ray bursts (GRBs) (for review see e. g. [22] and references therein). The newborn fireball expands with relativistic velocity, corresponding to the Lorentz factor $\Gamma_f \gg 1$. The relevant parameter of a fireball is the total baryonic mass

$$M_0 = E_0/\eta c^2 \simeq 5.6 \cdot 10^{-6}E_{52}\eta_3^{-1}M_\odot,$$

(14)

where baryon-loading mass parameter $\eta = 10^3\eta_3$. The maximum possible Lorentz factor of expanding fireball is $\Gamma_f = \eta + 1$ during the matter-dominated phase of fireball expansion [17, 20]. During the initial phase of expansion, starting from the radius of the ‘inner engine’ $R_0 \sim 10^6 - 10^7$ cm, the fireball Lorentz factor increases as $\Gamma \propto r$, until it is saturated at the maximum value $\Gamma_f = \eta \gg 1$ at the radius $R_\eta = R_0\eta$ (see e. g. [22]). Internal shocks will take place around $R_{sh} = R_0\eta^2$, if the fireball is inhomogeneous and the velocity is not a monotonic function of radius, e.g. due to the considerable emission fluctuations of the inner engine [23]–[25]. The fireball expands with the constant Lorentz factor $\Gamma = \eta$ at $R > R_\eta$ until it sweeps up the mass $M_0/\eta$ of ambient gas and loses half of its initial momentum. At this moment ($R = R_\gamma$) the deceleration stage starts [21]–[27].

Interaction of the fireball with an ambient gas determines the length of its relativistic expansion. In our case the fireball propagates through the massive envelope with a mean gas number density $n_{env} = \rho_{env}/m_p = n_910^9$ cm$^{-3}$ as it follows from Eq. (4). Fireball expands with $\Gamma \gg 1$ up to the distance determined by the Sedov length

$$l_S = \left(\frac{3}{4\pi \rho_{env} c^2}E_0\right)^{1/3} \simeq 1.2 \cdot 10^{15}n_9^{-1/3}E_{52}^{1/3} \text{ cm.}$$

(15)

Fireball becomes mildly relativistic at radius $r = l_S$ due to sweeping up the gas from the envelope with the mass $M_0\eta$. The radius $r = l_S$ is the end point of the ultrarelativistic fireball expansion phase. Far beyond the Sedov length radius ($r \gg l_S$) there is the non-relativistic Newtonian shock driven by the decelerated fireball. Its radius $R(t)$ obeys the Sedov–Taylor self-similar solution [28], with $R(t) = (E_0/\rho_{env})^{1/5}$. The corresponding shock expansion velocity is $u = (2/5)[l_S/R(t)]^{3/2}c \ll c$. 

7
2.4 Cavity and Shocks

We show here that relativistic fireballs from a dense central cluster of NSs produce the dynamically supported rarefied cavity deep inside the massive gaseous envelope.

The first fireball sweeps out the gas from the envelope producing the cavity with a radius $l_S$. This cavity expands due to the next fireballs, which propagate first in a rarefied cavity and then hit the boundary pushing it further.

Each fireball hitting the dense envelope is preceded by a shock. Propagating through the envelope, the shock sweeps up the gas ahead of it and gradually decelerates. The swept out gas forms a thin shell with a density profile given by Sedov self-similar solution. The next fireball hits this thin shell when it is decelerated down to the non-relativistic velocity. Moving in the envelope, the shell accumulates more gas, retaining the same density profile, and then it is hit by the next fireball again. After a number of collisions the shell becomes massive, and the successive hitting fireballs do not change its velocity appreciably. In this regime one can consider the propagation of massive non-relativistic thin shell with a shock (density discontinuity) ahead of it. The shock speed $v_{sh}$ is connected with a velocity $v_g$ of gas behind it as $v_{sh} = (\gamma + 1)v_g/2$, where $\gamma$ is an adiabatic index. The density perturbation in the envelope propagates as a shock until $v_{sh}$ remains higher than sound speed $v_s$. In the considered case, the shock dissipates in the middle of the envelope. For the Sedov solution the shock velocity changes with distance $r$ as

$$v_{sh}(r) = \frac{2}{5} \alpha_S^{-1} \left( \frac{E_{sh}}{\rho_{env}} \right)^{1/2} r^{-3/2},$$

where $\alpha_S$ is the constant of self-similar Sedov solution; when radiative pressure dominates $\alpha_S = 0.894$. The other quantities in Eq. (16) are $E_{sh} = (1/2)E_{tot} = 2 \cdot 10^{56}$ erg/s is the energy of the shock, which includes kinetic and thermal energy (the half of a total energy is transformed to particles accelerated in the cavity), and $\rho_{env}$ is a density of the envelope given by Eq. (8). From Eqs. (16) and (9) it follows that $v_{sh} > v_s$ holds at distance $r < 1 \cdot 10^{18}$ cm $\sim 0.6 R_{env}$, i.e. that shock does not reach the outer surface of the envelope. In fact the latter conclusion follows already from energy conservation. The gravitational energy of the envelope $V_0$ is

$$V_0 = \kappa \frac{GM_{env}^2}{R_{env}} > 9.2 \cdot 10^{56} \text{ ergs},$$

(17)
where $\kappa$ depends on a radial profile of the gas density in the envelope $\rho(r)$, and changes from $3/5$ to $1$. This energy is higher than a total injected energy $E_{tot} \sim 4 \cdot 10^{56}$ ergs, and thus the system remains gravitationally bound. When a shock reaches the boundary of the envelope, the gas distribution changes there. It has the form of a thin shell with gravitational energy $V_e = GM_{env}^2/2R_{env}$. To provide the exit of the shock to the surface of the envelope, a total energy release must satisfy the relation $E_{tot} > V_0 - V_e$, where the minimum value of $V_0 - V_e$ is $1.5 \cdot 10^{56}$ ergs for $\kappa = 3/5$. Actually $E_{tot}$ must be higher because (i) part of the injected energy goes to heat, (ii) more realistic value of $\kappa = 1$, and (iii) the shell has a non-zero velocity, when the shock disappears, with a gravitational braking taken into account. We conclude thus that for $E_{tot} \sim 4 \cdot 10^{56}$ ergs, shock dissipates inside the envelope.

The cavity radius grows with time. For the stage, when a shell moves non-relativistically, the cavity radius calculated as a distance to the shell in the Sedov solution is

$$R_{cav}(t) = \left( \frac{E_{sh}}{\alpha_S \rho_{env}} \right)^{1/5} t^{2/5}. \quad (18)$$

At the end of a phase of the hidden source activity, $t_s \sim 10$ yr, the radius of the cavity reaches $\sim 3 \cdot 10^{17}$ cm, remaining thus much less than $R_{env}$.

The cavity is filled by direct and reverse relativistic shocks from fireballs. Reverse shocks are produced by decelerated fireballs, most notably when they hit the boundary of the cavity. The expanding fireballs inside the cavity have a shape of thin shells \cite{29} and are separated by distance

$$R_c = c t_c \simeq 2.2 \cdot 10^{14} N_0 (v/c)^{-31/7} \text{ cm}. \quad (19)$$

The gas between two fireballs is swept up by the preceding one. A total number of fireballs existing in the cavity simultaneously is $N_f \sim R_{cav}/R_c \gg 1$, and this number grows with time as $t^{2/5}$.

Shocks generated by repeating fireballs are ultrarelativistic inside the cavity and mildly relativistic in the envelope near the inner boundary. Collisions of multiple shocks in the cavity, as well as inside the fireballs, produce strongly turbulized medium favorable for generation of magnetic fields and particle acceleration.
3 High Energy Particles in Cavity

There are three regions where acceleration of particles take place.

(i) NS cluster, where fireballs collide, producing the turbulent medium with large magnetic field. This region has a small size of order of virial radius of the cluster $R \sim 10^{13}$ cm, and we neglect its contribution to production of accelerated particles.

(ii) The region at the boundary between the cavity and the envelope. During the active period of a hidden source, $t_s \sim 10$ yr, the fireballs hit this region, heating and turbulizing it. The large magnetic equipartition field is created here. This boundary region has density $\rho \sim \rho_{env}$, the radius $R \sim R_{cav}$ and the width $\Delta < 0.1 R_{cav}$.

(iii) Most of the cavity volume is occupied by fireballs, separated by distance $R_c$. Due to collisions of internal shocks, the gas in a fireball is turbulized and equipartition magnetic field is generated \[22, 30\].

In all three cases the Fermi II acceleration mechanism operates. For all three sites we assume existence of equipartition magnetic field, induced by turbulence and dynamo mechanism:

\[
\frac{H^2}{8\pi} \sim \frac{\rho u_t^2}{2},
\]

where $\rho$ and $u_t$ are the gas density and velocity of turbulent motions in the gas, respectively. Since turbulence is caused by shocks, the shock spectrum of turbulence $F_k \sim k^{-2}$ is valid, where $k$ is a wave number. Assuming equipartition magnetic field on each scale $l \sim 1/k$, $H^2 \sim kF_k$, one obtains the distribution of magnetic fields over the scales as

\[
H_l/H_0 = (l/l_0)^{1/2},
\]

where $l_0$ is a maximum scale with the coherent field $H_0$ there.

The maximum energy of accelerated particles is given by

\[
E_{max} \sim eH_0 l_0
\]

with an acceleration time

\[
t_{acc} \sim \frac{l_0}{c} \left(\frac{c}{v}\right)^2.
\]

For the turbulent shell at the boundary between the cavity and envelope, assuming mildly relativistic turbulence $u_t \sim c$ and $\rho \sim \rho_{env}$, we obtain
The maximum acceleration energy is \( E_{\text{max}} = 2 \cdot 10^{21} \text{ eV} \), if the coherent length of magnetic field \( l_0 \) is given by the Sedov length \( l_s \), and the acceleration time is \( t_{\text{acc}} = 4 \cdot 10^4 E_{52}^{1/3} n_q^{-1/3} \text{ s} \). The typical time of energy losses, determined by \( pp \)-collisions, is much longer than \( t_{\text{acc}} \), and does not prevent acceleration to \( E_{\text{max}} \) given above:

\[
t_{pp} = \left( \frac{1}{E \frac{dE}{dt}} \right)^{-1} = \frac{1}{f_p \sigma_{pp} n_{\text{env}} c} \approx 2 \cdot 10^6 n_q^{-1} \text{ s},
\]

where \( f_p \approx 0.5 \) is the fraction of energy lost by HE proton in one collision, \( \sigma_{pp} \) is a cross-section of \( pp \)-interaction, and \( n_{\text{env}} \) is the gas number density in the boundary turbulent shell.

The turbulence in the fireball is produced by collisions of internal shells, and a natural scale for coherence length \( l_0 \) is a width of the internal shell in the local frame \( \delta' \). The maximum energy in the laboratory frame \( E_{\text{max}} \sim eH_{eq}' \delta' \), where \( \delta' \) is the corresponding width in the laboratory frame. Since \( H' \propto 1/R \) and \( \delta \propto R \), the maximum energy does not change with time, and can be estimated as in Ref. \[30\], \( E_{\text{max}} \sim 3 \cdot 10^{20} \text{ eV} \). Note that in our case a fireball propagates in the very low-density medium.

A gas left in the cavity by preceding fireball, as well as high energy particles escaping from it, are accelerated by the next fireball by a factor \( \Gamma_2^2 \) at each collision. This \( \Gamma^2 \)-mechanism of acceleration works only in pre-hydrodynamic regime of fireball expansion, after reaching the hydrodynamic stage, \( \Gamma^2 \)-mechanism ceases \[31\].

We conclude, thus, that both efficiency and maximum acceleration energy are very high. We assume that a fireball transfers half of its energy to accelerated particles.

### 4 Neutrino Production and Detection

Particles accelerated in the cavity interact with the gas in the envelope producing high energy neutrino flux. We assume that about half of the total power of the source \( L_{\text{tot}} \) is converted into energy of accelerated particles \( L_p \sim 7 \cdot 10^{47} \text{ erg/s} \). As estimated in Section 2.1, the column density of the envelope varies from \( X_{\text{env}} \sim 10^2 \text{ g/cm}^2 \) (for very heavy envelope) up to \( X_{\text{env}} \sim 10^4 \text{ g/cm}^2 \) (for the envelope with mass \( M \sim 10^8 M_\odot \)). Taking into account the magnetic field, one concludes that accelerated protons loose in the envelope a large fraction of their energy. The charged pions, produced in
pp-collisions, with Lorentz factors up to $\Gamma_c \sim 1/(\sigma_{\pi N} n_{env} c \tau_{\pi}) \sim 4 \cdot 10^{13} n_9^{-1}$ freely decay in the envelope (here $\sigma_{\pi N} \sim 3 \cdot 10^{-26}$ cm$^2$ is $\pi N$-cross-section, $\tau_{\pi}$ is the lifetime of charged pion, and $n_{env} = 10^9 n_9$ cm$^{-3}$ is the number density of gas in the envelope). We assume $E^{-2}$ spectrum of accelerated protons

$$Q_p(E) = \frac{L_p}{\zeta E^2},$$

(25)

where $\zeta = \ln(E_{max}/E_{min}) \sim 20-30$. About half of its energy protons transfer to high energy neutrinos through decays of pions, $L_\nu \sim (2/3)(3/4)L_p$, and thus the production rate of $\nu_\mu + \bar{\nu}_\mu$ neutrinos is

$$Q_{\nu_\mu + \bar{\nu}_\mu} (> E) = \frac{L_p}{4\zeta E^2}.$$  

(26)

Crossing the Earth, these neutrinos create deep underground the equilibrium flux of muons, which can be calculated as 

$$F_\mu (> E) = \frac{\sigma_0 N_A Y_\mu(E_\mu)}{b_\mu} \frac{L_p}{4 \xi E^2} \frac{1}{4 \pi r^2},$$

(27)

where the normalization cross-section $\sigma_0 = 1 \cdot 10^{-34}$ cm$^2$, $N_A = 6 \cdot 10^{23}$ is the Avogadro number, $b_\mu = 4 \cdot 10^{-6}$ cm$^2$/g is the rate of muon energy losses, $Y_\mu(E)$ is the integral muon moment of $\nu_\mu N$ interaction (see e. g. [2, 32]). The most effective energy of muon detection is $E_\mu \geq 1$ TeV [32]. The rate of muon events in the underground detector with effective area $S$ at distance $r$ from the source is given by

$$\dot{N}(\nu_\mu) = F_\mu S \simeq 70 \left( \frac{L_p}{10^{48} \text{ erg s}^{-1}} \right) \left( \frac{S}{1 \text{ km}^2} \right) \left( \frac{r}{10^3 \text{ Mpc}} \right)^{-2} \text{ yr}^{-1}.$$  

(28)

Thus, we expect about 10 muons per year from the source at distance $10^3$ Mpc.

5 Accompanying Radiation

We shall consider below HE gamma-ray radiation produced by accelerated particles and thermalized infrared radiation from the envelope. As far as HE gamma-ray radiation is concerned, there will be considered two cases: (i) thin envelope with $X_{env} \sim 10^2$ g/cm$^2$ and (ii) thick envelope with $X_{env} \sim 10^4$ g/cm$^2$. In the latter case HE gamma-ray radiation is absorbed.
5.1 Gamma-Ray Radiation

Apart from high energy neutrinos, the discussed source can emit HE gamma-radiation through $\pi^0 \rightarrow 2\gamma$ decays and synchrotron radiation of the electrons. In case of the thick envelope with $X_{env} \sim 10^4$ g/cm$^2$ most of HE photons are absorbed in the envelope (characteristic length of absorption is the radiation length $X_{rad} \approx 60$ g/cm$^2$). In the case of the thin envelope, $X_{env} \sim 100$ g/cm$^2$, HE gamma-radiation emerges from the source. Production rate of the synchrotron photons can be readily calculated as

$$dQ_{\text{syn}} = \frac{dE_e}{E_\gamma} Q_e(> E_e),$$

(29)

where $E_e$ and $E_\gamma$ are the energies of electron and of emitted photon, respectively. Using $Q_e(> E_e) = L_e/(\eta E_e)$ and $E_\gamma = k_{\text{syn}}(H) E_e^2$, where $k_{\text{syn}}$ is the coefficient of the synchrotron production, one obtains

$$Q_{\text{syn}}(E_\gamma) = \frac{1}{12} \frac{L_p}{\eta E_\gamma^2}.$$  

(30)

Note, that the production rate given by Eq. (30) does not depend on magnetic field. Adding the contribution from $\pi^0 \rightarrow 2\gamma$ decays, one obtains

$$Q_\gamma(E_\gamma) = \frac{5}{12} \frac{L_p}{\eta E_\gamma^2};$$

(31)

and the flux at $E_\gamma \geq 1$ GeV at the distance to the source $r = 1 \cdot 10^3$ Mpc is

$$F_\gamma(> E_\gamma) = \frac{5}{12} \left( \frac{1}{4\pi r^2} \right) \frac{L_p}{\xi E_\gamma}$$

$$\simeq 2.2 \cdot 10^{-8} \left( \frac{L_p}{10^{47} \text{ erg s}^{-1}} \right) \left( \frac{r}{10^3 \text{ Mpc}} \right)^{-2} \text{ cm}^{-2} \text{ s}^{-1},$$

(32)

i. e. the source is detectable by EGRET.

5.2 Infrared and Optical Radiation

Hitting the envelope, fireballs dissipate part of its kinetic energy in the envelope in the form of low-energy e-m radiation. This radiation is thermalized in the optically thick envelope and then re-emitted in the form of blackbody radiation from the surface of the envelope. It appears much more later...
than HE neutrino and gamma-radiation. The thermalized radiation diffuses through the envelope with a diffusion coefficient \( D \sim c l_{\text{diff}} \), where a diffusion length is \( l_{\text{diff}} = 1/(\sigma_T n_{\text{env}}) \) and \( \sigma_T \) is the Thompson cross-section. A mean time of the radiation diffusion through the envelope of radius \( R_{\text{env}} \) is

\[
t_d \sim \frac{R_{\text{env}}^2}{D} \sim 1 \cdot 10^4 \text{ yr},
\]

(33)

independently of the envelope mass. This diffusion time is to be compared with a duration of an active phase \( t_s \sim 10 \) years and with a time of flight \( R_{\text{env}}/c \sim 2 \) years.

Since the produced burst is very short, \( t_s \sim 10 \) yr, the arrival times of photons to the surface of the envelope have a distribution with a dispersion \( \sigma \sim t_d \). An average surface black body luminosity is then

\[
\bar{L}_{bb} \sim E_{\text{tot}}/t_d \sim 1 \cdot 10^{45} \text{ erg/s},
\]

(34)

with a peak luminosity being somewhat higher. The temperature of this radiation corresponds to IR range

\[
T_{bb} = \left( \frac{\bar{L}_{bb}}{4\pi R_{\text{env}}^2 \sigma_{SB}} \right)^{1/4} \simeq 8.4 \cdot 10^2 \text{ K}.
\]

(35)

Thus, in \( \sim 10^4 \) years after neutrino burst, the hidden source will be seen in the sky as a luminous IR source. Since we consider a model of production of high-luminosity AGN, the object is typically expected to be at high redshift \( z \). Its visible magnitude is

\[
m = -2.5 \log \left( \frac{L_{bb} H_0^2}{16\pi(z + 1 - \sqrt{1 + z})^2 f_0} \right)
\]

(36)

where \( H_0 = 100 h \) km/s Mpc is the Hubble constant and the flux \( f_0 = 2.48 \cdot 10^{-5} \) erg/cm²s. For \( L_{bb} = 1 \cdot 10^{45} \) erg/s, \( z = 3 \) and \( h = 0.6 \), the visible magnitude of the IR source is \( m = 22.7 \). Such a faint source is not easy identify in e.g. IRAS catalogue as a powerful source, because for redshift determination it is necessary to detect the optical lines from the host galaxy, which are very weak at assumed redshift \( z = 3 \). The non-thermal optical radiation can be also produced due to HE proton-induced pion decays in the outer part of the envelope, but its luminosity is very small. Most probably such source will be classified as one of the numerous non-identified weak IR source.
5.3 Duration of activity and the number of sources

As was indicated in Section 2.2 the duration of the active phase $t_s$ is determined by relaxation time of the NS cluster: $t_s \sim t_{rel} \sim 10 - 20$ yr. This stage appears only once during the lifetime of a galaxy, prior to the MBH formation. If to assume that a galactic nucleus turns after it into AGN, the total number of hidden sources in the Universe can be estimated as

$$N_{HS} \sim \frac{4}{3} \pi (3c t_0)^3 n_{AGN} t_s / t_{AGN},$$

(37)

where $\frac{4}{3} \pi (3c t_0)^3$ is the cosmological volume inside the horizon $c t_0$, $n_{AGN}$ is the number density of AGNs and $t_{AGN}$ is the AGN lifetime. The value $t_s / t_{AGN}$ gives a probability for AGN to be observed at the stage of the hidden source, if to include this short stage ($t_s \sim 10$ yr) in the much longer ($t_{AGN}$) AGN stage and consider (for the aim of estimate) the hidden source stage as the accidental one in the AGN history. The estimates for $n_{AGN}$ and $t_{AGN}$ taken for different populations of AGNs result in $N_{HS} \sim 10 - 100$.

6 Conclusions

Dynamical evolution of the central stellar cluster in the galactic nucleus results in the stellar destruction of the constituent normal stars and in the production of massive gas envelope. The surviving subsystem of NSs submerges deep into this envelope. The fast repeating fireballs caused by NS collisions in the central stellar cluster produce the rarefied cavity inside the massive envelope. Colliding shocks generate the turbulence inside the fireballs and in the cavity, and particles are accelerated by Fermi II mechanism. These particles are then re-accelerated by $\Gamma^2$-mechanism in collisions with relativistic shocks and fireballs.

All high energy particles, except neutrinos, can be completely absorbed in the thick envelope. In this case the considered source is an example of a powerful hidden source of HE neutrinos.

Prediction of high energy gamma-ray flux depends on the thickness of envelope. In case of the thick envelope, $X_{rad} \sim 10^4$ g/cm$^2$, HE gamma-radiation is absorbed. When an envelope is thin, $X_{rad} \sim 10^2$ g/cm$^2$, gamma-ray radiation from $\pi^0 \rightarrow 2\gamma$ decays and from synchrotron radiation of the secondary electrons can be observed by EGRET and marginally by Whipple detector at $E_\gamma \geq 1$ TeV.
In all cases the thickness of the envelope is much larger than the Thompson thickness \( x_T \sim 3 \, \text{g/cm}^2 \), and this condition provides the absorption and X-rays and low energy gamma-rays.

A hidden source is to be seen as a bright IR source but, due to slow diffusion through envelope, this radiation appears \( \sim 10^4 \) years after the phase of neutrino activity. During the period of neutrino activity the IR luminosity is the same as before it. A considered source is a precursor of most powerful AGN, and therefore most of these sources are expected to be at the same redshifts as AGNs. The luminosity \( L_{IR} \sim 10^{45} - 10^{46} \, \text{erg/s} \) is not unusual for powerful IR sources from IRAS catalogue. The maximum observed luminosity exceeds \( 1 \cdot 10^{48} \, \text{erg/s} \) \([3]\), and there are many sources with luminosity \( 10^{45} - 10^{46} \, \text{erg/s} \) \([4]\). Moreover, for most of the hidden sources the distance cannot be determined, and thus they fall into category of faint non-identified IR sources.

Later these hidden sources turn into usual powerful AGNs, and thus the number of hidden sources is restricted by the total number of these AGNs.

In our model the shock is fully absorbed in the envelope. Since the total energy release \( E_{tot} \) is less than gravitational energy of the envelope \( E_{grav} \sim GM_{env}^2/R_{env} \), the system remains gravitationally bound, and in the end the envelope will collapse into black hole or accretion disc.

The expected duration of neutrino activity for a hidden source is \( \sim 10 \, \text{yr} \), and the total number of hidden sources in the horizon volume ranges from a few up to \( \sim 100 \), within uncertainties of the estimates.

Underground neutrino detector with an effective area \( S \sim 1 \, \text{km}^2 \) will observe \( \sim 10 \) muons per year with energies \( E_\mu \geq 1 \, \text{TeV} \) from this hidden source.

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