CARBON STARS FROM LAMOST DR2 DATA

WEI JI1,2, WENYUAN CUI1,3, CHAO LIU2, ALI LUO2, GANG ZHAO2, and BO ZHANG1

1 Department of Physics, Hebei Normal University, Shijiazhuang 050024, China; wenyuancui@126.com
2 Key Lab of Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; liuchao@bao.ac.cn
3 School of Space Science and Physics, Shandong University at Weihai, Weihai 264209, China

Received 2016 May 10; revised 2016 June 20; accepted 2016 June 20; published 2016 August 31

ABSTRACT

In this work, we present the new catalog of carbon stars from the LAMOST DR2 catalog. In total, 894 carbon stars are identified from multiple line indices measured from the stellar spectra. We are able to identify the carbon stars by combining the CN bands in the red end with C2 and other lines. Moreover, we also classify the carbon stars into spectral sub-types of C–H, C–R, and C–N. These sub-types show distinct features in the multi-dimensional line indices, implying that in the future they can be used to identify carbon stars from larger spectroscopic data sets. While the C–N stars are clearly separated from the others in the line index space, we find no clear separation between the C–R and C–H sub-types. The C–R and C–H stars seem to smoothly transition from one to another. This may hint that the C–R and C–H stars may not be different in their origins, instead their spectra look different because of different metallicities. Due to the relatively low spectral resolution and lower signal-to-noise ratio, the ratio of 12C/13C is not measured and thus the C–J stars are not identified.

Key words: catalogs – stars: carbon – stars: statistics – surveys

Supporting material: machine-readable table

1. INTRODUCTION

Carbon stars, recognized by Secchi (1869), are peculiar objects with optical spectra characterized by strong carbon molecular bands, namely CH, CN, and C2, as well as SiC2 and C3 in cooler stars. Compared to normal stars, carbon stars show an inversion of the C/O ratio (C/O > 1). Most carbon stars in the galaxy are dwarf carbon stars. Both dwarf carbon stars and C–H stars inherited their atmospheric carbon by mass transfer from an asymptotic giant branch (AGB) companion which is now a white dwarf (Iben & Renzini 1983; Boothroyd & Sackman 1988). Most such white dwarfs have already cooled sufficiently to be undetectable in spectroscopy. The inversion of the C/O ratio in the cool and luminous carbon stars (C–N type) is due to the ongoing third dredge-up in the AGB phase. The origin of the enrichment of C–R stars is still in debate, since long-term radial-velocity observations revealed that they do not seem to be in binary systems (McClure 1997). This leads to the conclusion that they are the product of a merger, and mergers are known to produce fast rotators. Theoretical works have suggested that the merging of a He white dwarf with a red giant branch star is the most favorable progenitor, because a strong off-center He flash led by rotation of the He core formed after the merger is expected to provoke the mixing of carbon into the envelope (Izzard et al. 2007; Domínguez et al. 2010). Almost all the excess of carbon in carbon stars is produced through the triple-α reaction during helium fusion in red giant stars.

As the carbon-rich AGB stars are very luminous and easily identified by the strong band heads in their spectra, they are usually used as kinematical and dynamical probes of the Galaxy at large distances. For example, carbon stars have been used to measure the velocity dispersions of the Galactic halo (e.g., Mould et al. 1985; Bothun et al. 1991) and the Galactic rotation curve (Demers & Battinelli 2007; Demers et al. 2009; Battinelli et al. 2013). The mean apparent magnitude of carbon stars has also been used to estimate the distance moduli of NGC 205 and NGC 300 (Richer et al. 1984; Richer & Crabtree 1985).

To date, a series of surveys has been conducted to search for Galactic carbon stars, such as the Automatic Plate Measuring survey (Totten & Irwin 1998; Ibata et al. 2001), the First Byurakan Spectral Sky Survey (Gigoyan et al. 1998), and infrared objective-prism surveys (Alksnis et al. 2001, and references therein). In particular, Alksnis et al. (2001) published a catalog containing 6891 carbon stars, which is the revised version of the General Catalog of Cool Carbon Stars maintained by B. C. Stephenson of the Warner and Swasey Observatory (Stephenson 1973, 1989).

Carbon stars are mainly identified from the optical C2 Swan bands, the near-infrared CN bands, and the 11.2 μm band of SiC. They can be classified into several sub-types from the spectral features (Keenan 1993). C–R stars often show strong continuum in blue, slightly enhanced Ba, and strong isotopic C bands. C–N stars show strong and diffuse blue absorption, enhanced Ba lines, and weak isotopic C bands. C–H stars have strong CH absorption and weak Ca and Fe lines (Barnbaum et al. 1996). In addition, there are other sub-types such as C–J (strong 13C/12C ratio) and dC (dwarf carbon) stars. Note that these classifications are not directly related to their origin.

Among these spectral sub-types, C–N and C–H stars are of more interest because the former are mostly in the AGB stage and the latter are found mostly in halo populations (Goswami 2005). Increasing the number of samples for either type of carbon stars would be very helpful in improving our knowledge about how a star ends its life (through C–N stars) and the formation history of the stellar halo (through C–H stars). Based on the low-resolution spectra of the Sloan Digital Sky Survey (SDSS; York et al. 2000), 39 and 251 faint (R > 13) high-latitude carbon stars (FHLCs) were identified by Margon et al. (2002) and Downes et al. (2004), respectively. Recently, Green (2013) retrieved 1220 FHLCs from SDSS DR7 through cross correlation of stellar spectra with the SDSS

1
carbon star templates. Si et al. (2014) found 202 new carbon stars from SDSS DR8 using the label propagation algorithm.

From the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) pilot survey (Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012), Si et al. (2015) identified 158 new carbon stars using the manifold ranking algorithm. In a survey, the fraction of carbon stars that are dwarfs depends sensitively on the magnitude limit of the survey. The relatively brighter limiting magnitude \((r \sim 18)\) of the LAMOST survey tends to find more giants and AGB stars, whereas the SDSS spectroscopy survey \((r \sim 21)\) reveals many more dwarfs than giants (nearly 70%).

In this paper, we identify more carbon stars from LAMOST DR2, which contains almost 4 million stellar spectra, based on the spectral line indices. The paper is organized in the following manner. In Section 2, we briefly introduce the basic data from LAMOST DR2 and give a detailed description of the method used to search for carbon stars. In Section 3, we show the results of the classification of the carbon stars. In Section 4, we summarize the distribution of different sub-types of carbon stars in line indices and multi-band photometric space. Finally, a short conclusion is drawn in Section 5.

2. DATA

2.1. The LAMOST Data

The LAMOST, also called the Guo Shou Jing telescope, is a 4 m reflective Schmidt telescope with 4000 fibers on a 20 square degree focal plane (Cui et al. 2012; Zhao et al. 2012). The unique design of LAMOST enables it to take 4000 spectra in a single exposure to a limiting magnitude as faint as \(r = 18\) at the resolution \(R = 1800\). The LAMOST survey will finally obtain more than 5 million low-resolution stellar spectra after its five year survey (Deng et al. 2012). Previous works have shown that LAMOST observations are biased more to giant than dwarf stars, since the limiting magnitude is relatively brighter (Liu et al. 2014a; Wan et al. 2015). By the end of 2014, the LAMOST team had released the DR2 catalog, which contains 4,136,482 targets including 3,784,461 stars. In DR2, there are about 0.5 million late type giant stars (Liu et al. 2015a), implying that there should be large numbers of carbon stars.

2.2. Line Indices

The typical spectra of carbon stars are characterized by strong \(C_2\), CN, and CH absorption bands (Secchi 1869). Therefore, we measure the line indices of carbon related molecular lines to identify carbon stars. We show several sample LAMOST spectra for typical carbon stars in Figure 1. The features of the \(C_2\) swan bands at 4737, 5165, and 5635 \(\AA\), and red CN molecule bands at 7065 and 7820 \(\AA\) are prominent in these spectra, while the detailed features are different in different sub-types. Compared to the traditional approach to classifying spectral types, using line indices allows a semi-automatic classification. With multiple spectral line indices, various spectral types may transitionally change from one to another, which naturally reflects the variation of the astrophysical parameters, e.g., effective temperature, surface gravity, and metallicity, from type to type (Liu et al. 2015b).

In order to identify carbon stars, we adapt the Lick line indices defined by Worthey (1994) and Worthey & Ottaviani (1997). For the LAMOST DR2 spectra, we use the measured results from Liu et al. (2015b). The \(Ba II\) (4554 \(\AA\)), molecular bands \(C_2\) (around 5635 \(\AA\)), \(CN\) (7065 \(\AA\)), and \(CN\) (7820 \(\AA\)) are also measured based on the wavelength definition listed in Table 1.

The line index in terms of equivalent width (EW) is defined by the following equation (Worthey 1994; Liu et al. 2015a):

\[
EW = \int \left(1 - \frac{F_\lambda}{F_C}\right) d\lambda,
\]

where \(F_\lambda\) and \(F_C\) are the fluxes of the spectral line and continuum, respectively, which are functions of wavelength \(\lambda\). The pseudo-continuum \(F_C\) is estimated via linear interpolation of the fluxes located in the “shoulder” region on either side of each index bandpass. The line index under this definition is in ångströms. For the spectra with a signal-to-noise ratio (S/N) larger than 20, the typical uncertainty of the EWs of the atomic lines is smaller than 0.1 \(\AA\), while for the molecular band it becomes a few ångströms, and may be systematically affected due to difficulty in defining the continuum.

3. IDENTIFICATION OF CARBON STARS

We first select the stellar spectra with S/N larger than 10 in the \(i\) band from LAMOST DR2, and obtain 2,434,289 stellar spectra in which only one epoch of the multiply observed objects is included. Then we locate the distribution of the

---

Table 1: Line Indices Definition Used in This Work

| Name       | Index Bandpass (Å) | Pseudo-continua (Å) |
|------------|--------------------|----------------------|
| Ba II      | 4550–4559          | 4538–4545 4559–4563  |
| C2         | 5235–5640          | 5165–5235 5640–5730  |
| CN7065     | 7065–7190          | 7025–7065 7190–7230  |
| CN7820     | 7820–8000          | 7790–7820 8000–8065  |
known carbon stars in the CN7820 versus CN7065 plane (see the top panel of Figure 2), so that we can determine the intrinsic location of the carbon stars. There are 1093 stars marked as carbon stars in the LAMOST DR2 catalog. These marks are added from a template matching technique (Luo et al. 2015). The automatic pipeline may mistakenly identify normal stars or those with lower S/N as carbon stars, while many carbon spectra without a good match in their incomplete templates are missed. We inspect the stars with carbon marks by eye and finally confirm that 243 are real carbon stars with S/N > 20 in both the g and i bands (S/N (g) and S/N (i) hereafter). Moreover, we find 34 common carbon stars by cross-identifying LAMOST DR2 (S/N > 20 in both the g and i bands) with the carbon star catalog provided by Alksnis et al. (2001).

It can be seen that, in the top panel of Figure 2, the branch from the central region to the top-right corner is dominated by the carbon stars. We then adopt the following empirical criteria in the CN7820 versus CN7065 plane so that most of the stars located in the branch toward the top-right corner are included. With these cuts, we obtain 87,160 carbon star candidates. The criteria are:

\[
48.5 \text{/} 44 \times \text{CN7065} - 31 \times \text{CN7820} < 49/10
\]

\[
\times \text{CN7065} + 11/10
\]

\[
1 < \text{CN7065} < 44
\]

\[
1.5 < \text{CN7820} < 71.
\]

In the central region around the origin point of our selected branch in Figure 2, different types of stars and low S/N spectra are mixed together. Hence, for the highly contaminated region,


| Step | Criteria | Selected Candidates |
|------|----------|---------------------|
| 1    | S/N (i) > 10 and leave only one epoch for multiply observed stars | 2434289 |
| 2    | Equations (2)-(4) | 87160 |
| 3    | CN7065 > 4 or CN7820 > 8 | 4490 27789 |
|      | CN7065 < 4 and CN7820 < 8 with S/N (g) > 20 and S/N (i) > 20 | 23299 |
| 4    | CN7065 > 2 and C4, C6 < -13 | 11254 |
| 5    | $K_s < 14.5$ and $J - K_s > 0.45$ | 6309 |
| 6    | inspect by eye | 894 |

Table 2: Steps to Identify Carbon Stars

mag, we can remove well most of the warm star contaminators located in the bluer group (marked as gray asterisks). From the cuts in the color–magnitude diagram, 6309 candidates are left. It is noted that some bluer carbon stars (like the “G-types” in Green 2013) may not be included. The “G-type” stars are thought to be a kind of dC star, which show weak CN and relatively blue colors, and are probably the most massive dCs still cool enough to show C2 bands.

Finally, we inspect the spectra for all 6309 stars by eye for confirmation. The CN, C2, CH, and TiO2 features are used to judge whether the candidate spectra are real carbon stars. This procedure was performed at least twice by the same people and was independently confirmed by others to avoid severe bias of the judgment. The whole selection process for carbon stars is listed in Table 2, and we finally identify 894 carbon stars, which are listed in Table 3.

Figure 4 shows the normalized histograms of EW for C2 (5635 Å, left panel) and TiO2 (6191 Å, right panel) for the 894 carbon stars, the remaining 5415 candidates, and the total 6309 candidates. We note that many of (but not exclusively) the visually selected carbon stars are found in the region of strong C2 (>−30) and weak TiO2 (<2.5). However, some unselected candidates are also located in the weak-TiO2 strong-C2 region. These were double-checked and it was confirmed that they are contaminants due to noise in the spectra. Some of the weak-TiO2 stars also show strong C2, most of them are not carbon stars but their C2 measures are affected by the local spikes in the spectra.

We further map the carbon stars C2 versus Ba4554 in Figure 5 and surprisingly find that some carbon stars are located in a clump mostly occupied by ejected O-rich stars. We select the clump with two straight-line cuts at C2 = −16 and Ba II (4554 Å) = 1.2 (blue dashed lines shown in the plot) and obtain 105 samples located in the clump. We double-check these samples and find that they do show C2 in their blue spectra and the CN band in the red, which are very likely features of early type carbon stars. Figure 6 shows a few sample spectra selected from this group of stars. Because in this work we do not directly measure C/O, which should be determined from a comparison with a set of proper model spectra, it is not clear whether the C/O ratio is larger than 1 for these stars. Therefore, we label them in Table 3 with a question mark and call them suspected carbon stars in the rest of the paper. Alternatively, these stars may be the so-called strong-CN stars (Gray & Corbally 2009). More investigations of these stars should be performed in future works.

4. SUB-CLASSIFICATION

4.1. Criteria for Spectral Sub-type

According to the revised MK carbon star classification system of Keenan (1993), there are five types of carbon stars, i.e., C–R stars, C–N stars (roughly corresponding to the Harvard R and N stars), C–J stars, C–H (or CH) stars, and C–Hd (hydrogen deficient) carbon stars. Here, we mainly focus on the types C–R, C–N, and C–H.

C–N stars can easily be distinguished from the other types because of the strong absorption in the blue part of the spectrum (generally little or no flux bluer than 4400 Å according to Keenan (1993)). On the other hand, C–H stars are difficult to distinguish from C–R stars. In general, C–H stars are more metal-poor and most of them are recognized as high-velocity halo objects. However, there are still some indicators which can be used to distinguish C–H stars from C–R stars based on low-resolution spectra: (1) C–H stars show quite a strong G band; (2) they have an exceptionally strong P-branch head near 4342 Å; (3) they show weaker CaI at 4227 Å; (4) they show enhanced lines of s-process elements (e.g., Ba II lines at 4554, 5853, and 6496 Å) and weaker Fe-group elements (Keenan 1993; Barnbaum et al. 1996; Si et al. 2015).

According to the low-resolution LAMOST spectra, we select a set of the most prominent criteria, which are summarized in Table 4, to classify the sub-types of the carbon stars. Since we do not use any quantified approach in the procedure, mis-classification may occur for a few carbon stars with insignificant features, in particular for those between C–R and C–H. Applying the criteria listed in Table 4, we find 108 C–N, 259 C–R, 339 C–H, and 83 unknown stars. The sub-type for each carbon star is listed in Table 3.

After manually classifying the carbon stars, we can determine more features of the sub-types in their spectral and photometric data. These features will be very helpful in better understanding the physics of these stars and can provide some suggestions to improve the approaches to sub-classification. In the following two sub-sections, we discuss the features of the C–N stars and C–R/C–H stars, respectively.

4.2. C–N Stars

Among the three sub-types discussed in this work, C–N stars are the easiest one to classify from the spectra, since they show very weak fluxes in blue wavelengths. Hence we develop a color index, denoted as F4600/F8000, by dividing the median flux between 4300 and 4600 Å by the value between 8000 and 8700 Å. We do not use fluxes bluer than 4300 Å because they are more affected by noise. Figure 7 shows that most of the C–N stars are located on the left side with very low flux in the blue wavelength. It also displays that the EW of C2 is slightly anti-

Much previous work has demonstrated that infrared photometry is very helpful to identify the C–N stars. Figure 8 shows...
that the C–N stars are concentrated in the red end of the stellar locus in the $J - H$ versus $J - K_s$ diagram, specifically redder than the boundary defined by $J - K_s > 49 \times (J - H) / 35.1 - 5.8/35.1$, $J - K_s > 5/3.25 - (J - H)/3.25$, and $J - H > 0.5 \times (J - K_s) + 0.15$.

Figures 7 and 8 provide two different means to identify C–N stars. Based on our sample, for the low-resolution spectroscopic data, if we classify the C–N as those bluer than $F4600/F8000 < 0.22$, the completeness of this simplified criterion can reach 100% with 16% contamination. For the photometric data, if we apply the criteria of $J - K_s > 49 \times (J - H) / 35.1 - 5.8/35.1$, $J - K_s > 5/3.25 - (J - H)/3.25$, and $J - H > 0.5 \times (J - K_s) + 0.15$, we can identify 73% from the full sample of C–N stars with a contamination rate of 8%.

4.3 C–R and C–H Stars

We show the distributions for the C–R and C–H stars in the Ba II (4554 Å)–Fe–Ca I (4227 Å) space\(^4\) in Figure 9. It is seen that, although on average C–R stars are more metal-rich than C–H stars, no clear boundary is found between the two classes. The suspected carbon stars (gray unfilled asterisks) are also shown in the figure. The left panel shows that most of the C–H stars have similar Ba but lower Ca compared to the C–R stars. The right panel shows that the EWs of Ba for both the C–R and C–H stars are well correlated with Fe, while the suspected carbon stars are isolated above the C–R and C–H stars with larger Fe. It is not easy to directly estimate whether the C–H

\(^{4}\) The averaged EW for nine Fe Lick line indices located between 4000 and 6000 Å.
stars are more Ba-rich than the C–R stars simply from the line indices, because the line indices are not only affected by the abundance, but are also correlated with effective temperature.

Figure 5. Distributions of identified carbon stars in this work (red unfilled triangle) in the C2 (5635 Å) vs. Ba II (4554 Å) plane. The gray unfilled represent the suspect carbon stars, and the green filled asterisks represent the candidates from LAMOST DR2. The blue dashed line shows the line cuts (C2 = −16, Ba II(4554 Å) = 1.2) by which we define the suspect carbon stars.

Figure 6. Three sample spectra for the suspected carbon stars located in the bottom-left corner of Figure 5.

stars are more Ba-rich than the C–R stars simply from the line indices, because the line indices are not only affected by the abundance, but are also correlated with effective temperature.

Figure 7. Distributions of the identified C–N (blue unfilled triangles), C–H (magenta unfilled circles), and C–R (black asterisks) in the C2 (5635 Å) vs. F4600/F8000 plane. The green line is F4600/F8000 = 0.22, at which we can separate all of the C–N stars from the C–H and C–R stars.

Figure 8. Stellar locus in the J − H vs. J − Ks diagram. The red dashed lines are the line cuts, which are J − Ks > 49 × (J − H)/35.1 − 5.8/35.1, J − Ks > 53.25 − (J − H)/3.25, J − H > 0.5 × (J − Ks) + 0.15, and are used to select C–N stars. The contours indicate the location of the normal stars from the LAMOST DR2 catalog. The rest symbols are the same as in Figure 7.

Table 4
Criteria for Classifying Carbon Stars

| Sub-type | Criteria |
|----------|----------|
| C–N      | (1) No flux at λ < 4400 Å; some very late type C–Ns can be flat even at λ < 5000 Å<br>(2) Strong Ba II at 6496 Å<br>(3) Weak Hα |
| C–H      | (1) Strong G band (CH),<br>(2) Strong CN at 4215 Å and weak Ca at 4227 Å<br>(3) Strong Ba II at 4554 Å or 6496 Å<br>(4) Strong Hα |
| C–R      | (1) Strong CN at 4215 Å and strong Ca at 4227 Å<br>(2) Weak Ba II at 4554 Å relatively weak Ba II at 6496 Å compared to Hα, |
surface gravity log, and overall metallicity. Therefore, we use the line index ratio $\text{Ba}4554/(4+\text{Ca}4227)$ as the indicator of $\left[\text{Ba}/\text{Fe}\right]$, since the Ca line can be approximately treated as a proxy of the metallicity without being sensitively affected by the effective temperature. However, the Fe lines are more sensitive to the effective temperature and hence cannot be directly used as a proxy of the metallicity. Figure 10 shows that, although they are quite similar, the Ba abundance for the C–H stars is statistically larger than that for the C–R stars.

In Figure 11, the C–R and C–H stars are compared to the normal K giant stars in term of effective temperature and metallicity via two line indices: $H/\delta$, which is sensitive to the effective temperature, and Fe (5015), which is sensitive to the metallicity (Liu et al. 2014b). We find that the C–R stars are more metal-rich and slightly cooler than C–H stars. Interestingly, the suspected carbon stars (the gray unfilled asterisks) are mostly supersolar metal-rich stars.

The C–H stars are believed to be in binary systems, in which the companions have evolved to white dwarfs and mass transferring may be responsible for the enrichment of the carbon at the surface of the C–H stars. The origin of the C–R stars, in particular the early type C–R stars, is still not quite clear. It seems that they are not post-AGB stars due to their lower luminosity and some observational evidence shows that they are also not mass transfer binaries (McClure 1997). Although McClure (1997) suggested that the C–R stars may have been coalesced, Wallerstein & Knapp (1998) found that no additional rotation signature is found from the width of the spectral lines for the sample of McClure. Theoretical works have suggested that a merger of a helium white dwarf to a red giant branch star can shift the helium-flash to the outskirts of the core, allowing more carbon elements to mix in the convective envelope (Izzard et al. 2007; Domínguez et al. 2010), while another scenario of red giant mergers may not create a peculiar helium-flash and additional carbon at the surface (Piersanti et al. 2010). The larger Ba abundance of C–H stars is likely due to mass transfer from an AGB companion.

4.4. Distributions

Figure 12 shows histograms of magnitude $K_s$ for dC, C–H, C–R, and C–N stars. It can be seen that the C–N stars are the brightest, followed by C–R and C–H, with dCs the faintest, as
Since C–N stars are N-type AGB stars with high luminosity, they show very bright $K_s$ magnitude. dCs are dwarf stars with the lowest luminosity, thus they are concentrated at the faintest end. Most C–R and C–H stars are giants, thus have moderate distributions of magnitude. The identification of dCs is discussed in Section 5.

Finally, Figure 13 shows the spatial distribution for the identified carbon stars in Galactic coordinates. As expected, the C–N stars are quite concentrated in the disk mid-plane, while the C–H stars are mostly distributed in the high Galactic latitude region. The C–R stars are in the middle, most of them are concentrated at low Galactic latitudes but a few are located at high latitudes.

5. DISCUSSION AND CONCLUSION

Previous works have shown that many carbon stars are in fact carbon dwarf stars. However, it seems very difficult to distinguish dwarf stars from the spectral features. Hence, we identify the possible dwarf stars from the reduced proper motion. The reduced proper motion is defined as

$$H_\mu = K_s + 5 \log \sqrt{\mu_\alpha^2 + \mu_\delta^2} - 10,$$

where $H_\mu$ is the reduced proper motion, $K_s$ is the $K$-band photometry from the 2MASS catalog, $\mu_\alpha$ and $\mu_\delta$ are the proper motion in milli-arcseconds per year from the PPMXL catalog (Roeser et al. 2010). Because most of the stars in the Milky Way have relatively similar motion speed, then the transversal angular velocity, i.e., the proper motion, is generally larger (smaller) when the star is nearer (farther) to the Sun. Consequently, the proper motion can be very roughly considered as the proxy of the parallax and thus $H_\mu$ can be roughly treated as the absolute magnitude of a star according to Equation (5). Figure 14 shows $H_\mu$ versus $J - K_s$ for the carbon stars as well as the distributions for the normal K giant stars (defined as $\log g < 3.5$ and displayed as the red contours) and K dwarf stars (defined as $\log g > 4$ and displayed as the green dashed contours) selected from the LAMOST DR2 catalog. The two distributions for the normal K giant and dwarf stars can be used as the probability density functions for the two luminosity types in the plane. The middle points between the two probability density functions are indicated by the solid thick green line, which can be used as the separation line for the giant/dwarf stars. The stars located above the line are very likely giant stars and the stars located below are likely dwarf stars. Applying this empirical giant/dwarf separation line to the 894 carbon stars, we find 84 possible carbon dwarf stars, 53 of them are C–H stars and 22 of them are C–R stars. None of the
possible dwarf stars are classified as C–N or suspected carbon stars.

We investigate the 243 confirmed carbon stars with carbon flag in the LAMOST catalog, and 219 are left after the cuts in CN7820, CN7065, C₂, Kᵣ, and J – Kᵣ. When we inspect the spectra for the 6309 candidates we do not check the carbon flag. Finally, all of the 219 confirmed LAMOST carbon stars are again identified as carbon stars and show up in the final catalog. This confirms that the inspection of the spectra is quite stable and reliable.

In this work, we combine the manual inspection of spectra with cuts in the line index space and color–magnitude diagram, and successfully identify 894 carbon stars from the LAMOST DR2 catalog. Of these suspected samples, 105 have a weak C₂ band with a weak TiO₂ band, which is not a typical feature of carbon stars. However, to keep the catalog complete, we leave them in the final catalog with marked as type C?.

The largest fraction of the stars, i.e., 339 of 894, are classified as C–N stars, which are Bα enhanced and more metal-poor; 259 of the carbon stars are classified as C–R stars and 108 are C–N stars. We suggest using F4600/F8000, the median flux ratio of the blue (4300–4600 Å) and red (8000–8700 Å), to select the C–N stars with a completeness of 100% and a contamination rate of only 16%. We model that although 2MASS photometry is able to identify C–N stars with reasonably low contamination, it may have relatively lower completeness.

We would be very interesting to perform follow-up time-domain photometric and high-resolution spectroscopic observations in the future in order to identify carbon stars and further investigate their nature.

We thank the anonymous referee for positive and constructive comments that greatly helped to improve this paper, and thank Dr. Sarah Bird for her kind help in language editing. This work was supported by the National Key Basic Research Program of China 2014CB84570, the National Natural Science Foundation of China (NSFC) under grants U1231119, 11321064, 11390371, 11273011, 11473033, and the China Postdoctoral Science Foundation under grant 2013MS51587.

CL acknowledges the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, Grant No. XDB09000000, and the NSFC under grants 11373032 and 11333003. The Guoshoujing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Alksnis, A., Balklavs, A., Dzervitis, U., et al. 2001, BaltA, 10, 1
Barnbaum, C., Stone, R. P. S., & Keenan, P. 1996, ApJS, 105, 419
Battinelli, P., Demers, S., Rossi, C., & Gigoyan, K. S. 2013, APADS, 56, 68
Boothroyd, A. I., & Sackmann, S. G. 1988, ApJ, 328, 671
Bothun, G., Elias, J. H., MacAlpine, G., et al. 1991, AJ, 101, 2220
Cui, X., Zhao, Y. H., Chu, Y. Q., et al. 2012, RAA, 12, 1197
Demers, S., & Battinelli, P. 2007, A&AR, 473, 143
Demers, S., Battinelli, P., & Forest, H. 2009, in IAU Symp. 254, The Galaxy Disk in Cosmological Context, ed. J. Ansersen, J. Bland-Hawthorn & B. Nordstrom (Dordrecht: Kluwer), 20
Deng, L., Newberg, H. J., Liu, C., et al. 2012, RAA, 12, 735
Domínguez, I., Piersanti, L., Cabezón, R., et al. 2010, MmSAI, 81, 1039
Downes, R. A., Margon, B. M., Anderson, S. F., et al. 2004, AJ, 127, 2838
Gigoyan, K. S., HamBaryan, V. Y., & Azzopardi, M. 1998, APADS, 41, 545
Goswami, A. 2005, MNRAS, 359, 531
Gray, R. O., & Corbell, C. J. 2009, Stellar Spectral Classification (Princeton NJ: Princeton Univ. Press)
Green, P. 2013, ApJ, 765, 12
Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001, ApJ, 551, 294
Iben, I., Jr. & Renzini, A. 1983, ARA&A, 21, 271
Izzard, R. G., Jeffery, C. S., & Lattanzio, J. 2007, A&AR, 470, 661
Keenan, P. C. 1993, PASP, 105, 905
Liu, C., Cui, W. Y., Zhang, B., et al. 2015a, RAA, 15, 1137
Liu, C., Fang, M., Wu, Y., et al. 2015b, ApJ, 807, 4
Liu, X. W., et al. 2014a, in Proc. IAU Symp. 298, 310, ed. S. Felzing, G. Zhao, & N. A. Walton, (Cambridge: Cambridge Univ. Press) arXiv:1306.5376
Liu, Deng, L. C., Carlin, J. L., et al. 2014b, ApJ, 790, 110
Luo, A. L., Zhao, Y. H., Zhao, G., et al. 2015, RAA, 15, 1095
Margon, B., Anderson, S. F., Harris, H. C., et al. 2002, AJ, 124, 1651
McClure, R. D. 1997, PASP, 109, 256
Mould, J., Schneider, D. P., Gordon, G. A., Aaronson, M., & Liebert, J. 1985, PASP, 97, 130
Piersanti, L., Cabezón, R. M., Zamora, O., et al. 2010, A&A, 522, 80
Richer, H. B., & Crabtree, D. R. 1985, ApJL, 298, L13
Richer, H. B., Crabtree, D. R., & Pritchet, C. J. 1984, ApJ, 287, 138
Roessler, S., Demleitner, M., & Schilbach, E. 2010, AJ, 130, 2440
Secchi, A. 1869, AN, 73, 129
Si, J., Li, Y. B., Luo, A. L., et al. 2015, RAA, 15, 1671
Si, J., Luo, A. L., Li, Y. B., et al. 2014, SCPMA, 57, 176
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stephenson, C. B. 1973, PW&SOS, 1, 4
Stephenson, C. B. 1989, PW&SOS, 2, 2
Totten, E. J., & Irwin, M. J. 1998, MNRAS, 294, 1
Wallerstein, G., & Knapp, G. R. 1998, ARA&A, 36, 369
Wan, J. C., Liu, C., Deng, L. C., et al. 2015, RAA, 15, 1166
Worthey, G. 1994, ApJS, 95, 107
Worthey, G., & Ottaviani, D. L. 1997, ApJS, 111, 377
York, D. G., Adelman, J., Anderson, J. E., et al. 2000, AJ, 120, 1579
Zhao, G., Zhao, Y., Chu, Y., Jing, Y., & Deng, L. 2012, RAA, 12, 723

Figure 14. Reduced proper motion (Hᵥm) vs. J – Kᵣ for the carbon stars as well as the distributions for the normal K giant stars (defined as log g < 3.5 and displayed as the red contours) and K dwarf stars (defined as log g > 4 and displayed as the green dashed contours) selected from the LAMOST DR2 catalog. The solid thick green line indicates the middle points between the two probability density functions, which can be used as the separation line for giant/dwarf stars.