THE IMAGES OF EXTRAGALACTIC RADIO SOURCES IN THE DIFFUSION MODEL

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ABSTRACT. The distribution of the spectral index and radio lobes' isophots were derived by numerical methods in the diffusion model of extragalactic radio sources. The kinetic equation for the distribution function of relativistic electrons is considered. Regions of electron injection, associated with hot spots, are considered as moving. Velocities of hot spots and the diffusion velocity of electrons determined the correlation of transverse and longitudinal lobes' sizes. Observed changes of lobes at various frequencies accord with the diffusion model. The reabsorption in the lobes leads to the asymmetry of them, depending on source's rotation relatively to the line of sight.

Key words: extragalactic radio sources: hot spots, lobes, diffusion model, spectral indexies, asymmetry.

1. Introduction

Spatial structures of extragalactic radio sources (ERS) have been detected due to their numerous observations. Images of ERS (Leahy, Bridle, and Strom, 1995) demonstrate four basic morphological components: core, jets, hot spots and lobes. The physical model explaining these four morphological structures is known as the jet model (Begelman, Blandford, and Rees, 1984). The radio core corresponds to the AGN. Jets extend from the core and end at hot spots. Energy from the AGN is transported by jets to the radio-emitting lobes and at hot spots jets convert some of their kinetic energy into relativistic particles, and magnetic fields. We assume that the hot spots are sources of relativistic electrons (accelerated by shock waves). Electrons propagate due to the diffusion, lose the energy because of the synchrotron emission, and form the lobes. We introduce the motion of the injection regions which naturally explains the lobes size asymmetry and the displacement of the hot spots with respect to the center of the lobes (Valtaoja, 1982, Gestrin, Kontorovich and Kochanov, 1987).

2. The diffusion model with moving sources of relativistic electrons

The distribution function N for the relativistic electrons satisfies to the kinetic equation with moving source:

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial E}\left(\beta E^2 N\right) - D_0\left(\frac{E}{E_D}\right)^{\mu}\Delta N = \qquad (1)$$

$$= Q\delta\left(x - x_0\left(t\right)\right)\delta\left(y\right)\delta\left(z\right)E^{-\gamma_0}\Theta\left(t\right)\Theta\left(E_2 - E\right)\Theta\left(E - E_1\right)$$

The second term $\frac{\partial}{\partial E}\left(\beta E^2 N\right)$ describes the synchrotron and Compton losses:

$$\beta = \left(\frac{32\pi}{9}\right)\left(\frac{e^2}{mc^2}\right)\frac{\omega_H + \omega_r}{m^2 c^3},$$

where $\omega_H + \omega_r$ is the energy density of the random magnetic field and the radiation.

To simplify the model, disregard the possible coordinate dependence of the diffusion coefficient D, and the magnetic field H, the power-law dependence on the energy is taken for the diffusion coefficient:

$$D = D_0\left(\frac{E}{E_D}\right)^{\mu}.$$

The right side in the kinetic equation (1) corresponds to the point source $\left(x_0\left(t\right), 0, 0\right)$ of relativistic electrons (the hot spot) moving along the x-axis; the injection spectrum is taken as the power-law dependence on the energy $E^{-\gamma_0}$ in the range $E_1 < E < E_2$ and zero outside it.

To derive the distribution function, apply the Laplace transformation with respect to time to the kinetic equation (1):

$$N^*\left(E, \vec{r}, p\right) = \int\limits_0^{+\infty} exp\left(-pt\right) N\left(E, \vec{r}, t\right) dt.$$

Then this equation for $N^*\left(E, \vec{r}, p\right)$ can be reduced to the diffusion equation. The expression for the

$N^*(E, \vec{r}, p)$ is used with the Melline transformation to derive the distribution function $N(E, \vec{r}, t)$ for $x_0 = vt$ (GKK 87):

$$N\big(E, t, \vec{r}\big) = \frac{Q_0 E^{-2}}{8\pi^{3/2}\beta}\big(1-\mu\big)* \qquad (2)$$

$$*\left(\frac{\beta\big(1-\mu E_D{}^{\mu}\big)}{D_0}\right)^{\big(\gamma_0-1\big)\big(1-\mu\big)} *$$

$$* \int\limits_{\lambda^2(E)}^{\lambda^2(E_2)} d\lambda_0^2 \frac{\lambda_0^{2\big(\gamma_0-1\big)\big(1-\mu\big)-2}}{\big(\lambda^2-\lambda_0^2\big)^{3/2}} \Theta\big(D_0 t - \big(\lambda^2-\lambda_0^2\big)\big)$$

$$exp\left(\frac{-\Big(x - vt + \frac{v}{D_0}\left(\lambda^2-\lambda_0^2\right)\Big)^2 - y^2 - z^2}{4\left(\lambda^2-\lambda_0^2\right)}\right).$$

In this expression for the distribution function, $\lambda^2 = \frac{D_0 E^{\mu-1}}{(1-\mu)E_D^{\mu}\beta}$ is the square of the diffusion length (Berezinskiy, Bulanov, Ginzburg, et al., 1984).

The radio spectrum for electrons is found from the formulas for the synchrotron emission (Ginzburg, 1987):

$$I(\nu) = \int\limits_{-\infty}^{s_0} dsdEN(E, t, \vec{r})\, p(E, \nu), \qquad (3)$$

where the integration corresponds to the integration along the line of sight, s_0 is the observation point. And $p(E, \nu)$ is the synchrotron radiation flux density from single electron. With the accuracy sufficient for comparison with observations the synchrotron radiation flux density can be put (σ_T is the Thomson cross section):

$$p(\nu) = \frac{\sqrt{2}\sigma_T mc^2 H}{12\sqrt{3}\,0.29\pi e r^2}\nu\delta(\nu - \nu(E)),$$

$$\nu(E) = \frac{0.29\sqrt{3}eH}{2\pi\sqrt{2}mc^2}\left(\frac{E}{mc^2}\right)^2.$$

In the case when the reabsorbtion is considered, we have the radio spectrum of the lobe (with $N^*(E, \vec{r}, p)$ from (2)):

$$I(\nu) = \int\limits_{-\infty}^{s_0} ds_1 dEN(E, t, \vec{r})\, p(E, \nu)\, exp\left(\frac{1}{c}\int\limits_{s_0}^{s_1} ds_2\mu\right).$$

where μ is the reabsorbtion factor. The common expression for μ (Ginzburg and Syrovatskii, 1964, Zheleznyakov, 1997):

$$\mu(\nu) = -\frac{c^2}{32\pi^2\nu^2}\int \frac{\partial N}{\partial E} p(\nu, E)\, dE.$$

3. Numerical calculatons' results and conclusion

As it has been shown in (GKK 87) the dependence of the radio flux on the distance to the hot spot (transverse to the motion direction) of the source 3C 196 is close to theoretical one from the diffusion model.

We see from expressions for the distribution function (2) and the radio spectrum (3) that the external shape of radio lobes is determined by the relation between the electron diffusion velocity $v_{diff} = \frac{D_0}{\lambda}$ and the velocity $v_\perp$ of the source in the mapping plane (the longitudinal component vanishes on the integration along the line of sight), both of these are appearing in the expression for the distribution function.

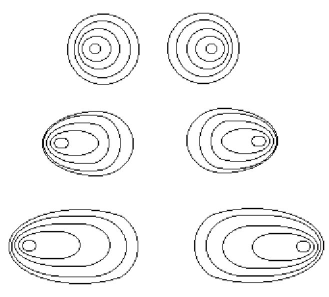

Figure 1: Radio sources' isophots produced by the diffusion of relativistic electrons for various correlations of hot spots' velocities in the mapping plane and the electron diffusion velocities: $v_\perp/v_{diff} = 1, 4, 8$. $\gamma_0 = 2$.

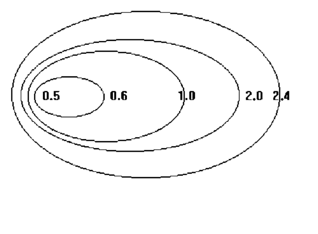

Figure 2: The distribution of the spectral index for $\gamma_0 = 2$ and $v_\perp = 8v_{diff}$.

For $v_\perp \ll v_{diff}$, one has approximately a sphere with diameter $l \approx 4\lambda$ and the hot spot near the center, while for $v_\perp \geq v_{diff}$, the lobe is an ellipsoid with the major axis $L \approx \left(\frac{v_\perp}{D_0}\right)\lambda^2 + 4\lambda$ and the minor axis $l \approx 4\lambda$, while the hot spot is near the outer edge. For $v_\perp \gg v_{diff}$, the lobe has a broad tail and a relatively narrow head, in which the hot spot lies. The

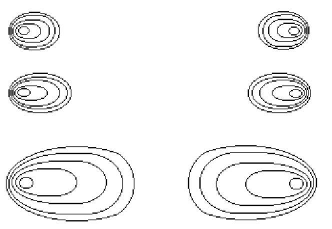

Figure 3: Radio source isophotes derived at three frequencies: 150 Mhz, 450 Mhz, 900 Mhz. $\gamma_0 = 2$, $v_\perp/v_{diff} = 8$.

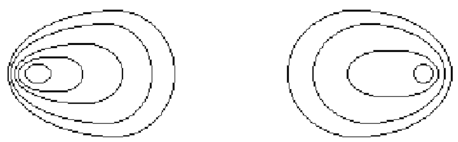

Figure 4: Isophots of the rotated at 10 degrees radio source (the left lobe is closer to the observation point). The reabsorbtion is taken into account. $\gamma_0 = 2$, $v_\perp/v_{diff} = 8$.

external pressure (neglected in this model) will undoubtedly alter lobe's configuration, but the main characteristics should persist. Figure 1 shows examples of radio sources for various correlations of $v_\perp$ and v_{diff} derived numerically. The distribution of the spectral index (Carilli and Barthel, 1996) show that relativistic particles lose energy the more faster the more energy they have. Figure 2 shows the distribution of the spectral index α ($I(\nu) \propto \nu^{-\alpha}$) derived numericaly in the diffusion model.

The longitudinal size L and transvers one l of the lobe provide estimations for $D(E)$ and $v_\perp$:

$$v_\perp \approx \beta E\,(L - l)\,,$$

$$D = D_0 \left(\frac{E}{E_D}\right)^\mu = \frac{l^2 \beta E}{4\,(1-\mu)} \propto v_{diff}\frac{l}{4},$$

where E is the electron energy corresponding to the observation frequency $\nu = \nu(E)$.

The increase of lobes' size when the observation frequency is reduced agrees with predictions of the model, which shows that the transverse size varies as $\nu^{-1/4}$ for $D =$ constant. The variation of the L and l correlation we explain by various correlations of $v_\perp$ and v_{diff} at various observation frequencies. As we see from expresion for $N(E, \vec{r}, t)$ and $I(\nu)$ only electrons with the ehergy more than the energy corresponding to the observation frequency $\nu = \nu(E)$ make contribution to the radiation. Therefore, the square of the diffusion length decreases and effective v_{diff} increases (figures 3).

Figure 4 show the example of the source (isophots) derived with account for the reabsorbtion. This leads to the asymmetry of radio lobes.

The diffusion model thus describes the situation close to the observation data, the account for the reabsorbtion and simple incorporation of hot spot's motion relativly to the medium provides conclusions applicable to the real extended extragalactic radio sources, where the model can explain the major observed characteritics.

References

Begelman M.C., Blandford R.D., Rees M.J.: 1984, *Rev.Mod.Phys.*, **165**, 395.

Berezinskiy V.S., Bulanov S.V., Ginzburg V.L., et al.: 1984, *Astrophisics of cosmic rays.* -Moscow, Nauka.

Carilli C.L., Barthel P.D.: 1996, *As. Ap. Rev.*, **7**, 1.

Gestrin S.G., Kontorovich V.M., Kochanov A.E.: 1987, *Kinem. i Fiz. Neb. Tel.*, **3**, N 4, 57.

Ginzburg V.L.: 1987, *Theoretical Physics and Astrophysics.*-Moscow, Nauka.

Ginzburg V.L., Syrovatskii S.I.: 1964, *Origin of cosmic rays.* -Pergamon Press.

Kaiser C.R., Alexander P.: 1999, in: *Observational Cosmology: The development of galaxy systems,* eds. G.Giuricin, M.Mezetti, P.Salucci, *ASP Conf. Ser.,* **176**, 377.

Leahy J.P., Bridle A.H., Strom R.G.: 1996, *IAU*, **175**, 157.

Valtaoja E.: 1982, *As. Ap.,* **111**, 213.

Zheleznyakov V.V.: 1997, *Radiation in astrophysical plasma.* -Moscow.: Yanus-K.