RADIO EMISSION OF STARS IN THE MONOCEROS CONSTELLATION

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In the present paper, the optical identifications of the bright stars from the Monoceros constellation with strong radio sources have been suggested. The Monoceros constellation is projected on the bright region of the Milky Way, where the densities of the stars and gas are rather high. 17 stars brighter than 11^m are located within the one square degree plate under investigation. All these stars were identified with radio sources from NVSS survey of NRAO observatory. Considerable radio refraction was revealed in the interstellar medium. It was found that twelve stars among seventeen ones exhibited radio emission characterized by non-thermal spectrum.

Key words: coordinates system, optical identification of radio objects, interstellar space.

Citation: A.A. Lipovka, N.M. Lipovka, Radio emission of stars in the Monoceros constellation, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 11 (3) (2018) 104–111. DOI: 10.18721/JPM.11312

Introduction

The existence of the interstellar medium was first hypothesized by Vasily Struve, who concluded in 1847, based on theoretical considerations, that the space between the stars is filled with gas. Struve's hypothesis was later confirmed by the independent observations made by Vorontsov-Velyaminov and Trumpler, who both discovered the absorption of light by the interstellar medium. Observations of outer space in the meter and centimeter wavelengths began with the advent of radio astronomy in the 1930s; independent experimental data proving that the interstellar space is filled with gas ionized by nearby stars were obtained after World War II [1]. Propagation of radio waves in outer space and in the Earth's ionosphere and atmosphere depends on the properties of the interstellar medium, which is why these properties should be taken into account in studies on celestial radio sources and identifying these sources with optical objects.

The distribution of radio emission in the Milky Way (i.e., its "radio brightness"), obtained from observations at 6.4 cm with the 12 m parabolic radio telescope [2] and the Large Pulkovo Radio Telescope (LPRT) 100 m in diameter [3], confirmed that ionized hydrogen (HII) is concentrated towards the Galactic plane, where the stellar density is high.

Analysis of all radio data was carried out in [3] for the distribution of radio brightness of the northern sky in the frequency range from 0.4 to 7,700 MHz. It was found that the Galactic corona is radio emission produced by relativistic electrons moving in the magnetic field of this corona (synchrotron radiation) and therefore has a non-thermal character, covering an area of 20 Ч 25 kiloparsecs around the center of the Galaxy. The size of the Galactic corona turned out to be two times larger than previously assumed [1]. The characteristics of the radio medium (relativistic electrons and magnetic field) in the Galactic corona [3] were calculated in accordance with the mechanism of synchrotron radio emission of relativistic electrons in a magnetic field [4].

The mismatch between the radio and optical coordinates of celestial objects was first discovered when radio astronomy emerged as an independent branch of astrophysics. The first error in matching the radio emission of celestial objects to the optical sky was made when the updated 3C Catalog [5] was introduced in 1962 as reference without listing which observed radio objects corresponded to the optical ones.

However, this was not particularly critical at the time, since the survey was carried out with poor angular resolution ($\Theta = 13.6' \times 4.6°$) at a frequency of 178 MHz, in fact, averaging all the positions of the radio sources located in a plate of one square degree. The reason for this error was that the radio telescope had a high-directivity pencil beam pattern [5].

Studies on optical identification of radio and optical sky, carried out in 1990 at the National Institute of Astrophysics, Optics and Electronics (Tonantzintla, Mexico), confirmed the mismatch between optical objects with diffuse image and radio sources [6].

A survey of the northern sky was carried out in 1993–1997 at the National Radio Astronomy Observatory (NRAO), VA, USA, via a radio telescope with high sensitivity and good resolution ($\Theta = 45''$) at 1400 MHz. The mismatch between radio and optical objects was reconfirmed by this survey [7]. It was hypothesized based on the data obtained that the sources of radio emission are mainly distant celestial objects (quasars and distant galaxies with redshifts greater than unity) [7], while the interstellar and intergalactic media are empty spaces where radio beams propagate along null geodesics and reach the most distant objects with millisecond precision.

Based on these considerations, the 2009 General Assembly of the International Astronomical Union Congress recommended the International Celestial Reference Frame (ICRF2) system [8] to match the radio and optical objects. The catalog included 3,414 reference radio sources. The identifications in the catalog were obtained by cross-correlation of the coordinates of celestial radio and optical objects, with these objects taken as reference. The majority of the reference objects were radio sources that randomly coincided with distant optical objects of a quasi-stellar structure whose density was very high. This was where the error made in ill-considered attempts to identify radio objects with optical ones originated from.

The goal of this study has been to carry out alternative optical identifications of bright stars from the Monoceros constellation, which are strong radio sources.

Substantiating why the radio object J(062153.45-041807.69) cannot be accepted as reference

In this study, we have considered a sky plate projected onto the local Galactic arm with high densities of both stars and the gas component of the interstellar medium consisting mainly of atomic and ionized hydrogen. A radio source recommended as a reference object for matching radio and optical objects by the ICRF2 catalog [8] is located at the edge of this plate.

Fig. 1 shows the image of the radio object J(062153.45-041807.69) as isophotes (lines of equal radio emission intensity) [7] superimposed on the image of the optical sky based on the data in [9]. Evidently, the given radio object has a two-component structure, and more than 15 other optical objects of the quasi-stellar structure fall into the region of this object. For this reason, it is impossible to determine which of the optical objects emits radio waves, and therefore the radio object J(062153.45-041807.69) should be excluded from the list of reference objects of the catalog [8], where it is recommended for high-precision matching of the radio and optical skies.

In addition, if we use the reference proposed in catalog [8], not a single radio source coincides with any optical object in the immediate vicinity of the reference object, which has a size of about two square degrees. Notably, the coordinates of the radio object J(062153.45-041807.69) included in the reference catalog [8] were determined in the meter wavelength range [10], where significant radio refraction is observed in the Earth's ionosphere; this phenomenon was not taken into account when radio coordinates of this object were determined.

In 1962, Komesaroff carried out a survey of the sky at a frequency of 19.7 MHz in Australia and New Zealand and discovered that radio waves experience significant radio refraction in the meter wavelength range in the Earth's ionosphere at altitudes over 350 km [11].

At present, it has been established that the coordinates of radio objects obtained in the centimeter wavelength range have been altered by radio refraction in the Earth's troposphere and, as a result, differ from the coordinates of radio objects obtained in the meter range.

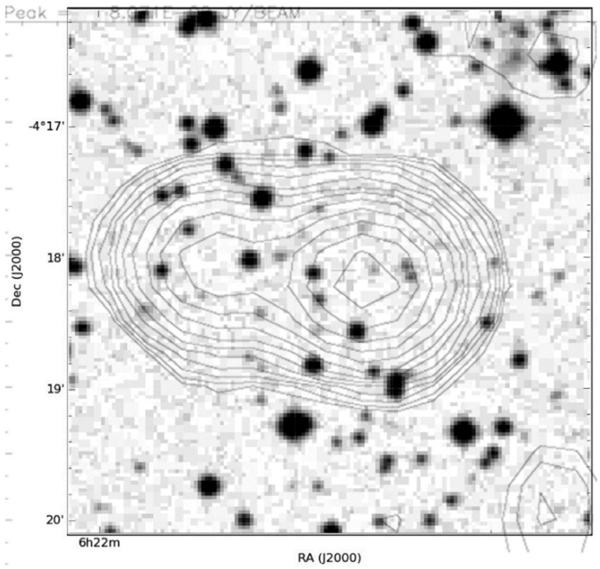

Fig. 1. The coordinates of the reference radio object J(062153.45041807.69) (according to [8]) superimposed on the optical image: the radio object is shown as isophotes superimposed on an image of a region of the optical sky (plate). Coordinates for the epoch J2000.0 are plotted on the axes. RA is the right ascension (h, min) and DEC is the declination (deg, min)

The errors made in the matching radio and optical objects are discussed in detail in [12]. Identifications of celestial radio sources with optical object should take into account the parameters of the medium which affects the nature of radio wave propagation in interstellar and intergalactic media.

According to our procedure for matching radio and optical objects [13], identification was assumed to be correct if three or more radio sources matched the objects visible in the optical wavelength range for a given plate of one square degree. This is also necessary for taking into account the azimuth slew of the given plate, often occurring in scans of sky regions of one square degree with a radio interferometer [14].

Identification of radio objects with stars in the Monoceros constellation

We have carried out the first optical identifications at the National Institute of Astrophysics, Optics and Electronics (INAOE, Tonantzintla, Mexico) in 1985, 1990, 1993 and 1994 using a Zeiss blink comparator with the precision of

$$\sigma\mathrm{RA} \times \sigma\mathrm{DEC} = 1.5'' \times 1.5''$$

according to standard astrometric practices.

We have found that radio objects fall into an empty field in the optical image of the sky [6]. The general consensus on the reason for the mismatch between radio sources and optical celestial objects, which still exists today, has long been that radio emission comes from very distant compact objects (radio galaxies and quasars) located at the edge of the observable Universe.

The advent of computer technologies and the Internet has offered countless new opportunities for astrophysics and other sciences. In fact, virtually all observations of celestial objects in the radio and optical ranges can be found on the Internet, giving the perfect opportunity to reconsider the existing identifications of radio and optical objects.

In 2007, we carried out further identifications of these objects and found that radio objects were incorrectly matched with optical ones and that most bright stars emit in the RF range.

We have developed and successfully used the method for identifying radio and optical objects based on matching radio sources to bright stars (the Lipovka – Kostko – Lipovka method, or LKL) [13].

In this study, we have identified radio sources with stars in the Monoceros constellation based on the NVSS radio survey of the NRAO observatory [14]. The given sky plate (Fig. 2) is projected onto the local arm of the Galaxy with high stellar density.

Matching radio objects to stars (Fig. 2) confirmed significant radio refraction in the interstellar medium, which is rather predictable, since this region of the sky is located in the local spiral arm characterized by a high content of gas. This region also has a high stellar density, which is why 17 stars brighter than 11^m have been identified with radio objects. In addition, seven faint stars were identified with "weak" radio sources whose flux density lies below the detection threshold (P < 2.5 mJy); such a threshold value was taken in [14]. These stars are denoted by the letter "a" in Fig. 2 and are not considered in this paper, since they are absent in catalog [15]. However, 7 faint stars

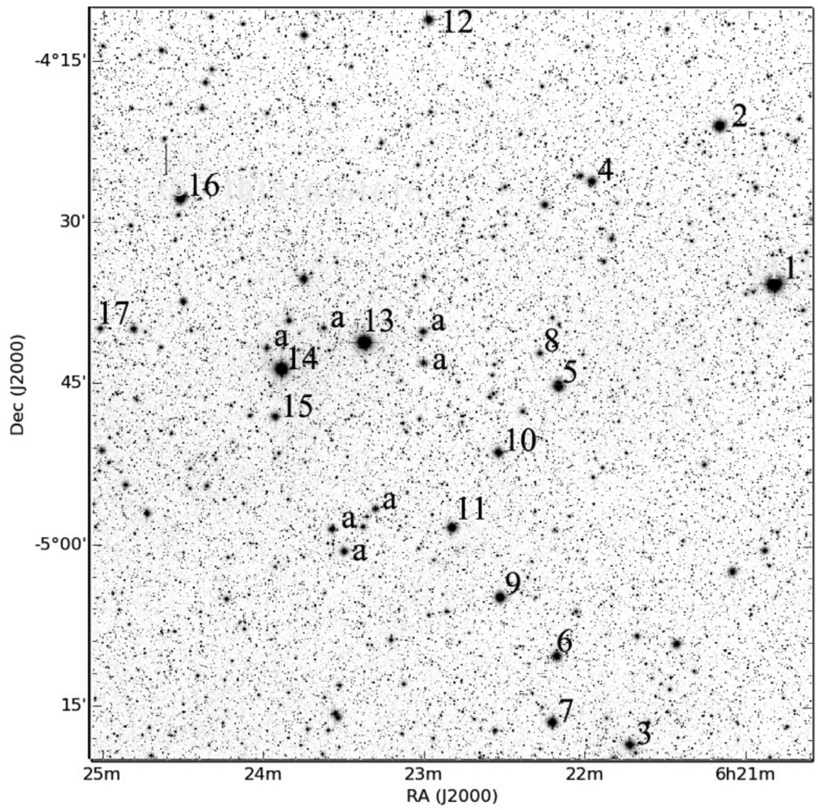

Fig. 2. Image of the sky plate with 17 stars (numbered) identified with strong radio sources according to the data of radio surveys [9, 14];
celestial objects marked with "a" have been identified with very weak radio sources and are not considered in this paper.

matching 7 weak radio sources in a plate less than 0.2 square meters in size confirms that the identifications given in Fig. 2 and in Table 2 are correct.

The method we have developed for matching the radio to the optical sky (the LKL method [13]) is based on the data from fundamental catalogs of stars [16], and radio sources are identified with stars whose density and accuracy of measured coordinates are sufficient to confidently match the coordinates of celestial radio objects to objects detected through optical observations.

The conventional names for stars [16] and their equatorial coordinates according to the UCAC3 catalog [17] for the epoch J2000.0 are given in Table 1 (columns 3 and 4). The parallaxes for the stars are given in column 5, and the stellar magnitudes in column 6.

No single radio source could be identified with an optical object in the given region of the sky based on the NVSS survey [14], while using our method for matching the radio objects [13] made it possible to identify 17 strong radio sources with bright stars (see. Fig. 2 and Table 2).

Table 2 shows the equatorial coordinates of radio sources at a frequency of 1400 MHz (columns 2 and 3) according to the data of [15], which we obtained by identifying the optically observed stars (see Table 1 and Fig. 2).

The coordinates of radio objects whose matches to stars were corrected are given in columns 6 and 7 (Table 2).

The numbering of radio sources in Table 2 corresponds to the numbering of stars in Table 1 and Fig. 2. Flux density based on the data in [15] is given in column 4 of Table 2.

Flux density measurements are available for several radio sources located in this plate (see Fig. 2), at frequencies $\nu = 150 - 1400$ MHz according to catalog [15]. The spectral index of

Table 1

Names [16] and coordinates of stars according to the UCAC3 catalog [17] for the epoch J2000.0

Star		RA(J), h m s	DEC(J) deg, min, s	ε Pos mas	Mag *m*
No.	Name				
1	HD 44286	06 20 50,466	−04 35 43,70	1270	6,68
2	HD 44335	06 21 10,845	−04 21 00,18	10	7,84
3	HD 44457	06 21 43,488	−05 18 34,15	26	8,92
4	HD 294985	06 21 58,328	−04 26 14,34	34	9,02
5	HD 44546	06 22 10,445	−04 45 13,06	11	7,92
6	HD 44565	06 22 10,867	−05 10 20,73	29	8,80
7	HD 44566	06 22 12,414	−05 16 31,21	26	8,38
8	HD 294989	06 22 17,423	−04 42 10,80	21	10,74
9	HD 44620	06 22 31,967	−05 04 53,95	91	8,18
10	HD 44619	06 22 32,671	−04 51 26,77	18	9,02
11	HD 44678	06 22 49,984	−04 58 25,83	32	8,30
12	HD44702	06 22 59,160	−04 11 13,50	22	8,50
13	HR 2295	06 23 22,793	−04 41 15,20	376	6,89
14	HD 44841	06 23 53,623	−04 43 43,88	102	6,99
15	HD 44856	06 23 53,863	−04 48 09,35	32	9,29
16	HD 295031	06 24 31,450	−04 27 58,40	42	8,44
17	HD295031	06 25 01,010	−04 40 00,00	20	10,08

Note. The numbers of the stars correspond to those shown in Fig. 2.

Notations: RA(J) is the right ascension, DEC(J) is the declination, ε Pos mas is the optical parallax, Mag *m* is the stellar magnitude.

radio emission α was calculated for these objects (Table 2, column 5). The radio spectrum of these stars turned out to be non-thermal; the radio flux density is $P \sim \nu^{-\alpha}$, where ν is the frequency of observation in the radio range.

Table 3 shows corrections to the coordinates of radio sources for three groups of objects. These corrections have different values because the given objects are located at different distances from the observer and because of the apparently significant radio refraction in this direction of the interstellar medium. The numbers of radio sources in each of the three groups are given in column 1 and correspond to the numbers in Tables 1, 2 and in Fig. 2.

These corrections have different values because the given objects are located at different distances from the observer and because of the apparently significant radio refraction in this direction of the interstellar medium.

These corrections (columns 2, 4, Table 3) should be added (taking into account the sign) to the coordinates measured in the radio range (Table 2, columns 2, 3) in order to obtain the corrected coordinates of radio objects matched to optical objects (Table 2, columns 6, 7).

Conclusion

Prior to our study, the method for matching the radio to the optical sky proposed in the NVSS survey [14] proved unsuccessful for matching any radio sources to optical objects within the given region of the sky [14, 15]; the method uses the ICRF2 catalog [8] recommended for identifying radio objects with optical ones.

The method for matching the radio and optical sky that we have proposed and used (the LKL method) increased the number of radio sources identified with optical objects by tens of times. We have established that radio sources are primarily identified with stars. The corrections obtained for the radio coordinates are due to a number of factors:

Table 2

Data comparison for radio sources in the NVSS survey and the corrected matches to the stars

No.	NVSS data [14, 15]]				Corrected coordinates	
	RA(J) h m s	DEC(J) deg, min, s	*P* MJy	α	RA(J) h m s	DEC(J) deg, min, s
1	06 19 13,97	−04 35 53,2	13,5	0,60	06 20 48,8	−04 34 50,0
2	06 19 37,76	−04 22 21,0	46,7	0,70	06 21 12,7	−04 21 17,8
3	06 21 54,53	−05 27 22,6	26,7	0,86	06 21 47,6	−05 18 15,0
4	06 20 26,93	−04 27 13,1	51,7	–	06 22 01,4	−04 26 09,0
5	06 22 20,51	−04 53 57,6	319*	–	06 22 08,8	−04 44 49,3
6	06 22 17,87	−04 55 48,8	37,7	–	06 22 12,0	−05 10 03,5
7	06 22 23,71	−05 19 10,8	23,9	0,57	06 22 15,0	−05 16 25,0
8	06 22 26,70	−05 25 32,0	15,3	–	06 22 10,9	−04 41 38,8
9	06 22 47,48	−05 01 03,7	7,3	0,80	06 22 22,0	−05 05 14,4
10	06 22 28,50	−05 19 25,5	46,1	–	06 22 35,8	−04 52 00,0
11	06 22 42,36	−05 11 27,4	10,0	–	06 22 49,3	−04 57 17,0
12	06 21 19,50	−04 12 33,1	8,8	–	06 22 54,4	−04 11 29,0
13	06 23 17,87	−04 55 48,8	37,7	0,40	06 23 24,7	−04 41 38,1
14	06 23 43,57	−04 58 28,2	246,8	0,80	06 23 50,4	−04 44 18,2
15	06 22 21,56	−04 49 43,4	60,7	0,60	06 23.55,8	−04 48 49,4
16	06 24 38,40	−04 37 41,5	114,9	0,75	06 24 26,7	−04 28 34,5
17	06 24 49,73	−04 53 59,5	174,4	0,70	06 24 55,8	−04 39 49,0

Note. The numbers of the stars correspond to those shown in Fig. 2 and in Tables 1 and 2.

Notations: *P* is the flux density of radio objects, α is the spectral index of radio emission of these objects ($P \sim \nu^{-\alpha}$, ν is the frequency of observation in the radio range). The rest of the notations are given in Table 1.

Table 3

Corrections for coordinates of radio objects matched to optical data for stars

Star number	ΔRA	$\pm\sigma_1$	ΔDEC	$\pm\sigma_2$
	m s	s	min, s	s
1, 2, 4, 12, 15	1 30	2.9	−10 00	35.5
8, 9, 10, 11, 13, 14, 17	−7	1.3	−14 00	15.2
3, 5, 6, 7, 16	10	1.2	−7 00	10.6

Notes. 1. The numbers of stars correspond to the ones in Fig. 2 and in Tables 1 and 2.
2. To obtain the corrected coordinates for each star, the corrections have to be added (taking into account the sign) to the coordinates of the radio source from the NVSS survey [14, 15] (see Table 2).

Notations: σ is the absolute correction error. The rest of the notations are given in Table 1.

accuracy in matching radio and optical objects;

accuracy in measuring radio coordinates;

presence of radio refraction in the given region of space.

Our findings are conclusive proof that optical identifications for the NRAO (National Radio Astronomy Observatory, VA, USA) and DSS (Palomar Observatory, CA, USA) surveys should not be performed based on coordinate matches of radio sources and objects visible in the optical wavelength range, since these matches are incorrect. Each one-degree astronomical plate scanned in the NVSS survey should be matched to the optical sky using the LKL method, regardless of the given coordinate match.

Applying the proposed method yields correct information about the astrophysical characteristics of the identified objects in a wide wavelength range (for radio and optical objects).

Based on the results obtained, we have resolved the paradox that stars do not emit radio waves. Given the correct identification of radio and optical skies, 17 stars brighter than 11m were matched in the plate under consideration.

Identifications of radio and optical objects carried out in our study also confirmed the presence of interstellar medium in the given region of space, which is further confirmed by the image of this sky region in the infrared wavelength range.

Acknowledgments

The authors express their gratitude to the staff of the Palomar Observatory and the National Radio Astronomy Observatory for compiling a survey of the sky in the optical and radio wavelength range, to the creators of the UCAC database (USNO CCD Astrograph Catalog) and to all those involved in compiling the database for general use.

The authors express their gratitude to the Astronomical Data Center of Canada (CADC) for the opportunity to obtain all available information on celestial objects for scientific research.

The authors express their gratitude to the researchers of the Special Astrophysical Observatory of the Russian Academy of Sciences O.V. Verkhodanova, S.A. Trushkina and others for creating a database of radio catalogs.

REFERENCES

[1] **S.A. Kaplan, S.B. Pikelner,** Mezhzvezdnaya sreda [Interstellar medium], Fizmatgiz, Moscow, 1963, P. 11–118.

[2] **Y.N. Parijsky, V.Y. Golnev, N.M. Lipovka,** The preliminary results of observations of the Milky Way at the wavelength of 6.4 cm obtained at the Pulkovo Observatory, Bulletin of the Main Astronomical Observatory in Pulkovo. 24(6(182)) (1967) 199–203.

[3] **N.M. Lipovka,** Radioizlucheniye korony Galaktiki [Galactic-corona radiation], Soviet Astronomy. 54 (6) (1977) 1211–1220.

[4] **V.L. Ginzburg,** Teoreticheskaya fizika i astrofizika. Dopolnitelniye glavy [Theoretical physics and astrophysics. Supplementary chapters], Nauka, Moscow, (1976) 70–99.

[5] **A.S. Bennett,** The revised 3C catalog of radio sources, MNRAS, 125 (1962) 75–86.

[6] **E. Chavira-Navarrete, N.M. Lipovka, A.A. Lipovka,** Opticheskiye polozheniya 748 slabykh diffuznykh obyektov i galaktik v okrestnosti radioistochnikov RC kataloga [Optical positions of 748 faint diffuse objects and galactics in the vicinity of radio sources from RC catalogue], Special Astrophysical Observatory of RAS, St. Petersburg, Preprint No. 88 (1993) 1–47.

[7] **J.J. Condon, W.D. Cotton, E.W. Greisen, et al.,** The NRAO VLA Sky Survey, Astron. J. 115 (5) (1998) 1693–1716.

[8] **A.L. Fey, C. Ma, E.F. Arias, et al.,** The second extension of the International Celestial Reference Frame: ICRF-EXT. 1, Astron. J. 127 (6) (2004) 3587–3608.

[9] Digital Sky Survey System (DSS) – Canadian Astronomy Data Centre, DSS, CADC, URL: www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/dss/.

[10] **J.N. Douglas, F.N. Bash, F.A. Bozyan, Ch. Wolfe,** The Texas survey of radio sources covering –35.5 degrees < declination < 71.5 degrees, Astron. J. 111 (4) (1996) 1945–1963.

[11] **M.M. Komesaroff,** Ionospheric refraction in radio astronomy. I. Theory, Aust. J. Phys. 13 (2) (1960) 153–167.

[12] **A.A. Lipovka, N.M. Lipovka,** Problems of connection of radio sky to optical sky. History and perspective, Geodesy. 10 (2013) 2–7.

[13] **A.A. Lipovka, N.M. Lipovka,** Sposob privyazki koordinat nebesnykh radioistochnikov k opticheskoy astrometricheskoy sisteme koordinat.

LKL [Method of referencing of celestial radio sources coordinates to optical astrometrical coordinate system, Lipovka – Kostko – Lipovka, (LKL), Patent No. 2 010107938/28(011185), 2011.

[14] The NRAO VLA Sky Survey, URL: http://www.cv.nrao.edu/NVSS/.

[15] **O.V. Verkhodanov, S.A. Trushkin, H. Andernach, V.N. Chernenkov,** Current status of the CATS database, Bulletin SAO. 58 (2005) 118–129. (arXiv:0705.2959), URL: http://www.sao.ru/cats/.

[16] Canadian Astronomy Data Centre, www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/.

[17] **N. Zacharias, C. Finch, T. Girard, et al.,** The third US Naval Observatory CCD Astrograph Catalog (UCAC3), URL: http://vizier.u-strasbg.fr/viz-bin/VisieR.

Received 05.04.2018, accepted 07.05.2018.

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