Astrophysics, Vol. 49, No. 2, 2006

THE RADIO SOURCE Z0254+43: z = 4.067

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In January 2005 spectral observations of the radio source Z0254+43 were made on the BTA at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences (RAN) and its red shift was found to be z=4.057. The BVRI magnitudes were found to be 22.68, 21.19, 19.94, and 19.23, respectively. Photometric observations in December 2005 on the Zeiss-1000 at the SAO revealed no significant variation in the optical emission from this object over that year. We can discuss its variability on an hourly time scale with some caution. The variability of the flux from Z0254+43 was observed from 1990-2005 on the RATAN-600 over a wide range of frequencies. It turns out that the amplitude of the variability is minimal at a frequency of ~8 GHz. A model for the variability has been constructed which yields an estimate of ~28° for the orientation of the jet of Z0254+43 to the line of sight. The luminosity of Z0254+43 in the optical range is ~2·10^{26} W/Hz and in the radio frequency range, ~2·10^{27} W/Hz.

Keywords: *Radio sources: spectrum: red shift - individual: Z0254+43*

1. Introduction

Since 2001 the LSFVO of the SAO RAN and the "RATAN-600" laboratory at the Shternberg State Astronomical Institute (GAISh) have been working with great success on the optical identification of radio sources in the Zelenchuk GAISh survey and determining their red shifts.

As a continuation of these studies, on January 12-13, 2005, the authors obtained an optical spectrum of the radio source Z0254+43 on the BTA with the SCORPIO reducer [3]. This object was first observed in October-November 1990 in the zenith (unpublished) region of the Zelenchuk GAISh survey. The survey was conducted simultaneously at frequencies of 3.9 and 7.5 GHz at the zenith of RATAN-600, with right ascensions of 0-24 hours and declinations in the range 43°38'-44°02' [2]. At the epoch of the observations, in these bands the object had the following fluxes:

$$S_{3.9} = 108 \pm 7.5\,\text{mJy} \quad \text{and} \quad S_{7.5} = 148 \pm 12.5\,\text{mJy}$$

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Original article submitted September 22, 2005; accepted for publication February 17, 2006. Translated from Astrofizika, Vol. 49, No. 2, pp. 209-220 (May 2006).

 0571-7256/06/4902-0184

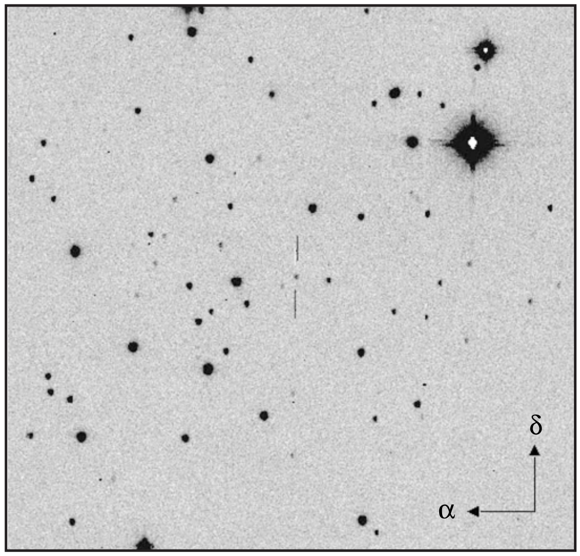

Fig. 1. A 3.2'×3.2' image of the field of Z0254+43. Obtained on the Zeiss-1000 in the *V* band.

The coordinates of the object are $\alpha_{2000} = 02^{h}57^{m}59^{s}.1$, $\delta_{2000} = 43^{o}38'37''$.

Its position on the celestial sphere is indicated in Fig. 1, which was obtained with the Zeiss-1000 at the SAO with a *V* filter and an exposure of 240 s.

2. Optical observations

Spectral observations were made in two bands: 4000-7500 Å (VPHG550G grism) and 6000-9000 Å (VPHG550R grism). The spectral resolution was 15 Å. In each band, four 600-second exposures were taken. The standard AGK81D266 was observed for calibrating the "blue" spectrum and G191B2B, for the "red" spectrum. The spectral data were processed using a package of programs written by V. R. Amirkhanyan aided by active consultations with V. L. Afanas'ev and S. N. Dodonov. The resulting spectrum of the object is shown in Fig. 2. This spectrum contains the standard broad lines of distant quasars: strong Lyα, SiIV+OIII, and CIV. The narrow semiforbidden OIII line appears to be associated with the outer regions of the object. The FeII 1636 line is dubious. Lyβ manages to break through the "forest" of absorption lines. The red shift of the object calculated from these lines is 4.067. The observed effective width of the Lyα line is ~120 Å.

Multiplying the known spectral characteristics of the Johnson-Cousins system *BVRI* filters by this spectrum and calculating the corresponding stellar magnitudes of the object yields m_B = 22.68, m_V = 21.19, m_R = 19.94, and m_I = 19.23. The color index *B-R* = 2.74 corresponds to "Palomar" O-E~3 for objects with $z > 4$ [4-5].

A study of the data from the first (POSS-1) and second (POSS2) Palomar surveys suggested a variability in the brightness of this object.

The USNO-1B catalog [6] for the epoch 1957 (POSS-1) yields m_R = 19.22 and for the epoch 1989.8 (POSS-2), m_R = 19.67. The first Palomar survey did not record this object in the *B* band. But the object is reliably observed in the

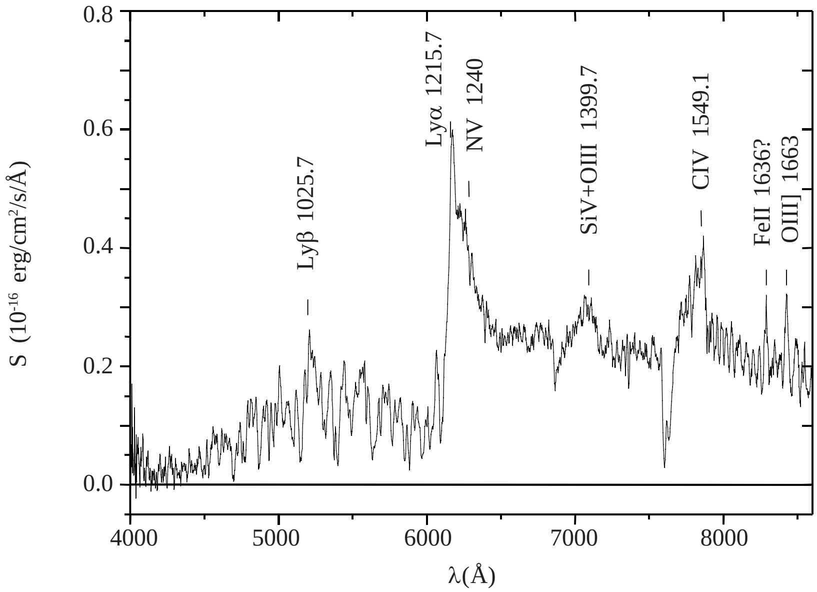

Fig. 2. An optical spectrum of Z0254+43.

"blue" chart of the second Palomar survey and the USNO-1B catalog gives a magnitude of $20^m.04$ for the epoch 1993.7. And although the error in the USNO is fairly large and the B magnitude in POSS-2 appears to be excessive, we have attempted to estimate the possible variability.

First, we processed the five direct images in the *R* band obtained on the BTA during the spectral observations. It turned out that over four hours the brightness of Z0524+43 rose by $0^m.1$ (Fig. 3a).

We estimated the change in the brightness of the object over a year starting from the time its spectrum was obtained, as well as over times of tens of minutes.

On the night of 29-30 December 2005 we made BVRI photometric observations of Z0254+43 on the Zeiss-1000 telescope at the SAO. The atmosphere was very calm with good transparency and an image quality of 1.2 angular seconds. A series of 9 exposures was made in each filter with sequential change of the filter after each exposure. The exposure times for the BVRI filters were 300, 240, 180, and 180 s, respectively. In the middle of the series the photometric standards in the field NGC 1275 were observed for absolute calibration. This field lies close to Z0254+43, both in terns of declination and in terms of right ascension.

This analysis led to the following values of the stellar magnitudes for Z0254+43:

$$m_B = 22.58 \pm 0.05,\ m_V = 20.04 \pm 0.05,\ m_R = 19.84 \pm 0.1,\ m_I = 19.42 \pm 0.08.$$

These observations made it possible to calibrate the objects in the field and to identify the direct pictures from the BTA with them. As a result, we obtained a photometric estimate of the magnitude of Z0254+43 on January 12, 2005 of m_R = 19.83±0.1, which differs from the "spectral" estimate by $0^m.09$. These estimates are mainly determined by the errors for the standards in the field NGC1275. In order to reduce them and try to estimate the variability of the object over the course of a night, we plotted a relative light curve in each filter band, as described in Ref. 7. More than one hundred objects in the field were used for the mutual calibration of each pair of images. Figure 3b shows the *BVRI*-band light curves obtained from the observations of December 29, 2005 on the Zeiss-1000. In this graph the ordinate scale for the *R* and *I* band light curves has been changed by a factor of 4.

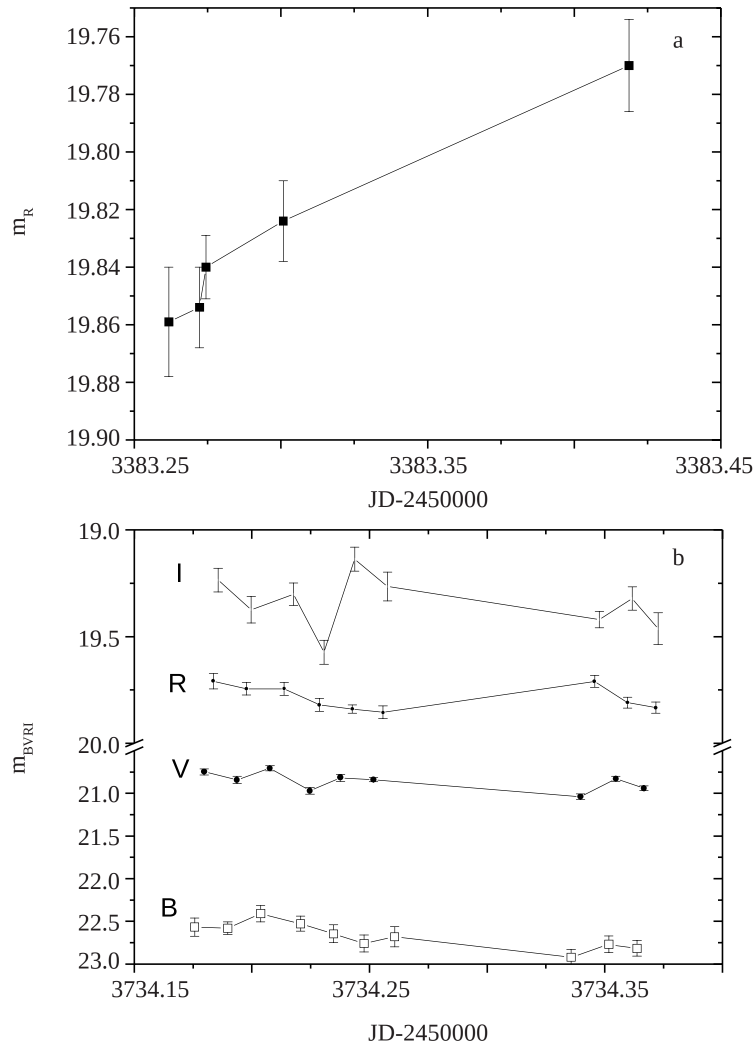

Fig. 3. Light curves obtained (a) on the BTA in the *R* band and (b) on the Zeiss-1000 in the *BVRI* bands.

These results show that no significant change in the brightness of the object was observed over a year. We also believe that any conclusions based on these light curves regarding any actual rapid variability of the object must be drawn with great caution. Some hope is offered by the cross correlation of the *V* and *B* band light curves, which reaches a maximum of 0.85 (Fig. 4). The autocorrelation function for the V band is also shown in this figure for comparison. Since the observations in the two bands are independent processes, the relationship between the light curves may be an argument in favor of variability. The variations in the *R* band brightness observed on the BTA and the Zeiss-1000 substantially exceed the errors. However, we should be alert to the fact that the correlation between the *V* and *R* bands is unconvincing.

The activity of the object in the blue portion of the spectrum can be explained by making a very simple and very bold assumption, namely that we are observing the variability of radiation that is not from the object itself, but the variability of the optical thickness of a region which absorbs most of the energy at wavelengths shorter than 1216 Å.

Evidently, these observations must be extended and longer series of data have to be analyzed.

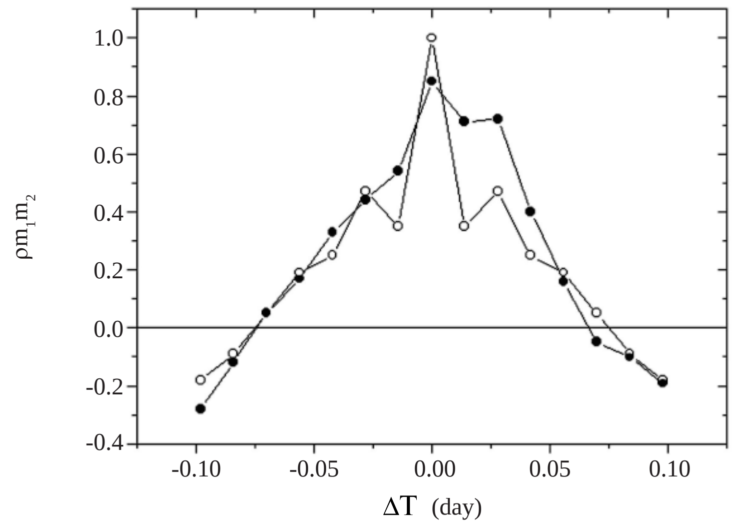

Fig. 4. The autocorrelation function of the *V* band light curve (hollow circles) and the cross-correlation function between the *V* and *B* band light curves (solid circles).

3. Radio observations

In order to clarify the current state of the object in the radio frequency bands, we asked M. G. Mingaliev to observe it at RATAN-600 on March 2-3, 2005, at five frequencies 2.3, 4.8, 7.7, 11.2, and 21.7 GHz. In addition, in his archives Yu. A. Kovalev has found multifrequency observations of Z0254+43 at RATAN-600 for November 2001, April and June 2003, and March 2005, which he made as part of a program to monitor the radio spectra of active objects. Mingaliev

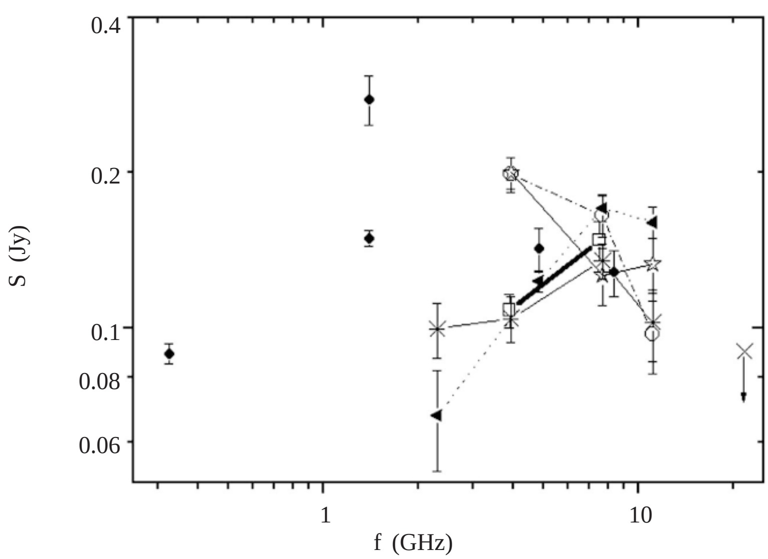

Fig. 5. The radio spectrum of Z0254+43 over 1990-2005. Notation: —□— GAISh, October 1990; —✳— Kovalev, November 2001; --○-- Kovalev, April 2003; —☆— Kovalev, June 2003; ···◄··· Mingaliev+Kovalev, March 2005; ● published; × upper bound at 21.8 GHz.

and Kovalev have kindly provided us with all their observational data. The information was processed using the program developed by one of the authors of this paper, Amirkhanyan. These results are extremely important, since they make it possible to construct instantaneous spectra of the object in several epochs over a wide range of frequencies. Published data on this radio source [8-12], as well as the instantaneous spectra (joined by lines) obtained at RATAN-600, are shown in Fig. 5. Since the object could not be observed at 21.7 GHz in any of the series of observations, we could only make an upper bound estimate of the flux in this band, ~0.09 Jy.

4. Model for the variability of the radio source

We shall use the observations of Z0254+43 from 1990 through 2005 to estimate the variability of its flux as a function of frequency. To do this we break up the range of observed frequencies into four intervals and calculate the traditional variability index

$$V = \frac{S_{max} - S_{min}}{S_{max} + S_{min}},$$

which, of course, does not take the measurement errors into account. In each interval we use the χ^2 criterion and calculate the probability P that the flux form the object is constant and equal to its weighted average over all the measurements,

$$\langle S \rangle = \frac{\sum_{i=1}^{n} S_i / \sigma_i^2}{\sum_{i=1}^{n} 1/\sigma_i^2},$$

where S_i is the measured flux, σ_i is the error in the measurements, and its spread is determined only by the measurement errors, so that

$$\chi^2 = \sqrt{\sum_{i=1}^{n} \frac{\left(S_i - \langle S \rangle\right)^2}{\sigma_i^2}}.$$

The results of the calculations are listed in Table 1. Here f_{min}-f_{max} denotes the range of frequencies within which the variability has been determined, N is the number of observations in that interval, $\langle S \rangle$ is the average flux in the interval f_{min}-f_{max}, $\langle\sigma\rangle$ is the average error in the flux, P is the probability of a stable flux, and V_{exp} is the variability index.

Experience shows that in most objects the variability index increases with increasing frequency. For example, in Ref. 13 the average variability index over 379 quasars was found to increase from 0.14 to 0.24 as the frequency was changed from 2.3 to 22 GHz. But this paper also shows instantaneous spectra of objects obtained during 1997-2001 which show that the radio sources 0007+10 0906+01, and 2121+05 have the opposite variability-frequency dependence. The radio source 1741-03 has a minimum variability at ~6 GHz.

This behavior of the variability index has a natural explanation in the model of Ref. 14, which considers the evolution of the spectrum of radiation from a cloud of relativistic electrons moving an angle θ relative to the line of sight of the observer in a radial magnetic field.

We have constructed a version of this model in which a central machine ejects a continuous series of clouds, with

TABLE 1. Frequency Dependence of the Variability of Z0254+43.

f_{min} - f_{max}	N	$\langle S \rangle$	$\langle \sigma \rangle$	χ^2	P	V_{exp}
1.4-2.3 GHz	4	0.137 Jy	0.005 Jy	58.2	1.44 Å-12	0.6
3.9-4.8 GHz	6	0.129 Jy	0.009 Jy	61.7	5.4 Å-12	0.3
7.5-8.4 GHz	6	0.147 Jy	0.005 Jy	11.7	0.039	0.148
11.2 GHz	4	0.13 Jy	0.007 Jy	14.6	0.002	0.24

uniformly distributed, random times of creation. An observer detects radiation from an ensemble of clouds at different stages of evolution, whose number can be controlled. In order to account for the spatial anisotropy of the radiation from the radio source, the luminosity of the ensemble of clouds is multiplied by the directional diagram of the jet and combined with the spherically symmetric radiation of the normal component. The parameters of the directional diagram are taken from Ref. 15.

Since the creation of the clouds and their emergence from the field of view are a random process, the observed number of clouds may fluctuate significantly relative to the average. The variability of the flux owing to this process is also a random process. Numerous model calculations showed that if the number of observed clouds is specified to be in the range 0.1-40, then the power spectrum of the light curve has a power law dependence with an index ~-1, like flicker noise. This type of spectrum for the variability is characteristic of many extragalactic radio sources [16].

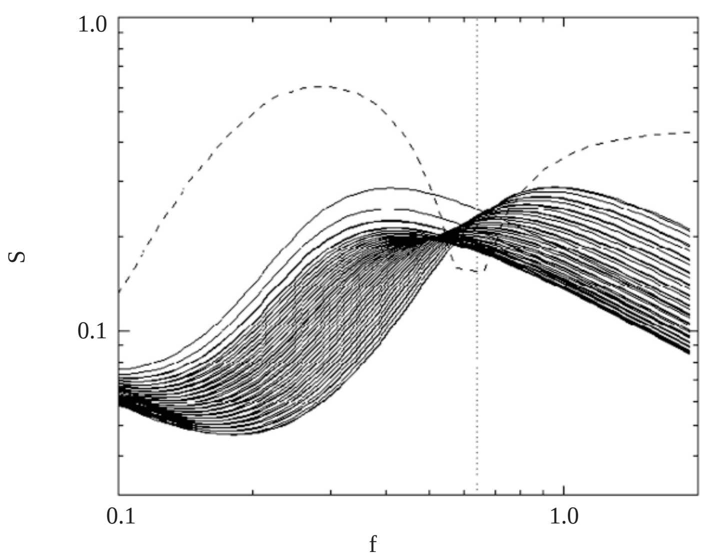

Fig. 6. Evolution of the radiation spectrum of an ensemble of clouds of relativistic electrons. The dotted curve is the variability index as a function of frequency. The dotted vertical line is the position of the minimum in the variability index.

Figure 6 shows the evolution of the spectra generated by the model for an angle $\theta = 28^{o}$, an electron energy spectrum ~$E^{-2.5}$, and ~0.4 simultaneously observable clouds (the fluxes and frequencies are given in arbitrary units). The variability index corresponding to the numerical simulation is indicated by a dotted curve in this figure. The calculations showed that the values and position of the extrema of the index depend mainly on the angle of orientation and, to a much lesser extent, on the density of the clouds. As the orientation angle increases, the extrema shift to higher frequencies, while the variability index decreases, both at the maximum and at the minimum.

It is natural to try to use this dependence to estimate the orientation of the jet of the radio source relative to the observer's line of sight.

In order to obtain a model dependence of the variability index at the minimum V_{min} and at the maximum V_{max} on the orientation, for each value of the angle q we have carried out ten numerical simulations and determined the average values of V_{min} and V_{max}, as well as of $\langle S_{min} \rangle / \langle S_{max} \rangle$, the ratio of the average fluxes at the frequencies of the minimum and maximum (Fig. 7). In this figure the dotted lines indicate the minimum (0.15) and maximum (0.6) values of the variability index of Z0254+43, taken from Table 1, and the ratio of the fluxes (1.07). As a result, we obtained three close estimates for the orientation angle for this object: 30, 28, and 26 degrees. Of course, it is also possible to use the dependence of V_{min}/V_{max} on θ. But a favorable situation in which both extrema fall within the range of the observations would be most unlikely, especially for objects with large red shifts. More often, we would only record only the maximum of the index, which is, unfortunately, less sharp than the minimum. If the orientation angle $\theta < 5^{o}$, then the extrema are very indistinct and the index increases monotonically with increasing frequency. If $\theta > 70^{o}$, then the extrema "shoot" upward with frequency and the variability is so small that measuring its parameters becomes difficult because of the measurement errors.

Figure 8 shows the luminosity spectrum of the object (optical and radio frequencies). The luminosity was calculated using the standard formula

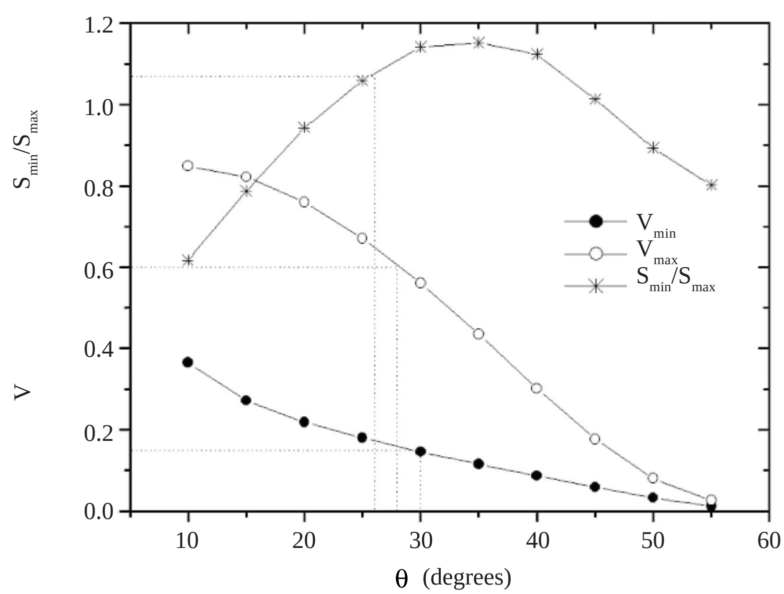

Fig. 7. The minimum and maximum values of the variability index, and the ratio of the average fluxes at the frequencies of the minimum and maximum, as functions of the orientation of the radio source to the observer's line of sight.

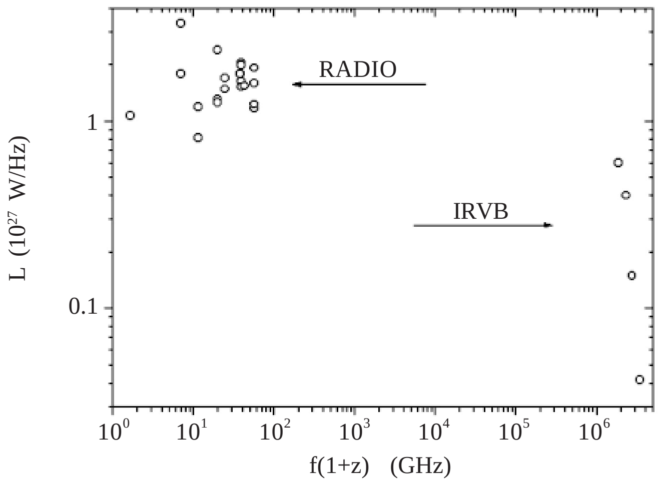

Fig. 8. The luminosity spectrum of the object at z = 4.067.

$$L_{f(1+z)} = 4\pi\left(\frac{c}{H}\right)^2 l_b^2 S_f (1+z)^{-1} ,$$

where S_f is the flux at the observation frequency f, $L_{f(1+z)}$ is the luminosity in comoving coordinates at the frequency f(1+z), and $l_b = 2\frac{\Omega z + (\Omega - 2)(\sqrt{1+\Omega z} - 1)}{\Omega^2}$ is the bolometric separation.

The calculations were done for H = 75 km/s/Mpc and $\Omega = 1$. The luminosity in the radio band is ~$2\cdot10^{27}$ W/Hz and that at optical frequencies is an order of magnitude lower. It is possible that during the burst of 1993, the optical luminosity was comparable to the radio luminosity. These numbers were obtained assuming spherical symmetry of the directional diagram. If we include the anisotropy of the diagram [15] and its orientation angle of 28°, then the luminosity of the object in the radio band is 2.5 times higher.

5. Conclusions

We have obtained an optical spectrum and determined a red shift z = 4.067 for the radio source Z0254+43. The spectrum contains a strong, broad Lyα line, after which the spectrum drops sharply and the Lyβ line can be seen against a background of absorption lines. In the “red” part of the spectrum, broad SiIV+OIII and CIV lines can be seen reliably, as well as a narrow semiforbidden OIII line. The luminosity spectrum of the object has been determined at optical and radio frequencies. We were not able reliably to detect variability of the object in the optical range, either on a time scale of a year or over short times. One possible sign of optical variability is the “blue” POSS-II map, on which the magnitude of Z0254+43 is estimated to be $20^m.04$ in USNO, which is $2^m.6$ higher than our values. In the red band the difference between our measurements and the Palomar surveys is considerably less and this may be attributable both to variability of Z0254+43 and to errors in USNO-1B.

There is no doubt of the variability of this object at the radio frequencies. Here we have encountered the rare situation in which the amplitude of the variability in the visible passes through a minimum. We have been able to match the observations with a model for the radio source in which a central core constantly ejects compact clouds of relativistic electrons into a dipole magnetic field and, from the experimental values of the minimum and maximum of the variability index, to obtain an estimate of ~26-28° for the orientation angle of the jet relative to the line of sight.

We thank V. L. Afanas'ev and S. N. Dodonov for their great help in writing the programs for processing the spectral observations, as well as M. G. Mingaliev and Yu. A. Kovalev for observing this object at RATAN-600 and providing us with all their original observational data.

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