АСТРОФИЗИКА

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INVESTIGATION OF FAINT GALACTIC CARBON STARS FROM THE FIRST BYURAKAN SPECTRAL SKY SURVEY. II. EARLY-TYPE CARBON STARS

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In this paper, second in this series, we discuss the nature of 66 faint carbon (C) stars which have been discovered by scrutinizing the plates of the First Byurakan Survey (FBS). These plates display low-resolution spectra of objects located at high Galactic latitudes and have a limiting magnitude of about $V=16$. Our sample of 66 objects is part of a total of 120 stars found in the FBS and confirmed spectroscopically to be C stars. These 66 objects are those which show early-type spectra (not N-type). To better characterize these objects, medium-resolution CCD spectra were obtained and are exploited for them all, together with consideration of their 2MASS near-infrared (NIR) colors and their optical variability. First, we establish criteria for getting a spectral classification by using our medium-resolution spectra. Then, 57 objects show spectral features which are typical of CH-giants, while 4 can be classified as a R-type stars. Five objects in our sample are reported to be probably carbon dwarf according to previous studies. We derive effective temperatures from photometry. Finally, the optical variability of our objects are studied by using the data of the Catalina Sky Survey (CSS). It is found that the vast majority does not display variability. However, for some of them, the phased light curve may indicate the presence of a secondary component. We estimate the detection range (in kpc) for each class of carbon stars detected in the FBS. Finally, our studies of C stars found at high galactic latitude are discussed in the context of the Gaia mission.

Key words: *stars: survey: early-type carbon stars: classification: temperatures*

1. *Introduction*. Carbon (C) stars (showing prominent C_2, CN, and CH molecule absorption bands in their optical spectra) have been studied for more than a century. They can be roughly divided into late-type objects (N-type) which are red luminous Asymptotic Giant Branch (AGB) stars, and early-type objects which may be CH giants, R stars, and dwarf Carbon (dC-stars). CH stars (recognized to be population II giants) and dC stars are known also as binary systems, and are generally older than the N-type sources (for a review of C stars, see Wallerstein and Knapp [1], and Lloyd Evans[2]).

Faint High-Latitude Carbon Stars (FHLCs, $R>13^m$ and $|b|>20^\circ$) have been the subject of many works in the last two decades. They were not easily found until recently, and some of them were found serendipitously [3,4]. Many FHLCs are distant giants, especially useful for dynamical studies of the Galactic Halo [5,6].

In the first years of FHLCs studies, most of the discoveries were due to objective prism surveys, such as those of Case [7], Michigan [8], Byurakan [9,10] and Hamburg/ESO [11]. However, an important sample of red FHLCs was discovered through optical POSS colour selection with slit-spectroscopic confirmation by Totten and Irwin [12]. The work by Mauron et al. [13] (and reference therein) followed this line of research, but was based on exploiting the 2MASS NIR data (Two-Micron All Sky Survey online available at http://irsa.ipac.caltech.edu/2mass/) and its catalogue [14]. After slit-spectroscopy of selected candidates, more than 100 new AGB halo C stars were found. In parallel, efforts based on the Sloan Digital Sky Survey (SDSS) permitted to identify a sample of 251 FHLCs (verified spectroscopically [15,16]). Recently Green [17] expanded this SDSS sample of FHLCs to 1220 objects. These discoveries are based on photometric selection, fiber spectroscopy of candidates, and cross-correlation of the spectra with C template stars. All SDSS spectra can be found at http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=V/139/) and they reveal that the vast majority are dwarfs. One can finally note the works of Goswami and collaborators [18-20] to classify through slit-spectroscopy the FHLCs sample of the Hamburg/ESO survey of Christlieb et al. [11].

The goal of this paper (second in this series) is to present the nature of 66 moderately faint C stars discovered in the First Byurakan Survey (FBS) [21]. Their red magnitudes range from 9.7 to 15.1 and they show early-type carbon star characteristics. Medium-resolution optical spectra and NIR colors are exploited. Note that the first paper of the present series was devoted to the variability of 54 N-type AGB stars [22]. The photometric data for part of the early-type C stars studied in this paper are included in the "Revised and Updated Catalogue of the First Byurakan Survey of Late-Type Stars (LTSs) [23]. This catalogue also includes N-type stars. Additionally, 24 new FHLCs [10,24] and more than 50 M-type stars were found by scrutinizing the Digitized First Byurakan Survey (DFBS) [25] database (online access at http://ia2.oats.inaf.it/). The carbon-rich nature for all 120 discovered C stars has been confirmed by moderate-resolution CCD spectroscopy [9,10,24].

In Section 2 we establish a set of spectroscopic and photometric features which are used for the determination of the spectral class of our objects. In Section 3 the effective temperatures are derived from the photometric data, and in Section 4 the resulting classification is given for the 66 stars. NIR color-color plots are considered. In Section 5 the detection ranges (in kpc) are estimated for each group of C stars detected in the FBS. Finally, a discussion and concluding remarks are given in Section 6.

2. *C Stars Spectral Types*. Many papers in the literature are devoted to the spectroscopy of C stars, and these studies have been done with various spectral resolutions and various spectral regions. The spectral properties of C

stars were explained by the unusual chemical composition of their atmospheres. This feature makes them very interesting objects in the later spectral classes, and they are especially important for developing a theory of stellar evolution [26]. The Henry Draper classification divided C stars into two groups, N and R-types, on the basis of their spectral features. N stars exhibit strong depression of radiation in the violet part of the spectrum. R stars, on the other hand, have warmer temperatures. The CH stars (known also as a high-velocity objects [26]) were mostly classified as R stars before they were recognized as a separate class. The main distinguishing spectral features of CH stars are very strong CH band at 4300 Å, and enhanced lines of s-process elements (such as BaII). Many R stars have also strong CH and it is difficult to distinguish between CH and R stars from low-resolution spectra, because they are very similar [26].

2.1. *Early-Type C stars*. A set of spectroscopic and photometric criteria and features, based on moderate-resolution spectra and developed by different researchers are used here to clarify the group of 66 FBS C stars that display early-type spectra. Moreover, spectra for all 66 stars are compared with the "Moderate-Resolution Spectral Atlas of Carbon Stars" by Barnbaum et al. [27] and with the medium-resolution spectra of known stars. The main spectroscopic features based on moderate-resolution spectra and used to specify the C-CH and C-R-type classes can be summarized as: the presence of an intense G band of the CH molecule at 4300 Å with secondary P branch head at 4342 Å, which is the most useful indicator of the difference between CH and R stars; presence of intense Ba II lines at 4554, 4935 and 6496 Å, Sr II lines at 4077 and 4215 Å [18]; intense lines of Balmer series, strength/weakness of the Ca I feature at 4226 Å [26].

2.2. *Dwarf Carbon (dC) Stars. Luminosity Discriminants*. Spectroscopically, the distinction between dwarf and giant C stars is less obvious[28]. Spectra of dC stars contain an enhanced C_2 bandhead at 6191 Å that is less pronounced in spectra of C giants. A known set of the photometric and spectroscopic luminosity discriminants is considered also for early-type C stars to search for dC star candidates among the FBS sample. The simplest discriminant is proper motion, which is the most powerful way to separate dwarf and giant C stars. One can also consider anomalous NIR colors and the following features: strong C_2 (0, 2) bandhead at λ6191Å [28], and the presence of the multiple bands of CaH molecule at λ6382, 6750, 6903 Å which can be seen in low-resolution spectra [15].

The spectra of our 66 early-type FBS C stars were examined regarding the spectroscopic features described above. Their proper motions were checked in optical multi-color and multi-epoch databases, like the PPMXL (Catalog of Positions and Proper Motions of the ICRS) [29] (online access at http://

vo.uni-hd.de/ppmxl/) and in SuperCOSMOS Sky Survey - SSS [30] (on-line at http://www-wfau.roe.ac.uk/sss/).

3. *Temperatures From Photometric Data*. Determination of the effective temperatures T_{eff} of chemically peculiar red giants are considered in many papers and are based on the optical and NIR color indices. To estimate T_{eff} for our 66 FBS C stars, we use an empirical relation between T_{eff} and the $J-K$ dereddened color obtained by Bessell et al. [31];

$$T_{eff} = 7070/[(J-K)+0.88]. \qquad (1)$$

All 2MASS JHK_S data were transformed to the system defined by Johnson [32], and the dereddened $J-K$ colors were obtained by adopting the interstellar extinctions given by the maps of Schlegel et al. [33]. The relation (1) has been calibrated using T_{eff} determination (with accuracy of about 250 K) from lunar occultation observations [34,35].

4. *Results*. Through examination of the spectral features described above, the membership of a star in a particular group is derived by comparing of the FBS C stars spectra with the spectra of a large amount of the early-type stars known. Spectra of C stars available in the atlas catalogue [27] are also used. 66 spectra allow us to classify 57 stars as CH-type, and 4 as R-type stars. Five objects had been classified as dC star candidates, presented in paper [10].

The main characteristics for our 66 early-type C stars are presented in

Table 1

DATA FOR 66 EARLY-TYPE C STARS

FBS And DFBS	USNO-A2.0 *R* mag.	Spectral class	T_{eff} (K)	Notes
1	2	3	4	5
0018+213	9.71	CH	4620	
0254+482	11.1	CH	3500	
0259+444	12.8	CH	3417	
0318+238	10.7	R	4517	
0324+236	13.7	CH	3620	
0644+616	11.5	CH	4210	
0754+109	12.1	CH	4270	
0845+466	13.9	dC?	-	(1)
0900+034	12.1	CH	3890	
0904+213	11.6	CH	4277	
0916+029	11.4	CH	4160	
0922+786	12.1	CH	3990	
1043+213	11.2	CH	3970	
1043+253	13.1	CH	3970	
1119+460	14.2	CH	3830	
1127+782	12.0	CH	4570	
1140+038	15.1	CH	4450	

Table 1 (The end)

1	2	3	4	5
1145-000	12.4	CH	3895	
1152-039	11.5	CH	3880	
1225+077	13.5	CH	4430	
1238-046	13.1	CH	4275	
1305+015	12.2	CH	4122	
1339+117	13.4	dC?	-	(1)
1406+027	12.8	CH	4298	
1418-031	12.0	CH	3717	
1418+018	11.8	CH	4000	
1431-079	12.7	CH	4040	
1440+263	12.4	R	3910	
1451+075	11.7	R	3750	
1547+046	12.2	CH	4330	
1552-002	11.3	CH	4300	
1553+119	12.4	CH	4342	
1609-058	12.3	CH	4065	
1612+262	13.1	CH	4166	
1615-048	12.6	CH	3432	
1619+160	11.8	CH	3538	
1715+172	12.2	CH	4340	
1728+216	11.1	CH	3838	
1811+462	13.2	CH	3631	
1825+272	12.1	CH	4648	
2029+101	11.8	CH	3768	
2100+123	12.7	CH	3454	
2123-104	12.9	CH	4142	
2158+197	12.5	CH	4735	
2203+198	13.2	CH	4030	
2207-095	12.7	CH	3876	
2217+100	13.3	CH	4196	
J003700.13+342234.0	11.9	CH	3582	
J004619.15+354537.3	13.2	CH	4416	
J075331.90+190344.3	11.0	CH	3813	
J083335.84-011939.1	11.0	CH	4144	
J111422.94+081442.7	10.8	CH	4234	
J112242.11+411020.1	12.4	CH	4415	
J113524.04+181623.3	11.5	CH	4447	
J115153.56+412232.9	12.9	CH	4526	
J135831.62+611042.7	12.9	CH	3888	
J143026.10+202233.7	14.1	CH	3826	
J145241.15+785923.8	13.3	dC?	-	(1)
J153938.95+124800.2	13.3	CH	4068	
J172834.59+651110.4	11.7	CH	3789	
J190034.62+440829.1	12.1	dC?	-	(1)
J213937.66+095250.4	13.5	CH	4348	
J222425.62-043801.6	13.0	R	4360	
J224217.04+251259.3	10.5	CH	4170	
J225342.28+241556.6	12.2	CH	4306	
J234043.43+353104.4	13.8	dC?	-	(1)

Notes to individual objects: (1) Investigation of these objects, which are dC stars candidates based on spectroscopy, is presented in papers [10,36]. For dC candidates, T_{eff} is not presented. Their blackbody temperatures based on analysis of multi-wavelength data will be discussed in a separate paper.

Table 1. In this Table, column 1 is the running FBS and DFBS number according to the LTS [23] and to papers [10,24]; column 2 is the spectral class that we found; column 3 is the red magnitude taken in the USNO-A2 catalogue (Vizier Online Data Catalogue - I/252); column 4 is the effective temperature T_{eff}, that we determined as explained above and based on $J-K$ color indices; finally, column 5 contains several notes to individual objects.

To illustrate the quality of the spectra used for our classification, we show in Fig.1, as an example, the spectrum of FBS 1825+272, obtained with the Byurakan Astrophysical Observatory 2.6 m telescope SCORPIO spectrograph. This star has a R magnitude of 12.1 and the CH band is strong. The exposure time was 600 seconds.

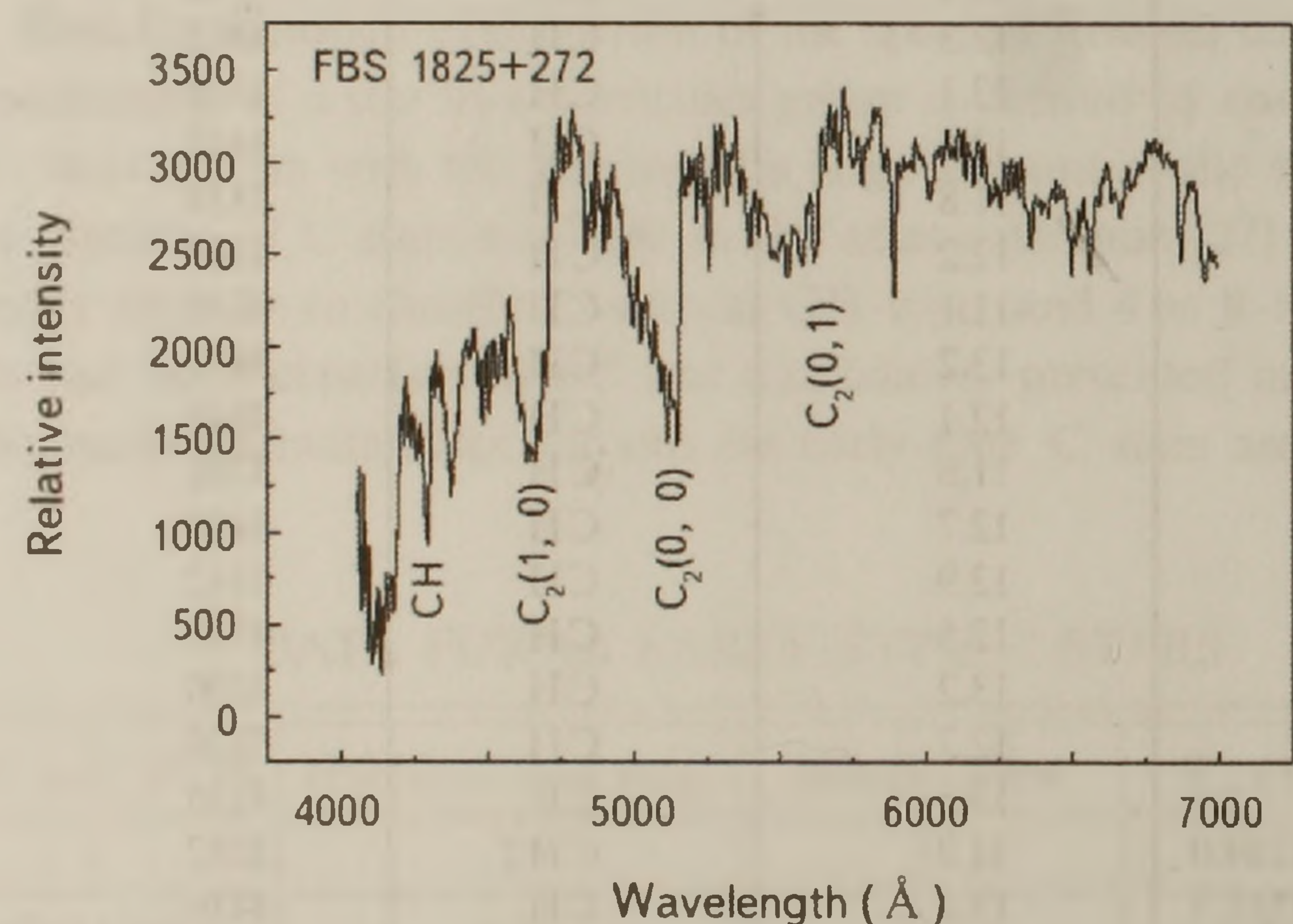

Fig.1. BAO 2.6 m telescope SCORPIO spectra for FBS 1825+272 in the wavelength range $\lambda\lambda 4000-7000$ Å obtained on 25 July 2004. X-axis presents wavelength (Å), Y-axis presents the relative intensity. Absorption bands of the $C_2(1, 0)$ 4737 Å, C_2 (0, 0) 5165 Å, $C_2(0, 1)$ 5636 Å Swan system and CH molecule G-band at 4300 Å are indicated.

Concerning variability, interrogation of the Catalina database showed us that the very large majority of our 66 objects are quite stable. More precisely, these objects are absent of the CSS catalogue of variable stars, or, if present in this database, the amplitude is very low, suggesting very little or no variability. This is consistent with them not being cool AGB stars. However, in Fig.2 (a, b), we show the Catalina Sky Survey (CSS) [37] phased light curves for FBS 0644+616 and DFBS J172734.59+651110.4, which are classified as CH-type stars. In these two cases, variability may be real, although the signal from these two stars are close to saturation.

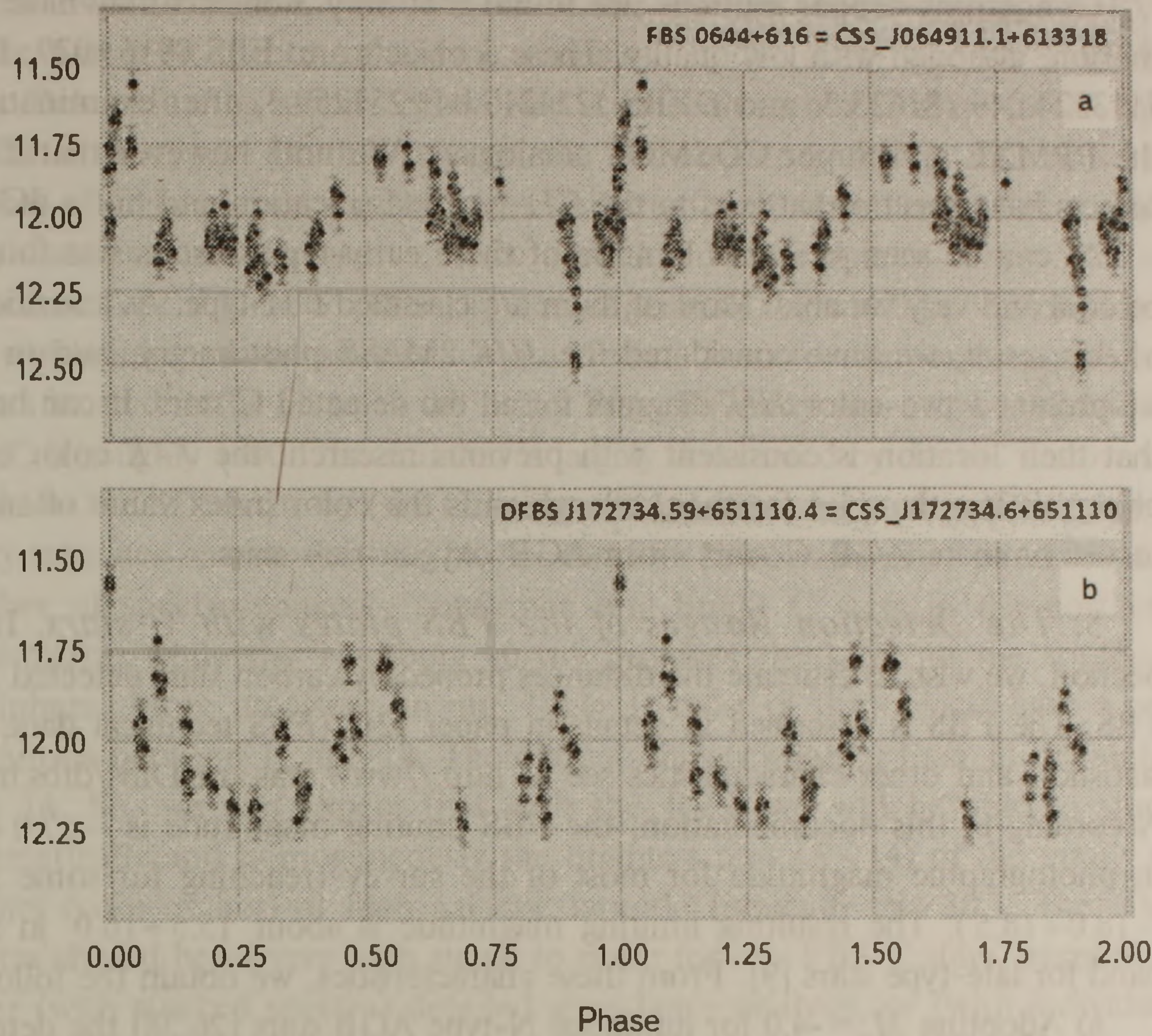

Fig.2. (a, b). Catalina Sky Survey (CSS) phase dependence light curve for FBS 0644+616 (CSS_J064911.1+613318) and for DFBS J172734.59+651110.4 (CSS_J172734.6+651110). *X*-axis presents the phase, and *Y*-axis presents the CSS *V*-band magnitude. The periodic variability is probably connected with the existence of a secondary components around them.

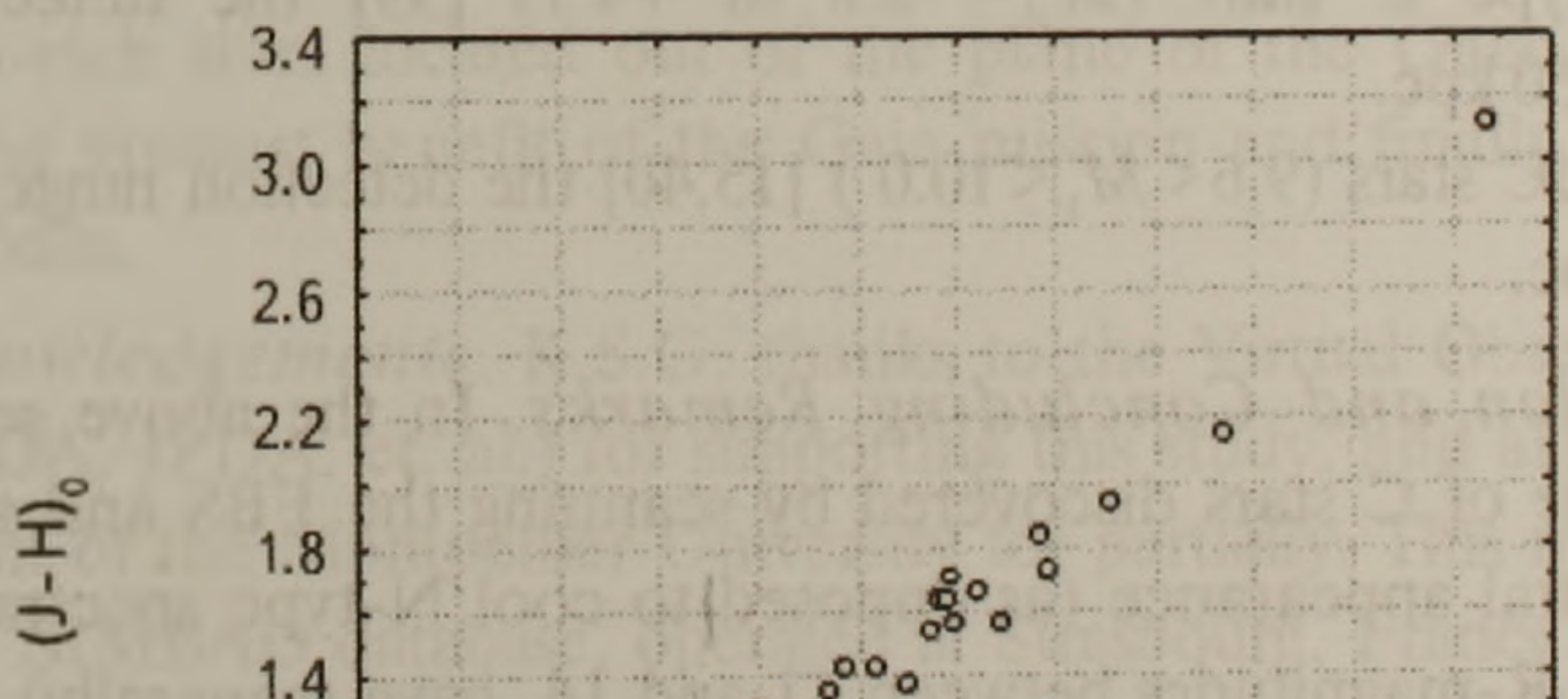

Fig.3. $(J-H)_0$ vs. $(H-K)_0$ dereddened two-color plots (2MASS *JHKs* data have been transformed to SAAO system [32], extinction calculations according to Schlegel et al. [33] map) for the 66 early-type C stars listed Table 1 and 54 N-type C stars [22]. Symbols are: open squares - CH stars, open circles - N-type stars, diamonds - R stars, and open triangles - dC star candidates.

Concerning proper motions, we found that only 3 objects may have some motion, although with low quality. These 3 objects are: FBS 0916+029, DFBS J113524.04+181623.3, and DFBS J224217.04+251259.3, after examination of the PPMXL and Super COSMOS catalogues. We note however that these 3 objects have spectra that lead to the CH-type classification and not a dC-type.

As can be seen in Table 1, none of these early-type C stars was found to be cool and very variable. Most of them are classified CH-type. As a verification of this result, we have considered the *JHK* 2MASS photometry, and in Fig.3 we present a two-color *JHK* diagram for all the detected C stars. It can be seen that their location is consistent with previous research: the $J-K$ color of our objects is less than 1.4 for them all, which is the color index value often used to discriminate AGB C stars from AGB oxygen-rich stars.

5. *The Detection Ranges of the FBS plates with C stars.* In this Section, we wish to estimate the distances probed by carbon stars detected in the FBS. The FBS is described in details in paper [21] (FBS technical data, zone statistics, and other characteristics see at http://www.aras.am/Dfbs/dfbs.html/). According to this documentation, the FBS limiting magnitude is $\sim 17.0 \div 17.5$ in photographic magnitude for most of the survey (reaching for some zones $\sim 18.0 \div 18.5$). The resulting limiting magnitude is about $15.5 \div 16.0$ in the V band for late-type stars [9]. From these characteristics, we obtain the following:

a) Adopting $M_V = -4.0$ for luminous N-type AGB stars [26,38] the detection range can be estimated up to ~100 kpc for the FBS.

b) For CH-giants ($0 < M_V < -2.5$) [11,26,38], can be detected them up to ~50 kpc.

c) For R-type C stars ($M_V = -2.8$ to $+4.1$) [39] the detection range estimation is ~50 kpc.

d) And for dC stars ($9.6 < M_V < 10.0$) [15,40] the detection range estimation is up to ~200 pc.

6. *Discussion and Concluding Remarks.* In the above sections, we studied a sample of C stars discovered by scanning the FBS and showing an early-type spectral appearance (as opposed to cool N-type spectra). Most of these stars have R-magnitudes between 11 and 14, have (generally) a CH-type classification, which put them up to distances of 50 kpc. These stars are much brighter than, and complementary of the giants found in the SDSS survey by Green, which have magnitudes around $17 \div 18$.

At this point, it is important to consider our results in the context of the Gaia [41] mission which is presently scanning all the sky routinely. While Gaia will provide photometry (and astrometry) up to a limiting magnitude $20 \div 21$, its spectrograph (Radial Velocity Spectrometer) will give usable spectra only for objects with $V < 14 \div 15$. Its resolution is 11500, and its spectral range is from 8470 to 8740 Å. While most of the science expected with the RVS will be based on spectra of K-type giants (or hotter stars), the RVS will be also efficient for the studies of evolved stars such as our C stars (of N-type or CH or R-type). In this respect, the present study which increases the number of CH-type stars at high galactic latitude will be of high value to help Gaia classification. Our stars can be considered as templates. They are also located out of the galactic plane, so that in general, there will be less crowding and overlapping of the spectra for our objects than for the large number of C stars located in the plane of the Milky Way. Presently, the number of known FHLC is roughly 1700. This number is largely dominated by the dC discovered thanks to the SDSS survey (see Green's work). Interestingly, the SDSS photometry saturates near magnitude 14. So, the FBS discoveries offer an interesting number of spectroscopically confirmed and bright C stars in the northern hemisphere, while the Hamburg survey provides the same in the southern hemiphere. More precisely, in our Table 1, most of the objects have a red magnitude between 11 and 14. There are 4 objects brighter than 11 or fainter than 14. So, we can expect that with the RVS, we will be able to study systematically and homogeneously the brightest part ($R < 14$) of the family of C stars (cool or hot) at high galactic latitude (typically $|b| > 20°$). The RVS spectra should be of very high signal to noise for our FBS C stars, permitting either (with stacked spectra) detailed abundance analysis, or (with individual spectra) detailed analysis of the radial velocity variation or photometric variation. It will also be interesting to compare effective temperatures derived in this work (from NIR colors) with the effective temperature derived from the RVS spectra and/or Gaia photometry. Further investigation of the diverse families of carbon-rich stars located out of the plane of the Galaxy is desirable to achieve the greatest benefit of the Gaia mission and finally better know the Galactic halo.

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ИССЛЕДОВАНИЕ СЛАБЫХ ГАЛАКТИЧЕСКИХ УГЛЕРОДНЫХ ЗВЕЗД ИЗ ПЕРВОГО БЮРАКАНСКОГО СПЕКТРАЛЬНОГО ОБЗОРА НЕБА. II

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В настоящей работе (второй в данной серии) обсуждается природа 66 слабых углеродных (С) звезд, выявленных на низкодисперсионных пластинках Первого Бюраканского Обзора неба (FBS) на высоких галактических широтах. Предельная звездная величина для этих пластинок оценивается до 16^m в визуальных лучах для звезд поздних классов. Наш список из 66 объектов, является частью списка из 120 FBS звезд, подтвержденных спектроскопически, которые представляют собой С звезды ранних подклассов. Для этих объектов были исследованы CCD спектры, полученные со средней дисперсией, 2MASS инфракрасные показатели, а также оптическая переменность. 57 объектов показывают особенности, характерные для CH звезд, 4 - классифицированы как R звезды. Пять объектов из 66, являются кандидатами в С карлики. Эффективная температура определена на базе фотометрических данных. Оптическая переменность исследована, используя данные из CSS (Catalina Sky Survey). Основная часть объектов не показывает заметную переменность. Для некоторых из них изменение яркости от фазы возможно объясняется присутствием вторичного компонента. Для обзора FBS нами оценены расстояния обнаружения (в кпк) для каждого класса С звезд. Важность изучения этих объектов на высоких галактических широтах обсуждается в рамках программы космического проекта Gaia.

Ключевые слова: *обзоры: С звезды ранних подклассов: классификация: температура*

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