

On the origin of galactic cosmic rays

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Abstract

It is shown that the relativistic jet, emitted from the center of the Galaxy during its activity, possessed power and energy spectrum of accelerated protons sufficient to explain the current cosmic rays distribution in the Galaxy. Proton acceleration takes place on the light cylinder surface formed by the rotation of a massive black hole carrying into rotation the radial magnetic field and the magnetosphere. Observed in gamma, x-ray and radio bands bubbles above and below the galactic plane can be remnants of this bipolar jet. The size of the bubble defines the time of the jet's start, $\simeq 2.4 \cdot 10^7$ years ago. The jet worked more than 10^7 years, but less than $2.4 \cdot 10^7$ years.

Keywords: cosmic rays, galactic center, relativistic jets

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1. Introduction

The traditional point of view on the origin of cosmic rays in the Galaxy is the concept of acceleration of charged particles at fronts of shocks from supernova explosions. Arguments in favour of this mechanism are sufficient mechanical energy that is released when the supernova explodes, as well as universal index of power law spectrum of particles, accelerated by strong shocks. Total power of cosmic ray sources in order to maintain their observed density of energy is $5 \cdot 10^{40} \text{ erg/s}$, which equals approximately 15% of the kinetic energy of supernova explosions. When the gas compression in a shock is equal to 4, the index of the power law energy spectrum of accelerated particles is equal to -2, $N(E) \propto E^{-2}$. It is in a good agreement with observed cosmic ray spectrum at energies $E < 3 \cdot 10^{15} \text{ eV}$. Beginning from the first works by Krymskii, 1977; Bell, 1978; Blandford & Ostriker, 1978, who proposed the mechanism of acceleration of charged particles on fronts of shocks propagating in the turbulent environment, much progress has been made to explain the observed characteristics of galactic cosmic rays in the belief that they are accelerated at the front of shocks.

On the other hand, there is no objections to generate galactic cosmic rays in one source in the Galaxy (Ptuskin & Khazan, 1981). This potential source

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can be the center of the Galaxy, which is the massive black hole of $M \simeq 4 \cdot 10^6 M_\odot$ mass. And while the luminosity of Sgr A* is small now, it is only 10^{36} erg/s, in the past the center could be much brighter because its Eddington luminosity equals $L_{Edd} = 5.2 \cdot 10^{44}$ erg/s. On the past activity of the center of the Galaxy shows newly discovered by Fermi Gamma-ray Space Telescope above and below the galactic plane big bubbles emitting gamma radiation in the range of 0.1 – 1000 GeV (Su et al., 2010). Such formations was previously observed in the x-ray range (1.5 – 2) KeV by ROSAT All-Sky Survey (Snowden et al., 1997) and in the microwave range (20 – 40) GHz by WMAP (Finkbeiner, 2004). Estimated energy stored in bubbles is of $10^{54} - 10^{55}$ erg (Sofue, 2000). As we will see below, bubbles of a relativistic gas could be formed by the jet, emitted from surroundings of the massive black hole. Here we provide an alternative mechanism of origin galactic cosmic rays, in which the nucleus of the Galaxy in the active phase injected the relativistic jet, which was the source of cosmic rays.

In the following sections we will calculate the power of the jet and the energy spectrum of protons in the relativistic jet, as well as describe the remnants of the relativistic jet injected from the center of the Galaxy, having the form of bubbles above and below the galactic plane. In the final section we will discuss correspondence of the scenario of the galactic cosmic rays origin provided with cosmic rays characteristics observed.

2. Relativistic jet

Sources of energy of active galactic nuclei are the accretion on a massive black hole, in which the gravitational energy of a falling gas transforms into radiation and heat, as well as the rotation of a black hole. Mechanism of extraction of energy and angular momentum from the black hole is called as the mechanism of Blandford-Znajek (1977). The energy of a rotating black hole is a large value, $E_{rot} = Mr_H^2 \Omega_H^2 / 2 = a^2 Mc^2 / 8 = 2.25 \cdot 10^{53} a^2 (M/M_\odot)$ erg. For the Galaxy $E_{rot} \simeq 9 \cdot 10^{59} a^2$ erg. Here we have introduced the dimensionless parameter of a , describing rotation of the black hole, $a = Jc/M^2G$, $a < 1$. J is the black hole angular momentum, G is the gravitational constant. Angular velocity of rotation of a black hole is proportional to the value of a , $\Omega_H = ac/2r_H$, r_H is the gravitational radius of not rotating black hole ($a = 0$), $r_H = 2MG/c^2$. Energy extraction is possible when there is a poloidal magnetic field B near the black hole horizon. In this case, rotating black hole acts as a Dynamo machine, creating a voltage $U = f_H \Omega_H / 2\pi c$ (Landau & Lifshits, 1984). The value of f_H is the flux of the poloidal magnetic field reaching the horizon of a black hole, $f_H \simeq \pi B r_H^2$. Voltage U generates the electric current $I = U/(R + R_H)$, which on the one hand is closed on the horizon of a black hole that has the resistance $R_H = 4\pi/c \simeq 377$ ohm. Resistance of the outer part of the current loop is R . Thus, the power, extracting from a rotating black hole, is $L = RI^2 = U^2 R / (R + R_H)^2 = a^2 B^2 r_H^2 R / 16(R + R_H)^2$, and reaches the maximum L_m at $R = R_H$, $L_m = a^2 B^2 r_H^2 c / 256\pi$. The value of L is proportional to the energy of the poloidal magnetic field near a black hole and can reach the Eddington

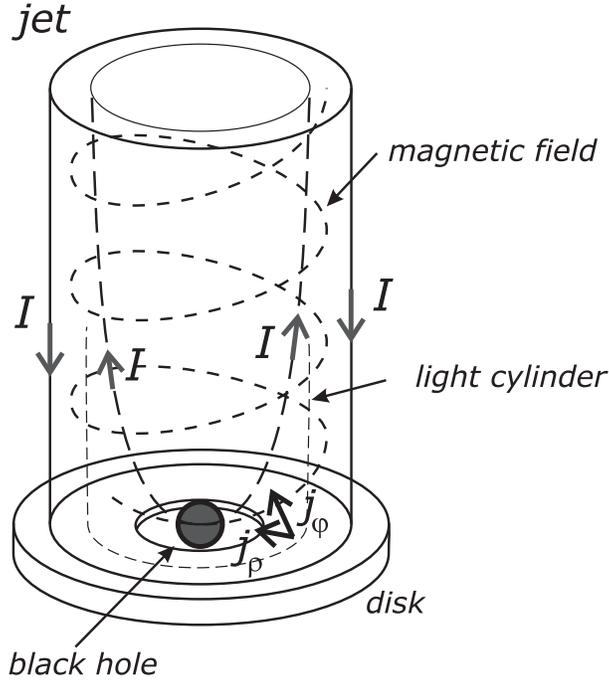


Figure 1: Configuration of the magnetic field and electric currents in the jet and in the disk.

luminosity at sufficiently large magnetic fields $B \simeq 10^6 a^{-1}$ Gauss in the center of the Galaxy. This field is accumulated near the horizon of a black hole in the process of accretion of a disk matter in which the magnetic field is frozen. Thus, for the effective work of the mechanism of Blandford-Znajek an accretion disk around a massive black hole is required, not as a source of the energy, but as the agent bearing the magnetic field to a black hole. In addition, the electric current I flows in the disk, this is the part of the current loop: in the disk, in the black hole horizon, then in the jet, closing at large distances in the interstellar matter (see Figure 1).

In the disk, in addition to the radial electric current $I_\rho = \int j_\rho ds = -I$, stronger toroidal current j_ϕ , $j_\phi \simeq 10^2 j_\rho$, flows also (Istomin & Sol, 2011), it generates the radial magnetic field B .

The rotating black hole brings into rotation the radial magnetic field in the magnetosphere of a black hole above and below the disk. Angular velocity of rotation of the magnetic field lines, the same as rotation of the magnetospheric plasma, Ω_F , is proportional to the angular velocity of rotation of the black hole Ω_H , $\Omega_F = \Omega_H R / (R + R_H)$ (Thorne et al., 1986). Plasma rotation is the drift motion in crossed radial magnetic field and electric field of plasma polarization. Thus, there appears so-called the light cylinder surface in the black hole magnetosphere, where the magnitude of the electric field is compared with that of the

magnetic field and the rotation velocity approaches the speed of light c . The radius of the light surface is $r_L = c/\Omega_F = 2a^{-1}r_H(R + R_H)/R > r_H$. On the light surface charged particles get considerable energy and angular momentum of rotation. Energy density of particles on the light surface is compared with the energy density of the electromagnetic field $(E_L^2 + B_L^2)/8\pi = B_L^2/4\pi$ (Istomin, 2010). All energy passes to protons, $\gamma = \mathcal{E}_p/m_p c^2 \gg 1$. Electrons are practically not accelerated due to large synchrotron losses in a strong magnetic field (Istomin & Sol, 2009). Energetic protons, accelerated near the light surface, and whose energy is mainly in the azimuthal motion, create the jet. Jet's power is $L_J = B^2 r_H^2 c (\omega_{cH} r_H / c)^{-1/4} / 2$ (Istomin & Sol, 2011). Here ω_{cH} is the non relativistic cyclotron frequency of protons in the magnetic field near the black hole, $\omega_{cH} = eB/m_p c$. Jet arises when the power extracted from the rotating black hole L becomes greater than the jet power L_J , $L > L_J$. This imposes a limitation on the value of the magnetic field

$$\frac{\omega_{cH} r_H}{c} \geq (128\pi)^4 a^{-8} \left[\frac{(R + R_H)^2}{4RR_H} \right]^4. \quad (1)$$

For $R = R_H$ it gives

$$B \geq 2.7 \cdot 10^{11} a^{-8} \frac{M_\odot}{M} \text{Gauss}. \quad (2)$$

For the center of the Galaxy, the magnetic field must satisfy the condition $B \geq 6.75 \cdot 10^4 a^{-8}$ Gauss. We see that to generate a jet, less massive black holes should have a stronger poloidal magnetic field near the horizon, $B \propto M^{-1}$. In addition, rotation must be fast, close to the critical value of $a \simeq 1$, because of strong dependence of the expression (2) on a . It should also be noted that the resistance of the external current loop R , on which the jet power L_J depends, is not the ohmic one R_c , which turns out to be small, $R_c \ll R_H$ (Istomin & Sol, 2011), but is the effective resistance R_J , which can be attributed to the jet, receiving energy from the rotating black hole. If $L = L_J$ the resistance of the jet is $R_J = R_H$. Under the equality in the expression (1) when a rotating black hole can begin to generate a jet, the expression for the jet's power becomes universal

$$L_J = 2^{48} \pi^7 m_p c^2 \left(\frac{m_p c^3}{e^2} \right) a^{-14} = 2.5 \cdot 10^{41} a^{-14} \text{ erg/s}. \quad (3)$$

All jet energy are in the energy of protons, and, as we can see, is sufficient for the production of galactic cosmic rays.

3. Energy spectrum of fast particles in jet

Istomin and Sol (2009) had shown that on the light surface, produced by the rotating radial magnetic field, which is carried into rotation by a black hole, protons gain considerable energy. The Lorentz factor γ becomes equal to $\gamma = (\gamma_0 \gamma_i)^{1/2}$. The value of γ_i is the Lorentz factor of particles in the magnetosphere of a black hole before crossing the light surface. And the value of

γ_0 is the maximum of the Lorentz factor, which could be achieved by a particle in this acceleration mechanism, $\gamma_0 = \omega_{cL}/\Omega_F$. Here ω_{cL} is the cyclotron frequency of rotation of protons in the poloidal magnetic field near the light surface. When $\gamma = \gamma_0$ the cyclotron radius of a proton is compared with the radius of the light surface. For non relativistic particles of the black hole magnetosphere, $\gamma_i \simeq 1$, the Lorentz factor of accelerated particles is equal to $\gamma = \gamma_0^{1/2} = (\omega_{cL}/\Omega_F)^{1/2}$. Crossing the light surface at different distances z from the accretion disk plane, particles gain different energies, since the magnetic field decreases with distance from the black hole. For a radial magnetic field $B \propto (z^2 + r_L^2)^{-1}$. Thus, $\gamma = \gamma_m(1 + z^2/r_L^2)^{-1/2}$, where γ_m is the maximal Lorentz factor of accelerated particles near the accretion disk. Accelerated protons of the jet are collected from various parts of the light cylinder surface of r_L radius, but located at different distances z . Therefore, the number of particles is $dN \propto ndz$, where n is the density of protons in the magnetosphere near the light surface. Connecting values z and γ , we get

$$\frac{dz}{r_L} = -\frac{\gamma_m d\gamma}{\gamma^2(1 - \gamma^2/\gamma_m^2)^{1/2}}.$$

Considering that the vertical size of the magnetosphere is larger than the light surface radius, the density n can be taken as constant. As a result we get the distribution function of relativistic protons in the jet, $F(\gamma) = dN/d\gamma$,

$$F(\gamma) = \text{const} \cdot \gamma^{-2}(1 - \gamma^2/\gamma_m^2)^{-1/2}, \quad \gamma < \gamma_m. \quad (4)$$

We see that in the range $\gamma \ll \gamma_m$ the spectrum of relativistic protons is the power law spectrum with the index -2. This spectrum is observed in gamma radiation from bubbles above and below the Galactic plane by Fermi Gamma-ray Space Telescope (Su et al., 2010). Considering that the gamma radiation occurs due to collisions of relativistic protons with interstellar gas through meson production (Crocker & Aharonian, 2011), and the distribution of photons is similar to the distribution of protons, one can conclude that the jet from the center of the Galaxy actually existed, and bubbles are filled with relativistic protons of the jet. The value of γ_m is (Istomin & Sol, 2011)

$$\gamma_m = \left(\frac{\omega_{cH} r_H}{c}\right)^{1/2}, \quad (5)$$

and for $R = R_H$ equals (see the expression (1))

$$\gamma_m = (128\pi)^2 a^{-4} = 1.6 \cdot 10^5 a^{-4}.$$

The spectrum of protons (4) breaks at $\gamma = \gamma_m$ and has there the root singularity (integrable) that is smoothed considering the thermal dispersion of particles in the magnetosphere of the black hole, $\Delta\gamma_i = \mathcal{E}_p/m_p c^2$. The distribution (4) is shown on Figure 2. The value of γ_m is chosen to be equal to the Lorentz factor of the break in the observed spectrum of cosmic rays at the energy $E = 3 \cdot 10^{15}$ GeV, $\gamma_m = 3.2 \cdot 10^6$. This corresponds to the rotation parameter $a = 0.47$. The

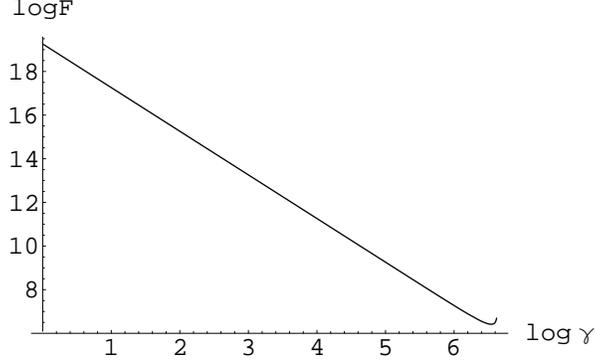


Figure 2: Distribution function of relativistic protons in the jet, $\gamma < \gamma_m$. The value of γ_m corresponds to the break in the spectrum of the cosmic ray. The slope is equal to -2.

power of the jet (3) is $L_J \simeq 8.9 \cdot 10^{45}$ erg/s. That is in agreement with estimated from observations powers of jets ejected from active galactic nuclei— $10^{45} - 10^{46}$ erg/s (Mao-Li et al., 2008).

Relativistic protons with the spectrum (4) are formed from thermal particles of the black hole magnetosphere, $\gamma_i \simeq 1$. But in addition to thermal particles in the magnetosphere there can exist accelerated protons. The turbulent motion of the accreting disk matter in the presence of the frozen magnetic field leads to acceleration of particles, which have the power law energy spectrum, $f(\gamma) = \text{const} \cdot \gamma^{-\beta}$, $\gamma < \gamma_1$, $\beta \simeq 1$ (Istomin & Sol, 2009). The disk must be turbulent to provide for the abnormal gas transport. Getting onto the light surface, accelerated protons are converted to more energetic, $\gamma \rightarrow (\gamma_0 \gamma)^{1/2}$. Their distribution function becomes equal (Istomin & Sol 2009) $f'(\gamma) = 2 \text{const} \cdot \gamma_0^{\beta-1} \gamma^{-2\beta+1}$, $\gamma_0^{1/2} < \gamma < (\gamma_0 \gamma_1)^{1/2}$. Thus, there is another component of jet relativistic protons, their number is equal to

$$N \propto \int_0^\infty dz \int_{\gamma_0^{1/2}}^{(\gamma_0 \gamma_1)^{1/2}} \gamma_0^{\beta-1} \gamma^{-2\beta+1} d\gamma, \quad \gamma_0 = \gamma_m^2 (1 + z^2/r_L^2)^{-1}. \quad (6)$$

Transforming the integration area in (6), we get

$$N \propto \int_1^{\gamma_m} \gamma^{-2\beta+1} d\gamma \int_{(\gamma_m^2/\gamma^2-1)^{1/2}}^{(\gamma_m^2 \gamma_1/\gamma^2-1)^{1/2}} \left(1 + \frac{z^2}{r_L^2}\right)^{1-\beta} \frac{dz}{r_L} + \int_{\gamma_m}^{\gamma_m \gamma_1^{1/2}} \gamma^{-2\beta+1} d\gamma \int_0^{(\gamma_m^2 \gamma_1/\gamma^2-1)^{1/2}} \left(1 + \frac{z^2}{r_L^2}\right)^{1-\beta} \frac{dz}{r_L}. \quad (7)$$

The first term in Eq. (7) corresponds to relativistic protons with energies $\gamma < \gamma_m$ similar to protons (4), accelerated from the thermal gas. Their distribution

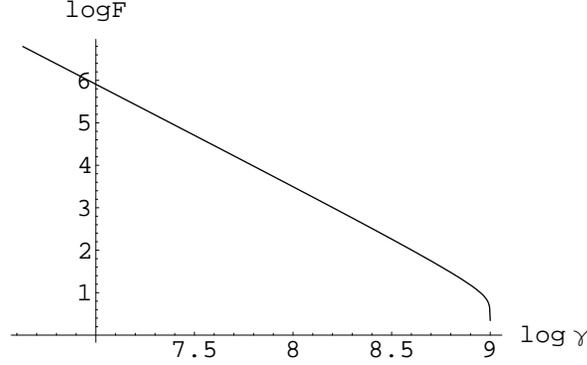


Figure 3: The distribution function of relativistic protons in the jet, $\gamma > \gamma_m$. The value of γ_m corresponds to the break in the cosmic ray spectrum. The spectral index equals -2.4. The maximum energy is 10^{18} eV.

function equals

$$F(\gamma) = const \cdot \gamma^{-2\beta+1} \int_{(\gamma_m^2/\gamma^2-1)^{1/2}}^{(\gamma_m^2\gamma_1/\gamma^2-1)^{1/2}} \left(1 + \frac{z^2}{r_L^2}\right)^{1-\beta} \frac{dz}{r_L}.$$

In the energy range $\gamma \ll \gamma_m$ this distribution has the same power law spectrum (4), $F(\gamma) \propto \gamma^{-2}$. But since the number of accelerated particles in the magnetosphere of the black hole is much less than that of thermal particles, the contribution of these particles into the total distribution at $\gamma < \gamma_m$ can be neglected. The second term in Eq. (7) describes the distribution of relativistic protons at $\gamma < \gamma_m < \gamma_m\gamma_1^{1/2}$

$$F(\gamma) = const \cdot \gamma^{-2\beta+1} \int_0^{(\gamma_m^2\gamma_1/\gamma^2-1)^{1/2}} \left(1 + \frac{z^2}{r_L^2}\right)^{1-\beta} \frac{dz}{r_L} = \frac{1}{2} const \cdot \gamma^{-2\beta+1} [B(1, \beta - 3/2, 1/2) - B(\gamma^2/(\gamma_m^2\gamma_1), \beta - 3/2, 1/2)]. \quad (8)$$

Here $B(x, a, b) = \int_0^x t^{a-1}(1-t)^{b-1}dt$ is the incomplete Beta function, $B(1, \beta - 3/2, 1/2) = \pi^{1/2}\Gamma(\beta - 3/2)/\Gamma(\beta - 1)$, $\Gamma(x)$ is the Gamma function. The distribution (8) with $\beta = 1.7$, $\gamma_m = 3.2 \cdot 10^6$ and $\gamma_1 = 10^5$ is shown on Figure 3. For energies $\gamma < \gamma_m\gamma_1^{1/2}$ the distribution of relativistic protons is the power law with index $-(2\beta - 1)$. At $\gamma \simeq \gamma_m\gamma_1^{1/2}$ the distribution falls down, for $\gamma_m = 3.2 \cdot 10^6$ and $\gamma_1 = 10^5$ the maximum energy is $\simeq 10^{18}$ eV.

We have chosen the value of $\beta = 1.7$ from the fact that indices of spectrum of cosmic rays before and after the break at energy $3 \cdot 10^{15}$ eV differ on the value of 0.4 – the spectrum becomes more soft with the index -3.1 . The same difference in indices must be in the source of cosmic rays, which in our case is the relativistic jet. At $\beta = 1.7$ the index of the spectrum (8) equals -2.4,

while the index of the spectrum (4) is equal to -2. It should be noted that the distribution function of relativistic protons (4) at energies $\gamma < \gamma_m$, and (8) at energies $\gamma > \gamma_m$, is continuous, i.e. $F(\gamma = \gamma_m - 0) = F(\gamma = \gamma_m + 0)$. This is because the acceleration on the light surface undergo protons of the black hole magnetosphere with a unique spectrum – thermal at low energies, turning into the tail of fast particles up to the energy $\gamma = \gamma_1$. If their energy distribution function is $F_i(\mathcal{E}_i)$, then the distribution of particles, accelerated on the light surface, have also the continuous distribution $F(\mathcal{E}) = F_i[\mathcal{E}_i(\mathcal{E})]d\mathcal{E}_i/d\mathcal{E}$, $\mathcal{E}_i = \mathcal{E}^2/\gamma_0 m_p c^2$.

Here and hereafter, we talk about protons, bearing in mind that they are ‘heavy’ particles, unlike electrons. Nuclei of m mass and Ze charge will be accelerated effectively also on the light surface. As we saw above, the efficiency of acceleration depends on the value of $\gamma_0^{1/2} = (\omega_c/\Omega_F)^{1/2}$. Thus, nuclei will receive energy per nucleon $(Zm_p/m)^{1/2} \simeq 2^{-1/2}$ times less than protons.

4. Jet’s remnants

The center of the Galaxy, being active, created a relativistic jet, particles of which spread in the Galaxy, forming isotropic background of cosmic rays. If one consider that the angular momentum of the massive black hole in the center of the Galaxy coincides with that of the Galaxy, than the direction of the jet propagation is perpendicular to the plane of the Galaxy. The jet length can be quite large, so jet in M87 extends $\simeq 2$ kpc. Therefore, above and below the Galactic plane (if we have two almost symmetrical jets) one can see traces of the jet.

Let us consider a simple diffusive model of propagation of relativistic particles, whose source is located in the center of the Galaxy ($\mathbf{r} = 0$), in an interstellar medium

$$\frac{\partial N}{\partial t} + \mathbf{u}\nabla N - \nabla\hat{D}\nabla N = Q(t)\delta(\mathbf{r}). \quad (9)$$

Here \mathbf{u} is the velocity of the interstellar matter. We consider the region outside the stellar galactic disk, then the velocity \mathbf{u} is the speed of the galactic wind, which is along the coordinates z which is perpendicular to the plane of the Galaxy. The value of \hat{D} is the diffusion coefficient, which can be anisotropic. Diffusion depends on the intensity of the magnetic field B , falling exponentially with the distance z from the galactic plane, $B = B_0 \exp(-z/z_1)$, $z_1 \simeq 2$ kpc. Diffusion of charged particles is determined by their motion in the magnetic field, and the diffusion coefficient is inversely proportional to the magnetic field strength, $D \propto B^{-\alpha}$. So, for the most strong Bohm diffusion $D = cr_c/3$, r_c is the proton cyclotron radius, $\alpha = 1$. Thus, the particle diffusion increases exponentially with the coordinate z , $D = D_0 \exp(z/z_0)$, $z_0 = z_1/\alpha$. Such a strong dependence of the diffusion on the coordinate z leads to effective non diffusion expansion of particles along this coordinate and decreasing its density. To take into account this effect we insert the function $\varphi = N \exp(z/z_0)$. Eq.

(9) becomes

$$\exp\left(-\frac{z}{z_0}\right) \frac{\partial\varphi}{\partial t} + u \exp\left(-\frac{z}{z_0}\right) \left(\frac{\partial\varphi}{\partial z} - \frac{\varphi}{z_0}\right) + \frac{D_0}{z_0} \frac{\partial\varphi}{\partial z} - D_0 \left[\frac{\kappa}{\rho} \frac{\partial}{\partial\rho} \left(\rho \frac{\partial\varphi}{\partial\rho} \right) + \frac{\partial^2\varphi}{\partial z^2} \right] = Q(t) \frac{\delta(\rho)\delta(z)}{2\pi\rho}. \quad (10)$$

We consider the distribution of particles as azimuthal symmetric depending on the distance z and the cylindrical radius ρ . The value of κ is the ratio of the transverse diffusion coefficient D_\perp , perpendicular to z , to the longitudinal one D_\parallel , along z , $\kappa = D_\perp/D_\parallel$. We see that in the equation of particle motion there appears the effective velocity along z , $u_0 = D_0/z_0$. It arises as a result of the exponential growth of the particle diffusion over z . For characteristic values of $D_0 = 5 \cdot 10^{28} \text{ cm}^2/\text{s}$ and $z_0 = 2 \text{ kpc}$ the velocity u_0 is of $u_0 \simeq 10^2 \text{ km/s}$. This speed is much larger than the speed of the galactic wind u , which at distances of several kpc from the galactic plane is less than 30 km/s (Ptuskin, 2007). Although the wind velocity increases with distance z , the exponential factor $\exp(-z/z_0)$ in Eq. (10), allows us to ignore the velocity of the galactic wind in comparison with the velocity u_0 . Values of D_0 and z_0 specify scales of length and time, so it is convenient to go to the dimensionless variables in Eq. (10) $z' = z/z_0$, $\rho' = \rho/z_0$, $t' = t(D_0/z_0^2)$, $\varphi' = \varphi z_0^3$. Eq. (10) becomes (primes are omitted)

$$\exp(-z) \frac{\partial\varphi}{\partial t} + \frac{\partial\varphi}{\partial z} - \frac{\partial^2\varphi}{\partial z^2} - \frac{\kappa}{\rho} \frac{\partial}{\partial\rho} \left(\rho \frac{\partial\varphi}{\partial\rho} \right) = Q(t) \frac{\delta(\rho)\delta(z)}{2\pi\rho}. \quad (11)$$

At $z > 1$ the propagation (first derivative over z) predominates over the diffusion (second derivative), and Eq. (11) makes easy

$$\varphi = \frac{Q[t - (1 - e^{-z})]}{4\pi\kappa z} \exp\left(-\frac{\rho^2}{4\kappa z}\right).$$

From this solution one can see that to the point z come particles, which were emitted by the source at the retarded time $t' = t - (1 - e^{-z})$. If the time of the jet's start is $t = 0$, particles will lift to the maximum height of $z_m = -\ln(1 - t)$, $t < 1$. Formally at $t = 1$ particles come to infinity during the finite time, that is impossible. The velocity limitation implies the condition $z_m < (cz_0/D_0)t$, c is the speed of the light, which is not difficult to hold because $cz_0/D_0 \simeq 3.6 \cdot 10^3$. Knowing the value of z_m from observation one can estimate the time t_1 when the power source of cosmic rays in the center of the Galaxy begins to work, i.e. when the jet starts, $t_1 = 1 - \exp(-z_m)$. In dimensional units $t_1 = t_0[1 - \exp(-z_m/z_0)]$, $t_0 = z_0^2/D_0$. When $z_0 = 2 \text{ kpc}$ and $D_0 = 5 \cdot 10^{28} \text{ cm}^2/\text{s}$ the time t_0 is $t_0 = 7.6 \cdot 10^{14} \text{ s} = 2.4 \cdot 10^7 \text{ yr}$. The gamma radiation observed above and below the galactic plane extends to the height of about 8 kpc (Su et al., 2010), i.e. $z_m \simeq 4$. This means that in fact $t_1 = t_0$. In addition, one can find the time t_2 when the source turns off. If the jet worked a short time, all particles would have lifted in height at $z \geq 1$, and we would see their

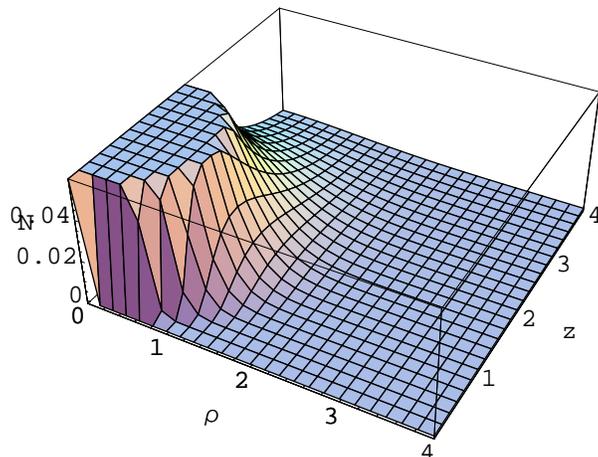


Figure 4: The density distribution of relativistic particles (12) above the galactic plane in dimensionless coordinates: z , the distance from the plane of the Galaxy, and ρ , the cylindrical radius.

absence near the galactic plane. Since this is not observed in bubbles, then $t_2 < t_0(1 - 1/e) \simeq 0.6t_0$.

Knowing the solution for φ at $z > 1$ we can find the density of relativistic particles $N(t, z, \rho)$ in the same region

$$N = \frac{Q[t - (1 - e^{-z})]}{4\pi\kappa z_0^3} \exp \left[- \left(\frac{\rho^2}{4\kappa z} + z + \ln(z) \right) \right]. \quad (12)$$

The distribution $N(z, \rho)$ (12) for the permanent source, $Q = const(t)$, is shown on Figure 4. We also draw levels of the constant density N , $\rho^2/4\kappa z + z + \ln(z) = const$, Figure 5. The value of κ , the anisotropy of diffusion, is chosen to be equal to $\kappa = 0.14$ from those considerations that the observed ratio of bubble's scales $z/\rho \simeq 8kpc/3kpc = 8/3$ would be consistent with the forms of the constant density profiles painted on Figure 5. It seems that such value of κ indicates that the magnetic field in the halo of the Galaxy near the center is mostly vertical. And this is natural because for the cylindrical symmetry radial and azimuthal magnetic field components should approach zero on the axis $\rho = 0$.

5. Discussion

We have shown that whereas in the past the center of the Galaxy was active and radiated the jet, its energy and composition are sufficient to explain the origin of cosmic rays in the Galaxy. Bubbles of a relativistic gas observed in gamma, x-ray and radio bands above and below the galactic plane, apparently, are remnants of the bipolar jet emitted from the vicinity of the massive black

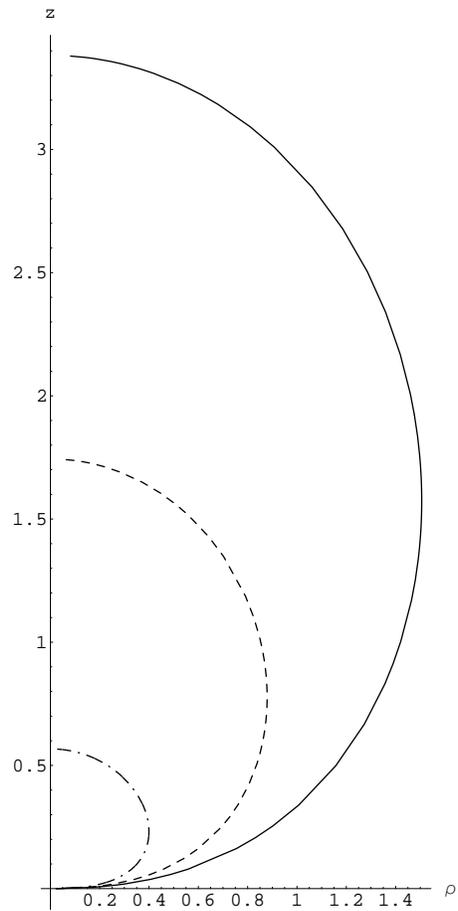


Figure 5: Levels of the constant density of relativistic particles specified by the distribution (12).

hole in the center of the Galaxy. The vertical size of the bubble $z \simeq 8$ kpc permits us to estimate the time of switching on of the jet, $t_1 \simeq t_0 = 2.4 \cdot 10^7$ years ago. We can also estimate the lower limit of the jet's work, $\Delta t = t_1 - t_2 > 0.4t_0 \simeq 10^7$ yr. During the time Δt the jet got the energy $L_J \Delta t \simeq 8.9 \cdot 10^{45}$ erg/s $\times 3 \cdot 10^{14}$ s $\simeq 2.7 \cdot 10^{60}$ erg, that is slightly larger than the energy stored in the black hole rotation $\simeq 10^{60}$ erg. However, if we estimate the mass of the accreted matter, absorbed by the black hole at the same time, it can reach a large part of the mass of the black hole, $\Delta M \simeq \dot{M}_{Edd} \Delta t = 9.2 \cdot 10^{-2} M_\odot \text{ yr}^{-1} \times 10^7 \text{ yr} \simeq 10^6 M_\odot$, $\Delta M \simeq M/4$. Transmitted to the black hole by the accreted matter, the angular momentum ΔJ can even exceed its initial value (Istomin, 2004). The jet's energy $\simeq 10^{60}$ erg is enough to fill by cosmic rays as the disk (10^{55} erg), as the halo ($10^{57} - 10^{58}$ erg) of the Galaxy. Filling of the disk of the Galaxy by relativistic particles is described by the same Eq. (11), but there should be $|z| < 1$. Therefore, we can ignore the dependence of the diffusion coefficient on the distances z , and solve the pure diffusion equation

$$\frac{\partial N}{\partial t} - D_{\parallel} \frac{\partial^2 N}{\partial z^2} - D_{\perp} \frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial N}{\partial \rho} \right) = Q(t) \frac{\delta(\rho) \delta(z)}{2\pi\rho}.$$

Here we are interested in distribution of particles in the disk on the transverse distances ρ , so we average this equation over z and get

$$\frac{\partial \bar{N}}{\partial t} - \frac{D_g}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial \bar{N}}{\partial \rho} \right) = Q(t) \frac{\delta(\rho)}{2\pi\rho}, \quad (13)$$

where the value of $D_{\perp} = D_g$ is the diffusion coefficient of cosmic rays in the galactic disk. The solution is

$$\bar{N} = \frac{1}{4\pi D_g} \int_0^{t_1} \frac{1}{\tau} \exp\left(-\frac{\rho^2}{4D_g\tau}\right) Q(t_1 - \tau) d\tau.$$

The time t_1 is the start time of the jet. If the jet had worked with constant power Q and switched off at the time t_2 , then the density distribution of cosmic rays in the disk is

$$\bar{N} = \frac{Q}{4\pi D_g} \int_{\rho^2/4D_g t_1}^{\rho^2/4D_g(t_1-t_2)} x^{-1} e^{-x} dx. \quad (14)$$

The solution (14) shows that if $\rho^2/4D_g t_1 < 1$ then the distribution of the density over the radius ρ is almost uniform. For $\rho^2/4D_g(t_1 - t_2) > 1$ it is logarithmic, $\bar{N} \propto -\ln(\rho^2/4D_g t_1)$, and for $\rho^2/4D_g(t_1 - t_2) < 1$ it is constant, $N \propto \ln(t_1/(t_1 - t_2))$. The diffusion coefficient of cosmic rays in the disk equals $D_g = 2.2 \cdot 10^{28} \gamma^{0.6} \text{ cm}^2/\text{s}$ (Ptuskin, 2007). The condition $R^2/4D_g < t_0$, $R \simeq 15$ kpc is the disk radius, imposes a lower limit on the energy of protons, homogeneously filling the galactic disc, $\gamma > 400$. Apart the diffusion particles can move freely along the regular magnetic field of spiral arms of the galactic disk. The necessary for filling velocity $R/t_0 \simeq 6 \cdot 10^7 \text{ cm/s} = 2 \cdot 10^{-3} c$ does not contradict the

observed anisotropy of cosmic rays δ , $\delta \simeq 10^{-3}$. Since the dependence of the distribution (14) over the energy is determined not only by the energy spectrum of the source $Q(\gamma)$ but also the dependence of the diffusion coefficient $D_g \propto \gamma^{0.6}$ over the energy, the spectrum of particles in the disk will be softer than that in the source. Thus, the discussed mechanism of origin of galactic cosmic rays by the jet, emitted from the center of the Galaxy, satisfactorily explains the observed spectrum, the index -2.7 (-2.6 for the jet) before the break, and the index -3.1 (-3.0 for the jet) after the break.

Cosmic rays, filling simultaneously the galactic disk and the halo, flow out from the Galaxy. Their lifetime τ is determined by as the energy loss time τ_E , as the time of diffusion leakage from the Galaxy after the source of relativistic particles stopped, τ_D . The time τ_E is estimated as $\tau_E \simeq 3 \cdot 10^7$ yr (Strong & Moskalenko, 1998). It is larger than the time of the jet's start t_1 , i.e. beginning of the filling of the Galaxy by cosmic rays, $\tau_E > t_1$. The diffusion time $\tau_D = r^2/4D$ is determined by the distance r that particles travel during the period from the switching on of the source $r = (4Dt_1)^{1/2}$. Thus, $\tau_D \simeq t_1$ does not depend on the energy of particles. This time is also larger than the time of jet's switching off t_2 , $t_2 < 0.6t_1$. We see that to now the distribution of relativistic particles, generated by the jet, does not change noticeable.

Aknowlegements

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