ON THE INFLUENCE OF MHD TURBULENCE ON THE STRUCTURE OF THE RADIOGALAXY LOBES

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ABSTRACT. There is considered the evolution of the shape for the radio galaxy lobes of FRI and FRII types from the point of view on changing the configuration of large-scale structure of magnetic field, and energy transport in the turbulent MHD waves. There have been studied the interaction and transformation of waves in the active regions of the lobes, and so studied the role of MHD waves and vortexes in media-mixing processes and in the amplification of the average magnetic field. The transport of low-energy e-cosmic rays (e-CRs) responsible for the radio emission in the MHz band (recorded at the UTR-2 and GURT telescopes) is analyzed for the sources like to the Cygnus A and M87. It is shown that the transport of e-CRs mainly corresponds to the diffusion of CRs on MHD and turbulence scatter, and the entrainment of CRs by quasi-regular post-jet flows inside to the lobe. So, the MHz radio emission that observed emphasizes the peculiarities in the lobe which arising when the magnetic field is in reorganization.

АБСТРАКТ. Розглянуто еволюцію форми пелюстки радіогалактик FRI і FRII типів з точки зору зміни конфігурації великомасштабної структури магнітного поля, і перенесення енергії у вигляді турбулентних МГД хвиль. Досліджено взаємодію і трансформацію хвиль; роль МГД хвиль та вихорів в процесах змішування середовищ і в посиленні середнього магнітного поля. Проаналізовано перенесення е- космічних променів (е-КП) малих енергій, відповідальних за радіовипромінювання в МГц діапазоні (реєстроване на телескопах УТР-2 і ГУРТ), на прикладі джерел Лебідь А і М87. Показано, що за перенесення е-КП, головним чином, відповідають процеси дифузії КП на МГД турбулентності, і захоплення космічних променів квазірегулярним пост-джетовим потоком всередині пелюстки. В ближній околиці горячої плями FRII радіогалактики космічні промені виносяться регулярною течією разом з пост-джетовим потоком швидше, ніж дифузійним механізмом. Регулярне перенесення і дифузія на вихровій турбулентності малих масштабів визначають поширення е-КЛ малих енергій лише у внутрішній частині пелюсток радіо галактики; в той же час, як дифузійне поширення променів, що відбувається за рахунок розсіювання на МГД хвилях, є домінуючим механізмом перенесення КЛ в зовнішніх шарах пелюсток радіогалактик. В FRI радіогалактиках переважно домінує перенесення е-КП з течією. Електронні КП малих енергій дифундують повільніше за енергійні е-космічні про-

мені, і вони щільніше прилягають до ліній магнітного поля; в результаті чого, МГц- випромінювання, що спостерігається, підкреслить всі особливості пелюстки, які виникають при перебудові магнітного поля, і ретельніше промалює структуру переднього краю пелюсток в радіогалактиках обох типів.

Key words: radio galaxy, lobes, FRII, Cygnus A, FRI, M87, cosmic rays, magnetic field, MHD turbulence, transport of CRs, diffusion.

1. Introduction

The model of radio galaxy (RG) as the Jet-Lobe structure is formed at the second part of the 20th century (see Begelman, et al., 1984), and then it was developed in much works, such as Kino, et al. (2004), Canvin J.R., et. al. (2005), Mathews, Guo (2011, 2012), Guidetti et al., (2011), and others. It was shown that the magnetic fields in the RG lobes are approximately in equipartition with the cosmic-ray pressure, so that from the radio observations of synchrotron radiation it is possible to estimate the magnetic field strengths. A more detailed analysis (Pudritz et al., 2012), based on wide-ranging RG observations, has now shown that, for most lobes, the magnetic pressure is much less than the plasma pressure, while the magnetic pressure is approximately comparable to the pressure of the thermal and relativistic plasma only inside the jet. Thus, the condition of smallness of the magnetic field inside the lobe indicates that the law of freezing of the magnetic field in the plasma of the lobe should be interpreted as the entrainment of magnetic fields together with the heat plasma streams, and the thermal medium of the lobe is in the processes of constant mixing the intra cluster matter with the substance of post-jet flow.

The evolution of the lobe is accompanied by a number of physical processes. Jet and post-jet streams entrain magnetic fields into the lobe. In the boundary of flow layers, the Kelvin-Helmholtz instability is excited, which converts the energy of the flows into the energy of MHD and eddy (vortex) turbulence, and they, in turn, accompany the processes of amplification of the large-scale quasi regular (average) magnetic field in the jet and in the lobe. The relativistic jet is effectively supported by viscous forces, and by quasi regular magnetic fields that fro-

zen in the jet. In the lobes, there are also processes of mixing media, and accelerating the comic rays on shock gaps of jet and post-jet streams. The presence of e-CRs is detected in observations at the form of synchrotron (radio) and inverse Compton (X-ray) radiations.

In this paper, based on the HD-approximations, the formation of the jet-lobe structure and the structure of quasi regular magnetic fields in FRI-FRII radio galaxies are considered. Furthermore, MHD waves are "superimposed" on these lobe structures, and vortex perturbations that participate in mixing processes of the post-jet flow media with CRs and ICM. Finally, we consider the transport of CRs in the RG-lobes with the characteristic parameters of media in both Cygnus A (FRII type) and M87 (FRI type) radio galaxies, taking into account the propagation of CRs in diffuse-scattering by magnetic field fluctuations from MHD and eddy turbulence, and its quasi regular flows with the matter. Conclusions are made about the features of the shape of the lobes visible in the MHz radio band, and about the correlation of the visible shape of the lobe with the physical processes of mentioned above.

2. Magnetic fields and flow structure in the RG-lobe

The quasi-regular magnetic field of the lobe consists of two components: a poloidal B_p-magnetic field, elongated along the post-jet streams of matter, and a toroidal B_φ-magnetic field, wrapping the jet and amplified by the diffusion currents. So, the poloidal component of the field is formed under the influence of dynamic flows in the lobe of radio galaxies, and the toroidal field is formed by the diffusion currents associated with the advance of relativistic plasma with cosmic rays into the lobe.

In the case of FRII-lobes, the B_p-component of the field is formed under the influence of the Hill vortex (Tsvyk, 2015) dynamically sweeping up the ICM, adjacent to the wind-flow from the viscous post-jet relativistic plasma "blown" out from the hot spot (HS: the point where the jet is "reflected" in a collision with ICM). This Hill vortex accompanies the formation of a cavity in the FRII lobes, with a large content of rarefied relativistic plasma and CRs coming from the post-jet substance. The structure of the Jet - HS - Hill vortex is a consequence of the steady advancement of a powerful subrelativistic flow which has the high viscous within the rarefied jet-channel medium ($\eta/\rho = 10^{30}$ cm^2/s, see Table 1). So, the B_p-magnetic field lines follow along the jet flow, then they follow along the vortex lines flow near the HS, and they go away the lobe near the lobe surface and bow shock.

At the same time, a lobe-tail is formed in the FRI-RGs, they are the less powerful than FRII-RG sources, which show a viscous dissipation of a jet and a post-jet flow, supported by strong B_φ magnetic fields. Here: $\eta/\rho = 10^{25}$ cm^2/s (see Table 1). The evolution of this viscous jet can be described within the framework of a simple hydrodynamic model (see, for example: Landau, Lifshitz, 1986); and only consider the magnetic fields as a small addition to the medium pressure. At the same time, it is the magnetic fields that effectively trap the CRs inside the RG-lobes, and the transport of the CRs, as well as their distri-

bution, are closely related to the structure of the large-scale magnetic fields in the lobe.

3. MHD waves in RG lobes and diffusion of media

The quasi-regularly magnetic fields of the lobes change dynamically and are strongly perturbed by large-scale MHD waves (Alfvén and fast magneto-sonic, with wavelengths of $\lambda_w \sim (0.01…0.1)$ $r_{HS} > 1$ kpc), and small-scale vortex perturbations ($\lambda_{mix\_vx} \sim c_s$ min(τ_{ii}, τ_{ia}) ~ 0.1-3 pc), accompanying the mixing of post-jet plasma and ICM (with small part of atoms, $\rho_a < 10^{-4}$ ρ_{ICM}). Vortex perturbations dissipate when they interacting with relativistic particles from post-jet plasma, and their intensity is maximum in the inner part of the lobe ($B_{vx}/B_0 \sim 0.1$-0.3), where the rate of dissipation of the perturbations is balanced with the rate of their build-up in the processes of diffusion mixing of media. So, the intensity of the MHD waves is maximal in the vicinity of the hot spot, and at the shock front layers ($B_w/B_0 \sim 0.3$), and they decreases with distance from these places, both inside and outside the lobe (up to $B_w/B_0 \sim 0.003$); while, outside the lobe, the magnetic fields again become chaotic ($B_{vx}/B_0 \sim 0.7$).

Inside the lobe of the RG, the characteristics of the MHD waves also change. Thus, according to the MHD concepts (Akhiezer, 1974), the Alfven waves ($B_{w,A} \sim 0.3$ B_0) accompanying the jet flow (with Doppler shifted velocity, $v_{g\_A} \sim c_A + u_{j0} \sim c_A + c/3$) effectively propagate near the jet, and weakly damped in FRII-RG. These waves are accompanied by a rapid energy transfer along the FRII-jet along with the flux of relativistic low-density ρ_{jet} plasma (with a large content of the electron-positron component). They also participate in focusing the wave energy inside the jet channel when the phase matching conditions for wave perturbations (B_0^2/ρ_{jet} = const) are fulfilled in it, and ensure the formation of a bow shock front in the head of the jet. Reflection of A-waves on fluctuations in the density of the jet flow forms a flux of fast MS waves ($B_{w\,MS} \sim 0.1$ B_0), diverging from the jet inside the lobe.

In FRI-radio galaxies A-waves dissipate faster than fast MS waves (see table 1); and the dissipation of A-waves is stronger because of the phase-spreading mechanism in the propagation of waves in an inhomogeneous medium. Thus, in low-power FRI-radio galaxies, the jet accompanies a stream of fast MS waves: with MS-waves, $B_{w\,MS} \sim 0.2$ B_0, that propagating along the jet at the velocity of $v_{g\,MS} \sim c_s + c_A + u_{j0}$.

Inside the lobe, there is a constant mixing of media on pc-scales, λ_{mix_Vx}. The vortex perturbations, excited in these processes, determine the diffusion of the matter of the post-jet flow and the CRs to come they on the periphery of the lobe; and the mixing-diffusion of the ICM to come it inside the lobe, with a diffusion coefficient: $D_{diff\_th\_Vx} \sim \lambda_{mix,Vx} c_s \sim 10^{30}$ cm^2/s.

At the same time, the ICM is pushed out the lobe under the pressure of the post-jet substance, which is accompanied in FRII-lobes by the blowing out of the post-jet relativistic plasma from the HS, and the formation the dynamic Hill in the head-end of the jet, which first pushes out the ICM medium from the lobe-bubble, and then diffusively returns it to the inside of the lobe.

Table 1: The model of the parameters of FRII-radio galaxy (Cygnus A) and FRI-radio galaxy (M87) recovered under the assumption of the Jet-HS-Lobe structure with viscous fluxes. The main parameters of the sources give by Mathews, Guo (2012, 2011); the other parameters (see right part of table) are calculated by model approximation, according to this paper, Tsvyk (2015) and Toptygin (2007).

Main parameters	Cygnus A	M 87	Model parameters	Cygnus A	M87
Jet-lobe power: L_{jet}, erg/s	$\sim 5\ 10^{46}$	$\sim 10^{45}$	Sound velocity, $<c_s>/c$	0.0012	0.0017
Lobe density: $<\rho>/m_p$, cm^{-3}	0.02	0.04	Alfven velocity, $<c_A>/c$	0.001	0.00013
Magnetic field, B, mkG	300..20	15..5	Collision time, τ_{ii}, Myr	0.1..1	3..10
Lobe presser, $<P>$, dyne/cm^2	$<10^{-8}$	$<10^{-9}$	Collision time, τ_{ia}, kyr	10..100	0.1..1
HS position, r_{HS}, kpc	70	13	Kinematic. visc., $<\eta_K/\rho>$, cm^2/s	10^{26}	10^{24}
Lobe length, R_{Lobe}, kpc	110	90..120	Magnetic visc., $<\eta_B/\rho>$, cm^2/s	10^{17}	10^{16}
HS velocity, u_{HS}/c	0.01	$<0.1\ c_s/c$	Viscosity in HS, $\eta_{K\ HS}/\rho$, cm^2/s	10^{30}	10^{28}
Bow shock or flow velocity, $u_{tail\ (Bow\ shock)}/c$	25 $c_{s,ext}/c$	$\sim c_s/c$	Dumping length, $\lambda_{dump\ A}$, kpc	10..100	0.1
RG age, t_{age}, Myr	10	30	Dumping length, $\lambda_{dump\ MS}$, kpc	1..3	1

4. The transport of the e-CR in the RG-lobes. The features of MHz-radio emission

The evolution of the post-jet flow and the transport of e-CRs in the lobes were considered using the toy-model of radio galaxies: the FRII type, like of Cygnus A (see the characteristic parameters inside the lobe at Mathews, Guo (2011) and Table 1), and the FRI type, like of the M87 (see characteristic parameters inside the lobe at Mathews, Guo (2012) and Table 1).

It was assumed in the model that e-CRs are produced from the jet-HS at these distances from AGNs: r_{HS} = 70 kpc (for Cygnus A) and 13 kpc (for M87) (see Table 1). Next, we considered: the regular transport of the e-CRs together with the fluxes of post-jet plasma (which determines the characteristic "radiation" age of the e-CRs, $\Delta t_{age} = |\vec{r} - \vec{r}_{HS}|/u_{flow}$; and diffusion transport of CR due to their scattering by small-scale vortex and large-scale MHD turbulences. In FRII radio galaxies, the post-jet stream is controlled by a dynamic Hill vortex, spinning at a transonic velocity near the HS ($\Delta t_{age} \sim$ 0..10 Myr); and in FRI-RG there is an inertial advance of the post-jet flow from the HS with subsonic speed in the form of a viscous expanding jet-tail ($\Delta t_{age} \sim$ 0..30 Myr).

The diffusion transport of the e-CRs at each given moment can be characterized by $\gamma = E/(m_e\ c^2)$, the diffusion-path length for the CRs of a given energy. In these cases, the diffusion of CRs in scattering by small-scale vortex turbulence is characterized by a coefficient that not varies from CR energy ($D_{diff\_CR\_Vx} \sim D_{diff\_th\_Vx}$), and the coefficient

for CR-diffusion on MHD fluctuations of the magnetic field depends on the CRs energy as (Toptygin, 1986):

$$D_{diff\_MHD}(\gamma,..) \sim \left(\Lambda_{\|Be}(\gamma,..)\cdot c/3\right)\cdot fct(B_\|, B_\varphi);$$

$$\Lambda_{\|Be}(\gamma,..) \sim (B_w/B_0)^{-2}\left(\frac{L_0}{R_{gB}}\right)^{2/3} R_{gB}\ \gamma^{1/3},$$

$$L_0 \sim \lambda_{dump,A} + \lambda_{dump,MS} = \rho(\eta_K + \eta_M)^{-1}\cdot c_A^{\ 3}\omega_{A0}^{\ -2} + \tfrac{1}{2}\rho(\eta_K + \eta_M)^{-1}\cdot c_S^{\ 3}\omega_{MS0}^{\ -2},$$

here $R_{gB}(B_0)$ is gyro radius of low energy e-CR at γ=2, L_0 is correlation length of the MHD fluctuations, that is proportional to the wave-dumping lengths (at waves frequency of $\omega_{A0} \sim \omega_{MS0} \sim 10^{-5}\ yr^{-1}$).

The Figures 1 and 2 show the maps of the characteristic diffusion transport lengths for the FRII RG (Cygnus A) and the FRI RG (M87): (a) - for the post-jet flow matter; and (b)- for the e-CRs with energies of γ =30..300 (it corresponds to the synchrotron radio emission in the MHz band with a magnetic field strength of $\sim$ 5..20 mkG). It was believed that the post-jet relativistic plasma is transported from the jet due to the quasiregular flow, and the diffusion by eddy turbulence:

$$\lambda_{pj\_Diff,reg} \sim \left(D_{diff\_rel\_Vx}\cdot \Delta t_{age}\right)^{1/2} + (0.1..1)c_s\Delta t_{age},$$

and the e-CRs are transported due to the quasiregular flow, and the diffusion by eddy turbulence and MHD waves:
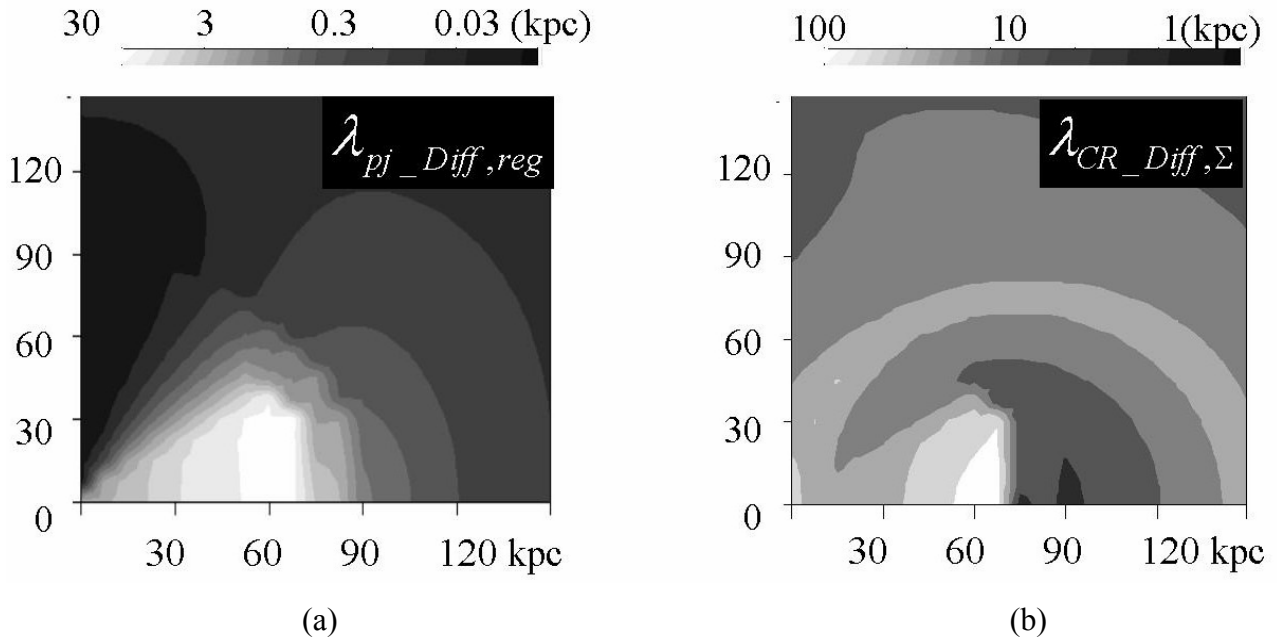
Figure 1: The maps of the characteristic matter transport lengths for the FRII radio galaxy (like Cygnus A): (a) – for the post-jet matter; and (b) – for the e-CRs with energies of γ =30 (it corresponds to the synchrotron radio emission in the MHz band with a magnetic field strength of 20 mkG).
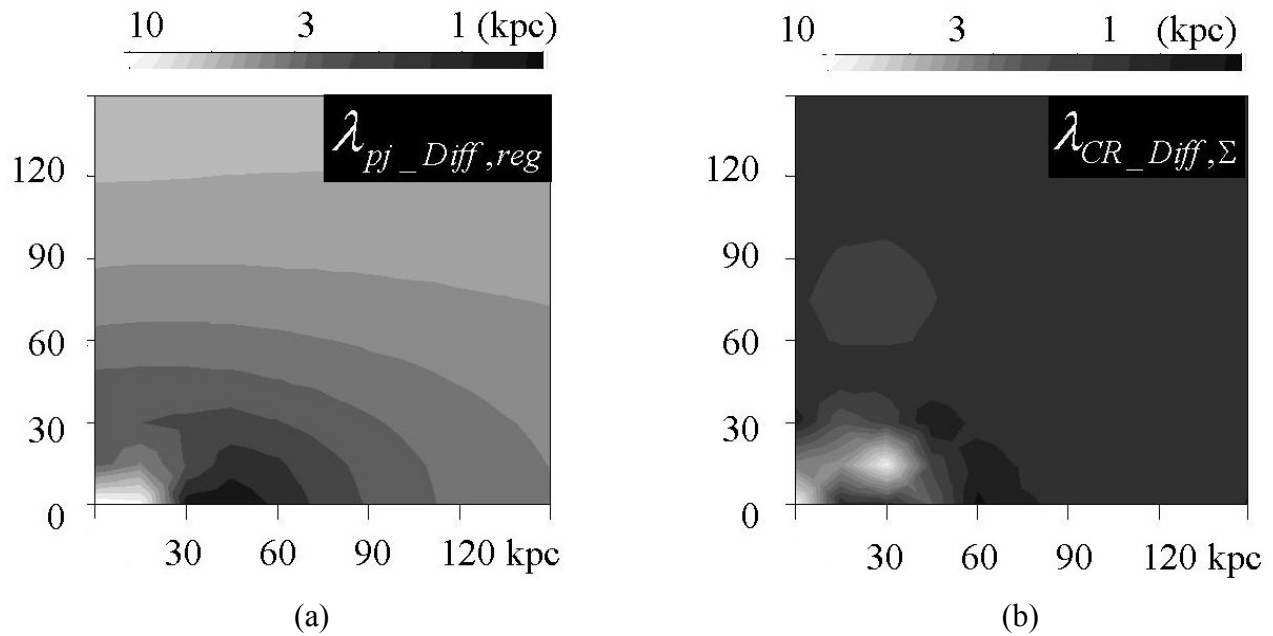

Figure 2: The maps of the characteristic matter transport lengths for the FRI radio galaxy (like M87): (a) – for the post-jet matter; and (b) – for the e-CRs with energies of γ =300 (it corresponds to the synchrotron radio emission in the MHz band with a magnetic field strength of ~ 5 mkG).

$$\lambda_{CR\_Diff,\Sigma} \sim \left((D_{diff\_MHD} + D_{diff\_Vx}) \cdot \Delta t_{age} \right)^{1/2};$$

$$\lambda_{CR,\Sigma} \sim \lambda_{pj\_reg} + \lambda_{CR\_Diff,\Sigma}.$$

It can be seen from the calculations (Fig. 1) that in FRII RG the transport of CRs is mainly determined by the diffusion of CRs, with vortex turbulence responsible for the transfer within the lobe, and MHD waves in the outer layers of the lobe. So: $\lambda_{pj\_Diff,reg}$ = (1-7) kpc; $\lambda_{CR\_Diff,\Sigma}$ = (0.1-10) kpc. Only in the near vicinity of HS RG carried out a regular flow along with the post-jet stream a little faster than the diffusion mechanism.

Then, in FRI-radio galaxies (Fig. 2), the diffusion mechanism carries the CRs more slowly than the regular flow: $\lambda_{pj\_Diff,reg} \sim \lambda_{pj\_reg}$ = (1-10) kpc; $\lambda_{CR\_Diff,\Sigma}$ =(1-3) kpc. Although, in the anterior part of the post-jet lobe-tail, the diffusion of CRs at $\gamma \sim 300$ by MHD turbulence overlaps its regular floating of the lobe, and becomes the diffusion as the determining mechanism in the CR-transport.

5. Conclusions

Thus, it was shown that regular transport and diffusion on small-scale eddy turbulence determine the propagation of low-energy e-CR only in the inner part of the RG lobes; while the diffusion propagation due to scattering by MHD waves is the dominant mechanism for the transfer of CR in the outer layers of the RG-lobes. In this case, the radio emission of CRs in the MHz band will emphasize the features of the structure of the magnetic field in the lobes, outlining the areas of locking the CR of low energies, so that observations of the UTR-2 and GURT can monitor the tuning of the quasiregular magnetic field of the lobe, revealing the regions of brightness of the MHz radio emission in the lobes of the radio galaxy.

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