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DETERMINATION OF THE RED SHIFTS OF SELECTED IVS PROGRAM OBJECTS. I

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The spectroscopic red shifts of seven optical objects whose coordinates coincide with those of radio sources in the IVS (International VLBI Service for Geodesy and Astrometry) program list are determined from observations with the 6-m BTA telescope at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences. A comparison of these spectra and red shifts with data in the radio frequency range shows that four of the objects discussed here are correctly identified, while the other three require further study. The distances to the radio sources derived from our measurements yield more accurate estimates of the cosmological model parameters than those based on the proper motions of these objects derived from geodesic VLBI observations.

Keywords: *red shift: radio sources: optical identifications: spectra: cosmological parameters*

1. Introduction

In 1966 it was shown [1] that, in terms of the general theory of relativity, with anisotropic expansion of the universe, systematic effects describable by second-order vector spherical harmonics may show up in proper motions of distant objects.

Three possible explanations for these effects were offered: anisotropic expansion of the universe, rotation of the universe, and primary gravitational waves of poloidal and toroidal character. The expected magnitude of these effects is no greater than a few tens of arc microseconds per year. At that time [1], it was impossible to detect these effects, but now such an undertaking has a good chance of success using VLBI measurements of the proper motions of extragalactic radio sources.

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Preliminary estimates showed that these motions contain statistically significant harmonics that can be described by second order spherical harmonics and become greater with increasing red shift [2,3]. The systematic effects increase from 10±3 ms/year for sources with red shifts of 0-0.7 (with an average of z = 0.44) to 25±8 ms/year for sources with red shifts of 1.5-3 (average z = 2.23). For sources with z > 1.7, a sharp increase in the amplitude of the proper motions (58±10 ms/year) was noted; this may be the result of inadequate observational data for sources with large red shifts, which reduces the reliability of the results. Besides second order vector spherical harmonics, first order vector spherical harmonics have also been observed (dipole and rotational components) with amplitudes of 10-20 ms/year and a mean square error of 1-2 ms/year. The dipole component is apparently caused by an accelerated motion of the center of mass of the solar system about the center of the galaxy [5-10], while the rotational component probably arises from an imprecise determination of the precession constant.

The data obtained thus far are based on geodesic VLBI observations made in the S/X bands since the late 1970's and stored in the IVS data base of the International VLBI Service for Geodesy and Astrometry.* The total number of observed radio sources approaches 5000, but only about 1000 of these have been observed long enough (more than 10 years) for a reliable estimate of their apparent motions. For the most actively observed radio sources, with up to several hundred thousand observations over an interval of more than 30 years, a formal estimate of the accuracy in their coordinates gives 10 arc ms, with the real accuracy that is roughly an order of magnitude higher [4]. Such a large difference between the formal and real errors is explained, first of all, by the complicated, variable structure of the sources, which are mostly active galactic nuclei with bright jets. This leads to a shift in the centroid of the radio brightness of a source and, thereby, to the appearance of a fictitious proper motion. These proper motions can be as high as a few hundred arc ms per year, and often are nonlinear [11,12]. This leads to a significant increase in the random error in estimates of the vector spherical harmonics, and can also lead to systematic errors.

This effect can be reduced by increasing the number of radio sources brought into the analysis. These sources must have a sufficiently long observational history and a known red shift. However, the red shifts of most of the sources observed in the geodesic VLBI programs have not been measured [13,14]. One of the set tasks of the proposed program of observations is, in fact, to increase the number of astrometric radio sources with known distances (red shifts). It was assumed that, as a result, we should be able to solve two interrelated problems:

1. increasing the number of radio sources with known proper motions and distances; and
2. increasing the overall number of geodesic radio sources with known distances for predominant use in the planned observational programs.

In this paper we present the first results of observations in this program.

2. List of program objects

Determining red shifts is a rather laborious process that also involves, in this case, optical identification of radio sources. Because of the faintness of most of the objects, this task can only be carried out with large telescopes.

* http://ivscc.gsfc.nasa.gov

TABLE 1. List of Observed Sources and their Coordinates for the Epoch J2000.0

IERS number	RA h, min, s	DE deg, min, s
1751+288	17 53 42.4736	+28 48 04.938
1923+210	19 25 59.6053	+21 06 26.162
2013+163	20 16 13.8600	+16 32 34.113
2023+503	20 25 24.9725	+50 28 39.536
2030+547	20 31 47.9585	+54 55 03.139
2152+226	21 55 06.4585	+22 50 22.281
2302+232	23 04 36.4364	+23 31 07.610

Because of the limited availability of such telescopes, massive determination of z for the sources in the IVS program is not possible. Thus, it is important to distinguish priority sources, for which there is a special interest in determining their z. These includes the sources with the longest observational histories, since they have the greatest weight in an analysis of the velocity field of the radio sources obtained from the astrometric VLBI observations. This sort of ordered list of priority sources was first compiled in 2007 and has been revised as VLBI observations are accumulated and new sources with known z appear. The most recent edition of the list is given in Ref. 14.

After observational time on the BTA 6-m telescope at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences was offered in August 2008, a sample of objects which are most conveniently observed during that time at this latitude was chosen from that list. This sample is listed in Table 1.

3. First observations, techniques, and results

The first series of observations of the optical spectra of program objects was carried out on August 24 and 28 on the BTA 6-m telescope at the SAO with the SCORPIO multi-mode spectrograph [15] operating in the "long slit" mode. The width of the slit of the spectrograph was 1" and the detector was an EEV-CCD42-40 CCD array (chip size 2048×2048 pixels and readout noise 1.8 e). Spectra over a wavelength range of 3100-7300 Å were obtained with a VPHG-550G grism, an instrument resolution of 10 Å, and a reciprocal dispersion of 2.1 Å/pixel. The data were processed in the standard fashion using the MIDAS program package developed at ESO.*

Besides images of the spectra of the objects, several comparison spectra from an He-Ne-Ar lamp and spectra of the twilight sky were obtained during the observations.

Figure 1 shows our optical spectra of the objects with the identified spectrum lines indicated. Our interpretation

* http://www.eso.org/sci/data-processing/software/esomidas/

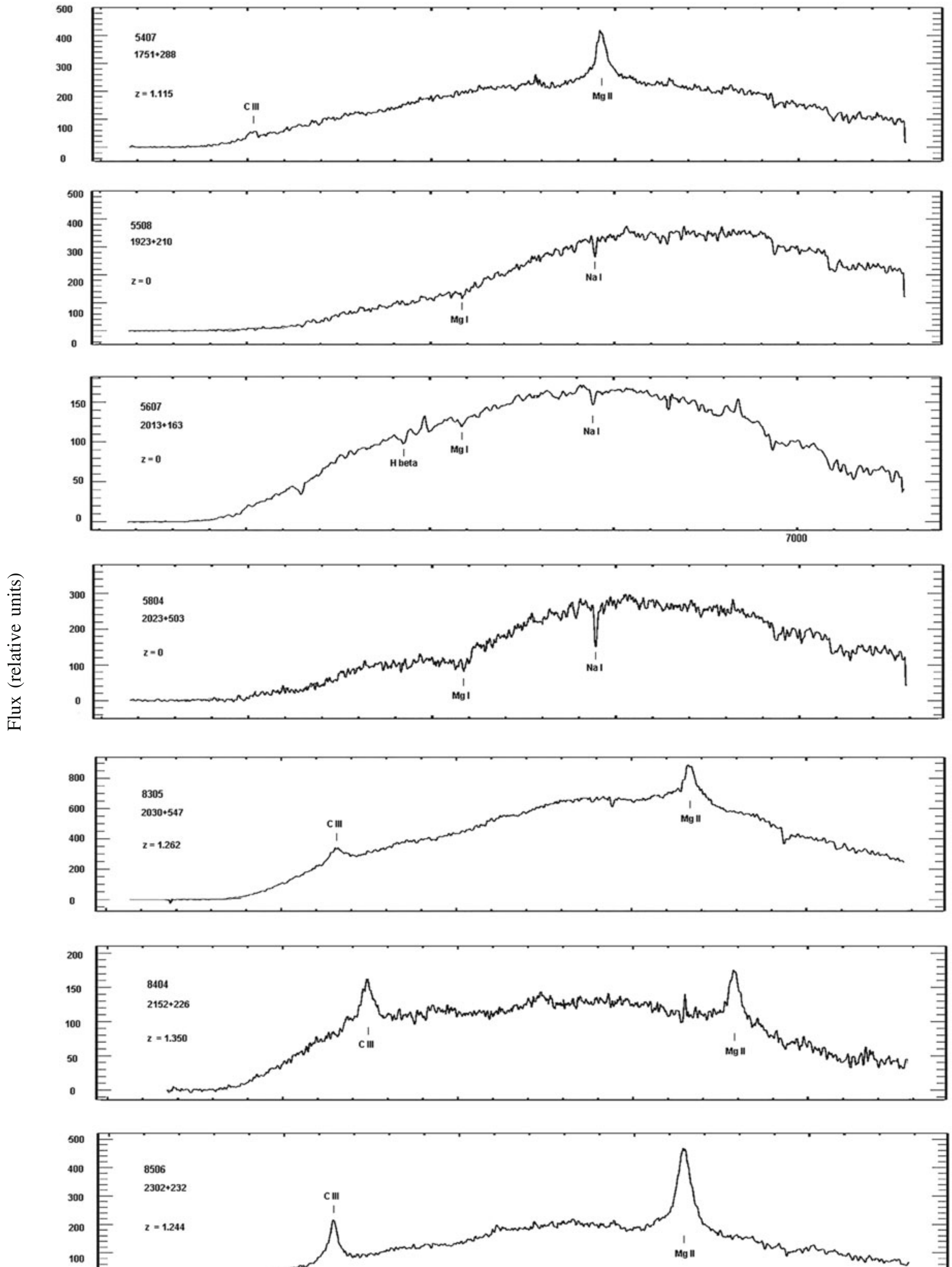

Fig. 1. Optical spectra of the sources, from top to bottom: 1751+288, 1923+210, 2013+163, 2023+503, 2030+547, 2152+226, 2302+232.

of the optical spectrum of each object and its classification are given below.

3.1. IVS 1751+288. The spectrum contains bright C III 1909 and Mg II 2798 Å emission lines. The red shift is z = 1.115. This object is classified as a quasar.

3.2. IVS 1923+210. The spectrum of this object contains no significant emission lines, but does contain the Mg I 5170 and Na I 5893 1751+288, 1923+210, 2013+163, 2023+503, 2030+547, 2152+226, 2302+232 absorption lines, which do not undergo a red shift. The classification of this object is ambiguous: VLBI charts of this source in the RRFID data base of the US Naval Observatory* are typical of an extended source or an active galactic nucleus with a jet, but these are inconsistent with our spectrum which is typical of a star. The NED data base** refers to this object as an "extended source at 327 MHz, possibly galactic," but also identifies it with a optical object (the only one in the angular neighborhood of the radio source) which we observed. A review entitled "A Westerbork synthesis radio telescope 327 MHz survey of the galactic plane" [16] refers to this object as being in the Galaxy. A possible explanation of this contradiction may be that this radio source is very faint in the optical wavelengths, probably fainter than ~21^m, and appears near a brighter star of the galaxy on the celestial sphere.

3.3. IVS 2013+163. The spectrum contains the Hβ 4861, Mg I 5170, and Na I 5893 Å absorption lines, which do not undergo a red shift. As in the previous case, in the radio range this source has the characteristic shape of an AGN with a distinct jet according to the RRFID data. However, the form of the spectrum corresponds better to a star than to a galaxy or AGN.

3.4. IVS 2023+503. The spectrum of this object contains the Mg I 5170 and Na I 5893 absorption lines without red shifts. Unlike the two preceding cases, in the radio range this source does not have a shape characteristic of an AGN, i.e., a clearly distinct jet, possibly because of insufficiently sensitive radio frequency observations (Yu. Kovalev, personal communication). Our spectrum is classified as belonging to a star. No other optical sources brighter than ~21^m were found in the neighborhood of the radio source.

3.5. IVS 2030+547. The spectrum obtained for the fairly bright source 2030+547 contains broad C III 1909 and Mg II 2798 emission lines, according to which the red shift is z = 1.262. For this red shift, the presence of just these two lines is typical of quasars.

3.6. IVS 2152+226. The spectrum of this source contains the C III 1909 and Mg II 2798 emission lines and the red shift is z = 1.350. This object is classified as a quasar.

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*http://rorf.usno.navy.mil/RRFID/
** http://nedwww.ipac.caltech.edu/

3.7. IVS 2302+232. The radio source is identified with a quasar in whose spectrum 2 bright emission lines, C III 1909 and Mg II 2798, stand out. The red shift for this source is $z = 1.244$.

4. Conclusion

We obtained optical spectra of seven objects which presumably belong to radio sources in the IVS program. The spectra of four of these objects have bright emission lines characteristic of quasars, as well as significant red shifts. Thus, we consider these optical objects to be reliably identified with the radio sources. We estimate the accuracy of our determinations of z to be 0.001. The other three objects we observed have spectra that are characteristic of stars, with a radial velocity close to zero with the same accuracy. This conflicts with cartographic data in the radio range, according to which these sources have a structure characteristic of active galactic nuclei. It is possible in this case that we have a superposition (on the celestial sphere) of an optically faint extragalactic object on a star in the Galaxy.

It should be noted that a conflict between spectra typical of stars and a radio structure typical of extragalactic objects has occurred for three out of seven program objects. That an optically faint radio object and a star should be randomly projected onto a single point of the celestial sphere in all of these cases (given that, within a radius of 10-15 angular seconds there are no other resolvable optical objects) seems improbable. Finally, during the process of selecting objects for the spectral observations from a list [11] derived from optical charts of the DSS survey, more than once we noticed a complete absence of any images in these charts at the positions of the radio objects. (For example, the sources IVS 1932+204, IVS 1922+155, and IVS 1955+335, and, perhaps, IVS 2000+148 and IVS 1951+355, are five "empty fields" found in a random sample of 30 objects.) This question also requires study.

This work represents an important step toward solving the general problem of determining the distance to all, or at least all of the most frequently observed, radio sources in the IVS program. However, the list of the latter is far from exhausted, so work will continue when more observational time on the BTA telescope becomes available. Given that the competition among observational programs for this telescope is intense, other ways of extending this work are being considered. First, an application has been made for observational time on the ESO telescopes in Chile. Second, in order to speed up the work, it can be divided into two stages. In the first stage, relatively less demanding but more massive photometric determinations of z can be undertaken, although with reduced accuracy on the order of 0.03-0.1. Later, it should be possible to obtain more precise values of z for the most interesting objects.

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