АСТРОФИЗИКА

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NEW ASYMPTOTIC GIANT BRANCH CARBON STARS IN THE GALACTIC HALO

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For the first time the data on the eight confirmed or candidate carbon (C) stars found mainly from objective-prism plates are presented. By using the Catalina database of lightcurves, we find that all these stars are pulsa- ting, allowing a distance to be estimated through the K-band Period-Luminosity (PL) relation. This relation does not depend on spectral type (M or C) and distances are reliable even for C candidates. Seven stars are more than 10 kpc from the galactic plane, suggesting they do not belong to the galactic disk. We also find one star located at about 180 kpc from the Sun, being one of the most distant star in the Galaxy. Many of these new C stars are relatively blue. Some comments are also provided on seven other known halo carbon stars for which either a pulsation period is obtained, or because they were not included in previous works on halo C stars.

Key words: *stars: carbon stars: surveys: Galactic halo: Galaxy: stellar content*

1. *Introduction.* Stars evolving on the asymptotic giant branch (AGB) can be either carbon-rich (hereafter noted C), or oxygen-rich (M-type). Many studies have been devoted on C stars because the overabundance of carbon means that dredge-up has been occurred and certifies the status of the AGB phase. In the galactic disk, AGB C stars are in general well understood and their progenitor mass is around $1.3\,M_{\odot}$ (Solar masses). The presence of AGB C stars in a galaxy indicates that an intermediate-age population exists. The M-type AGB stars may be much older since one finds them in globular clusters.

In comparison with the disk, the understanding of AGB stars located in the halo is less clear. Many observational works have been done on C stars because their discovery is made easier owing to their particularly red color, or to their spectra displaying pronounced C_2 and CN bands. Totten and Irwin [1] published the first survey for red AGB halo C stars. Mauron, Gigoyan and collaborators found many AGB C stars by selecting them either on objective-prism plates or through a near-infrared (NIR) color-color selection and follow-up spectroscopy [2-10]. Huxor and Grebel [11] made a synthesis and a new analysis of the subject of halo C stars. They concluded that the majority trace the Sgr Tidal Arms, but the sample is small compared to other samples like the one of M-type giants [12]. Some of the halo C stars may belong to other halo overdensities, but again the sample is poor. Therefore, any new additional C stars are of interest. Despite these difficulties, it is interesting to note that some AGB C stars are far enough, more than 100 kpc away, to probe the outer halo (Deason et al. [13], Bochanski et al. [14]).

In this context we present eight new confirmed or candidate AGB C stars located at $|b| > 20°$. One is at 180 kpc from the Sun. Also, we add some comment on seven other pulsating C stars with peculiarities (Section 2). In Section 3, we discuss our results, and conclude in Section 4.

2. *New Pulsating Carbon Stars in the Halo.* Objects 1 to 8 in Table 1(a) are halo C stars which were discovered on Hamburg Quasar Survey, Hamburg - ESO survey digitized databases (online at http://www.hs.uni-hamburg.de/DE/For/Exg/Sur/hqs/online/index.html/)/ or the First Byurakan Survey [8]. All three surveys are a collection of objective-prism plates with various depth and sky coverage. All objects presented here display a clear spectrum showing a C-rich nature (Fig.1), except for objects No 3, which shows a wedge-like spectrum with very low S/N. Objects No 1, 4, and 7 has been confirmed with slit spectroscopy (Fig.2 and 3).

Table 1(a)

NEW HALO C STARS

No	2MASS Coordinates	l	b	K	$J - K$	P(d)	Status	D (kpc)	Z (kpc)
1	015806.13+383918.4	136.9	-22.3	6.857	1.141	303	New C	7.0	-3
2	045631.15-312932.7	233.3	-37.0	10.651	1.243	146	New C	41.0	-24
3	084925.07+205855.2	205.2	+34.9	13.828	1.408	297	?	182.0	104
4	122040.61+491844.0	135.8	+67.0	11.711	1.246	182	New C	49.0	45
5	131216.45+083435.9	318.7	+70.8	12.385	0.996	138	?		
6	151351.03-064838.6	353.6	+41.6	12.152	1.223	148	New C	52.0	34
7	171130.98+083430.6	29.2	+26.0	10.841	1.103	138	New C	27.0	12
8	214341.14-341431.1	10.9	-49.3	10.980	1.224	159	New C	32.0	-24

Table 1(b)

KNOWN CARBON STARS UNDER DISCUSSION

No	2MASS Coordinates	l	b	K	$J - K$	P(d)	Status	D (kpc)	Z (kpc)
9	012847.03+264742.2	148.4	-31.2	8.624	1.525	274	*HG2-13	16.0	-8
10	144448.86-011056.3	351.4	+50.6	10.751	1.536	301	*HG2-41	45.0	35
11	151840.24+145903.1	20.9	+53.7	7.342	1.451	301	*HG2-44	9.0	7
12	171447.49+524006.6	79.9	+35.6	9.333	1.366	201	NotHG	18.0	10
13	193008.56-701452.1	325.2	-28.6	7.270	2.307	389	NotHG	11.0	-5
14	195149.53-312500.7	9.1	-25.8	9.122	2.307	265	NotHG	19.0	-8
15	223153.02-191740.9	83.0	-32.5	9.215	1.400	265	NotHG	22.0	-12

Note to Table 1(b). *HG (Huxor and Grebel [11]).

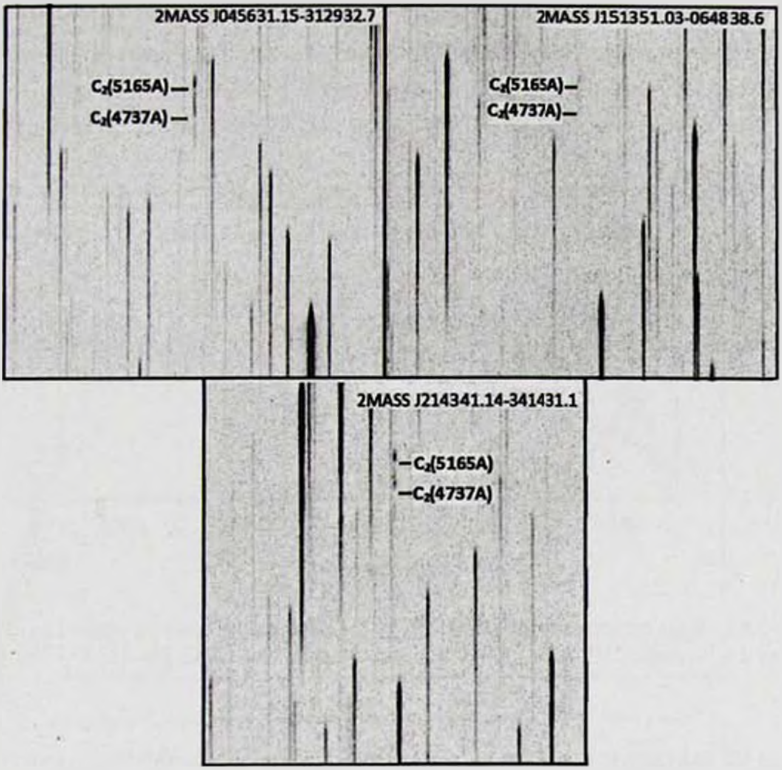

Fig.1. Hamburg/ESO Survey digitized objective-prism (resolution is 15A) spectral shapes for three objects of Table 1(a). Absorption bands of C_2 molecule are very well expressed. The fields are $12' \times 12'$.

Table 1 (a, b) includes coordinates from 2MASS (Two Micron All-Sky Survey [15] (online available at http://irsa.ipac.caltech.edu/Missions/2mass.html/), galactic coordinates, K and $J-K$ from 2MASS, period from the light-curves of the Catalina Sky Survey - CSS) (online at http://nesssi.cacr.caltech.edu/DataRelease/) database [16], a status column, and finally estimates of distances (D) and high above the galactic plane (Z) in kpc. There is in general little uncertainty on periods (a few days only). Distances were derived with the K-band Period-Luminosity (PL) relation from Whitelock et al. [17];

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

As can be seen, all stars are between about 10 to 50 kpc from the Sun, except object No 1. For one remarkable source (No 3), the distance reaches 180 kpc. For this object, the spectral type is uncertain, although the faint wedge-like plate spectrum points to a C star. However, this uncertainty does not affect the

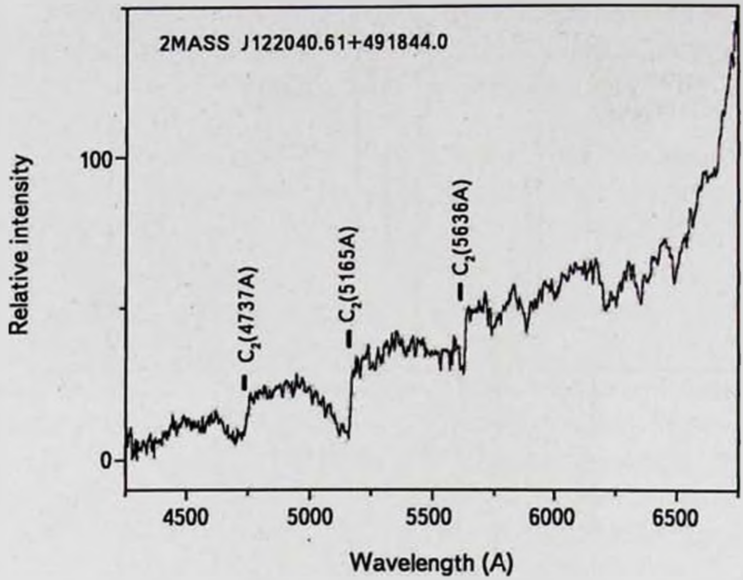

Fig.2. 2.6 m BAO telescope spectra for 2MASS J122040.61+491844.0 in range $\lambda\lambda 4250 \div 6750$A obtained on 15/16 April 2016 with SCORPIO spectrograph and CCD TK 1024×1024 (resolution ~10A).

derivation of its distance. As far as we know, it is most distant long period variable in the halo.

In Table 1(b), we list several known C stars with some peculiarities. Objects No 9, 10 and 11, were considered not to be pulsating by HG [11], but examination on the Catalina data does provide a reasonable period. Objects No 12 and 15 were known C stars, but they were not included in the HG sample. Object No 12 was found by Gigoyan et al. [8], and object No 14 is from Reid et al. [18]. Object No 15 (from Totten and Irwin [1]) is not periodic: in this case, we assumed a period of 300 days, leading to $D = 22$ kpc. If one adopts $M(K) = -7$ (the average of $M(K)$ for the halo C stars), one finds $D = 17$ kpc.

3. *Optical Spectroscopy*. Moderate-resolution CCD spectra for three objects of Table 1(a) (No 1, 4, and 7) were obtained at the 2.6 m telescope of the Byurakan Astrophysical Observatory (BAO, Armenia). Spectra for object No 4 (2MASS J122040.61+491844.0) were obtained on 15/16 April 2016 with the SCORPIO spectrograph and TK 1024×1024 pixel ($24\,\mu$m pixel size) CCD, dispersion is 3A/pix. For objects No 1 and 7 2MASS J015806.13+383918.4 and 2MASS J171130.98+ 083430.6 spectra were obtained on 8/9 September 2016 with the same SCORPIO spectrograph and EEV 42-40 2048×2048 pixel CCD (pixel size is $13.5\,\mu$m, resolution 6A).

Fig.1 presents Hamburg/ESO objective-prism survey low-resolution two-dimensional digitized spectral shapes for some objects Table 1(a), where absorption bands of C_2 molecule are well expressed. Fig.2 and 3 presents BAO 2.6 m telescope moderate-resolution CCD spectra for objects noted above.

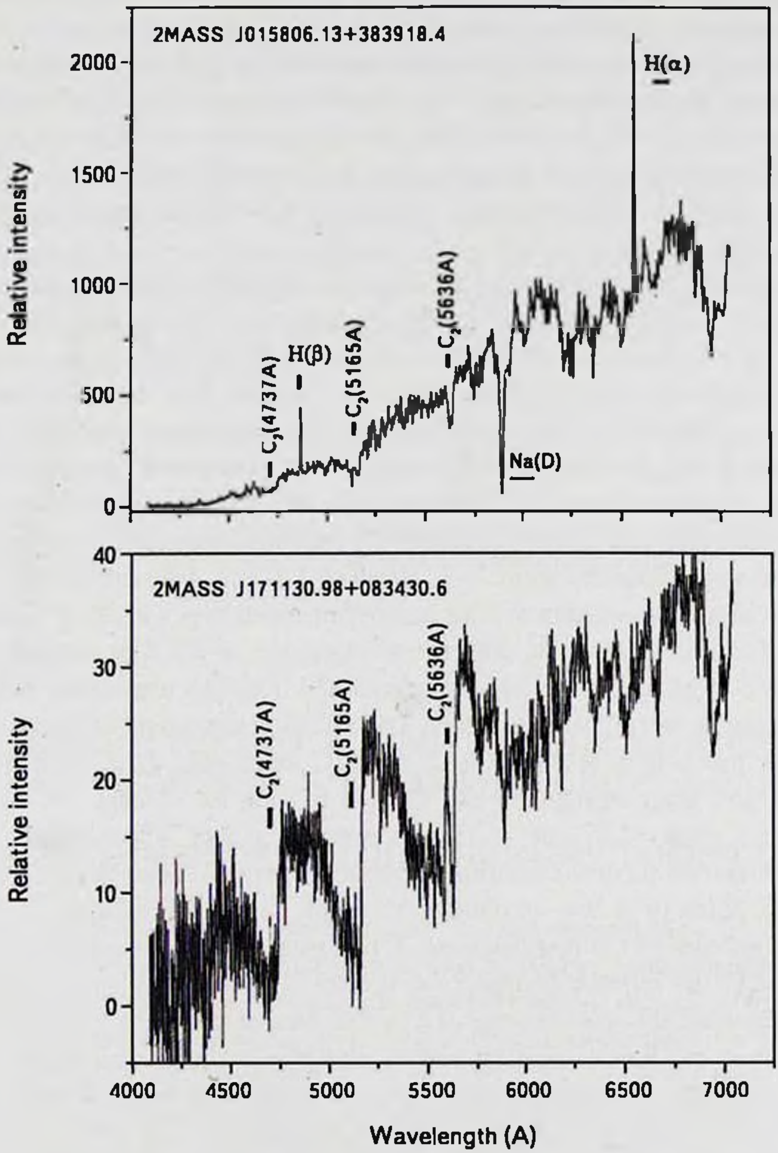

Fig.3. 2.6 m BAO telescope spectra for objects 2MASS J015806.13+383918.4 and 2MASS J171130.98+083430.6 obtained on 08/09 September 2016, with SCORPIO spectrograph and EEV 42-40 2048×2048 pixel CCD (spectral resolution, ~6A) in range $\lambda\lambda 4000 \div 7250$A. Absorption bands of C_2 molecule are indicated.

4. *Discussion.* There are several noteworthy points concerning the stars presented in Table 1(a). We can first remark that it is still possible to find new C-rich stars in the halo, despite considerable efforts to find them in previous surveys. This shows that previous surveys for AGB C stars were incomplete. Our method of scanning plates to look for sources with characteristic carbon molecular features is rewarding, though it is slow.

The second point is that these C-rich new stars have a $J-K$ surprisingly small. Excluding object No 3 which is not firmly established as being C star, all other have $J-K$ less than 1.3. This is lower than the classical limit at $J-K=1.4$ which is often used to separate C and M-type stars. In our small sample, one is even at $J-K=0.99$. There is strong evidence that all our new C stars are of the AGB type because they pulsate.

In the works by Mauron and collaborators [2-7], candidate C stars were selected with photometric criteria, especially in specific locus in two-color diagram of 2MASS photometry. In particular, they limited their research to $J-K$ over 1.2. In practice, they found few C-stars with $J-K$ less than 1.3, because the contamination by M-type stars is very large. This contamination had for consequence that they naturally concentrated their search with $J-K$ over 1.3. Some details are given here. A total of 38 candidates having $J-K$ between 1.2 and 1.3 were observed with slit spectroscopy, and only one C star was found; a 3 percent efficiency. In comparison, 66 candidates were observed with $J-K$ between 1.3 and 1.4, and 15 C were discovered, a 22 percent efficiency. The number of candidates with $J-K$ between 1.2 and 1.3, and not followed up with slit spectroscopy, is 55. This suggests that only one or two more C stars would have been found from this unobserved sample. Here we present 4 new C stars listed in Table 1 with this range of color. And this does not taken into account the 3 other C stars with $J-K<1.3$. These consideration give some strength to our method to look for C stars.

The second point of interest is the discovery of object No 3, which is at 180 kpc if one derives its distance from its pulsation period. It can be first noted, if it is not a Mira or a low-amplitude Mira for which the relation $P-K$ is applicable, it pulsates in the first overtone. If it is true, its distance would be even larger. Secondly, the number of objects as distant as that is very small. Deason et al. [13] presented slit spectroscopy of a list of stars at more than 80 kpc from the Sun. In that list, blue-horizontal objects and blue stragglers dominate. Five of them are between 100 and 150 kpc. Also, there are eight AGB C-rich stars, and three of them reach 150 kpc. Bochanski et al. [14] have discovered two M-type giants at 240 and 270 kpc. In this context, our AGB objects is one of the most distant stars of the halo, and its radial velocity should not be too difficult to obtain since its R magnitude is 17. The main lesson of this finding is that our method can provide relatively easily very distant stars.

5. *Conclusion*. In this small study, some results from on-going study of AGB halo stars were presented. It is shown that one can discover several carbon stars bluer in $J-K$ than 1.3. This suggests that a population of these relatively blue pulsating C stars may have been missed in previous survey. We also found a long-period variable as distant as 180 kpc. Therefore, this encourages to look carefully for supplementary long-period variables in the halo. Combining informat-ion from objective-prism plates and from the Catalina light-curve database is particularly fruitful, together with the use 2MASS photometry and the Period-Luminosity relation.

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НОВЫЕ ЗВЕЗДЫ АСИМПТОТИЧЕСКОЙ ВЕТВИ ГИГАНТОВ В ГАЛАКТИЧЕСКОМ ГАЛО

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Впервые приводятся данные для 8 подтвержденных (и кандидатов) углеродных звезд (С), открытых на пластинках, снятых объективными призмами. Используя кривые изменения блеска, нами обнаружена пульсация этих объектов, а также оценены расстояния, используя соотношения период-светимость (ПС) в полосе K. Это соотношение не зависит от спектрального типа (M или C), а расстояния применимы также для С звезд. Семь звезд находятся на расстоянии более чем 10 кпк от галактической плоскости, что указывает на то, что эти объекты не являются объектами диска галактики. Для одного объекта расстояние оценивается в ~180 кпк. Этот объект является одним из наиболее удаленных С звезд галактики. Многие из новых С звезд являются сравнительно голубыми.

Рассмотрены также семь других известных C звезд гало, для которых оценены периоды пульсаций. Они не были включены в предыдущих работах по C звездам галактического гало.

Ключевые слова: *звезды: углеродные звезды: обзоры: галактическое гало: галактика*

REFERENCES

1. *E.J.Totten*, *M.J.Irwin*, Mon. Not. Roy. Astron. Soc., **291**, 1, 1998.
2. *N.Mauron*, *M.Azzopardi*, *K.S.Gigoyan et al.*, Astron. Astrophys., **418**, 77, 2004.
3. *N.Mauron*, *T.R.Kendall*, *K.S.Gigoyan*, Astron. Astrophys., **438**, 867, 2005.
4. *N.Mauron*, *K.S.Gigoyan*, *T.R.Kendall*, Astron. Astrophys., **463**, 969, 2007.
5. *N.Mauron*, *K.S.Gigoyan*, *T.R.Kendall*, Astron. Astrophys., **475**, 843, 2007.
6. *N.Mauron*, Astron. Astrophys., **482**, 151, 2008.
7. *N.Mauron*, *K.S.Gigoyan*, *P.Berlioz-Arthaud et al.*, Astron. Astrophys., **562**, A24, 2014.
8. *K.S.Gigoyan*, *N.Mauron*, *M.Azzopardi et al.*, Astron. Astrophys., **371**, 560, 2001.
9. *K.S.Gigoyan*, *D.Russeil*, *A.M.Mickaelian et al.*, Astron. Astrophys., **544**, A95, 2012.
10. *K.S.Gigoyan*, *A.M.Mickaelian*, Mon. Not. Roy. Astron. Soc., **419**, 3346, 2012.
11. *A.P.Huxor*, *E.K.Grebel*, Mon. Not. Roy. Astron. Soc., **453**, 2653, 2015.
12. *S.R.Majewski*, *M.F.Skrutskie*, *M.D.Weinberg et al.*, Astrophys. J., **599**, 1115, 2003.
13. *A.J.Deason*, *V.Belokurov*, *N.W.Evans et al.*, Mon. Not. Roy. Astron. Soc., **425**, 2840, 2012.
14. *J.J.Bochanski*, *B.W.William*, *N.Caldwell et al.*, Astrophys. J., **790**, L5, 2014.
15. *M.F.Skrutskie*, *R.M.Cutri*, *R.Stiening et al.*, Astron. J., **131**, 1163, 2006.
16. *A.J.Drake*, *M.J.Graham*, *S.G.Djorgovski et al.*, Astrophys. J. Suppl. Ser., **213**, 9, 2014.
17. *P.A.Whitelock*, *M.W.Feast*, *F. van Leeuwen*, Mon. Not. Roy. Astron. Soc., **386**, 313, 2008.
18. *I.N.Reid*, *K.L.Cruz*, *J.D.Kirkpatrick et al.*, Astron. J., **136**, 1290, 2008.