АСТРОФИЗИКА

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NEW CARBON STARS IN THE CATALINA CATALOG OF PERIODIC VARIABLES

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This study is about carbon stars detected in a program of spectral type determinations for a large amount of optically faint periodic variables. These variables are taken from the Catalina Survey Data Release-1 (CSDR1) data set. As much as 967 objects were studied. Spectral classification uses the objective-prism scanned plates of the Hamburg Quasar Survey (HQS), and of the Hamburg/ESO Survey (HES). Spectra from the Sloan Digital Sky Survey (SDSS), and LAMOST (Large Sky Area Multi-Object Fiber Spectroscopic Telescope) are also exploited. The majority of the variables in CSDR1 have not been known before. While the majority of stars are found to be F, G, K, M giants and dwarfs, a few dozens of known carbon (C-type) stars are recovered. Six are new. Some supplementary spectra obtained with the Byurakan Observatory 2.6-m telescope are shown. We study in more details eight C-type stars. Their periods are in the range 120 ÷ 400 days and their V-band magnitude are 14 ÷ 16.5 mag. With the assumption that they are classical asymptotic giant branch (AGB) stars and obey the Miras period-luminosity (P-L) relation, large distances (5 up to 100 kpc) are obtained. Three of them are angularly close to C stars attributed to the Sgr tidal leading arm. However, one of these seven stars, CRTS J092231.7+510740 shows significant proper-motion, as given by the recent Sloan catalog. If this motion is confirmed, e.g. by Gaia, and it is a dwarf C star, which is supported by its colors, it is at about 100 pc from the Sun. But in this case its periodic variability remains to be explained. Our work supports the view that the known sample of distant halo C stars can be increased by our method and that great care must be adopted in distance determination.

Key words: *catalogs-Galaxy: late type stars: variables: carbon stars*

1. *Introduction.* Cool variable carbon stars (hereafter noted C stars) have long be known as very useful objects for a diversity of astrophysical problems. In addition to considerations dealing with stellar evolution and their formation, investigations of a population of C stars seen in a Galaxy inform on its metallicity [1] and it stellar formation history [2]. The search for C stars in the Galactic halo has a long history, and various methods have been used, such as scanning objective-prism plates (Gigoyan et al., 2001) [3] or spectroscopy of infrared-selected candidates (Mauron, 2008) [4]. Huxor and Grebel [5] have summarized the up-to-date literature and focused on the membership of halo C stars to the Sagittarius tidal arms. One of the problem of these investigations is whether the sample of known C stars in the halo is complete. In the compilation by Huxor and Grebel [5], there are 121 C stars that are periodic variables and 75 "irregulars"

for which no periods have been found in the Catalina light curves of the Data Release-2. The reader may find information of the Catalina variable catalog in Drake et al. [6] based on the DR1 data set. Additional data are available on the Catalina web site (http://nesssi.cacr.caltech.edu/Data Release/). Of these 196 C stars, approximatively half were found from the infrared survey method, but the other half is due to various other studies and various methods. Because variability is one of the basic properties of cool C stars, it is obvious that the search for halo C stars may be based on catalog of variable objects. One of the goal of our project centered on cool evolved objects out of the Galactic plane is to achieve a spectral classification of the Catalina DR1 stars. Here we are studying the northern hemisphere, more precisely approximately $\delta > -22^{\circ}$. For each Catalina objects, we search for spectral information. We begin with objective-prism plates information, but add also information from spectra published by the LAMOST group [7] and from spectra from the SDSS DR14 (http://skyserver.sdss.org/dr14). These two surveys provide low resolution optical spectra. We note that Gaia (http://sci.esa.int/gaia-58060-gaia-mission/) will soon present to the community a wealth of spectra for $V > 14^{m}.0$ in the region of the calcium triplet it about 8500 Å. Therefore, it will be interesting in the future to compare spectra from our study to Gaia spectra if available.

In this paper, we present first results from our classification of 967 Catalina variable objects, and report here our findings which concern the C stars. In Section 2, some useful details on the surveys that we use are given. In Section 3, we present the results concerning C stars, the methods used to find them, their properties and their location in the Galaxy. We also present a few spectra obtained with the 2.6-m telescope of the Byurakan Astrophysical Observatory (BAO). In Section 4, we discuss one of the possibly discovered dwarf C star (dC). We finally conclude in Section 5.

2. *Surveys used in this work.* The Catalina catalog of variable stars (Drake et al., 2014) [6] contains information for 47055 periodic objects. It is worthy to note that it does not include irregular variables, which, for the case of halo C stars, represent about 40% of this population (see Huxor and Grebel [5]). This catalog probes up to magnitude $V = 20^{m}.0$, with an area of $20000\,\mathrm{deg}^{2}$, and $\delta > -22^{\circ}$. The Catalina survey does not cover the crowded Milky Way and avoids galactic latitudes less than 10-15 degrees. The Catalina instrument saturates at V magnitude about $11^{m}.0$ and brighter objects are not in the catalog. The number of cool long period variables with these characteristics is only about 500, that is roughly 1 percent of all variables. This number is based on the Catalina Data Release-1. Additionally, for any of the DR1 objects, it is possible to access supplementary data with the DR2 dataset, and make some checks. An important

fact is that the southern hemisphere ($\delta < -22°$) has also been recently covered by the Catalina experiment (Drake et al., 2017 [8]; CDS VizieR catalogue J/MNRAS/469/3688/). With a limiting magnitude of nearly $19^m.5$, they find as many as 1500 long period variables. This larger number suggests that in the northern hemisphere, the number of long period variables may even increase in the future when sensitivity is improved.

Concerning the spectral classification, we use four sources of information. First, the northern Hamburg Quasar Survey (HQS) and the southern Hamburg/ESO survey (HES) are objective-prism plates archives. Full details for these surveys are in http://hs.uni-hamburg.de/DE/For/Exg/Sur/hqs/online/index.html/. Useful quantities for our work are the covered area and the limiting magnitude. For HQS, they are 13600 deg^2 and $B(\text{lim}) = 19^m.0$; for HES 6400 deg^2, and $B(\text{lim}) = 18^m.0$. HQS offers a low-resolution(1390 Å /mm at $H\gamma$) from 3400 Å to 5400 Å, while it is 3200 Å to 5300 Å (450 Å /mm near $H\gamma$) for HES. Both surveys avoid the Galactic plane (typically $|b| > 30°$). Consequently, it can be expected that low latitude Catalina objects will be missed. Christlieb et al. (2001) [9] published a systematic search of (essentially) warm C stars from the HES. To our knowledge, no such work was carried out with the northern HQS. Supplementary spectral information is also given by the SDSS DR14 database and the LAMOST survey [7] (CDS VizieR catalog V/149). Both surveys provide spectra with moderate-resolution over the entire optical range. The search for dC stars in the SDSS was carried by Green [10]. They found about 1200 dwarf C stars. Note that their selection criteria were not particularly suited for cool C stars. The search for C stars thanks to the LAMOST DR2 survey was done by Wei et al. [7]. They found 894 C stars. A recent paper by Li et al. [11] deals with LAMOST DR4 spectra, but the DR4 spectra are not available at the time this paper was written. Finally, for each object under investigation, we check for any spectral information in the (http://simbad.u-strasbg.fr) Simbad database.

3.1. *Detected C stars. Results*. Among the large number of variables in Catalina catalog, we investigate those with a period $P \geq 10$ days. Presently, 967 stars were examined and 732 could be classified. The unclassified remaining stars were either too faint or out of the HES or HQS sky coverage. Our stars are also checked for associations in the CDS SIMBAD database with a search radius of 60 arcsec. An association exists for only for 107 objects out of the 967 stars.

We now focus on the C stars that we found. Of the 967 stars under investigation, 61 N-type stars were found, and 48 were known in SIMBAD. Data for five N-type C stars were published in paper [12].

In Table 1, the characteristics coming from the Catalina DR1 catalog (or DR2 when improvement is achieved) for eight carbon stars are presented, together with

Table 1

DATA FOR 8 CRTS PERIODIC VARIABLES CONFIRMED AS CARBON STARS

No	CRTS Identifier	<V> (mag.)	Period (days)	HES/HQS Association	LAMOST Number
G1	J034339.5+351831	14.08	318		J034339.54+351831.1
G2	J042800.2+383115	13.91	302		J042800.18+383116.1
G3	J052128.4+155434	13.05	311		
G4	J052215.9+083739	14.32	407		J052215.92+083739.1
G5	J092231.7+510740	14.96	128	hs092231+510740	J092231.76+510738.8
G6	J150622.0-104157	14.00	131	he150622-104157	
G7	J151343.5-073444	16.27	415	he151343-073444	
G8	J151351.0-064838	15.79	149	he151351-064838	

Note to Table 1: Objects G1 and G4 are presented in catalogue "Carbon Stars From LAMOST DR2 Data" [7], the remaining 6 C stars are new discoveries.

their associations. Column 1 is the abbreviated name, Gigoyan-1 i.e. G1, G2, etc., column 2 is the CRTS identifier, column 3 is the median V-band magnitude, column 4 is the period in days. Columns 5, 6 are the associated name for HQS, HES and LAMOST surveys. Note that objects G1 and G3 are in the LAMOST catalog of C stars by Luo et al. (CDS VizieR catalog V/149).

Fig.1 illustrates corresponding HES low-resolution spectra for objects G6 (CRTS J150622.0-104157) and G7 (CRTS J151343.5-073444), which confirms the C-rich nature for these two objects.

Fig.2 presents the LAMOST spectra for the objects G1, G2, G4, and G5 of Table 1. We discuss below in detail the case of G5. From Table 1, one can

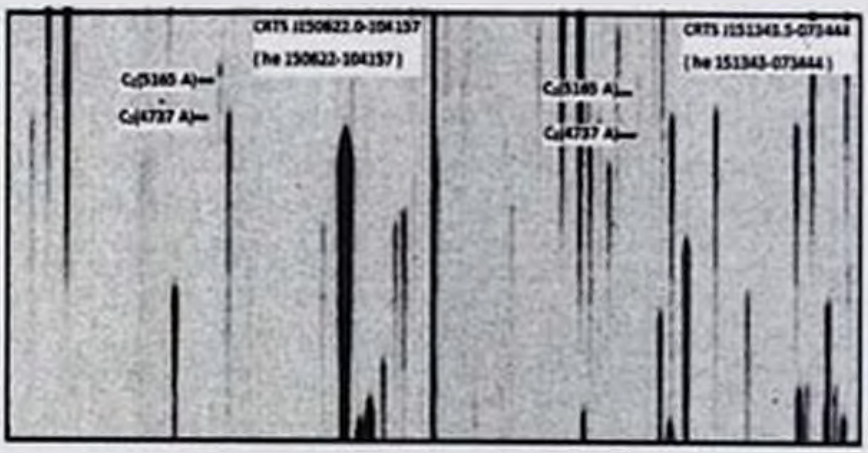

Fig.1. HES low-resolution spectra in the range λ3400 – 5400Å for the two new confirmed N-type carbon stars CRTS J150622.0-104157 and CRTS J151343.5-073444. The absorption bands of C_2 molecule at 4737 Å and 5165 Å are indicated. Both fields are 10′ × 10′.

note that we probe C stars up to magnitude <V> = 16^m.3, which gives an approximate limiting magnitude of our C star research. One notes also two stars (G4 and G7) to have large periods: G7 is particularly interesting since its latitude B is +41°. In Table 2, we see that G4 is near the galactic plane and is relatively bright in infrared. This is probably a member of the disk. In contrast G8 is at B = +41° and much fainter and cannot be from the disk. Another interesting

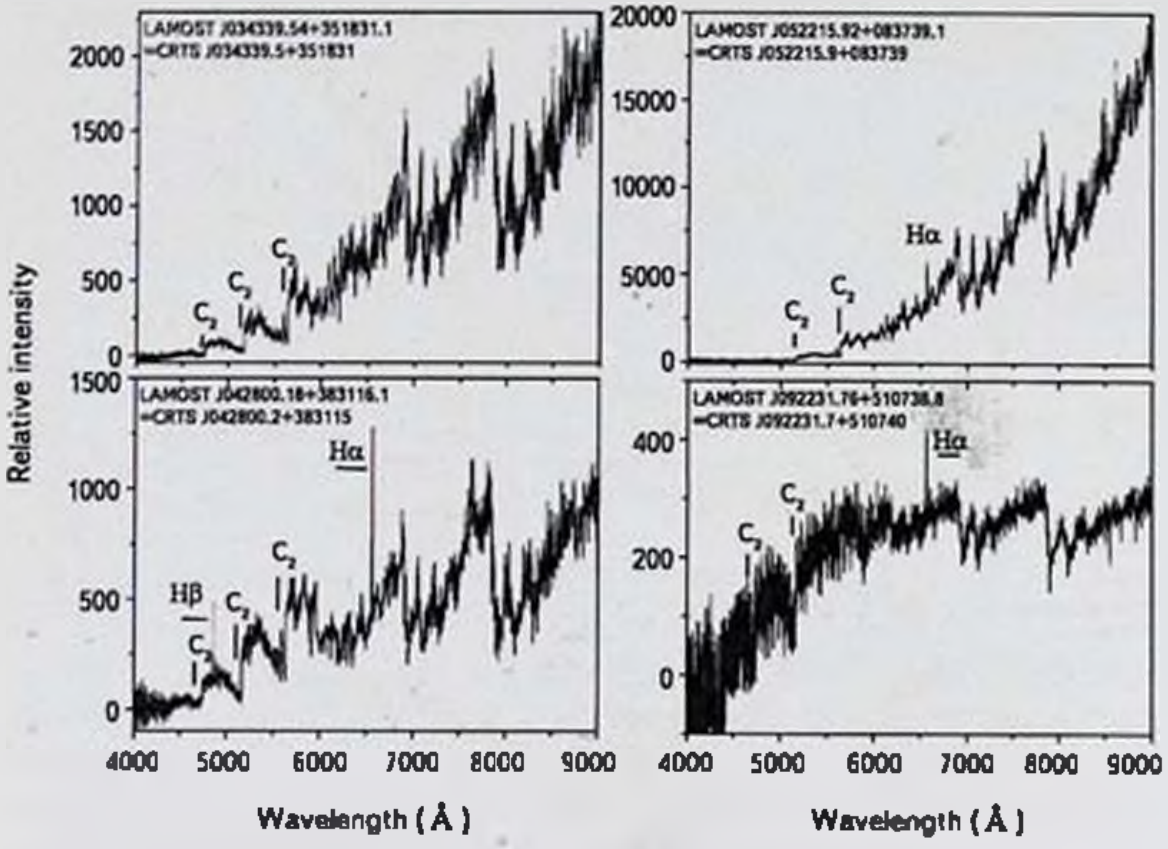

Fig.2. The LAMOST telescope spectra in the range λ4000 – 9000Å is presented for the four objects of Table 2. Absorption bands of C_2 molecule is indicated.

consideration is that G6, G7, G8 are angularly close to each other, suggesting that they are part of the same structure in the halo. Further discussion below shows that they very probably belong to the Sgr tidal arms.

3.2. *Optical Spectroscopy*. For object G3 (CRTS J052128.4+155434) and G5 (CRTS J092231.7+510740), we could secured a medium resolution spectrum (Fig.3a, b) obtained on February, 2/3 and 3/4, 2018, at the 2.6 m telescope of BAO. We used the SCORPIO spectrograph, with grism no. 600. Its detector is an EEV 42-40 CCD. The spectral range is λ4000 – 7000Å, and the resolution is 5Å. The data are reduced with standard MIDAS procedures.

For some objects, the plate classification is unclear, and additional spectroscopy

is needed. We obtained 2.6-m telescope observations for 2 objects: CRTS J205716.6+073827, whose HQS spectrum is hardly visible, and CRTS J210157.5+003329, whose spectrum is not visible on HQS plates. Both are late M-type stars, and more discussion on them will be included in [13].

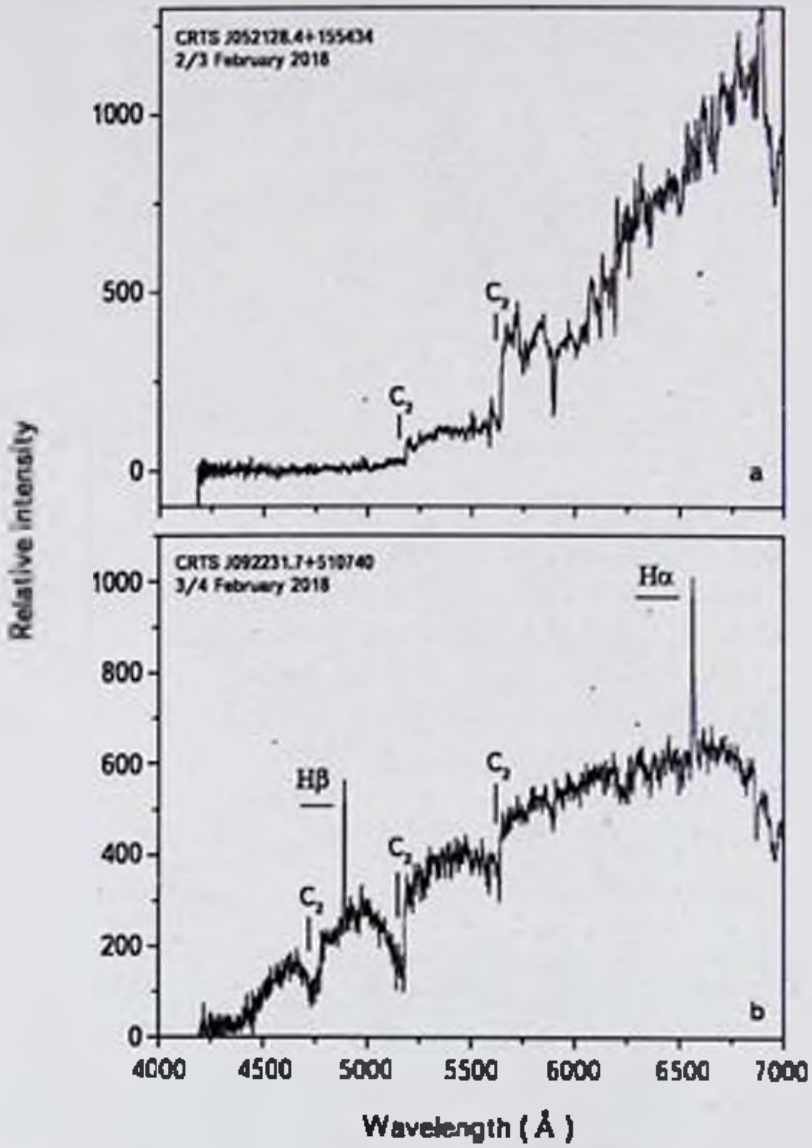

Fig.3. 2.6 m BAO telescope moderate-resolution spectra in the range λ4000 – 7000Å (Fig.3a) for N-type C star CRTS J052128.4+155434 and for CRTS J092231.7+510740 with emission lines in spectrum (Fig.3b).

3.3. *Infrared Colors and determination of distances.* For the 8 objects of Table 1, Table 2 includes the 2MASS (Two Micron All-Sky Survey) [14] association, Galactic coordinates (l, b), K_s and $J-K_s$ from 2MASS. In this table, K_s and $J-K_s$ are not corrected for interstellar extinction, but this extinction is taken into account for distance determination. This extinction, in the K band is;

0.13, 0.29, 0.13, 0.31, 0.004, 0.036, 0.022, and 0.024 magnitude, for G1 to G8, respectively.

Except for the first 4 objects, this extinction can be ignored because uncertainties on other quantities are larger. For example, uncertainty concern periods and absolute magnitudes, and the fact that K_s is a single-epoch measurement of stars with significant amplitudes in K. These extinctions are from the NASA extragalactic database extinction calculator (http://ned.ipac.caltech.edu//forms/calculator.html/) and based on the work of Shlafly and Finkbeiner [15].

Table 2

DISTANCE ESTIMATION FOR N-TYPE C STARS

No	2MASS Association	l (deg)	b (deg)	2MASS K_s mag.	J-K_s mag.	D (kpc)	Z (kpc)
G1	03433954+3518311	158.25	-15.4	9.10	2.25	20	-5.4
G2	04280018+3831160	162.65	-07.1	8.29	1.88	13	-1.3
G3	05212846+1554339	188.07	-11.7	7.15	2.71	8.0	-1.6
G4	05221592+0837391	194.51	-15.3	5.79	3.46	4.8	-1.3
G5	09223179+5107387	166.71	+44.1	12.10	0.91	45?	+32?
G6	15062206-1041574	348.34	+39.9	10.95	1.22	27	+17
G7	15134354-0734449	352.86	+41.1	12.43	1.10	120	+78
G8	15135103-0648386	253.60	+41.63	12.15	1.22	51	+34

The resulting distances (D) and high above the Galactic plane (Z), both in kpc, are based on the assumption that these objects obey the revised K-band Period-Luminosity (P-L) relation from Whitelock et al. [16]. But one possible exception is G5 that could be a dwarf and is discussed below. The P-L relation used here is;

$$M(K) = -3.51 \times (\log P - 2.38) - 7.15. \quad (1)$$

3.4. *Comments on individual objects.* From Table 2, it can be seen that G2 and G4 are probably member of the Galactic disk, due to their low Z. Object G1 is at 5 kpc from the plane, but is at a large distance. It is at 22 degrees from the Galactic anticenter (at $l = 180°$), so that its distance from the Galactic center is roughly 25 kpc, putting it beyond the galactic disk. More objects of this kind are needed. Objects G6, G7, and G8 are at different distances, from 25 to 120 kpc, but their position in the sky suggests membership of the Sgr Arm. They are close to objects HG79, HG81 and HG82 of Huxor and Grebel [5], who attribute them to the Sgr leading arm. However, these 3 HG objects are at 45 + 60 kpc, according to Huxor and Grebel [5]. G8 fits this range, but it is not the case of G6 and G7. Finally, a very curious case is G5. Its distance indicated in Table 2 relies on the applicability of the P-L relation, which is the charac-

teristic of genuine Mira variable. Its Catalina light curve is of high quality, regular, and with a peak-to-peak amplitude of $0^m.7$. Its period is very well determined. So, together with its carbon-rich chemistry, this supports the Mira variable status at a distance of 45 kpc. We have at our disposal 2 spectra of this object (Fig.1 and Fig.2). Both shows Hα in emission. Hβ is seen on the 2.6 m spectrum, while it is absent (or masked by the noise) in the LAMOST spectrum. These emission lines may be attributed to pulsation shocks. However, it has to be recognized that this star has possibly a significant proper motion. In the PPMXL catalog [17], $\mu(\alpha) = 17.7$ mas/yr and $\mu(\delta) = -35.5$ mas/yr. This is unlikely to be true if the distance is really 45 kpc, because it would imply a huge tangential V_t velocity. More precisely, for a distance D (kpc) and a proper motion μ (mas/yr), then this velocity is: $V_t = 4.75 \times \mu(\text{mas/yr}) \times D(\text{kpc})$. With D = 45 kpc, and μ = 40 mas/yr, one obtains a much too large 8500 km/s, typically 20 times the escape velocity of our Galaxy.

The proper motion may be incorrectly determined, but one notes that the SDSS provides essentially the same value ($\mu(\alpha) = 26.6 \pm 3.6$ mas/yr and ($\mu(\delta) = -40.2 \pm 3.6$ mas/yr)). Therefore, if this proper motion is true, then it becomes more likely that the star is a dwarf carbon (dC) star. With $r = 14^m.8$ (from SDSS catalog, Alam et al., CDS V/147/sdss12), and a typical r-band absolute magnitude $M(r) = 9.0 \pm 1.1$ (Green [10], section 10), then the distance would be close to 140 pc, and the tangential velocity would be around 30 km/s, a quite plausible value for disk stars. If it is a dC, then it is one of the brighter object of this kind ($g = 16.14$; see Fig.5 of [10]).

We note also that the 2MASS colors ($J - H = 0.596$, $H - K = 0.235$) are typical of dwarf C stars. It is also known that some dC stars have Balmer emission lines.

4. *Conclusion*. In this paper, we presented the first results, concerning carbon stars, of an extensive project for determining spectral types of Catalina CSDR1 variables. We use spectroscopic databases such as HQS, HES, SDSSDR14, and LAMOST. Correct spectral types of periodic variables is very important for studies of stellar populations. As part of many F, G, K, M-type giants and dwarfs, we focused this work on new C stars. Some are of N-type, and may be one is a dwarf. 5 N-type stars are new. Three objects are located in the sky on the path of the leading tidal arm of Sagittarius, but for 2 of them, there is some disagreement with the commonly accepted arm distance for this location. In particular, one of them would be as distant as at 120 kpc if it is actually a N-type star. One star in our list is more probably a dC star, but its variability needs further investigation. This work emphasizes the need to pursue the search for C stars, while it is of paramount importance to be prudent on distances. It is clear that the next Gaia data release will set this question, at least about distances and proper motions. Radial velocities are also one of the quantities that should be

measured in the future, particularly because Gaia will not measure them for magnitudes fainter than 14 for K giant type. The results of our spectral survey for not-carbon stars will hopefully come soon.

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НОВЫЕ УГЛЕРОДНЫЕ ЗВЕЗДЫ ИЗ КАТАЛИНСКОГО КАТАЛОГА ПЕРИОДИЧЕСКИХ ПЕРЕМЕННЫХ

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Настоящая работа посвящена новым углеродным звездам, которые были выявлены в рамках программы по определению спектральных типов большого числа оптически слабых периодических переменных. Данные об этих переменных приведены в первом выпуске Каталинского обзора (Catalina Survey Data Release1-CSDR1). Изучено более чем 967 объектов. Для спектральной классификации были использованы сканированные пластинки Гамбургского обзора квазаров (HQS), Гамбургского обзора ESO, данные обзора Слоан (SDSS), а также спектральные данные телескопа LAMOST. Большая часть переменных из баз каталога CSDR1 не была известна ранее. Среди классифицированных объектов есть как F, G, K и M гиганты и карлики, и углеродные (C) звезды.

Шесть из них были открыты впервые. Приводятся спектры, полученные на 2.6-м телескопе Бюраканской обсерватории. Детально изучены 8 звезд класса С. Периоды пульсации этих звезд находятся в пределах от 100 до 400 дней, а визуальные звездные величины (V) находятся в пределах от $14^m.0$ до $16^m.5$. Используя соотношение период-светимость (П-С) для асимптотической ветви гигантов (AGB), их расстояния оценены в пределах от 5 до 120 кпк. Три из выявленных звезд предположительно принадлежат карликовой галактике Sgr. По данным каталогов объект CRTS J092231.7+510740 показывает собственное движение. Расстояние этого объекта от Солнца оценивается в ~100 кпк. Однако периодическая переменность данного объекта нуждается в дальнейшем обосновании. Наша работа поддерживает ту точку зрения, где число известных далеких С звезд галактического гало может увеличиваться с увеличением расстояния обнаруженных объектов.

Ключевые слова: *каталоги-Галактика:звезды поздних классов:переменность: С звезды*

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