Results of investigation of radio galaxies of the survey “Cold”: photometry, colour redshifts and the age of the stellar population

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Abstract. BVRI data for the majority of the objects of the RC catalogue with steep spectra and $m_R < 24''$ are presented. These data have been used to estimate colour redshifts and the age of stellar systems of host galaxies. By way of example of distant radio galaxies it is shown that this approach gives an accuracy of redshift estimates close to that for field galaxies ($\sim 20\%$). The age estimates are less confident, however, the lower age limit for not too distant ($z < 1.5$) objects is determined quite reliably. Several galaxies have been detected that have an age above that of the Universe at the given $z$ in a simple CDM model of the Universe. A possibility of using such objects to specify the part played by “dark energy” is discussed. This paradox disappears in a model with the $\Lambda$-term equal to 0.6–0.8.

Key words: radio continuum: galaxies — surveys: galaxies — galaxies: fundamental parameters

1. Introduction

A population of powerful radio galaxies is observable with the available facilities practically to any distances. This allows one to follow the evolution of this population in the radio range from the moment it originated up to the present time.

However, a good deal of effort has to be undertaken to find new objects at $z > 3$ with application of rigorous methods of selection by radio, optical and infrared properties, which leads to inhomogeneous samples with regard to different parameters.

It is customary to assume that a population of very powerful radio galaxies of type FR II owes its origin to giant elliptical galaxies having supermassive ($10^9 M_\odot$) black holes at the centre. That is why the evolution of this population is related to the problem of formation of the largest stellar systems and to the problem of evolution of massive black holes. Besides, these objects are often associated with clusters and groups of galaxies and can be indicators of distant clusters formed in the nodes of the large-scale structure. At last, there is a number of suggestions for using them in estimation of parameters of their environment and even of the geometry of the Universe and its dynamics (Parijskij et al., 1998; Daly, 1994).

In contrast to quasar, in radio galaxies one can study in details the stellar population. As a rule, in objects with medium and weak energy release of the active nucleus in the optical and near infrared ranges, radiation of stars rather than gas dominates at $z < 1 - 1.5$. For this reason, one may attempt to apply the method of stellar evolution and evolution of synthetic colours of the stellar population to determination of “colour” redshifts and the age of the stellar population. When lucky, one can define the moment of star formation ($z$).

In the generally accepted scheme of the Unified Theory of active objects, radio galaxies of type FR II differ from quasars, BL Lac objects and other populations with powerful nucleus activity only in that at what angle the axis of rotation of the gas-dust tore, that screens the accretion disk around the black hole, is located with respect to the observer. And the data on evolution of these objects can be applied to other classes of objects.

At last, powerful galaxies with active nuclei (radio galaxies and quasars, predominantly “radio quiet”) supply much UV radiation to the Universe, and in combination with the integral optical depth by Thomson scattering of relic photons of the 3K background permit the moment of secondary ionization of the
Universe to be refined.

Deep optical investigations of host galaxies in this class of objects are impeded by the fact that their spatial density is by 5–6 orders of magnitude less than that of background galaxies, and this is why they are virtually lacking in ultimately deep frames of small size. In the HDF (Hubble Deep Fields) there is found but one distant \(z = 4.42\) radio galaxy of medium power. For this reason, sampling of fields for such investigations has to be started with preliminary selection on radio astronomy data with allowance made for all possible indirect criteria. The principles of selection of candidates for distant objects in the “Big Trio” project (Parijskij et al., 1994, 1096a,b) are similar to universally adopted (McCarthy, 1993). The list of objects presented below has been derived from the catalogue of the “Cold” survey (Parijskij et al., 1991, 1992) as a result of several selection steps: selection of comparatively faint sources having steep spectra \(\alpha < -1.0S + \nu\alpha\) and being of the FR II morphological type (Fanaroff, Riley, 1974) in the cm range \((10–100\,\text{mJy})\). Further selection was done according to the procedure described below.

The labour input for acquisition of quality spectroscopic data on distant and faint galaxies and radio galaxies forces to search for indirect methods for determination of the redshift and other characteristic features of these objects. With regard to the powerful radio galaxies, even photometric estimates proved to be helpful and they have so far been widely used (McCarthy, 1993; Benn et al., 1989; Parijskij et al., 2000a, b).

Over the last few years, colour characteristics of faint galaxies have come to be used in addition to the methods of photometric evaluation of the redshift, and this approach forms a basis for a number of major projects (e.g. see Szalay, 1996). As we have already noted, the colours of stellar systems make it possible to estimate their age as well. Generally speaking, the legitimacy of using colours for such estimations of evolution characteristics of the population of powerful radio galaxies requires a separate study because the effect the nuclear activity in these objects has on the colour characteristics is not sufficiently understood. The sites of “secondary” star formation may also tell the effect the nuclear activity in these objects has on the nuclear activity in these objects.

The present paper is a continuation of our programme of investigation of the radio galaxies detected in the RATAN-600 survey “Cold” with involvment of multicolour photometry data for assessment of colour redshifts and ages of stellar systems of host galaxies. Current use of these data is practically inevitable. Direct spectroscopy of faint objects required until recently a great deal of the 6 m telescope observational time when working with objects fainter than \(20''\). So, in 1995–1996 we managed to measure the spectroscopic redshift but in four bright objects (three quasars and one galaxy, all being brighter than \(m_R = 20.5''\)) and only in one faint galaxy, \(m_R = 23''\) (Dodonov et al., 1999). The redshift of the latter, \(z = 2.73\), was estimated from the only emission line. It is independently confirmed by our colour data: the negative B–V colour index agrees with identification of a strong line as \(L_{\nu\alpha}\), which is typical of radio galaxies.

During the last time, in connection with placing in service of more efficient spectral tools in SAO RAS, spectroscopy of faint objects is expected to substantionally improve. The spectra of another two objects, radio galaxy RCJ0908+0451 and quasar RCJ1154+0431, were obtained at the 6 m telescope in 2001 March with the aid of new equipment SCORPIO (Afanasiev and Moiseev, \[http://www.sao.ru/~moisaa/scorpio/scorpio.html\]). The spectral redshift for the radio galaxy is practically the same as the colour redshift. The data on the colour redshift will help improve the efficiency of spectroscopic observations.

This paper has the following structure. In the first section we present the data of multicolour BVRI photometry and also the latest results of identifications of the “Cold” survey radio sources. Further we describe the procedures of obtaining colour redshifts and ages of stellar systems from BVRI magnitudes with the use of present-day models of spectral energy distribution (SED). In the sections that follow we discuss the results obtained, evaluate model differences in the estimates of redshifts and propose new steps to improve the accuracy of estimations.

2. Multicolour photometry of RC objects

By the present time observations of about 60 RC objects (radio galaxies and quasars) of our sample have been carried out with the 6 m telescope of SAO RAS in four filters (B, V, R, I). In this paper we present the photometry results for 50 radio galaxies. The observations were made in 1994–1998. A CCD ISD015A of 580 × 520 pixels with a pixel size of 0.205″ × 0.154″ was employed in the 1994–1995 observations, and a CCD ISD017A (1160 × 1040, 0.137″ × 0.137″) was used in observations of 1996–1998. When reading the latter, the initial elements of the matrix were summed up to produce the output elements twice as large in both coordinates. The exposure time was defined in the course of observations, proceeding from brightness and colour of objects, from 1200–1800s (total) in the B band to 400–800s in the R band for a typical object of our sample having \(R = 22'' - 23''\), so that the resulting signal-to-noise ratio would be no worse than 4–5 in all the filters. At a seeing worse than 2″, we had to increase the exposure time by a factor of...
Tables 1 and 2: Examples of tabulated data

Table 1: A list of RC objects classified as QSO and excluded from this study

| Name         | RA(2000.0) | Dec(2000.0) |
|--------------|------------|-------------|
| RC J0038+0449| 00 38 34.65 | +04 50 50.5 |
| RC J0042+0504| 00 42 27.17 | +05 05 24.7 |
| RC J0126+0502| 01 26 16.11 | +05 02 09.9 |
| RC J0143+0505| 01 43 33.89 | +05 07 57.4 |
| RC J0226+0512| 02 26 19.80 | +04 46 32.5 |
| RC J0459+0456| 04 59 04.28 | +04 55 54.4 |
| RC J0506+0558| 05 06 25.00 | +05 08 19.3 |
| RC J1154+0431| 11 54 53.50 | +04 24 12.5 |
| RC J1740+0502| 17 40 33.96 | +05 02 42.3 |
| RC J2013+0508| 20 13 23.48 | +05 10 30.5 |
| RC J2036+0451| 20 36 56.93 | +04 49 52.7 |

Table 2: Characteristics of photometric bands

| Filter name | \( \lambda_{\text{eff}} \) | \( A/E(B-V) \) | \( C \) |
|-------------|------------------|-----------------|--------|
| Landolt B   | 4400             | 4.315           | 3.620  |
| Landolt V   | 5500             | 3.315           | 3.564  |
| Landolt R   | 6500             | 2.673           | 3.487  |
| Landolt I   | 8000             | 1.940           | 3.388  |

1.5–2.

Identifications of RC objects are presented in Fig. 5 (see after the references). The radio isophotes were plotted from the data of VLA observations and superimposed on the images of galaxies obtained with the 6 m telescope in the R filter. The VLA radio observations were carried out in the 1990s with different antenna configurations (Parijskij et al., 1996a). Besides, the VLA data for the RC objects from the MIT survey (Fletcher et al., 1996) and the FIRST survey (White et al., 1997) data were used. Images are also presented for the objects that we classified as QSO and which are excluded from the present study. The list of the objects is given in Table 1.

The processing of optical images was accomplished using the standard procedure in the MIDAS system. Subtraction of the averaged dark frame and element-by-element correction with the use of twilight sky frames were performed. The residual background inhomogeneity in the I filter, which is due to interference of night sky emission lines, was removed by means of the procedure of subtraction of the median sum of all working frames of a given night or several nights of one observing run. The calibration of photometric measurements for their conversion to the standard Johnson–Cousins system was done using the stars from Landolt’s (1992) list, which were observed several times during a night. To do photometry of the selected object, a circular aperture of one and the same size was used when measuring in different filters. The aperture size was chosen to be between 3″ and 12″, depending on the object luminosity. The typical size was 4″–5″. The background was measured with a circular aperture of sufficiently large radius in order not to cover the outer regions of the object being measured. When necessary, the neighbouring objects were removed by the procedure of interpolation of the surrounding background. The photometry accuracy was generally not worse than 0.1″ for galaxies brighter than 21″. It dropped down to 0.2″–0.25″ for 23″–24″ and was as low as 0.3″–0.5″ for galaxies fainter than 25″–25.5″.

To provide for the Galactic extinction, we used the charts from the paper “Maps of Dust IR Emission for Use in Estimation of Reddening and CMBR Foregrounds” (Schlegel et al., 1998), written in the form of FITS files. The conversion of stellar magnitudes to flux densities was implemented via the formula

\[
S(Jy) = 10^{C-0.4(m)}
\]

\( (\text{von Hoerner, 1974}) \) The values of the constant \( C \) for different filters are listed in Table 2, where the following characteristics are also given: name of filter, effective wavelength, coefficient \( A/E(B-V) \) of change-over from distribution of dust radiation to extinction in a given band under the assumption of extinction curve \( R_V = 3.1 \).

The stellar magnitudes of 50 galaxies of our sample, which were corrected for extinction in the four filters, are presented in Table 3.

3. Models of energy distribution in the spectra of host galaxies

In the late 1980s and early 1990s, attempts were made to use colour characteristics of radio galaxies for estimation of redshifts and ages of systems of host galaxies. There appeared numerous evolution models with which observational data were compared and results largely differing from one another were obtained (Arimoto & Yoshii, 1987; Chambers & Charlot, 1990; Lilly, 1987, 1990; Parijskij et al., 1996a). Over the past few years the models like PEGASE: Project de’Etude des Galaxies par Synthese Evolutive (Fioc & Rocca-Volmerange, 1997), and GISSEL’98 (Bruzual, Charlot, 1993; Bolzonella et al., 2000), in which an attempt was made to eliminate the shortcomings of the preceding versions, have been most commonly used.

In the “Big Trio” experiment (Parijskij et al., 1996a), we also tried to apply these methods to distant steep spectrum objects of the RC catalogue, for which we measured the magnitudes in the four filters (BVRI). This paper is distinguished from the paper of Parijskij et al. (1996a) by using more reliable identifications of radio sources, new photometric data and new models of energy distribution. Besides, we used in our work the smoothing procedure that makes it possible to model and predict the flux in the given filter at the specified SED with allowance for the filter throughput curve and also for the redshift effect.
Table 3: Stellar magnitudes of the sample radio galaxies corrected for extinction

| Source       | B   | V   | R   | I   | Source       | B   | V   | R   | I   |
|--------------|-----|-----|-----|-----|--------------|-----|-----|-----|-----|
| 0015+0503a   | 23.89 | 22.97 | 22.20 | 21.36 | 1155+0444 | 21.36 | 19.83 | 18.90 | 18.20 |
| 0015+0501    | 24.82 | 23.91 | 23.37 | 22.22 | 1213+0500 | 23.55 | 22.90 | 22.04 | 21.32 |
| 0034+0513    | 25.28 | 24.79 | 23.25 | 21.79 | 1235+0435b | 24.15 | 22.81 | 21.59 | 20.35 |
| 0039+0454    | 24.81 | 24.00 | 22.69 | 21.22 | 1322+0449 | 23.68 | 22.52 | 20.77 | 19.17 |
| 0105+0501    | 24.00 | 22.48 | 22.78 | 22.43 | 1333+0452 | 24.87 | 24.44 | 23.56 | 22.46 |
| 0135+0450    | 20.49 | 19.16 | 18.42 | 17.82 | 1339+0445 | 25.05 | 23.72 | 22.70 | 21.55 |
| 0152+0453    | 23.31 | 23.02 | 22.47 | 21.70 | 1357+0453 | 22.98 | 21.85 | 21.10 | 20.11 |
| 0159+0448    | 22.65 | 21.72 | 21.23 | 20.65 | 1429+0501 | 25.57 | 23.24 | 21.64 | 20.50 |
| 0209+0501a   | 20.37 | 19.19 | 18.43 | 17.78 | 1436+0501 | 23.90 | 23.86 | 23.39 | 22.70 |
| 0209+0501b   | 25.72 | 24.09 | 23.12 | 21.63 | 1446+0507 | 21.48 | 20.03 | 19.17 | 18.54 |
| 0318+0456    | 25.64 | 23.98 | 22.61 | 20.99 | 1503+0456 | 24.02 | 23.67 | 23.14 | 22.24 |
| 0444+0501    | 23.48 | 23.70 | 23.33 | 23.13 | 1510+0438 | 24.98 | 23.73 | 22.57 | 21.25 |
| 0457+0452    | 22.01 | 20.86 | 20.05 | 19.37 | 1551+0458 | 25.57 | 25.34 | 24.43 | 23.30 |
| 0836+0511    | 23.68 | 23.53 | 23.09 | 22.44 | 1626+0448 | 22.32 | 23.07 | 22.73 | 22.63 |
| 0837+0446    | 23.03 | 23.29 | 22.99 | 22.11 | 1638+0450 | 22.86 | 22.33 | 22.14 | 21.04 |
| 0845+0444    | 24.72 | 22.42 | 21.09 | 19.77 | 1646+0501 | 24.01 | 22.44 | 20.97 | 19.76 |
| 0908+0451    | 21.63 | 20.72 | 19.85 | 19.07 | 1703+0502 | 24.22 | 23.39 | 23.12 | 22.26 |
| 0909+0445    | 22.60 | 21.53 | 20.50 | 19.59 | 1706+0502 | 24.73 | 24.19 | 23.25 | 21.88 |
| 0934+0505    | 25.29 | 24.45 | 24.67 | 23.61 | 1722+0442 | 24.30 | 21.59 | 20.63 | 19.44 |
| 1011+0502    | 23.71 | 23.18 | 22.47 | 22.60 | 2029+0456 | 22.85 | 22.24 | 21.66 | 20.53 |
| 1031+0443    | 23.93 | 22.79 | 22.09 | 20.85 | 2219+0458 | 24.80 | 23.03 | 23.72 | 22.25 |
| 1043+0443    | 23.98 | 23.57 | 22.51 | 21.70 | 2224+0513 | 23.16 | 22.31 | 21.43 | 20.32 |
| 1124+0456    | 20.30 | 18.79 | 17.85 | 17.07 | 2247+0507 | 23.64 | 23.18 | 22.53 | 21.43 |
| 1142+0455    | 24.83 | 22.53 | 21.38 | 20.39 | 2348+0507 | 23.89 | 23.79 | 23.56 | 23.08 |

Figure 1: Hubble diagram R-value vs redshift for different radio galaxies taken from literature. The figure is reproduced from Pursimo et al. (1999).
These changes in the procedure enabled making the results of estimation more reliable as compared to our previous work.

We (Verkhodanov et al., 1999) preliminarily discussed applicability of the new methods to a population of distant ($z > 1$) radio galaxies with known redshifts, for which we managed to find in literature more or less reliable data of multicolour photometry in the optical and near infrared ranges in no fewer than three filters. It is shown, in particular, that redshifts can be estimated with an accuracy of 25–30% at $1 < z < 4$, given measured stellar magnitudes in more than three filters. And given at least one luminosity estimate in the infrared region, it suffices to use measurement in three filters. Estimates were made for two evolution models.

As one of the SED models the evolution model PEGASE (Fioc & Rocca-Volmerange, 1997) was employed for galaxies of the Hubble sequence both star forming and evolving in a passive fashion. One of the principal merits of this model is the extension to the near infrared range (NIR) of the atlas of synthetic spectra of Rocca-Volmerange & Guiderdoni (1988) with the revised stellar library including parameters of cool stars. The model covers a range from 220 $\AA$ to 5 microns. According to the authors the algorithm of the model makes it possible to follow rapid evolution phases such as red supergiants or AGB in the near IR. We used a wide set of SED curves from this model in a range of ages from $7 \times 10^6$ years to $19 \times 10^9$ years for massive elliptical galaxies.

From the library of synthetic spectra of the model GISSEL’98 (Bolzonella et al., 2000) derived with the aid of the evolution models of Bruzual & Charlot (1993, 1996), we used the computations for elliptical galaxies. The library of synthetic spectra was constructed with the following star formation parameters: simple stellar population (SSP), the duration of starburst activity is 1 billion years, the starburst activity decays exponentially. The solar metallicity was used in the model. The initial mass function (IMF) with an upper limit of 125 solar masses was taken from Miller & Scalo (1979). As Bolzonella et al. (2000) show the choice of IMF has no effect on the accuracy of redshift measurements. The mode tracks are computed in a wavelength range from 200 to 95800 $\AA$. We used the range specified by a redshift limit of 0 to 6 in our calculations.

The sets of evolution models employed are available at [http://sed.sao.ru](http://sed.sao.ru) (Verkhodanov et al., 2000).

### 4. Estimation of age and redshift

Before using the model transmission curves we performed their smoothing with the filter via applying the algorithm

$$S_{ik} = \frac{\sum_{j=0}^{n} s_{i-n/2+j} f_{jk}(z)}{\sum_{j=0}^{n} f_{jk}(z)},$$

where $s_i$ is the initial model curve of SED, $S_{ik}$ is the model curve of SED smoothed by the $k$th filter, $f_k(z)$ is the curve of transmission of the $k$th filter “compressed” $(1 + z)$ times when “moving” along the wavelength axis of the SED curve, $j = 1, n$ is the number of the pixel in the filter transmission curve. From the $k$ curves of SED thus formed (there are four of them in our case), we constructed a two-dimensional array ($\lambda$, filter) of smoothed spectra for further computations.

The evaluation of ages and redshifts was carried out by the method of choosing an “optimum” location of photometric magnitudes obtained in photometric observations of radio galaxies in different filters on the SED curves. We used the already computed and table-specified SED curves for different ages. The algorithm of selection of the optimum location on the curve was briefly as follows (for details see Verkhodanov, 1996): by way of shifting the points lengthwise (along the wavelength axis) and transverse (along the intensity axis) the SED curves, we defined the location at which the sum of squares of deviations of points from the corresponding smoothed curves is a minimum, i.e. the minimum of $\chi^2$ is actually calculated:

$$\chi^2 = \sum_{k=1}^{N_{\text{filters}}} \left( \frac{F_{\text{obs},k} - p \cdot \text{SED}_k(z)}{\sigma_k} \right)^2,$$

where $F_{\text{obs},k}$ is the observed stellar magnitude in the $k$th filter, $\text{SED}_k(z)$ is the model stellar magnitude for the given spectral distribution in the $k$th filter at a given $z$, $p$ is the free coefficient, $\sigma_k$ is the measurement error.

The redshift was found from the shift of location of the observed magnitudes at their best location on the SED curves from the “rest frame” position (position at $z = 0$). From the total set of curves for different ages we chose the ones on which the sum of squares of deviations for the given observations turned out to be a minimum.

Fig. 6 (see at the end of the paper) gives the results of the most plausible choice of evolution models for the photometry data and the corresponding function of plausibility.

### 5. Photometric redshifts for RC catalogue radio galaxies

To examine the potentialities of the method for determination of redshift and ages of the stellar population
of host galaxies from the data of multicolour photometry, we selected 40 remote radio galaxies with known redshifts, for which stellar magnitudes in no fewer than three filters are available in literature (Verkhodanov et al., 1998b, 1999).

It should be noted that literature photometric data are most inhomogeneous: they were obtained by different authors, different tools, with different filters; measurements for one and the same object were not always made in the same apertures, etc. This is why, only 42 out of 300 radio galaxies of the original sample remained. The subsamples of objects (3C, 4C, B2) with relatively homogeneous data are not large enough to be statistically compared. At first, using the collected photometric data obtained with the aid of the models PEGASE and GISSEL’98, only the ages of the stellar population of host galaxies with a fixed known redshift were derived. After that, a search for an optimum model SED curve, for the redshift and age of the stellar population simultaneously, was carried out, and the derived values were compared.

Thus, we estimated both the galaxy age and the redshift within the frames of the specified models (see Verkhodanov et al., 1998a, 1999). It is clear from general considerations that the reliability of the result at large redshifts shows a significant dependence on the availability of infrared data (up to the R range), because when fitting, we “cover” the region of rapid spectrum change (a jump) before the optical range of SED and thereby can reliably (with a well defined maximum of the plausibility curve) determine the location of our data. This can be proved as follows. When the available points are removed (to check the reliability of the procedure) with retaining only 3 points (one of which is in the K range), we obtain in fitting the same result on the curve of deviations as for 4 or 5 points. If the infrared range is not used, the result will then be more uncertain. However, as we show (Verkhodanov et al., 1999) the version of “tight” positioning of the four filters, as in our case of BVRI photometry, gave a good result in a sample of 6 galaxies, which is a good fit to the result obtained with using all the filters, including the infrared range.

A similar procedure was employed to estimate the redshift and the age for galaxies of the RC catalogue. The common distinction from the papers by Verkhodanov et al., 1998b, 1999 is that our observations were made only in 4 filters, BVRI, so, the infrared data are lacking.

Table 4 presents redshift and age estimates for the stellar systems of radio galaxies from the RC catalogue. The redshift \( z_c \), the age of the radio galaxy \( t \), the discrepancy \( \varepsilon \) and the age of the Universe \( T \) at \( z = z_c \) (\( H = 65, \Omega_m = 0.3, \Omega_\Lambda = 0.7 \) for standard Friedmann-Lemaitre-Robertson-Walker cosmology (Thomas & Kantowski, 2000)) are given in the table columns for the models GISSEL and PEGASE, respectively.

| Object RC J | \( z_c \) | \( t[\text{Myr}] \) | \( \varepsilon \) | \( T[\text{Myr}] \) | \( z_c \) | \( t[\text{Myr}] \) | \( \varepsilon \) | \( T[\text{Myr}] \) |
|-------------|----------|----------------|-------------|----------------|----------|----------------|-------------|----------------|
| 0015+0503a | 0.73     | 900            | 0.0412      | 7546           | 0.48     | 3000           | 0.0299      | 9237           |
| 0015+0501  | 0.81     | 1000           | 0.0334      | 7103           | 0.87     | 3250           | 0.0358      | 6797           |
| 0034+0513  | 0.98     | 16000          | 0.0729      | 6286           | 1.29     | 10000          | 0.0374      | 5130           |
| 0039+0454  | 0.95     | 16000          | 0.0346      | 6419           | 0.99     | 7000           | 0.0057      | 6242           |
| 0105+0501  | 0.28     | 500            | 0.0852      | 11032          | 4.21     | 9250           | 0.0839      | 1537           |
| 0135+0450  | 0.35     | 2500           | 0.0106      | 10350          | 0.10     | 7250           | 0.0018      | 13112          |
| 0152+0453  | 0.12     | 16000          | 0.0072      | 12855          | 0.81     | 640            | 0.0016      | 7103           |
| 0159+0448  | 0.13     | 2000           | 0.0093      | 12729          | 0.41     | 1900           | 0.0093      | 9813           |
| 0209+0501a | 0.39     | 1800           | 0.0067      | 9988           | 0.39     | 3500           | 0.0063      | 9988           |
Table 4: Colour redshifts and ages of stellar systems for the RC Catalogue radio galaxies (continued)

|   |     |     |     |     |     |     |     |     |     |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0209+0601b | 0.69 | 13000 | 0.0400 | 7783 | 0.70 | 6000 | 0.0468 | 13512 |
| 0318+0456 | 0.67 | 16000 | 0.0491 | 7906 | 0.71 | 6500 | 0.0071 | 7663 |
| 0444+0501 | 1.17 | 200 | 0.0365 | 5534 | 2.42 | 13000 | 0.0419 | 2870 |
| 0457+0452 | 0.40 | 2000 | 0.0092 | 9900 | 0.41 | 3500 | 0.0068 | 9813 |
| 0836+0511 | 0.77 | 250 | 0.0058 | 7319 | 0.81 | 286 | 0.0094 | 7103 |
| 0837+0446 | 0.98 | 200 | 0.0490 | 6286 | 0.99 | 202 | 0.0494 | 6242 |
| 0850+0511 | 0.49 | 1400 | 0.0322 | 9159 | 0.48 | 3250 | 0.0193 | 9237 |
| 0909+0445 | 0.67 | 1800 | 0.0145 | 7906 | 0.64 | 4000 | 0.0168 | 8096 |
| 0934+0505 | 1.72 | 1200 | 0.0785 | 4010 | 1.79 | 4250 | 0.0728 | 3865 |
| 1011+0502 | 0.46 | 300 | 0.0501 | 9397 | 0.50 | 453 | 0.0624 | 9082 |
| 1031+0443 | 0.86 | 2500 | 0.0188 | 6846 | 0.87 | 4250 | 0.0275 | 6797 |
| 1043+0443 | 1.19 | 3000 | 0.0138 | 5463 | 0.72 | 2200 | 0.0250 | 7604 |
| 1124+0456 | 0.35 | 10000 | 0.0025 | 10350 | 0.49 | 571 | 0.0386 | 1248 |
| 1152+0449 | 1.17 | 16000 | 0.0619 | 5534 | 1.33 | 8000 | 0.0069 | 5006 |
| 1155+0444 | 0.48 | 500 | 0.1161 | 1550 | 0.33 | 5750 | 0.0079 | 5099 |
| 1213+0500 | 0.70 | 700 | 0.0201 | 7723 | 0.68 | 2100 | 0.0162 | 7844 |
| 1235+0345b | 0.64 | 11000 | 0.0042 | 8096 | 0.68 | 5750 | 0.0083 | 7844 |
| 1322+0449 | 0.65 | 16000 | 0.1129 | 8032 | 0.78 | 7250 | 0.0702 | 7264 |
| 1333+0452 | 0.24 | 10000 | 0.0025 | 10350 | 0.35 | 14000 | 0.0421 | 10350 |
| 1339+0445 | 0.67 | 4500 | 0.0217 | 7906 | 0.71 | 5000 | 0.0136 | 7663 |
| 1357+0453 | 0.73 | 1400 | 0.0421 | 7546 | 0.41 | 4000 | 0.0409 | 9813 |
| 1436+0501 | 1.35 | 800 | 0.0157 | 4945 | 1.15 | 1680 | 0.0136 | 5606 |
| 1446+0507 | 0.35 | 5000 | 0.0140 | 10350 | 0.24 | 5750 | 0.0191 | 11451 |
| 1503+0456 | 0.78 | 500 | 0.0065 | 7264 | 0.83 | 1015 | 0.0023 | 6998 |
| 1510+0438 | 0.66 | 8000 | 0.0110 | 7969 | 0.75 | 5750 | 0.0074 | 7431 |
| 1551+0458 | 1.05 | 1200 | 0.0341 | 5991 | 1.11 | 4000 | 0.0294 | 5755 |
| 1626+0448 | 0.40 | 200 | 0.1268 | 13930 | 0.03 | 202 | 0.1282 | 14073 |
| 2.31 | 6000 | 0.1642 | 3011 | 2.30 | 3000 | 0.1814 | 3025 |
Table 4: Colour redshifts and ages of stellar systems for the RC Catalogue radio galaxies (continued)

| 1     | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|-------|------|------|------|------|------|------|------|------|
| 1638+0450 | 0.84 | 500  | 0.0315 | 6947 | 0.89 | 1015 | 0.0388 | 6699 |
| 1646+0501 | 0.65 | >5000 | 0.1171 | 8032 | 0.64 | 6750 | 0.0106 | 8096 |
| 1703+0502 | 0.81 | 600  | 0.0692 | 7103 | 3.56 | 640  | 0.0567 | 1874 |
| 1706+0502 | 0.07 | 2500 | 0.0431 | 13512 | 0.35 | 1680 | 0.0508 | 10350 |
| 1722+0442 | 1.02 | 1800 | 0.0339 | 6374 | 1.06 | 5750 | 0.0293 | 5951 |
| 2029+0456 | 0.81 | 800  | 0.0094 | 7103 | 0.88 | 2600 | 0.0107 | 6747 |
| 2219+0458 | 0.98 | 1200 | 0.1271 | 6286 | 1.36 | 7750 | 0.0555 | 4916 |
| 2224+0513 | 0.73 | 1200 | 0.0101 | 7546 | 0.77 | 3500 | 0.0072 | 7319 |
| 2247+0507 | 0.78 | 700  | 0.0094 | 7264 | 0.93 | 2500 | 0.0068 | 6510 |
| 2348+0507 | 1.43 | 450  | 0.0016 | 4715 | 1.24 | 571  | 0.0030 | 5293 |

Notes to Table 4

0034+0513 — the age of the stellar system in the two alternatives from the model GISSEL’98 is greater than that of the Universe at the given z; we choose the age where the difference is smaller despite a somewhat greater error.

0039+0454 — the age of the stellar system from the PEGASE model is inadmissibly large, it is about 3 times as large as that of the Universe at a given z. The same is observed in a number of other sources (0209+0501, 0845+0454, 1142+0455, 1152+0449, 1235+0435b, 1322+0449, 1510+0438, 1646+0501, 2219+0454). The cause of this has not been understood yet.

0105+0501 — in contrast to the majority of objects of our sample the redshift and the age from the two models are not consistent. Besides, the computation gives large errors in this case. The optical images (Soboleva et al., 2000) show that the bright line Lyα falls in the V filter. For this reason, the stellar magnitude is strongly corrupted.

0135+0450 — the redshift value lies between 0.34 and 0.10, but closer to 0.34. Note that from the GISSEL’98 model there is another minimum at z = 0.17 with the age 5750 Myr and a deviation of 0.0105. The values at the absolute minimum are discarded in the two models because of the discrepancy between the age of the system and that of the Universe.

0159+0448 — z = 0.09 (GISSEL’98) and z = 0.13 (PEGASE) lie outside the region of permissible values in the plane z − R (see Fig. 1; Pursimo et al., 1999). The age 15000 Myr in the GISSEL model does not conform to reality. We consider the alternative with z = 0.41 to be more reliable.

0209+0501a — z = 0.39 for both models. The age derived does not conform to real fact for a minimum deviation 0.0058 in the GISSEL model. Two other estimates yield a larger value of deviation.

0318+0456 — close redshifts for the models GISSEL’98 (z = 0.71) and PEGASE (z = 0.67). The age turns out to be ultimately small for both models.

0444+0501 — although to the value z = 1.17 for the PEGASE model corresponds a minimum deviation, the closest to the spectroscopic redshift (z = 2.73) is obtained in the GISSEL model (z = 2.42). The estimated age proves to be too great to be real, although z is close to real.

0836+0511 — the values z = 1.21 (GISSEL’98) and z = 1.14 (PEGASE) are close (to an accuracy of 6%) and practically have a minimal deviation. One can see here that the age of stellar systems turns out to be older in the GISSEL models.

0845+0444 — z = 5.29 (PEGASE) is not admissible both by age and by position in the plane z − R. 0908+0451 — the colour redshift (zp = 0.48) is confirmed by spectral measurements at the 6 m telescope of SAO RAS (zp = 0.5).

1142+9455 — z = 4.99 (GISSEL’98) and z = 5.20 (PEGASE) do not fall within the range of admissible values in the plane z − R. We choose z = 0.35, though in this case the age of the stellar system, according to the criterion of minimum of squares of deviations, proves to be somewhat larger than the age of the Universe.

1213+0500 — z = 5.15 (GISSEL) is outside of the region of acceptable values in the plane z − R, and the age of the stellar system in this case is 10 times that of the Universe. There are close redshift values in the region z = 0.7 for both models, a minimum χ²
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being consistent with this solution in the PEGASE model.

1322+0449 — the variant with \( z = 0.99 \) in the GISSEL model is unsuitable because the age of the stellar system is twice that of the Universe. A similar situation also occurs in the PEGASE model where the solution goes beyond the limits of acceptable age values. There is a stable minimum for \( z = 0.78 \) in the PEGASE model. In all the cases the redshift proves to be less than 1.

1357+0453 — assume \( z = 0.73 \) from PEGASE model, \( z = 0.41 \), however, for GISSEL model falls out of the plane \( z - R \). Note that there is one more local minimum for the GISSEL model, which corresponds to \( z = 3.86 \) in the plane of distribution of deviations, but the value of this minimum is 3 times as large as for \( z = 0.41 \), and the corresponding point also falls out of the plane \( z - R \).

1429+0501 — we fail to find acceptable values of the parameters for either model. This may be due to difficulties of separating a radio galaxy from a nearby star in the optical range (Parijskij et al., 1996a).

1436+0501 — accept the alternatives \( z = 1.18 \) (GISSEL) and \( z = 1.35 \) (PEGASE) with errors close to minimum. The difference between the redshifts in these models is then about 12%.

1446+0507 — at \( z = 0.11 \) the age of the galaxy in the GISSEL model turns out to be larger than the age of the Universe at a minimum of deviations, at \( z = 4.99 \) with a minimum error it does not fall within the range of admissible values in the plane \( z - R \) for radio galaxies, and the age of the stellar system is 5 times the age of the Universe. We retain \( z = 0.35 \) for PEGASE and \( z = 0.24 \) for GISSEL as possible alternatives.

1626+0448 — spectroscopic redshift for this object is \( z = 2.66 \) (Afanasiev et al., 2002). The current calculations have been carried out with no provision for the line \( Ly \alpha \). The data obtained show that \( z = 0.03 \) and \( z = 0.04 \) do not fall in the interval of acceptable values for radio galaxies in the plane \( z - R \). In all the cases the large errors are due to the fact that the bright line \( Ly \alpha \) falls on the B band (Parijskij et al., 1996a). The \( z \) values equal to 2.31 for PEGASE and 2.30 for GISSEL are quite close to the true values. When the line \( Ly \alpha \) is taken into account in the computations, the redshift value then turns out to be equal to the spectroscopic.

1638+0450 — choose \( z = 1.78 \) (GISSEL’98) and \( z = 1.67 \) (PEGASE), though \( z = 0.89 \) (GISSEL’98) and \( z = 0.84 \) (PEGASE) cannot be rejected either.

1703+0502 — the stellar magnitudes in all the filters can be affected by a nearby bright star (Parijskij et al., 1996a).

1722+0442 — the spectroscopic \( z = 0.7 \) (Afanasiev et al., 2002) is by 30% lower than the value derived by photometry for both models.

6. Discussion and results

1. The problem of colour redshifts of distant galaxies

As it was shown earlier (Verkhodanov et al., 1999), the model PEGASE yielded satisfactory results over 40 objects for which spectral measurements of redshifts are available. Analysis of Table 4 shows that the new model CISSEL often gives results only slightly differing from the PEGASE model (see also Verkhodanov et al., 2001a, b).

Fig. 2 presents a histogram of the ratio \((1 + z_{\text{GISSEL}})/(1 + z_{\text{PEGASE}})\). The distribution of errors is not normal, there is a nucleus with very small model errors, in which most of the objects (80%) fall, but 20% of the objects have very large errors. As a rule, the large errors are caused by getting of the strong line \((Ly \alpha)\) in one of the filters, illumination from a nearby bright object and complicated cases of SED deviation from the model. A number of such examples are described in notes to Table 4.

![Figure 2: Histogram characterizing the distribution of the ratio of colour redshifts from the GISSEL'98 \((z_{\text{GISSEL}})\) and PEGASE \((z_{\text{PEGASE}})\) models. The central part of the histogram, within which 80% of objects fall, is presented.](image-url)
It should be noted that we use the standard set of filters of the 6 m telescope, BVRI, which is satisfactory for not too distant objects (the colours of which have been measured yet). Measurements have to be extended to the H and K ranges. In a considerable number of cases, this will enable elimination of uncertainties in the estimates. The situation may change for ultimately distant objects with R > 24′′, and we have to wait until the observations are completed, prior to giving recommendations. It is clear from general considerations that there is a danger from “right” and “left”, that is, the secondary star formation sites may distort the blue region of the spectrum, but the dust at very great redshifts may deform the IR region. It can easily be shown that large discrepancies may point to possibilities of luminosity distortion by strong lines, and we hope to take this into account in the future. For z > 2, it is necessary to take into account, at least, the line Lyα. Considerable errors may arise because of the periodicity of series in Bor’s model, but here simple energetic considerations may be helpful (discrepancies in the colour and photometric estimates). This can be illustrated by the RC object J1703+0502 formally having a zero redshift. When adopting this estimate, the optical luminosity of this object will then prove to be so low that it cannot produce any perceptible radio radiation (note that \(P_{\text{radio}} \approx L_{\text{opt}}^{2.5}\); Iskudarian & Parijskij, 1964; Franceschini et al., 1998). When making use of the secondary criteria, we sometimes have to reject the variant with the smallest discrepancies and take the next one.

2. The age of stellar systems of host galaxies

As it is known, the age is much more difficult to assess than the redshift. The older the stellar population the larger the error may be. We have made a histogram (Fig. 3) of differences of ages determined from the models GISSEL \(t_{\text{giss}}\) and PEGASE \(t_{\text{peg}}\) for one and the same object. They are normalized to the age of the Universe with \(\Lambda = 0.7\) (T) for the moment that corresponds to the measured redshift \((t_{\text{giss}} - t_{\text{peg}})/2T\). The distribution of differences of ages derived from different models are far from normal, but there is a nucleus where 70% of objects fall.

\[
\begin{align*}
\text{Histogram of half-difference of colour ages} \\
\text{of host stellar systems obtained from the models GISSEL'98 } & t_{\text{giss}}, \text{ and PEGASE } t_{\text{peg}} \text{ vrs the age of the Universe with } \Lambda = 0.7 \text{ (T) for the moment corresponding to the measured redshift. The central part of the histogram is shown where 80% of objects fall.}
\end{align*}
\]

The situation of the galaxies with “young” objects is more complicated, their colour can be distorted by repeated star-formation bursts at merging of galaxies or under the action of close passings. The variant of “young” galaxy cannot be accepted, since we deal with powerful radio galaxies, for functioning of which a supermassive black hole is necessary (DMO — Dark Massive Object, Salucci et al., 1999) with the mass of about \(10^9 M_\odot\), that is not possible within the standard models of black hole formation (Franceschini et al., 1998). Only the primary black holes with masses \(10^4 \sim 10^6 M_\odot\), round of which galaxies form later on,
may be the alternatives of “merging”.

As a result, a careful conclusion can be drawn that at least the statistical estimates of the redshift and age for population of powerful radio galaxies give satisfactory results. The GISSEL model can be recommended not only for radio-quiet galaxies but also for powerful radio galaxies. It is advantageous to use all available data on the objects to obtain more reliable estimates, this will decrease the errors.

In conclusion we enumerate the results obtained.

1. The largest currently available body of data on BVRI magnitudes of host galaxies responsible for the origin of powerful radio galaxies is presented.

2. The colour redshifts for powerful radio galaxies show a satisfactory agreement with the spectral ones (the error is 10–20% with a small fraction of large errors). The recent 2001 spectral observations of the RC objects RCJ0908+0451, RCJ1154+0431, RCJ1626+0448, RCJ1722+0442 gave errors of redshift measurement by the techniques described above within 10–15% (Afanasiev et al., 2002).

3. The limited number of closely spaced filters as in our BVRI case may also yield satisfactory results even for large redshifts.

4. The redshift distribution for the studied objects of our sample (the subgroup of objects brighter than $m_R = 23.5^m$) shows a maximum near $z \sim 1$, i.e. in the range of maximum radio activity of the Universe. The group of objects with large colour redshifts ($z > 2.5 - 3$) requires a separate analysis. In any case, we do not consider yet the gap in the population of the region ($1.5 < z < 2.5$) to be real.

5. The colour data are generally not at variance with the stellar magnitudes in the filter $R$ (Parijskij et al., 1996a) when $R < 22.5^m$. Fainter objects show a higher dispersion of photometric redshifts at one and the same value of $R$. One can notice here two branches in the plane $(z - R)$ (Pursimo et al., 1999).

The search for differences in the morphology, radio luminosity, spectral indices has given no final result. Note that the objects with the steepest spectra and a large radio-to-optical luminosity ratio occur in the branch with large redshifts. However, further investigations are needed. Objects with low relative radio luminosity, as it was to be expected, prove to be either quasars or nearby galaxies.

6. The age of galaxies is determined less reliably, and results turn out to be of low significance for larger $z$. However, in practice one can always indicate the lower limit of the age of galaxies and, therefore, the minimum redshift of their formation. This age is always larger than the standard estimate of the object lifetime, and in a number of cases it exceeds the age of the Universe at an object redshift in a simple CDM model. There are no such galaxies in a model with a $\Lambda$-term of 0.6–0.8 (e.g. de Bernardis et al., 2000).

7. A programme has been developed and tested of automatic determination of colour redshifts and ages of galaxies, which is applicable to any redshifts with provision for transformation of the shape of the filters when changing over from the rest to the moving system of reading, available through the server [http://sed.sao.ru](http://sed.sao.ru).

We contemplate further investigation of colour and photometric techniques as applied to the population of distant radio galaxies. New more realistic models of colour evolution and refined methods of age evaluation in stellar systems will make it possible to obtain more reliable results for a great number of objects.

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Fig. 5. Optical identifications of RC sources: VLA radio isophotes overlaid on the 6m telescope R-band images, and R-band isolines overlaid on the VLA images.
The map (4860MHz, VLA) superposed on the R-band image (BTA)

The R-band contours (BTA) superposed on 4860MHz image (VLA)

Contour key
- 0.0007
- 0.0011
- 0.0018
- 0.0028
- 0.0044
- 0.0070
- 0.0111
Fig. 6. Fitted SED models and corresponding probability functions for RC objects.

PEGASE models for RC J0015+0503a: SEDs and probability function

GISSEL models for RC J0015+0503a: SEDs and probability function
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PEGASE models for RC J0015+0501

Object: 0015c

z=0.81
age=1000 Myr

GISSEL models for RC J0015+0501

Object: 0015c

z=0.87
age=3249.9 Myr

PEGASE models for RC J0034+0513

Object: 0034

z=0.98
age=16000 Myr

Redshift

Log Age (Myr)

Log Flux Density [Arbitrary Jy]

Wavelength [Angstrom]
Object: 0015a

$z = 3.82$

$\text{age} = 508.8$ Myr
Object: 0015c

z=3.71
age=508.8 Myr
Object: 0034

z = 5.98

age = 570.8 Myr
Object: 0015a

z = 0.47
age = 1600 Myr
Object: 0015a

Object: 0015a

z=0.70
age=1680 Myr
Object: 0015c

Wavelength [Ångstrom]

Log Flux Density [Arbitrary Jy]

z = 0.74

age = 1680 Myr
Object: 0034

Log Flux Density [Arbitrary Jy]

Wavelength [Angstrom]

z=5.98
age=2100 Myr
Object: 0034

z = 5.98
age = 2600 Myr
Object: 0015a

$z = 1.07$

$\text{age} = 3000 \text{ Myr}$
Object: 0034

Z = 1.10
Age = 8000 Myr
Object: 0034

z=1.29

age=10000 Myr
Object: 0034

z=1.11
age=15000 Myr