EXPERIMENTAL DETERMINATION OF PHYSICAL PROCESSES IN SPACE, LEADING TO DEVIATIONS OF RADIO SYNCHROTRON RADIATION SPECTRA FROM THE POWER LAW

A. V. Men’∗

We present universal formulas for spectral characteristics of cosmic radio sources of synchrotron radiation upon the presence of spectral density maxima at certain frequencies (spectra with negative curvature) taking into account most typical physical processes observed in space. On the basis of long-term observations of angular radiation structure of cosmic radio sources in the decameter wavelength range by the URAN radio interferometer system, we determine most probable physical processes resulting in spectra with extremum values for several quasars, radio galaxies, and their separate components. On the basis of these data, we estimate some parameters of cosmic medium, magnetic field, and angular sizes of compact radio sources and their components.

1. INTRODUCTION

As is known, non-thermal cosmic radio sources with synchrotron radiation mechanism are characterized by power-law dependence of spectral density of the radiation flux $S$ on the frequency $\nu$: $S \propto \nu^{-\alpha}$, where $\alpha$ is the spectral index. However, the observed spectra of some radio sources (no less than 20% of their total number) demonstrate significant deviations from the power law in some frequency range, which are related to different physical processes in space. In these cases, a maximum of the spectral density $S_{m}$ of the radiation is often observed on the spectral dependence $S(\nu)$ at a certain frequency $\nu_{m}$, below which the spectral density of radiation decreases with decreasing frequency.

It is of great interest to determine the physical processes responsible for such anomalous shape of spectral characteristics of cosmic radio sources of synchrotron radiation. In this case, parameters of cosmic plasma (electron temperature, emission measure, and electron density) can be estimated or the angular sizes of radiating objects and magnetic fields in them, transverse to the direction of motion of relativistic electrons, can be retrieved.

The spectra with extrema can result from various physical processes in space, such as self-absorption of synchrotron radiation (synchrotron reabsorption), absorption of the radiation from radio sources in the regions of cosmic plasma located on the radio-wave propagation path or in the plasma in the radiating objects themselves. The same result can be due to the Razin—Tsytovich effect (related to the deviation of the medium refractive index from unity), the deviation of the energy spectrum of relativistic electrons from the power law (in particular, a low-energy cut-off in this spectrum) and other effects. Obviously, in these cases the spectral characteristics of the sources contain information on the related physical processes, and one can determine which of them leads to the spectral dependence with an extremum for this object.

Since the radiation spectral characteristics are related to the angular structure of radiation of cosmic sources (i.e., with their radio images), these studies allow one in some cases to explain the difference between the radio images at different frequencies.

∗men@ri.kharkov.ua
In this paper, we study in detail the influence of the first three of the above-mentioned physical processes most frequently observed in space on the radiation spectral characteristics.

Although the possibility of simultaneous influence of several different physical processes on the spectral characteristics of radio sources is not excluded in general, this paper is devoted to an analysis of spectral characteristics of cosmic radio sources with separately taking into account each of the radiation absorption mechanisms mentioned above.

The spectral characteristics considered in this paper are found from the radiation transfer equation under the assumption of uniformity and isotropy of cosmic ion-electron plasma and flows of relativistic electrons radiating in the magnetic fields. In cases where such an idealization of a medium is insufficiently correct, the obtained relationships allow one to obtain the first approximation for estimating the medium parameters, which can be considered along with the data obtained by using other astrophysical methods.

The work was mainly performed on the basis of the studies of cosmic radio sources in the decameter range of wavelengths using the URAN radio interferometric system. The obtained theoretical relationships are compared with experimental data obtained for some intense cosmic radio sources with sufficiently accurately measured spectral characteristics $S(\nu)$ with the spectral density of the radiation flux in the maximum $S_m \gg 1$ Jy.

2. THEORETICAL RELATIONSHIPS

2.1. Reabsorption effect

In the general case, the frequency spectrum of a cosmic radio source of synchrotron emission in which the self-absorption of radiation (synchrotron reabsorption) takes place has the form [1]

$$S(\nu) = C_1 \nu^{5/2} [1 - \exp(-\tau(\nu))],$$

where $\tau(\nu)$ is the optical depth of the medium at a frequency $\nu$:

$$\tau(\nu) = \int \chi(l) \, dl = C_2 \theta \nu^{-\alpha - 5/2}.$$  \hspace{1cm} (2)

Here, $C_1$ and $C_2$ are constants independent of the frequency, $\chi(l)$ is the specific absorption coefficient along the propagation direction, $L$ is the absorbing-layer thickness, and $\theta$ is the angular size of a radio source or its separate components in which the reabsorption is observed. It follows from Eq. (1) that the dependence $S(\nu)$ has a maximum $S_m$ at the frequency $\nu_m$. According to [2, 3], at this frequency the size $\theta_0$ in arc seconds is

$$\theta_0 = S_m^{1/2} \nu_m^{-5/4} H_\perp^{1/4} [1 - \exp(-\tau_0)]^{-1/2} (1 + Z)^{1/4},$$  \hspace{1cm} (3)

where $S_m$ is the maximum spectral density of the radiation flux in Jy, $\nu_m$ is the frequency of the maximum radiation spectral density in MHz, $H_\perp$ is the cosmic magnetic field transverse to the direction of motion of relativistic electrons in $\mu$Oe, $Z$ is the object red shift, and $\tau_0$ is the optical depth at the frequency $\nu_m$.

On the basis of Eqs. (1) and (2), the value $\tau_0$ was obtained in [4] from the extremum condition $dS(\nu)/d\nu = 0$:

$$\exp(\tau_0) = 1 + \frac{2\alpha + 5}{2} \tau_0.$$  \hspace{1cm} (4)

Taking into account that at a high frequency $\nu_1 \gg \nu_m$, where the spectrum has the form $S(\nu) \propto \nu^{-\alpha}$, the optical depth $\tau_1 \ll 1$, from Eq. (1) it follows:

$$\frac{S_1}{S_m} = \left(\frac{\nu_1}{\nu_m}\right)^{5/2} \left(\frac{\tau_1}{\tau_0}\right)^2 \frac{\tau_1}{1 - \exp(-\tau_0)}, \quad \frac{\tau_1}{\tau_0} = \frac{\theta_1}{\theta_0} \left(\frac{\nu_1}{\nu_m}\right)^{-\alpha - 5/2}.$$  \hspace{1cm} (5)