THE EVOLUTION OF THE ACCELERATION MECHANISMS OF COSMIC RAYS AND RELATIVISTIC ELECTRONS IN RADIO GALAXIES

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ABSTRACT. There are estimated an efficacy for different acceleration mechanisms of e- and p-cosmic rays (CRs) in radio galaxies, using an evolution model for jet gaps and shock fronts with a turbulence. It is shown that diffusion shock acceleration of the CRs is the most efficient mechanism in the FR II radio galaxies (RGs). At the same time, there are a break-pinch mechanism (for a short-term at a jet gap moment), and a stochastic turbulent mechanism (for an all time when RG exist), that to play a grate part in acceleration of the CRs (give to 10-50 % of the all acceleration efficiency). It is predicted what properties of radio emission spectra give us to recognize a type of acceleration mechanisms of e-CR in the RG.

Key words: radio galaxies, acceleration mechanisms, cosmic rays, radio emission spectra

It is usually assumed that the acceleration of p- and e-CRs in the radio galaxies (RG) is associated with regular mechanism of diffusive shock acceleration (DSA) at the shock fronts. However, in the jet and cocoon of RGs can work the other mechanisms too: (PnA) – an acceleration on break-pinch and (StA) – a stochastic acceleration that occurs when CRs scatter on MHD turbulence waves. The PnA-acceleration is widely discussed in connection with the energy spectra of p-CR, which recorded by counters in extensive air showers. The spectra of these CRs have index s_{1Pn}=4.7 ($N \propto p^{-s_{1Pn}}$), which is consistent with the PnA-mechanism. The observed radio emission spectra of e-CR in the RG also give the average index of 0.8, which is consistent with the index PnA-spectrum s_{1Pn}. StA-mechanism is widely used to explain the radio and X-ray emission in galaxy clusters such as Coma. Also, it is closely connected with the shock fronts, as the shock is evolving always with the MHD and vortex turbulence.

There are in this paper analyzed the characteristics and conditions in RGs to work of these CR-acceleration mechanisms. We write the equations describing the acceleration of CRs in the whole volume of the RG, in a *unified* form that is easy to compare several concurrent mechanisms. The effectiveness of different acceleration mechanisms for p-and e-CR are estimated, considering the model of the spatial and temporal evolution of the turbulence with the jet and shock fronts in the RG. It is shown when you can "share" arrangements, and how to restore the correct properties of these mediums according to the spectra of radio galactic radiation.

The principles of the CR-acceleration mechanisms

To compare the efficiency of the PnA, regular DSA and stochastic acceleration mechanisms, we present a *unified* view of the equation by integrating the basic equations for the acceleration (injection) of the CRs in volume of $V(t)$, that filled at time moment (t):

$$\frac{\partial^2}{\partial p^2}\left(D(t,p)N\right) - \left(A(t,p) - \beta(t,p)\right)\frac{\partial}{\partial p}N + Q_0(t)\delta(p-p_0) = \left(\frac{N}{\tau^*(t)}\right) + \frac{\partial}{\partial t}N$$

The total number N of CRs in the volume $V(t)$ is determined by the source of injected particles $Q_0(t)$, and the terms $A(t,p)$ and $D(t,p)$ of acceleration efficiency. It should separate the areas in which different (or several together) acceleration mechanisms is working, and to consider the time-evolution of RG shape. We have interesting in quasi-stationary decision of this *uniform* equation.

PnA: the break-pinch acceleration mechanism. It works when a thin skinning jet of magnetized relativistic plasma is rapidly destructed. The initial PnA-equations are the Euler equations for a flow in a narrow channel approximation (Vlasov, et al., 1989). The particles are injected from the gap site and released into the environment during the time t<< a/c (a jet thin a divide to light velocity), filling the volume $V \sim ct \sim 10^2$ pc^3. We find the total number of CRs injected into the volume V at time t, which are free expanding into this area in vicinity of the jet break point, and the e-CRs loss its energy through synchrotron radiation.

Pn-acceleration gives a transient (pulse) emission of CRs, near the gaps (knots) of jet, which works in two phases: 1 – phase of pinch break, 2 – phase of induction.

Phase of jet break lasts of $t \sim T_{esc} \sim a/c \sim$ 1-100 years. At the moment of gapping, the magnetic field in the current thread is much greater than the energy of plasma, $B > 2J/ca$, which leads to injection of e-and p- plasma form jet into the CRs (an initial spectrum index is $s_{1Pn} = 4.7$). The e-CRs cool due to synchrotron losses in a magnetic field, disperse moving from a break point, and it changes they spectrum index to more steep, $s_{1syn} \geq s_{1Pn} + 1$, so the "jet breaks" moment become invisible in the radio emission.

When $t > a/c$, the phase turns to next (2), an induction acceleration of CRs at the jet gap, giving the p-CR spectra with $s_{2Pn} = 3$, and e-CR ones with $s_{2syn} \sim 4$. At this stage a local shock front forms in the vicinity of the jet knot, and the PnA-mechanism is transformed into DSA-mechanism, with no change of spectrum for e-CRs ($s \sim 4$).

The PnA-mechanism may provide CR-injection effectively in the pc-jets (in vicinity of a RG-core), that fills of ep-relativistic plasma. It is also possible to cascade injection of secondary e-CR in pc-jet knots due to the interaction of p-CRs with jet-shock fronts, and this process fills a jet of relativistic e-plasma at kpc-distances. This e-plasma has a larger magnetic viscosity then ep-ones, so the kpc-jet becomes more resistant to the "instantaneous" pinch breaks than the pc-jet.

DSA-mechanism: the regular acceleration at the shock. At fist, it described by equations of CR-particles transport through the shock front surface (Krymskyi 1977, Bykov, Petrosian 2008). DSA works in a bow- and jet-shocks within the radio galaxies. To integrate it over the area of volume $V(t)$ and filling of the CRs, which move inside the shock front at time t, we obtain the *unified equation* in which the effectiveness of regular acceleration is given by:

$$A_{sh}\frac{\partial N}{\partial p_1} \to \int_{r_{br}(p)}^{u_1 t} \frac{p_1}{3}\Delta u\, \delta(r - u_{sh}t)\frac{\partial f}{\partial p_1}\cdot 4\pi r^2 dr \to \frac{p_1}{s_{sh}T_{sh}(t)}\frac{\partial N}{\partial p_1}$$

Here $T_{sh}(t)$ is an effective time of the CR-acceleration; $T_{sh}(t) < t$. The total number N of CRs changes follow with their injection at the shock, $Q(t) \equiv Q_0\xi(t) \propto V(t)$, and for e-CRs it have to add the energy loss due to the synchrotron radiation (β-term). If $\xi(t) = t\cdot\exp(-t/\tau)$, we find a steady-state solution of the equation (1) for the total number of the CRs as: $N(p_1,t) \propto p_1^{-s_{sh}(t)}\xi(t)$. In it: $s_{sh}(t)$ is increasing with the t when the shock slope is steeping, and an index s will add +1 for a large CR-momentum (p_1) due to synchrotron losses of e-CR energy. So, e-CRs cool as they distance to the shock growing; and we got a smooth increase in the spectrum index of N- function at the some momentum energy range. The most part of overall CR-number accelerates at the bow shock of RG, which is gaining a particle of intergalactic plasma into the cocoon as the form of e- and p-CRs. The DSA-mechanism works during the bow shock exist, $\tau \sim 10^6$-10^7 yr for typical RGs.

StA: stochastic acceleration mechanism. It works in entire volume of RG-cocoon where the accelerated CRs is diffusion mixing by turbulence, and it is working continuously overall time when RG exists (longer then bow-shock exists). The volume of the RG-cocoon is order of 10^{14} pc^3; and StA can work more then 10^7 yr.

The terms of StA-mechanism are: $D(p_1,t) \to D_0(t)p_1^{\alpha}$, $A_{st}(t) = (\alpha - 2)D_0(t)\cdot p^{\alpha-2}$ (Brunetti., Setti, 2001; Cho, Lasarian, 2005). Those are related to the spectrum of turbulent MHD-waves, $W(k) = W_0 k^{-q}$ (occupying from $k \sim L_0^{-1}$ to $k \sim R_0^{-1}$; L_0 is a correlation scale of wave turbulence, R_0 is a Larmor radius for thermal-CRs), and they can be expressed in terms of the coefficients of the spatial diffusion of CRs: $D_{st} = ⅓\, p_1^2\kappa(p_1)L_0^{-2} \propto p_1^{4-q}$, where $\alpha \sim 4 - q$. We believe that the spatial diffusion κ is described the function by (Toptygin, 1983), as the CRs scatter on MHD-waves in resonance: $p_1 \sim 1/(kR_0)$.

Quasi-stationary solution of the CR-acceleration: the total number N of St-accelerated CRs takes the form of a power function by p_1^{-s} with $s \sim \alpha + 1$, and for the e-CR, the index (s) increases and N "exp-collapses" due to synchrotron and inverse-Compton radiations of e-CR at the large p_1-momenta.

The collaboration of DSA and StA-mechanisms of CRs inside the radio galaxy cocoon by shock bounded

We trace the evolution of the turbulence near the bow shock front of RG, and estimate how the effectiveness of the StA- and DSA-mechanisms change when the RG was a young, a developing and an old jet-ejection. We consider the RG of FRII type, with the following parameters at the stage of "developing" jet: a jet age is $t \sim \tau = 10^6$ yr, a pc-jet radius is 0.1 pc, a jet length is 30 kpc, and it equals of 0.5 of cocoon radius; the plasma density in jet is some less then ones in the cocoon that is 10^{-3} cm^{-3} (r/40 kpc)$^{-0.7}$ (decrease at r-distance). The parameters of bow shock and turbulence run with time as we show in fig.1 (the model).

Stage 1, $t_1 \sim 10^4$ years: it is "*young-ejection*" and a powerful shock front with turbulence. The power spectrum of MHD-turbulence $W(k)$ has an index q=1.9, and it is strongly developed in the range of $k \sim k_{min} \sim 1/L_0 \sim 10^{-13}$ cm^{-1} to $k \sim k_{max} \sim 1/R_0 \sim 10^{-10}$cm^{-1}, where it is pumped by the vortex-turbulence. During the time, a spectrum $W(k)$ expands slowly by k, mainly to low k-range. In this *Stage* 1, St-acceleration works in concert with the regular DSA-mechanism (so as α= 4-q~2). And if we have $D_0 > A_0$, it forms a hard CR-spectrum (s=3), because of StA is the most effectively. For e-CR, StA compensate its synchrotron losses at large p_1, up to $p_{max} \sim L_0/R_0$.

Stage 2, $t_2 \sim 10^6$ years: *developing ejection* of jet, a quasi-stationary shock front with the turbulence in the cocoon. It is DSA dominated and supplemented by StA (see fig.2). Turbulence spectrum: q =1.5..1.66, α=2.5.. 2.33, so $\kappa(p) \propto p^{2-q} \sim p^{0.5..0.33}$. StA affects on the spectrum of e-CR at large p_1, partially offset by synchrotron losses.

Stage 3, $t_3 \sim 10^7$ years: it is *the old jet* and a weak bow-shock with turbulence. Turbulence is dissipated from all k, and its spectrum becomes: q~1, $\alpha \to 3$. The shock dissipate too, and it give us $D > A$ in the main p_1-band of CR energy momentum. So, we have StA dominated again, at some range of large p_1, and this StA is described by Bohm transport diffusion of CRs, $\kappa \propto p_1$. This mechanism smoothes the spectrum of e-CRs to the $s(t) = \alpha + 1 \sim 4$ and corrects they energy losses (by synchrotron or inverse-Compton radiation cases). Alternative, at range of small p_1, the DSA-mechanism is working for both e- and p-CRs.

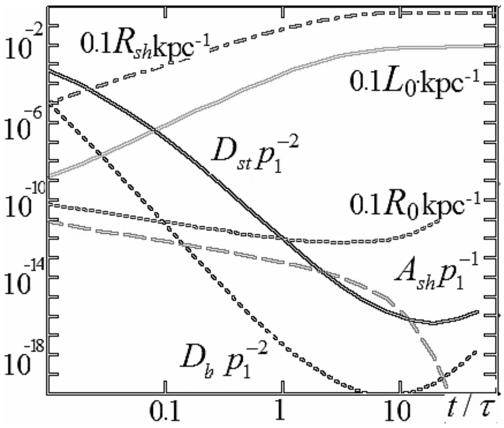

Figure 1: Dependence for turbulence characteristics (L_0 corr.-length, R_{sh} shock and R_0 Larmour radii) and A_{sh}, D_{st}, D_b acceleration terms (at p_1=1) from age-time of RG

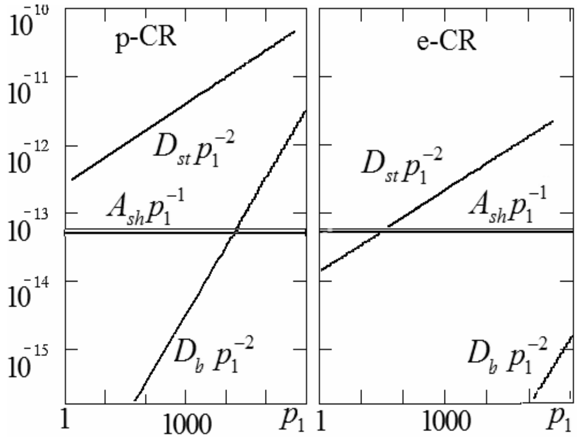

Figure 2: Dependence for $A_{sh}(p_1)$, $D_{st}(p_1)$, $D_b(p_1)$ acceleration terms from (p_1)-moments of energy for p- and e-CRs at the RG-age t=τ

D-term goes to zero at $p_1 \rightarrow 0$ and at the range of the most large $p_1 > L_0(t)R_0^{-1}$, because the correlation scale L_0 came to infinity and the turbulence spectrum $W \rightarrow 0$.

The collaboration of DSA and PnA in the RG

A particle number in the Pn-acceleration is obtained from the jet particles flow through the gap, which exists 1-100 yr. This number N_{Pn} are very small compared to a number N_{DSA} (CRs accelerated by bow shock in RG). So, PnA have a very low efficiency compared to the other mechanisms; but it is essentially CR-acceleration on some time-moments when jet is braking, and when we see the vicinity of this jet-brake point volume.

Conclusions

1. Pinch (PnA) mechanism contributes to the rapid destruction of the jet, and the short-term release of its e-plasma in the form of the CR in the hot spots and knots, where it formed local jet's shock fronts. It is predicted that the pinch point of jet's gap can be detected only at low radio frequencies, due to the fact that it gives the radio emission with a very steep spectrum. PnA is the most effective within the pc-jets and in the young RGs; and its relative effectiveness runs to less 1% (as a number of particles accelerated by PnA have divided to all CRs in the RG at fixed time).

2. Regular DSA-mechanism runs close to the shock front surface and fills the tiled-shock areas in RG by cosmic rays accelerated. It is the most effective mechanism in RG at the time when the bow shock is strong; and DSA relative effectiveness runs to 50-90% at that fixed time. DSA creates the spectra of CRs that the power index increases by the time, as the power of the shock have reduced; and it creates the emission spectra of e-CR with the index growing with distance from a shock because of Syn/IC losses. DSA is in competition with StA at all when RG exist.

3. The stochastic (StA) mechanism works continuously and almost the entire volume of the RG, and it creates a flat spectra in the radio emission observations. The p- and e-CRs are re-accelerated effectively by this mechanism in ahead of the shock front and inside the jet, as well as in the cocoon-periphery and in the halo of FR II-RGs. In this way, the synchrotron radiation losses on e-CRs compensate partially by this mechanism, and it "restrained" obstruction of their spectrum at high frequencies. The index of the CR-spectrum that accelerated by stochastic mechanism depends on the spectrum of a turbulence, and it increases towards the edges of the RG (going far from the jet and from the hot spot of the RG). StA relative effectiveness runs to 10-50% usually at fixed times, and it is the most effective in the last evolution stage of the RG.

At first, the type of acceleration mechanism can be found from the spectral index of the e-CR radiation. Then in reality, the indexes of the acceleration mechanisms overlapped in a wide range, and to determine the mechanism needs to involve the physical considerations about the evolution of turbulence with shocks in the RG.

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