DISTRIBUTION OF SYNCHROTRON RELATIVISTIC PLASMA EMISSION OVER QUASAR RADIO LOBES

V.M. Kontorovich, F.M. Kolesnikov
Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Kharkiv, Ukraine

Asymmetrical lobe structures of radio galaxies and quasars can be explained in the diffusion model with the moving hot spot (the source of ultra relativistic electron plasma) by the possible jet precession. The equation for the space-time nonuniform electron distribution function, describing the synchrotron losses and the diffusion of electrons from the hot spot into the lobes, is solved analytically. The space distributions of the synchrotron emission intensity and the spectral indices on the lobe are calculated numerically for different parameters of the jet precession and the diffusion.

PACS: 98.54.G

1. DEVIATION

Before to begin the main part of the report we will make some deviation. One of us (V.M.K.) was a student of A.I. Akhiezer in 1951/1952 years when he gave us lecture on electro-dynamics. He lectured brilliantly, interspersing his speech with jokes and fun. The same style was common for A.I. Akhiezer later on the scientific seminars during all the time the reporter knew him. These were the idioms, part of which is hard to translate from the Russian-Soviet slang. For example we'll cite some of them.

Pithy sayings of A.I. Akhiezer
(as V.M.K. remembered them):

"And where is the trickery?" (*А где же обман?*), "If there is no trickery it isn't (theor)physics but math!" (*Если нет обмана, то это уже не (теор) физика, а математика*), "Explain it to us in a common worker-peasant way!" (Объясни нам по рабоче-крестьянски), "They fool us about, the worker and peasants" (*Дурят нас, рабочих и крестьян*), "The fraud of the working people" (*Обман трудящихся*).

And finally:

"The author is probably right" (*Автор, вероятно, прав*). We hope you could say the last in the end of our story.

As the example we illustrate the told by funny slogans which were placed on the restaurant wall at the time of 50 years celebration of I.M. Lifshits - the friend and colleague of A.I. Akhiezer[1].

> The quasi-particles are not the same
> what you mean by particles.
> *I.M. Lifshits*

> The particles are not the same
> what you mean by quasi-particles.
> *A.I. Akhiezer*

These jokes of course were not told ever by their "authors" but they reflect the reality of Kharkiv scientific life of that time and some spirit of competition between the scientific schools.

The scientific field of our report on the first side is out of the circle of interests of AI. But if we look at the diagram (Fig 1) we see that in the astrophysical problem of AGN all physical links (arrows on the diagram) include the theoretical branches in which had worked AI: plasma physics, shocks, stability, kinetic equations, power low spectra, fluctuations and so on [1].

2. INTRODUCTION

With achievement of better angular resolution of radio telescopes the understanding of the structure and processes occurred in discrete cosmic radio sources varied rapidly – from radio stars at the dawn of radio astronomy to extragalactic sources later: radio galaxies and quasars. These latter appeared to have their extended components (lobes) being far off the optic galaxies and commonly symmetric to them (classical double radio sources). Whence the idea of the inflow into the extended components of the cosmic jets transporting the energy from the active galactic nuclei appeared. In powerful sources the jets end in hot spots, thought to be the regions of acceleration of electrons (on the shocks) being responsible for synchrotron emission of the lobes. Relativistic electrons fill up the lobes either by diffusing from or by flowing out of the hot spots loosing their energy mainly for the synchrotron emission. As the emission frequency depends heavily on the electron energy the lobe structure differs for different observation frequencies and is sensitive to the motion of source of electrons (hot spot).

Considered is a purely diffusion model with the moving hot spots which permits to obtain the component distribution of total intensity, emission polarization, spectral indices for different observation frequencies, angles to the line of sight, etc. accounting for different nature of the hot spot motion. The lobe

[1] "Квазичастицы – это вам не частицы"
И.М. Лифшиц
"Частицы – это вам не квазичастицы"
А.И. Ахиезер
"Uspekhi Il' Mekhanicheskih Nauk", №2, 1967 (the hand-made journal devoted the jubilee of I.M. Lifshits).

structures of radio galaxies and quasars can be explained within the diffusion model with the moving hot spot [2], being the place of the injection of ultra relativistic electrons [3, 4]. Both the longitudinal motion of the source of electrons and the transverse one, connected with the evolution of the radio source, are

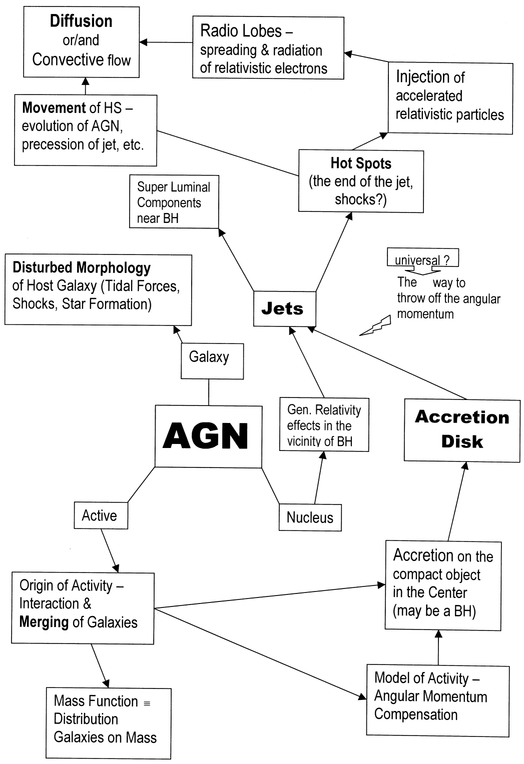

Fig. 1. *The general scheme of the extra galactic radio source (radio galaxies and quasars) problem*

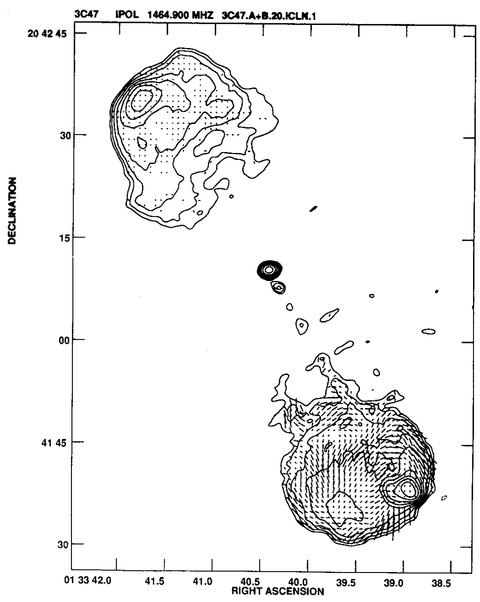

Fig. 2. *Contour map of the total intensity of 3C 47 at 1456 MHz (J.P. Fernini,et al. [8]) with polarization E– vectors (in our model do not considered). For this frequency total intensity maps the bottom southern-west lobe were calculated under the assumption of electron diffusion*

considered. The equation for the electron distribution function [5-7], describing the synchrotron losses and the diffusion of electrons, is solved analytically. The space distributions of the synchrotron emission intensity at 1400 MHz and the distribution of spectral indices on the lobe are calculated numerically for different velocities of the hot spot, parameters of the jet precession and the diffusion. Obtained maps of extended components are compared with the observed lobe structures of the quasar 3C 47 [8,9]. The structure of extended components is sensitive to the parameters of the jet precession cone, the diffusion and hot spot velocities ratios. The variation of parameters allows to obtain the double hot spots, corresponds to the old and new positions of the moving (due to the jet precession) electron injection region.

3. QUASAR 3C 47 AS AN EXAMPLE

We regard the problem by example of quasar 3C 47 (see Fig. 2). This radio source is one of the most powerful of FRII type. The redshift of 3C 47 is 0.425, with a scale of 4.4 kpc arcsec^{-1}, the linear size of the quasar radio emission is 305 kpc assuming a value for the Hubble constant H_o=75 km s^{-1} Mpc^{-1} and acceleration parameter q_o=0.5 [8]. The 4885 MHz total intensity map in Fig. 3 shows two completely resolved lobes with a jet linking the central core to the south-western lobe. The super luminal motion observed in 3C 47 implies that the knot is moving in a direction which is at most 31^0h away from the line of sight [10]. There are two spots in the south-western lobe, one component is more compact and spectral indices for more compact and less compact component 0.3 and 0.77 accordingly. The observed jet is gently curved through all of its length. Two hot components in the SW lobe, their different spectral indices can be explained in the way that the less compact component is the old position of the precessing jet, more compact component – the position of the jet end at the present of observation (hot spot). Projection of a spiral jet trajectory is seen like a curved jet. We calculated total intensity maps (at 1400 MHz) and spectral indices distributions (1400 MHz and 4900 MHz).

4. EQUATIONS AND PARAMETERS OF THE DIFFUSION MODEL

The kinetic equation for the space-time nonuniform electron distribution function $N = N(E,\mathbf{r},t)$:

$$\frac{\partial N}{\partial t} + \frac{\partial (B N)}{\partial E} - D \Delta N = Q ,$$

where

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} .$$

This equation describes diffusion of relativistic electrons (with synchrotron losses) injected by a moving point source. $D(E) = D_0\left(\frac{E}{E_D}\right)^{\mu}$ – the diffusion factor (in the calculations $\mu = 0$), $B(E) = -\beta E^2$ – the law of

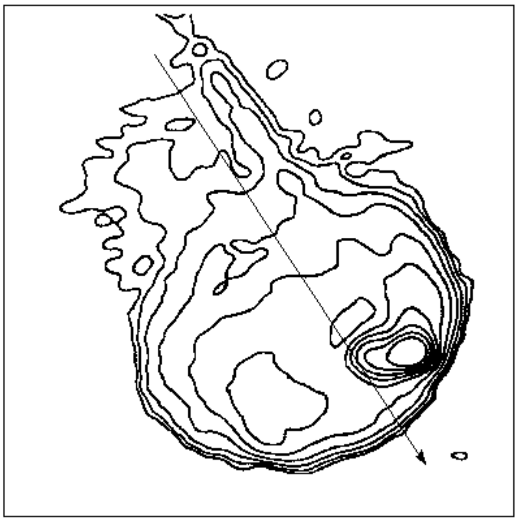

Fig. 3. *SW lobe of the quasar 3C 47 at 4885 MHz (J. P. Fernini,et al. [8]). Peak flux = 1.9608·10^{-1} Jy/beam, levels = 1.0·10^{-4}·(–2.0, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, 64.0, 128.0, 256.0, 512.0). We are interesting in SW lobe with two compact spots (I – new position of hot spot, J – its old one). A right side of the figure is the enlarged SW lobe. The arrow indicates the direction of axis x in our model (see Fig. 4). When we calculate total intensity maps and spectral indices, the jet does not considered*

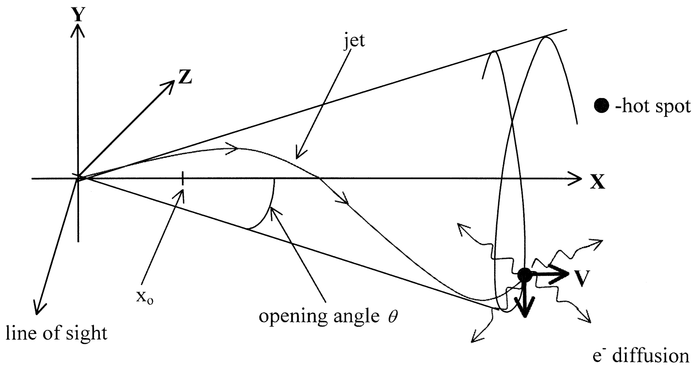

Fig. 4. *The scheme of jet precession (with the coordinate system and precession parameters)*

electron energy attenuation (due to synchrotron losses), where $\beta = \frac{32\pi}{9}\left(\frac{e^2}{mc^2}\right)^2 \frac{W_H + W_t}{m^2 c^3}$.

$Q(E,\mathbf{r},t) = Q_0\,\delta\,(x - x(t))\,\delta\,(y - y(t))\,\delta\,(z - z(t))$ $E^{-\gamma_0}\,\Theta\,(t)\,\Theta\,(E_2 - E)\,\Theta\,(E - E_1)$ – the point moving source of electrons with power law of injection, where $\Theta\,(x) = 0$ for $x < 0$ and $\Theta\,(x) = 1$ for $x > 0$, γ_0 – injection index (in calculations $\gamma_0 = 2$, that corresponds the acceleration on the strong shocks). The energies were chosen like E_2 corresponds to 1GHz and E_1 corresponds to 10 MHz respectively.

$x(t) = x_0 + Vt$, $y(t) = x(t)\,tg\theta\,\cos(\omega\, t + \psi)$, $z(t) = x(t)\,tg\theta\,\sin(\omega\, t)$ (see Fig. 4), where x_0 – the location of electron injection process [11-14] beginning at the moment $t = 0$ (in our calculations $x_0 = 0$), V – the source velocity projection at the axis x, θ – the jet opening angle, ω – the jet precession frequency, ψ – the phase difference (determine the form of precession cone). The main parameters of the model: $\tau \sim 1/(\beta\, E)$ – "life time" of a relativistic electron, $l_{dif} \cong \sqrt{D\tau}$ – "diffusion length" of electrons, $V_{dif} \cong \sqrt{D/\tau}$ – "diffusion velocity" of electrons.

5. SOLUTION OF KINETIC EQUATION FOR RELATIVISTIC ELECTRON DISTRIBUTION FUNCTION AND TOTAL RADIATION INTENSITY (FOR THE TRANSPARENT RESOLVED SOURCE)

The kinetic equation can be transformed to the diffusion equation by the Laplas transformation [2] or by transition to the derivation in the new line in the $t - E$ plane [15]. Here we solved the equation by transition to new two variables $t' = t - \tau$, where $\tau = \int \frac{dE}{B}$ and $\lambda = \int \frac{D}{B} dE$. Limits of integrating are chosen accordingly to initial conditions and the source characteristics. This transition transformed our equation

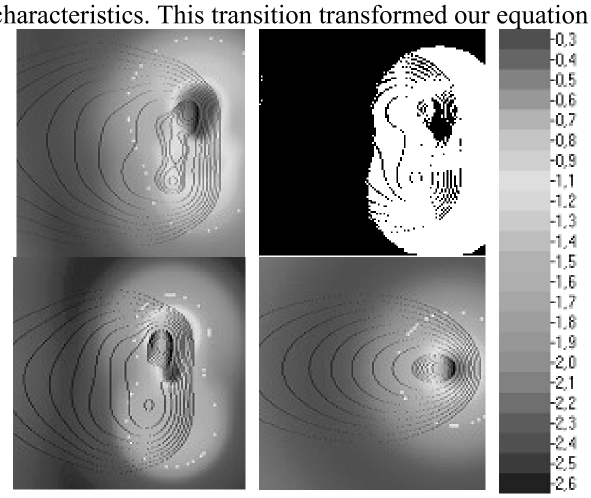

Fig. 5. *Calculated total intensitymaps at 1400 MHz with the spectral indices distributions for various "life time" of electrons τ (preliminary result). From the left map to the right map, from up to down "life time" of electrons is 0.25τ , 1τ , 2τ with jet precession and 1τ when there is no jet precession respectively. Levels= 2^k (k= 0, 1, ..., 9). For the regions of hot spots there are addition levels = 1.m (m= 0, 1,..., 9)*

to the diffusion equation with well-known solution and so we have the kinetic equation solution when $\mu = 0$:

$$N(E,\mathbf{r},t) = \frac{Q_0 \beta^{\gamma_0 - 2}}{8\pi^{3/2} E^2 D_0^{\gamma_0 - 1}} \int_0^{\lambda} d\lambda' \frac{\lambda'^{\gamma_0 - 2}}{(\lambda - \lambda')^{3/2}}$$

$$\Theta\left(E_2 - \frac{D_0}{\beta\lambda'}\right)\Theta\left(\frac{D_0}{\beta\lambda'} - E_1\right)\Theta\left(t - \left(\frac{\lambda}{D_0} - \frac{\lambda'}{D_0}\right)\right)$$

$$e^{-\frac{\left(x - x\left(t - \left(\frac{\lambda}{D_0} - \frac{\lambda'}{D_0}\right)\right)\right)^2 + \left(y - y\left(t - \left(\frac{\lambda}{D_0} - \frac{\lambda'}{D_0}\right)\right)\right)^2 + \left(z - z\left(t - \left(\frac{\lambda}{D_0} - \frac{\lambda'}{D_0}\right)\right)\right)^2}{4(\lambda - \lambda')}}$$

where, if we introduce designation

$$t^* = t - \left(\frac{\lambda}{D_0} - \frac{\lambda'}{D_0}\right),$$

we have

$$x(t^*) = x_0 + Vt^*,$$

$$y(t^*) = x(t^*)\, tg\theta \cos(\omega t^* + \psi),$$

$$z(t^*) = x(t^*)\, tg\theta \sin(\omega t^*).$$

Note that λ is the square of the "diffusion length". Expression for the total radiation intensity for the transparent resolved source:

$$I(\nu, \mathbf{r}, t) = \frac{\sqrt{3} e^3}{mc^2} \int dE \int dR\, N(E, \mathbf{r}, t) H \frac{\nu}{\nu_c} \int_{\frac{\nu}{\nu_c}}^{\infty} d\eta\, K_{5/3}(\eta)$$

where $\nu_c = \frac{3eH}{4\pi mc}\left(\frac{E}{mc^2}\right)^2$ is the frequency of

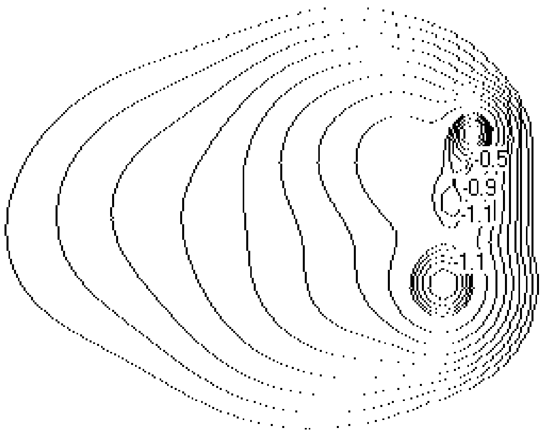

Fig. 6. *The figure shows the calculated map (V/V_{dif} =5, n=30, ψ =70^0, θ =2.8^0, α =90^0) with marked spectral indices (preliminary result). The hot spot component has a spectral index 0.3 (observed index 0.3 [8]) and the less compact component has 1.2 (observed index 0.77 [8]). Note that we have expected 0.5 for index value estimated as (γ_0 –1)/2, γ_0 =2 of hot spot component. We can't exclude the difference between these values may be the result of accumulated calculation error*

synchrotron radiation maximum. H is the mapping plan projection of magnetic field. $\int dE \int dR$ corresponds to the energy integrating and integrating along the line of sight respectively.

Returning to the beginning of the article we reproduce the copy of the page from the journal that we have mentioned in the footnote at the first page:

6. SUMMARY

The main equation of the diffusion model is the kinetic equation for the distribution function of relativistic electrons. It describes the diffusion of electrons with account for the synchrotron emission losses. Electrons diffuse from the moving source (hot spot), which has the power law of injection in some energy interval. Diffusing and losing their energy in magnetic fields, electrons due to synchrotron emission form the lobes – extended components of radio galaxies and quasars.

In our case we consider that the motion of a point HS is resulted from the jet precession. Such kind of the HS motion may explain the complex structure of lobes for a number of 3C 47 type radio sources.

In the case of an uniform straight-line motion of the HS the typical morphological structure was obtained by Valtaoja, 1982 and Gestrin, Kochanov and Kontorovich, 1987 – the extended component was elongated and the hot spot was placed near the border of the lobe as usually observed for quasars and powerful radio galaxies.

The spreading electron parameters of the model for a given observation frequency are: the "life time" of a relativistic electron (characterizes the magnetic field), its “diffusion length” and “diffusion velocity” of motion of electrons. They compete with parameters of the moving source of electrons: longitudinal and transverse HS velocities.

To solve analytically the equation for distribution function we reduced it to the nonstationary diffusion equation.

When we know distribution function, the distributions of total intensity, polarization, spectral indices and the sources’ spectra can be obtained in the integral form and the maps of the sources can be calculated for different parameters of the model.

The preliminary results of the paper are shown as total intensity maps and spectral index distribution maps for the lobe (see Fig. 5 and Fig. 6), which are in approximate agreement with the maps of 3C 47.

REFERENCES

1. A.I. Akhiezer, I.A. Akhiezer, R.V. Polovin, A.G. Sitenko, K.N. Stepanov. *Plasma electrodynamics*. 1974, Moscwa: ‘Nauka”, 719 p.
2. E. Valtaoja. Diffusion of electrons in radio galaxies // *A&Ap*. 1982, v. 111, №2, p. 213-219. S.G. Gestrin, V.M. Kontorovich, A.E. Kochanov. The diffusion model of extended radiocomponents and jets with the moving source of accelerated particles // *Kinematika i Fizika Nebesnih Tel.* 1987, v. 3, №4, p. 57-66.
3. M.C. Begelman, R.D. Blandford, M.J. Rees. Theory of extragalactic radio // *Rev. Mod. Phys*. 1984, v. 56, №2, p. 255-350; A.H. Bridle, R.A. Perley. Extragalactic radio jets // *ARA&Ap.* 1984, v. 22, p. 319-358.
4. B.D. Blandford, M.J. Rees. A 'twin-exhaust' model for double radio sources // *MNRAS.* 1974, v. 169, p. 395-544. *Hot Spots in Exlragalactic Radio Sources*, ed. K. Meisenheimer, H.J. Roser. Berlin: “Springer”, p. 45.
5. V.S. Berezinskiy, S.V. Bulanov, V.L. Ginzburg, et al. *Astrofizika kosmicheskih luchey*. 1984, Moscow: “Mir”, 486 p.
6. A.E. Kochanov, V.M. Kontorovich. Nonlinear spectra of radio sources at rigid injection // *Izvestiya VUZov. Radiofizika.* 1981, v. 24, №9, p. 1047-1053.
7. V.M. Kontorovich, F.M. Kolesnikov. The images of extragalactic radio sources in the diffusion model // *Odessa Astronomical Publications*. 1999, v. 12, p. 90-92.
8. A.H. Bridle, D.H. Hough, C.J. Lonsdale, et al. Deep VLA imaging of twelve extended #C quasars // *AJ.* 1994, v. 108, №3, p. 766-820. J.P. Fernini, J.P. Leahy, J.O. Burns, et al. Depolarization asymmetry in the quasar 3C 47 // *ApJ.* 1991, v. 381, №1, p. 63-71. G.H. Macdonald, S. Kenderdine. Ann C. Neville. Observations of the structure of radio sources in the 3C catalogue - I // *MNRAS.* 1968, v. 138, №3, p. 259-311.
9. A.V. Men’, S.Ya. Braude, S.L. Rashkovskiy, et al. Observation of the quasar 3C 47 with the interferometer URAN at the dekametric wavelength // *Izvestiya VUZov. Radiofizika*. 1995, v. 38, №6, p. 511-521.
10. R.C. Vermeulen, R.A. Bernstein, D.H. Hough, A.C.S. Readhead. Superluminal motion in the large, lobe-dominated quasar 3C 47 // ApJ. 1993, v. 417, №2, p. 541-546. B.R. Oppenheimer, J.A. Birerta. Test of unified schemes using jet opening angles // *AJ.* 1994, v. I07, p. 892-903.
11. M.C. Begelman, R.D. Blandford, M.J. Rees. Massive black hole binaries in active Galactic nuclei // *Nature.* 1980, v.287, p. 307. H.J. Lehto, M.J.

Valtonen. OJ 287 outburst structure and a binary black hole model // *ApJ.* 1996, v. 460, №1, p. 207-213.
12. R.M. Hjellming, K.J. Johnston. An analysis of the proper motions of SS 433 radio jets // *ApJ Letters*. 1981, v. 246, №1, p. 141-145.
13. A.C. Gower, P.C. Gregory, J.B. Hutchings, W. Unruh. Relativistic precessing jets in quasars and radio galaxies: models to fit high resolution data // *ApJ*. 1982, v. 262, №2, p. 478-496; R. Ekers et. al. GC326 - a radio galaxy with a precessing beam // *Nature.* 1978, v. 276, p. 588-590.
14. U.V. Baryshev. Precessing jet model for classical double radio sources // *Pis'ma v AZh*. 1983, v. 9, №10, p. 591-594.
15. V.M. Kontorovich, F.M. Kolesnikov. Diffusion model of extragalactic radio source extended components with precessive jet // *Radiophysics and Radioastronomy*. 2001, v. 6, №1, p. 32-44.