Cool carbon stars in the halo: A new survey based on 2MASS^{★,★★}

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Abstract. We present the first results of a new survey for finding cool N-type carbon (C) stars in the halo of the Galaxy. Candidates were first selected in the 2MASS Second Incremental Release database with JHK_s colours typical of red AGB C stars and $K_s < 13$, and subsequently checked through medium resolution slit spectroscopy. We discovered 27 new C stars *plus* one known previously and two similar objects in the Fornax and Sculptor dwarf galaxies. We determine and discuss the properties of our sample, including optical and near-infrared colours, radial velocities, as well as $H\alpha$ emission and variability that are frequent, all these characteristics being compatible with an AGB C-type classification. Surprisingly, of the 30 studied objects, 8 were found to have small but measurable proper motions (μ) in the USNO-B1.0 catalogue, ranging over $8 < \mu < 21$ mas yr⁻¹ and opening the possibility that some objects could perhaps be dwarf carbon stars. Yet, a detailed analysis based on comparison with the sample of known carbon dwarfs leads us to consider these μ as incompatible with the broader picture suggested by the other data taken as a whole. So, we adopt the view that all objects are of AGB type, i.e. luminous and distant. Because the stream of Sagittarius dwarf galaxy is known to be the dominant source of luminous C stars in the halo, we chose to determine distances for our sample by scaling them on the 26 known AGB C stars of the Sgr galaxy itself, which are found to be, in the K_s -band, ~ 0.5 mag less luminous than the average LMC C stars for a given $J - K_s$ colour. The obtained distances of our halo stars range from 8 to 80 kpc from the Sun. Then, examination of position and radial velocities show that about half belong to the Sgr stream. Our findings suggest that numerous AGB C stars remain to be discovered in the halo. Long term K_s -band monitoring would be of great value to ascertain distance estimates through the period-luminosity relation, because a large fraction of our sample is probably made of Mira variables.

Key words. stars: carbon – surveys – Galaxy: halo – Galaxy: stellar content

1. Introduction

Surveys of stellar populations located at high galactic latitude are important to characterize the halo and to understand how the Galaxy formed (see for example Majewski 1993, and references therein). Among the various types of stars that have been investigated with this goal, the case of carbon (C) stars has been the subject of much attention for some years. If such a C star is proven to be in the asymptotic giant branch (AGB) evolutionary phase (as is often the case for cool C stars in the galactic disk), with an R -band magnitude of the order of 15, its high

luminosity ($M_R \sim -3.5$) puts it as far as 50 kpc from the Sun. Therefore, the luminous C stars constitute valuable probes of the distant halo (e.g. Bothun et al. 1991). Considerable efforts have been accomplished, and are still in progress, in order to find such faint high latitude carbon stars (FHLCs). These rare objects have been discovered using two main methods. The first is by exploiting Schmidt objective-prism plates where C stars have a conspicuous spectral appearance (MacAlpine & Lewis 1978; Sanduleak & Pesch 1988; Gigoyan et al. 2001; Christlieb et al. 2001). The second method uses a preliminary selection of candidates with suitable photometric criteria, such as a very red $B-R$ colour index, as in the APM (Irwin 2000) survey of Totten & Irwin (1998; hereafter TI98), or multicolour properties as in the SLOAN carbon star survey of Margon et al. (2002), with subsequent verification of the carbon star nature of these candidates by follow-up spectroscopy.

One of the most striking results derived from these FHLC surveys, especially from the APM one, was the fact that the tidal stream of the Sagittarius dwarf spheroidal galaxy (Sgr)

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** Appendices are only available in electronic form at

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Fig. 1. *Left panel:* colour-colour diagram of known carbon stars with 2MASS photometry and located at high galactic latitude ($|b| > 30^\circ$); *Right panel:* colour-colour diagram of the targets for which slit spectroscopy have been obtained (circles). The new carbon stars found in this work are indicated by an overplotted + sign. Note that the abscissa and ordinate scales differ in the two panels.

orbiting the Galaxy could be traced for the first time by considering the spatial and kinematical properties of the distant cool C stars (Ibata et al. 2001a). The Sgr stream has now been detected through a number of other methods, such as deep mapping in limited portions of sky of specific populations, e.g., blue horizontal branch stars, metal poor K giants, turnoff stars, RR Lyr variables (Dinescu et al. 2002; Dohm-Palmer et al. 2001; Kundu et al. 2002; Vivas et al. 2001; Martinez-Delgado et al. 2001; Newberg et al. 2002), or with 2MASS selected M giants over the whole sky (Majewski et al. 2003). Yet, there are several reasons to pursue the search for cool luminous C stars all over the high latitude sky. Firstly, the detection of this stream with cool FHLCs currently involves only ~ 40 stars, so that enlarging the sample is naturally desirable. Secondly, cool AGB C stars are a population of intermediate age, and consequently their spatial distribution in the Sgr orbits might provide some interesting information on the history of the merging process. A fraction of these AGB C stars may also be Mira variables, and help to determine distances of these orbits through the period-luminosity relation. Finally, roughly half of the cool FHLC stars do not belong to the Sgr stream; their origin has to be investigated and increasing the size of the sample studied may possibly reveal other streams.

However, in the search for FHLCs, one has to take into account that the C stars in general are of various types and with diverse evolutionary origins (see Wallerstein & Knapp 1998 for a review). Compared to the bright AGB stars, one family consists of less luminous, warmer carbon-rich objects presently evolving as clump giants or located along the red giant branch, having accreted carbon from a more evolved companion (Knapp et al. 2001; Christlieb et al. 2001). Moreover,

it is now well established that a class of dwarf carbon stars exists (dCs; see e.g., Dahn et al. 1977; Green 2000; Margon et al. 2002; Lowrance et al. 2003, and references therein). These dCs have very low luminosity, are located within a few hundred parsecs, have generally measurable proper motions, and in fact are expected to outnumber the C stars of giant type as observations probe successively fainter magnitudes (Margon 2003).

In this context, we report here on the first results of a new systematic search for faint, red AGB C stars at high galactic latitude. Our survey is essentially a near-infrared based survey, since our candidates have been selected from the 2MASS Second Incremental Data Release point-source catalogue. About half of our ~ 200 best candidates have now been observed spectroscopically, resulting in the discovery of 27 new cool FHLCs which are presented and analysed in this work. After describing our selection method (Sect. 2), the spectroscopic observations are reported in Sect. 3. In Sect. 4, we examine the various properties of the sample, including radial velocities, variability and proper motions. These results are analysed in Sect. 5 together with a determination of distances and examination of membership to the Sgr stream. The main conclusions are finally summarized in Sect. 6.

2. Selection of candidates

In order to find new FHLC stars, we first considered all the FHLCs published in the literature and located at $|b| > 30^\circ$. After retrieving their JHK_s photometry from the 2MASS Second Incremental Data Release point-source catalogue (available when this work started and covering about half of the sky), we plotted them in a colour-colour JHK_s diagram (Fig. 1, left panel). Very similar diagrams, which inspired our

search method, have been published by Totten et al. (2000; TIW), and Liebert et al. (2000). It can be seen in Fig. 1 that the large majority of FHLCS have an $H - K_s$ colour of about 0.2. These stars are relatively warm, presumably CH-type objects and come mainly from the Hamburg/ESO sample of Christlieb et al. (2001). The cool N-type stars which we seek are located at $H - K_s$ larger than ~ 0.3 , and appear to form a relatively well defined locus up to $H - K_s \sim 1.1$, although the number of objects is progressively decreasing. The width of this locus is typically ~ 0.25 mag. This plot also suggests that the C star locus extends up to the two objects at $H - K_s \sim 1.6$, and such an extension is supported when one considers a similar diagram showing the LMC C stars listed the catalogue of Kontizas et al. (2001) (see also e.g., Nikolaev & Weinberg 2000, their Fig. 2). At still redder colours, Fig. 1 also shows also two exceptionally cool N-type stars with $H - K_s \sim 2.0$. These are the very dusty C stars IRAS 0846+1732, found by Cutri et al. (1989), for which $l = 210^\circ$, $b = +35^\circ$, $J - H = 2.37$, $H - K_s = 2.01$ and $K_s = 10.71$, and IRAS 03582+1819, found by Liebert et al. (2000), with $l = 210^\circ$, $b = -25^\circ$, $J - H = 2.59$, $H - K_s = 2.07$, and $K_s = 9.26$. The latter object is plotted in Fig. 1 despite having $|b| < 30^\circ$ because its height above the galactic plane is estimated by Liebert et al. to be in the range 6–15 kpc.

Our method for searching for cool C stars was therefore to select in 2MASS objects lying within a distance of ~ 0.15 mag to the median line formed by these template cases. In order to avoid a large number of ordinary (M-type) stars in our selection, we had also to set a limit on colours, e.g. $H - K_s > 0.4$, $J - H > 0.95$, meaning that we naturally miss the numerous warm but less luminous giant C stars that are much better selected by other techniques, e.g. through the SLOAN multi-colour criteria. Concerning the limits in galactic latitude, our nominal goal was to limit our search to $|b| > 30^\circ$. However, we also considered with a lower priority candidates located down to $|b| \sim 25^\circ$, especially if they showed an additional favourable property such as very red $B - R$ or $J - K_s$ colours, and 6 new C stars were found at these low latitudes (more details in Sect. 4).

Concerning the limit in brightness, our nominal limit was set by $K_s < 13$, which corresponds to the rather large distance of ~ 150 kpc from the Sun, if one adopts as a basis the typical not too red LMC C stars with $J - K_s = 1.6$, which have a mean K_s of 10.7 ($\sigma = 0.4$).

After selection in 2MASS which yielded ~ 1200 objects, we excluded the objects that were already known and catalogued in the SIMBAD database as M or C stars, young stellar objects, L dwarfs, galaxies or QSOs. We also excluded objects with USNOC-A2.0 colour $B - R$ bluer than 1.5, when these B and R magnitudes are provided by the 2MASS database. This is justified by the fact that many M stars and galaxies are excluded by this criterion, while N-type stars are expected to be much redder than this limit and have generally $B - R \sim 3$. Eventually, we found 6 new C stars with $2 < B - R < 3$ and 2 with $B - R = 1.9$ and 1.6 (see below). Inspection of POSS plates was also systematically used for further sample cleaning, and numerous supplementary cases of faint, contaminating galaxies were discarded. In addition, the objective-prism plates of the First Byurakan Survey were examined by one of us (K.G.)

Fig. 2. Proper motions of our C stars (filled octagons) as given in the USNO-B1.0 catalogue. Twenty objects are located at the (0, 0) coordinates with no motion. Empty octagons represent the dCs presently known (USNO-B1.0 data), but 7 dCs have too large a proper motion to be located within the limits of this diagram. The circle represents a motion of 21 mas yr^{-1} , that was the 3σ upper limit of TIW, enclosing 48 of the 50 APM C stars studied by these authors.

for relatively bright candidates located in the zones covered by this survey, and this allowed the elimination of a number of further M-type stars. This process resulted in a list of ~ 200 best candidates for which slit spectroscopy follow-up was begun.

3. Observations

The observations were carried out with the 193 cm telescope at Haute-Provence Observatory in France (OHP) and with the Danish 1.54 m telescope at the European Southern Observatory (ESO) in Chile. A journal of observations is given in Table 1, indicating the dates of the observing runs and the objects observed in each run. Because of clouds, no observations were done during Run 5, mentioned here for completeness.

At OHP we used the CARELEC spectrograph and its 1200 lines mm^{-1} grating blazed in the red to obtain a dispersion of $0.45 \text{ \AA pixel}^{-1}$ and to cover the $5700 \text{ \AA}$ – $6600 \text{ \AA}$ region. The detector is an EEV 42-20 CCD chip with 2048×1024 pixels of $13.5 \text{ }\mu\text{m}$. Due to poor seeing, the slit width had to be set to $2''$, and the resulting velocity resolution of the spectra is $\sim 90 \text{ km s}^{-1}$.

At ESO, we used the DFOSC focal reducer which permits both direct imaging and slit spectroscopy. After a 2 min image generally taken in the Bessel R filter for source identification, the spectrum was obtained through grism #8 which provides a range of 5800 to $8400 \text{ \AA}$ and a dispersion of $1.2 \text{ \AA pixel}^{-1}$ on the detector, a 2148×4096 EEV/MAT CCD with $15 \text{ }\mu\text{m}$ pixels (half of the CCD area is not used due to the reducer design). The slit width was $1.5''$ and the velocity resolution $\sim 120 \text{ km s}^{-1}$.

Table 1. Journal of observations.

Run # and dates	Site	# of observed objects
1 2001 Mar. 26–Mar. 30	OHP	2, 3, 5 to 10, 14
2 2001 Mar. 31–Apr. 01	ESO	4, 7, 11, 12, 13
3 2001 Sep. 09–Sep. 13	ESO	1, 16, 17, 19, 22 to 28
4 2001 Oct. 17–Oct. 22	OHP	15
5 2002 Feb. 14–Feb. 18	OHP	no observations (clouds)
6 2002 Aug. 29–Sep. 03	ESO	17, 18, 20, 21, 29, 30

4. Results

In our list of ~200 best candidates, slit spectroscopy has so far been secured for 97 of them: 30 were found to be C stars, including one that is member of the Fornax dwarf galaxy (#30) and one located in the direction of the Sculptor dwarf galaxy (#29) (see Table 2). The 67 other objects (not C stars) were found to be mainly M-type giants and will be the subject of future work.

The last two objects (#29 and #30) were under consideration as interesting comparison objects. No radial velocity could be determined by us for #29, and its membership to Sculptor needs further observations to be proven. This object is considerably redder ($J - K_s = 3.3$) than the other C stars known in Sculptor (Azzopardi et al. 1985; Aaronson & Olszewski 1987) for which $J - K_s$ is between 0.8 and 1.12. It appears very faint in the R -band POSS-II image, is invisible on blue plates, but is well seen in the I -band UKST digitized image. Concerning Object #30, this star was already noted by Demers et al. (2002) as a probable Fornax carbon star based on its 2MASS near-infrared magnitudes and colors: our spectrum confirms its carbon nature and proves its membership through radial velocity determination.

All of the C stars found have $K_s < 12.3$, with the exception of the Fornax C star at $K_s = 12.68$. We also observed a small supplementary list of 9 faint ($13 < K_s < 14$) objects, none of which were found to be C stars. The JHK_s colour-colour diagram of the observed targets is shown in Fig. 1 (right panel). During our survey, we also found ten L-type dwarfs, all with $12 < K_s < 14$, including seven which were not previously known (the three known cases had escaped our attention in the selection process). The discovery of these new L-dwarfs is reported in Kendall et al. (2003), and in the following, we focus on the new C stars and their properties.

4.1. General properties of the sample

Table 2 lists the 30 C stars found, their coordinates and some photometric data. Finding charts are not presented here, because all stars are NIR bright and very red, and can be identified unambiguously in the 2MASS survey images, and also in the POSS, ESO or UKST digitized images (note that the very red Object #29 is clearly visible only in the IV-N SERC-I digitized plate).

Here we shall ignore the last two C stars (#29 and #30) which are in the Fornax and Sculptor galaxies respectively. It can be seen that of the 28 remaining objects, 22 have been

found at $|b| > 30^\circ$. One star, #5, was erroneously rediscovered and was known as FBS 1056+399 or APM 1056+4000 (Gigoyan et al. 2001, TI98). Its 7500–8000 Å spectrum is in Gigoyan et al. (2001), and a 5700–6600 Å spectrum has been obtained here: it shows H α in emission and this new spectrum was used to derive an independent radial velocity measurement which is in very good agreement with that of Gigoyan et al. (2001).

In Table 2, the columns B and R , and corresponding $B - R$ index are from the USNO A2.0 catalogue, except for 8 objects which are not present in this catalogue, in which case the data from USNO-B1.0 are given (see the Notes of Table 2 for details). These B and R magnitudes provide only approximate optical photometry with probable errors of ~0.4 mag, and should also be considered with caution since many objects are clearly variable, and objects at $|b| < 30^\circ$ may also suffer some interstellar absorption (see below). However it is interesting to note that the magnitude range in R is between 10.5 and 19.8, and the median in R is 14.7. For comparison, the carbon stars of the APM survey (see Table 3 of TI98, with 41 stars labelled “APM”) have an R range 10.0–18.0 and a median of 13.6 mag. The median of our sample 14.7 corresponds to a distance of ~44 kpc if one adopts the absolute magnitude of $M_R = -3.5$ considered by TI98, and if no circumstellar or interstellar absorption in the red (A_R) is assumed (if $A_R = 1$ mag, one finds 27 kpc).

The columns $J, H, K_s, J - K_s$ are from the 2MASS Second Incremental release. The typical errors on this photometry are ~0.03 mag or better. All C stars of our sample have $J - K_s > 1.3$, which is largely due to our selection criteria excluding objects with $J - H < 0.95$ and $H - K_s < 0.4$. Therefore, they are distinctly redder in $J - K_s$ than most of the numerous warm C stars of the Hamburg-ESO survey. The colour-colour diagram of Fig. 1 also shows that no candidate redder than $J - K_s \sim 3.4$ was observed, essentially because C stars or candidates redder than this are very rare at high b .

4.2. Spectra

For clarity of the text, the atlas of all the spectra is shown in Appendix A. A detailed study of these spectra will be performed in a future paper, and only a few remarks will be made here.

First, all ESO spectra display a strong rising flux between 6000 and 7800 Å with a flux ratio of about 2 to 15. The OHP spectra have a too small domain to be considered similarly. This slope is clearly larger for our objects than for the warmer giant or dwarf SLOAN C stars shown by Margon et al. (2002), for which the 6000–7800 Å flux distribution is nearly flat. The cool APM stars and the two N-type C stars SDSS J144631.1–005500 and SDSS J122740.0–002751 (previously known as APM 1225–0011) shown in Margon et al. have spectra very similar with ours.

One notes also that H α is in emission in 13 of our 28 halo objects, i.e., 46%. This fraction is higher but comparable to the result of Maizels & Morris (1990) who surveyed 37 galactic “bright C stars” (presumably of AGB type, but no details

Table 2. List of discovered faint cool halo carbon stars. Coordinates α and δ (J2000) are given in the object names (2MASS Jhhmmss.ss $\pm$ ddmss.s). l , b are in degrees. B & R in mag are from USNO-A2.0 (± 0.4 mag approximatively), except for objects with a Note. JHK_s are from the 2MASS 2nd Incr. Release database (in mag; errors ± 0.02 – 0.03 mag or better).

No.	2MASS name	l	b	B	R	$B - R$	J	H	K_s	$J - K_s$	Notes
01	2MASS J021130.86–034943.8	165.80	–59.86	18.5	14.9	3.6	12.034	11.007	10.449	1.585	
02	2MASS J091331.86+193422.6	209.31	+39.79	16.9	11.5	5.4	9.043	7.953	7.363	1.680	
03	2MASS J091505.20+191737.8	209.81	+40.04	16.8	12.6	4.2	10.203	9.186	8.476	1.727	
04	2MASS J101525.93–020431.8	244.49	+42.43	20.9	16.3	4.6	14.045	12.861	11.987	2.058	(1)
05	2MASS J105923.83+394405.6	177.25	+63.60	16.9	13.3	3.6	11.082	10.080	9.442	1.640	
06	2MASS J110959.68–212201.1	273.53	+35.65	14.2	10.5	3.7	8.390	7.482	7.001	1.389	
07	2MASS J111719.00–172915.3	273.18	+39.88	19.4	16.5	2.9	13.464	12.403	11.632	1.832	
08	2MASS J120925.02+151618.4	261.33	+74.64	17.8	14.2	3.6	11.185	10.277	9.822	1.363	
09	2MASS J124904.76+132035.5	300.53	+76.20	19.3	14.5	4.8	12.606	11.604	11.136	1.470	
10	2MASS J135602.37–013626.2	333.93	+57.32	19.4	15.5	3.9	12.915	11.860	11.327	1.588	
11	2MASS J135920.63–302339.4	319.88	+30.23	–	19.8	–	14.577	13.072	11.798	2.779	(2)
12	2MASS J150106.92–053138.7	351.63	+44.74	20.4	16.8	3.6	13.571	12.348	11.506	2.065	(3)
13	2MASS J151511.06–133227.9	348.10	+36.43	18.7	17.1	1.6	12.594	11.516	10.785	1.809	(4)
14	2MASS J155842.22+185246.8	32.33	+46.37	17.5	14.6	2.9	12.269	11.387	10.966	1.303	
15	2MASS J172825.76+700829.9	100.83	+32.41	18.1	13.9	4.2	11.551	10.111	9.048	2.503	
16	2MASS J194219.01–351937.6	4.40	–25.06	18.6	16.7	1.9	12.633	11.142	10.068	2.565	
17	2MASS J194221.31–321104.1	7.70	–24.13	19.0	14.7	4.3	11.967	10.817	9.981	1.986	
18	2MASS J194850.65–305831.9	9.43	–25.08	–	17.7	–	12.998	11.215	9.862	3.136	(5)
19	2MASS J195330.17–383559.4	1.52	–28.07	19.2	13.9	5.3	11.292	10.088	9.244	2.048	
20	2MASS J201319.43–234144.2	19.07	–27.92	14.4	11.7	2.7	9.541	8.591	8.109	1.432	
21	2MASS J202027.66–144927.1	29.05	–26.26	19.4	14.7	3.7	11.849	10.162	8.711	3.138	(6)
22	2MASS J205454.55–282856.7	16.76	–38.23	18.6	14.3	4.3	12.407	11.451	10.858	1.549	
23	2MASS J220514.59+000846.0	60.31	–41.67	18.1	14.3	3.8	10.709	9.503	8.714	1.995	
24	2MASS J220653.66–250628.2	26.55	–53.17	18.0	15.1	2.9	10.934	9.756	8.922	2.012	
25	2MASS J221709.92–260703.3	25.64	–55.64	18.4	15.4	3.0	11.056	9.823	8.882	2.174	
26	2MASS J231721.08–241142.4	35.54	–68.63	17.8	15.5	2.3	13.750	12.750	12.280	1.470	
27	2MASS J231935.53–185623.7	49.28	–67.38	17.5	14.8	2.7	11.477	10.473	9.958	1.519	
28	2MASS J232531.39–301056.0	18.64	–70.94	18.4	14.6	3.8	13.409	12.028	11.029	2.380	
Two carbon stars in the direction of Sculptor (#29) and in Fornax (#30)											
29	2MASS J005953.68–333830.7	287.82	–83.24	–	20.2	–	14.877	13.144	11.591	3.286	(7)
30	2MASS J024103.55–344805.3	237.84	–65.37	23.3	18.3	5.0	14.445	13.397	12.682	1.763	(8)

Notes:

- (1) B and R are B_2 and R_2 from USNOC-B1.0 in which $R_1 = 18.5$; in the APM catalogue, one finds $R = 18.3$ and no data for B .
- (2) R is R_2 from USNOC-B1.0 in which no other data in R or B are given; in APM, $R = 20.25$ and no data in B .
- (3) B and R are B_2 and R_2 from USNOC-B1.0 in which $R_1 = 16.0$; in APM, the object is blended with neighbours.
- (4) B and R are B_2 and R_2 from USNOC-B1.0 in which $R_1 = 16.7$; in APM, $R = 17.1$ $B = 18.35$.
- (5) R is R_2 from USNOC-B1.0 in which $R_1 = 15.8$ but no data in B is given; in APM, $R = 18.2$ and no data in B .
- (6) B and R are B_2 and R_2 from USNOC-B1.0 in which $R_1 = 16.2$; no data in the APM catalogue for this position ($|b|$ is too low).
- (7) R is R_2 from USNOC-B1.0 in which no other data in R or B are given; in APM, $R = 20.3$ and no data in B ; membership to Sculptor requires supplementary observations and radial velocity determination.
- (8) B and R are B_2 and R_2 from USNOC-B1.0 in which $R_1 = 16.9$; in APM, $R = 18.3$ and no data in B ; this star was previously identified as probable C star by Demers et al. (2002) on the basis of its near-infrared photometry (#25 in their Table 1).

are given on the observed stars or their selection method) and found $H\alpha$ emission in 14 of them (38%). In the APM survey, examination of the spectra in Fig. 5 of TI98 indicates that 6 of 20 N-type stars have $H\alpha$ emission (30%), and 1 of 8 CH-type stars (12%). In contrast, among Margon et al.’s warm C stars, 5 out of 39 have $H\alpha$ emission (13%). Therefore the high fraction of $H\alpha$ emission in our sample and the above comparisons suggest that most of our stars are pulsating AGB stars (with a shock wave being the cause of the $H\alpha$ emission).

4.3. Radial velocities

During each run, we observed several times a small number of template carbon stars with known radial velocities (see Table 3). In the following, we shall call these stars “radial velocity standard”, although, for several reasons, they cannot be considered as classical standard stars with stable and accurately established velocities. Firstly, it is well known that the photospheric radial velocity of cool carbon stars may vary with

Table 3. Heliocentric radial velocities for template carbon stars. In columns labelled Run 1, Run 2, ..., Run 6 are listed the best fitted radial velocities determined for each run, v_{fit} , in km s^{-1} . The column v_{pub} is the value taken from the literature and adopted as a first approximation for the fits (see text and Notes). The column $< v_{\text{fit}} - v_{\text{pub}} >$ gives the average difference over the runs (in km s^{-1}).

Star	Run 1	Run 2	Run 3	Run 4	Run 6	v_{pub}	$< v_{\text{fit}} - v_{\text{pub}} >$	Note on v_{pub}
TW Oph	+21	+28	+10			+14	+6	(1)
APM 1406+0520	-25	-37				-21	-10	(2)
HR 3541 = X Cnc	-4					-3	-1	(3)
APM 0915-0327		+95				+79	+16	(2)
APM 0123+1233			-324			-302	-22	(2)
APM 0418+0122			+19	+27		+33	-10	(2)
APM 2225-1401			-103		-118	-113	+3	(2)
APM 0222-1337			-7		-24	-27	+11	(2)
RV Aqr			+6	-4		-10	+11	(2)
HD 16115			-6		+11	+4	-1	(4)
APM 2213-0017					-49	-44	-5	(2)
APM 2111+0010					-195	-208	+13	(2)

Notes:

- (1) v_{pub} is from the SIMBAD database; from the CO millimeter observations listed by Loup et al. (1993), a center of mass heliocentric velocity of $+15 \text{ km s}^{-1}$ is derived and is in very good agreement;
- (2) v_{pub} are from TI98; quoted uncertainties are $\leq 7 \text{ km s}^{-1}$;
- (3) TI98 indicate $v_{\text{pub}} = -1 \text{ km s}^{-1}$ with $\sigma = 12 \text{ km s}^{-1}$ (2 measurements); from the data in Loup et al. catalogue, one derives -6 km s^{-1} (heliocentric), and $v_{\text{pub}} = -3 \text{ km s}^{-1}$ was adopted;
- (4) we adopted $v_{\text{pub}} = +4 \text{ km s}^{-1}$ from TI98, who give $\sigma = 1 \text{ km s}^{-1}$ (3 measurements), but $v = +16 \pm 5 \text{ km s}^{-1}$ is given in SIMBAD.

amplitudes of the order of $\sim 10 \text{ km s}^{-1}$. Secondly, the number of independent radial velocities available in the literature for a given star is often small. Thirdly, the literature values are occasionally very discrepant: for example, in Table 4 of TI98, it is found that APM 0102-0556 & APM 0911+3341 have published values differing by as much as 50 km s^{-1} .

Therefore, the published radial velocities of these standards have been considered as a first approximation. For each run considered separately, we have cross-correlated the spectra of each standard with all the other standards observed during the run, and determined best fit radial velocities by minimizing the differences between our data and the published values. The results, listed in Table 3, appear fairly consistent, especially when comparing the velocities of the standards common to several runs and taking into account the velocity resolution of our experiments. The global rms scatter (1σ) of the residuals between fitted and published values is 12 km s^{-1} .

Then, the spectrum of each program carbon star was correlated with the spectra of the standards observed for the same run, and the velocities so obtained were averaged (details on the cross-correlation technique can be found in, e.g., TI98). In addition to the internal consistency provided by the standards, a further check is provided by two objects that were observed during two runs: for Object #7, we found $v_{\text{helio}} = +339$ and $+345 \text{ km s}^{-1}$ from Run 1 and 2 respectively; for Object #17, we found $v_{\text{helio}} = +135$ and $+127 \text{ km s}^{-1}$ from Run 2 and 6, respectively. A final independent check on our velocity scale is provided by Object #29 in Fornax, for which we find $v_{\text{helio}} = +40 \text{ km s}^{-1}$, in fair agreement with the mean velocity of this galaxy $v_{\text{helio}} = +53 \text{ km s}^{-1}$ (van den Bergh 2002),

since the difference of 13 km s^{-1} represents 1.1σ . In conclusion, we estimate that the uncertainty on our radial velocities is $\sim 12 \text{ km s}^{-1}$ (1σ).

4.4. Proper motions

Thanks for the recent release of the USNO-B1.0 catalogue (Monet et al. 2003), information on proper motions is available for all the objects. For 22 objects, the proper motion is found to be null, while for 8 objects, a measurable proper motion is provided. For these 8 objects, details are listed in Table 4, including the time interval between first and last plates on which the objects were detected, and the total motion probability as provided by USNO-B1.0.

We checked whether the objects for which a zero proper motion is given have been correctly observed in the scanned surveys. Because most of the objects are at a declination larger than $\sim -30^\circ$ and bright enough (R in the range 14 to 18), they have been well imaged in the first POSS-I survey: they are generally well detected in red plates and very often also in blue plates of POSS-I, and they are also well detected in subsequent red or near-infrared surveys (POSS-II, SERC, AAO, ESO), ensuring time baselines which are of the order of 30 to 50 years.

4.5. Variability

All objects were examined for variability in available digitized sky surveys with $5'$ size images retrieved from the USNO

Table 4. Data from the USNO-B1.0 database for objects with not null proper motions, where Δt is the epoch interval, N is the number of detections on the scanned plates, and Probab. is the total motion probability.

Object #	$\mu_\alpha \cos \delta$ (mas/yr)	μ_δ (mas/yr)	Δt (yrs)	N	Probab.
10	$+24 \pm 3$	2 ± 3	45	5	0.9
17	-12 ± 10	6 ± 1	35	5	0.7
18	-6 ± 3	-4 ± 0	33	3	0.7
20	-6 ± 3	14 ± 5	38	5	0.8
22	-16 ± 2	0 ± 3	36	4	0.9
24	-8 ± 2	6 ± 4	37	5	0.9
25	-12 ± 2	2 ± 5	41	4	0.9
26	-2 ± 3	8 ± 3	41	5	0.9

web site¹. Practically, we compared by eye the appearance of our C stars with neighbouring stars of similar brightness on these survey images and on our ESO CCD Bessel *R*-band images, when possible. One difficulty in doing so is that the photographic survey plates have been exposed with a variety of emulsions and filters. This complicates the comparison, especially because the C stars are very red and have relatively steep spectra compared to neighbouring field stars. For example, the available red plates for a given field may have the following various emulsions and filters: 103aE + RP2444 (POSS I), IIIaF + RG 610-3 (POSS II), IIIaF + OG590 (AAO-R) or IIIaF + RG 630 (ESO-R). Consequently, when examining these plates, we kept in mind possible band-pass effects and concluded the existence of variability only when the evidence was very strong. For several objects, there are pairs of plates with identical emulsion/filter combinations with exposures taken at quite different dates, in which case variability is much better assessed. In such cases, we noted “var 2r” or “var 2b”, corresponding to a pair of red or blue plates, respectively. In one case (Object #17), two CCD Bessel *R*-band images were obtained during 2 different runs, and differential photometric analysis of the frames very clearly establishes variability, by 0.28 ± 0.02 mag over a period of ~ 1 year.

As can be seen in Table 5, of the 28 FHLC stars in our sample, variability is found for 11 objects. Since our method is sensible to only large variations, it is most probable that a larger fraction of objects is actually variable. The Sculptor C star (#29) is also found to be variable. Concerning the Fornax C star (#30), the evidence for variability was not conclusive from the examined plates, but variability has been proven by the CCD optical imaging survey of Bersier & Wood (2002).

5. Discussion

5.1. Are there dwarf carbon stars in our sample?

One of the major issues is to estimate distances for our C stars, and the main problem is to know whether they are the distant evolved AGB stars which were targeted when defining our

selection criteria, or if some of them are cool dwarf carbon stars with much lower luminosity, as is suggested at first sight by the surprising fact that 8 have measurable proper motions.

Therefore, it is first useful to compare the properties of our sample to the population of dwarf carbon (dC) stars. Lowrance et al. (2003) give an exhaustive list of the 31 dCs presently known and consider their 2MASS *JHK_s* data (from the all sky release). They found that 20 dCs out of a total of 31 are detected by 2MASS, the undetected ones being too faint. Considering the *K_s* magnitude, one finds that the majority (15 dCs over 20 detected) have $K_s > 12$, and the brightest one is at $K_s = 10.48$. As for the $J - K_s$ colour, all have $J - K_s < 1.5$, and only 4 of 20 have $1.3 < J - K_s < 1.45$. In contrast, all our new C stars have $K_s < 12$ with the exception of Object #26 (we ignore #30 in Fornax) and more than half of the objects (17 over 28) are brighter than $K_s = 10.5$; concerning the colour, only 4 of our total of 28 are bluer than $J - K_s = 1.45$. Therefore, when one considers the photometric properties, the sample of our C stars is globally very different from the sample of known dCs.

Concerning the proper motions, we can also compare known dCs and our C star sample. We retrieved the USNO-B1.0 data for the 31 dCs, and plotted them in Fig. 2. For 2 dCs (PG 0824+289B and WIE93 2048-348), USNO-B1.0 gives null proper motions. For the first object, we adopted $\mu_\alpha = -28.2 \pm 1.4$ mas yr⁻¹, $\mu_\delta = 0$ from Heber et al. (1993), and for the second we adopted $\mu_\alpha = 15 \pm 24$ mas yr⁻¹, $\mu_\delta = -3 \pm 24$ mas yr⁻¹ from Warren et al. (1993). More importantly, *there are 7 dCs which lie outside of the diagram*, because their μ_α or μ_δ are larger than 100 mas yr⁻¹ in absolute value. We also plotted the USNO-B1.0 data for our C stars, with 20 lying at the (0, 0) coordinates (null proper motion) and 8 at not null proper motion. It can be seen that all dCs known have a larger μ than all our C stars except #10. If these C stars were in majority dCs, one would expect larger proper motions, since they are in majority brighter than the known ones and would be statistically closer to us.

In a complementary way, instead of a statistical approach, one can examine in detail the 8 objects with measurable USNO-B1.0 proper motion. Three (#10, #22 and #26) have $J - K_s \sim 1.5$ and K_s in the range 10.8 to 12.3. These parameters are not atypical of dCs (see above) although marginally so. A very rough estimate of their distances is possible. Following Lowrance et al. (2003; their Table 1, footnote), only three carbon dwarfs have determined parallaxes from which one derives $M_{K_s} \approx 6.3 \pm 0.3$. Although those dCs are warm and have $J - K_s \approx 0.95$ within 0.05 mag, let us adopt this luminosity for the moderately cooler Objects #10, #22 and #26; thus, we obtain distances of 100, 80 and 160 pc. Then, their proper motions (24, 16 and 8 mas yr⁻¹) imply transverse velocities of 11, 6 and 6 km s⁻¹ which, when compared to radial velocities of +43, +56 and -4 km s⁻¹, seem plausible. These data are marginally compatible with expected usual disk dCs kinematics, but one has to note that none of these 3 stars show the strong NaI lines or the C₂ λ 6192 bandhead, as seen in some cool dCs (Green et al. 1992).

If one similarly considers Objects #17, #18 and #20, they are either significantly brighter and/or redder than most known dCs ($J - K_s = 1.99, 3.14$ and 1.43 and $K_s = 9.98, 9.86$

¹ www.nofs.navy.mil/data/fchpix

Table 5. Properties of the halo carbon stars. Quantities l , b , R , K_s , $J - K_s$ are repeated from Table 2 for information. Variability derived from examination of various plate surveys is indicated by “var” (see text). “H α ” means H α in emission. μ is the USNO-B1.0 proper motion in mas yr $^{-1}$. A_R is the adopted R -band galactic extinction as given by Schlegel et al. maps, in mag. M_{K_s} is the adopted K_s -band absolute magnitude (see text). The distances d_R and d_K are in kpc. g_{A-type}^* is the Sloan g mag of an imaginary “A-type” population with $M_g = 1.0$ if it was at the distance d_K from the Sun; g_{A-type}^* is used to evaluate the membership of the sample C star to the Sgr stream. This membership is given in the last column by *yes* or *no* (see text). For objects #29 and #30, M_{K_s} and distances based on Sgr C stars templates are provided here only for information (see text).

No.	l	b	R	K_s	$J - K_s$	var	H α	μ	v_{helio}	A_R	M_{K_s}	d_R	d_K	g_{A-type}^*	Sgr ?
01	165.80	-59.86	14.9	10.449	1.585			0	-104	0.06	-7.35	39	36	18.8	yes :
02	209.31	+39.79	11.5	7.363	1.680		H α	0	-46	0.12	-7.45	8	9	15.8	no
03	209.81	+40.04	12.6	8.476	1.727		H α	0	-14	0.11	-7.50	13	16	17.0	no
04	244.49	+42.43	16.3	11.987	2.058	var		0	+202	0.09	-7.55	73	81	20.4	no
05	177.25	+63.60	13.3	9.442	1.640		H α	0	-162	0.04	-7.40	19	23	17.8	no :
06	273.53	+35.65	10.5	7.001	1.389		H α	0	+124	0.11	-7.05	5	6	14.9	no
07	273.18	+39.88	16.5	11.632	1.832	var 2b	H α	0	+342	0.12	-7.60	79	71	20.3	no
08	261.33	+74.64	14.2	9.822	1.363		H α	0	-27	0.09	-7.00	28	23	17.8	yes
09	300.53	+76.20	14.5	11.136	1.470			0	-22	0.08	-7.15	32	45	19.3	yes
10	333.93	+57.32	15.5	11.327	1.588	var 2r		24	+43	0.14	-7.35	49	54	19.7	yes
11	319.88	+30.23	19.8	11.798	2.779	var		0	+145	0.13	-7.30	-	66	20.1	no
12	351.63	+44.74	16.8	11.506	2.065			0	+85	0.22	-7.60	86	65	20.1	yes
13	348.10	+36.43	17.1	10.785	1.809		H α	0	+108	0.23	-7.60	99	47	19.4	yes
14	32.33	+46.37	14.6	10.966	1.303			0	+68	0.11	-6.75	33	35	18.7	no
15	100.83	+32.41	13.9	9.048	2.503			0	+158	0.10	-7.35	24	19	17.4	no
16	4.40	-25.06	16.7	10.068	2.565	var	H α	0	+135	0.71	-7.35	66	29	18.4	yes
17	7.70	-24.13	14.7	9.981	1.986	var 2r	H α	13	+129	0.38	-7.65	30	33	18.6	yes
18	9.43	-25.08	17.7	9.862	3.136			7	+132	0.46	-7.15	117	25	18.0	yes
19	1.52	-28.07	13.9	9.244	2.048	var 2r	H α	0	+165	0.21	-7.60	23	23	17.8	yes
20	19.07	-27.92	11.7	8.109	1.432			15	-177	0.36	-7.00	8	10	16.0	no :
21	29.05	-26.26	14.7	8.711	3.138			0	+55	0.21	-7.10	33	14	16.7	no
22	16.76	-38.23	14.3	10.858	1.549	var		16	+56	0.28	-7.25	27	41	19.1	yes
23	60.31	-41.67	14.3	8.714	1.995	var		0	-34	0.19	-7.60	28	18	17.3	no
24	26.55	-53.17	15.1	8.922	2.012		H α	10	+9	0.10	-7.55	42	20	17.5	yes
25	25.64	-55.64	15.4	8.882	2.174		H α	12	+9	0.06	-7.50	48	19	17.4	yes
26	35.54	-68.63	15.5	12.280	1.470	var 2r	H α	8	-4	0.07	-7.15	51	78	20.5	yes :
27	49.28	-67.38	14.8	9.958	1.519	var 2r		0	-27	0.08	-7.25	37	27	18.2	no :
28	18.64	-70.94	14.6	11.029	2.380			0	+94	0.05	-7.40	34	48	19.4	yes
29	287.82	-83.24	20.1	11.591	3.286	var		0	-	0.05	-6.90	-	50	-	Scu
30	237.84	-65.37	18.3	12.682	1.763	var		0	+40	0.06	-7.55	185	112	-	For

and 8.11 for these 3 objects respectively). Adopting again $M_{K_s} \approx 6.3$ leads to distance of 55, 52 and 23 pc, and to transverse velocities of 3.4, 1.7 and 1.6 km s $^{-1}$. The latter are found to be much too small compared to the radial velocities of +129, +132 and -177 km s $^{-1}$, a situation which is very improbable. This casts some doubt on the reliability of their proper motions, which are not large (13, 7 and 15 mas yr $^{-1}$) and have a probability of only 0.7–0.8. One could argue that the M_{K_s} value of 6.3 adopted above might be in error, but if cooler C dwarfs (redder in $J - K_s$) have lower luminosity as for M-type dwarfs, distances and transverse velocities would be found even smaller, worsening the case for dCs. One could also think to simply adjust the distance of these objects in such a way that transverse and radial velocities be roughly equal. This is obtained

by boosting the distances by a factor of ~ 50 , corresponding to $M_{K_s} \sim -1.2$: this luminosity is typically that of clump giants (Knapp et al. 2001), but this solution has to be rejected because the $J - K_s$ colours of our 3 objects (>1.4) are much too red to be R-type clump giants (see Table 1 of Knapp et al. 2001, and Ivanov & Borissova 2002)

Finally the two remaining objects # 24 and #25 form an astonishing pair of close twin objects, with all their parameters being almost equal: $J - K_s = 2.01$ and 2.18, $K_s = 8.92$ and 8.88, $R = 15.1$ and 15.4, $B - R = 2.9$ and 3.0, $v_{helio} = +9$ and $+9$ km s $^{-1}$. In addition, their angular separation in the sky is as low as 2.5°. These stars are exactly the kind of kinematically and spatially coherent objects which are tracers of halo streams! With these characteristics, especially the K_s

magnitude and the colours, it is extremely improbable that they are dCs, despite their proper motion ($\mu \approx 11 \text{ mas yr}^{-1}$ with a probability of 0.9 and $>3\sigma$ significance).

The above remarks, together with consideration of H α emission and/or variability being seen in 6 of the 8 objects with non zero μ , lead us to have some doubts on these μ measurements. These proper motions are quite small ($<25 \text{ mas yr}^{-1}$) and supplementary, independent measurements of μ are obviously needed to confirm them. We defer to a future work a deeper investigation of the question whether distant, very red, possibly variable stars might have inaccurate μ measurements in USNO-B1.0.

We tentatively conclude that our sample does not contain C dwarfs. Our stars are also too red in $J - K_s$ to be clump giants or stars on the first ascending giant branch like the Hamburg/ESO objects. Therefore, in the following sections, we shall adopt the view that all our stars are genuine distant AGB C stars, and examine their location with respect to the Sgr stream.

5.2. Distances

In order to estimate distances, we have assumed here that our C stars are similar to AGB C stars located in the Sagittarius dwarf galaxy. This working hypothesis can certainly be criticized, but it is suggested by the fact that half of the high latitude cool C stars previously known belong to the tidal debris of this dwarf galaxy (Ibata et al. 2001a; see also Sect. 1). Therefore, we adopt the AGB C stars of the Sgr galaxy as templates, and analyse their properties below to determine absolute magnitudes.

A first estimate of distances can be based on R -band magnitudes. Whitelock et al. (1999) published a list of 26 spectroscopically confirmed C stars in Sgr with membership established on the basis of radial velocities. For all of them, we retrieved the 2MASS data together with the USNO-A2.0 B and R magnitudes. These 26 R magnitudes range from 13.0 to 16.7, with an average of 14.4. An estimate of the extinction to each star was obtained from the Schlegel et al. (1998) tables, and the extinctions in the R band, called A_R , range from 0.23 to 0.48 mag. Then the mean absolute magnitude in R can be obtained. For this purpose, we adopt for Sgr a distance modulus $(m - M)_0 = 17.0$, which is intermediate between the value of 16.9 taken by Majewski et al. (2003) and 17.18 considered by Whitelock et al. (1999). If one outlier star (the faintest in R) is excluded, one finds for the C stars of Sgr $M_R = -3.1$ with 25 objects, $\sigma = 0.64$ (if all 26 stars are considered $M_R = -3.0$ and $\sigma = 0.79$). It can be noted that our $M_R = -3.1$ is 0.4 mag less luminous than $M_R = -3.5$ adopted by Totten & Irwin (1998), and this last value would have implied distances 20% larger.

For each halo C star, extinction in the R band was again found from the Schlegel et al. maps, and distances derived with $M_R = -3.1$ called d_R are listed in Table 5. These distances are admittedly very crude, due to the low accuracy of USNO photometry (~ 0.5 mag error), possible variability, uncertainty in M_R , and especially the effect of circumstellar dust

for the reddest stars with $J - K_s$ larger than ~ 2.0 . For information, Table 5 indicates the result of this distance scale for the Fornax C star (#30), which is not too red in $J - K_s$. No R is available in USNO-A2.0, but two R magnitudes are given in USNO B1.0: with $R_2 = 18.2$, one finds 180 kpc, while for $R_1 = 16.9$, one finds 96 kpc. These estimates are within 30% of the true distance, 135 kpc. In conclusion, the distances derived with R magnitudes, called d_R and listed in Table 5, are probably not better than $\sim 30\%$ in relative accuracy.

A second and probably surer estimate of distances is obtainable with 2MASS photometry. Considering again the 26 Sgr C stars of Whitelock et al. (1999) which all have 2MASS data, we compared their K_s magnitudes to the averaged K_s magnitudes of LMC C stars, this averaging being done over several different bins in $J - K_s$. The Sgr and LMC have similar mean reddening, $E(B - V) \sim 0.15$, which can be ignored in this comparison. We find that, for a given $J - K_s$, the C stars are fainter in *apparent* K_s magnitudes in Sgr than in LMC by an average of 0.98 mag (26 objects, $\sigma = 0.41$). By adopting $(m - M)_0 = 18.5$ and 17.0 for LMC and Sgr respectively, it is derived that, on average, the C stars of Sgr are less luminous by 0.50 mag in the K_s band than the C stars in the LMC. (this shift increases to 0.67 mag if one adopts, as Majewski et al. (2003), distance moduli of 18.55 and 16.9 for LMC and Sgr, and is roughly consistent with their Fig. 20 where *candidate* Sgr C stars are compared to *candidate* LMC C stars mean locus.)

We then used for template K_s -band luminosity the averaged K_s magnitudes of the LMC C stars corrected by the above 0.50 mag. In Table 5 are explicitly listed the adopted M_{K_s} for each program star, and the inferred distances called d_K . These distances based on JK_s are presumably more accurate than those based on R magnitudes, because of better photometric quality, smaller amplitude in K due to variability and reduced sensitivity to dust effects. However, for a given $J - K_s$, the scatter in K_s for LMC C stars is of the order of 0.4 to 0.5 mag (1σ). Although part of this dispersion is due to LMC depth and inclination effects that fairly cancel out when an average is taken, a natural dispersion ~ 0.2 – 0.3 mag is probably present in the LMC C stars' K_s luminosities (Weinberg & Nikolaev 2001). Taking into account possible variability effects for our stars (maybe ± 0.2 mag in K_s) and the uncertainty on the C stars luminosity shift between LMC and Sgr, one finds that the distances of our program stars derived from JK_s data are probably not better than ± 25 percent ($\pm 1\sigma$).

Looking at Table 5, it can be seen that distances derived from R and from near-infrared are often in fair agreement. There are a number of cases where d_R is obviously too large compared to d_K because the star is particularly red and is presumably embedded in dust: for stars #13 #16 #18 #21 #24 and #25, the ratio d_R/d_K is larger than a factor of 2 and their $J - K_s$ colours are 1.81, 2.56, 3.14, 3.14, 2.012 and 2.174, respectively. For object #11, no value of d_R is given because $R = 19.8$ would lead to an exceedingly large distance (360 kpc): its $d_K = 66$ kpc is clearly more plausible.

In the case of #29 (in Sculptor) and #30 (in Fornax), the scale adopted above is not necessarily applicable, but remains interesting to consider. It leads to distances d_K of 50 kpc

and 112 kpc, which are 0.57 and 0.83 times smaller than the generally adopted distances of Sculptor and Fornax, ~ 87 and 135 kpc, respectively. While d_K for #30 is acceptable, the small value of d_K for #29 suggests that our rule for NIR distances based on Sgr templates underestimates the K -band luminosity of this star by ~ 1.2 mag. Its membership to Sculptor remains to be definitively established through a radial velocity determination that our spectrum unfortunately could not provide. If it actually is member, its M_{Ks} is -8.11 , which is similar to the most luminous C stars in LMC for the same $J-K_s$ colour: in LMC with $(m - M)_0 = 18.5$, we find $\langle M_{Ks} \rangle = -7.42$, $\sigma = 0.53$ for $J - K_s = 3.3$, and the star's M_{Ks} is $+1.3\sigma$ above the mean.

Finally, if we exclude the 7 stars discussed above for which $d_R/d_K > 2$ and the two Sculptor and Fornax objects, one finds that the log ratio $x = \log_{10}(d_R/d_K)$ has a mean of -0.025 and a dispersion of $\sigma_x = 0.108$ ($N = 21$ objects). Adopting d_K as a reference, a discrepancy of 2σ means that R has a typical “error” by ~ 1.1 mag, which seems in reasonable agreement with the fact that USNO photometry is poor and R may also be variable with a comparable amount. In the following, the NIR-based distances d_K will be adopted as the surest estimates, which we recall are based on the Sgr C stars templates.

5.3. Location with respect to the Sagittarius stream

With positions, heliocentric radial velocities and distance estimates in hand, we can examine the likelihood of association of each star with the Sgr stream. Whereas the path in the sky is relatively well known, especially thanks to the recent analysis of Majewski et al. (2003) who employ 2MASS M-type giants as tracers, an accurate determination of the distances and kinematics of this stream and its multiple wrapped components is not yet available. Therefore, we have simply compared here our data with predictions of the model by Ibata et al. (2001a) that already accounts for several observed aspects of the Sgr stream and has a (dark matter) halo density flattening parameter $q_m = 0.9$.

The Fig. 1 of Ibata et al. (2001a) displays in two Aitoff projection maps the colour-coded heliocentric velocities and distances of a Sgr stream simulation. Their distances are coded as the SLOAN apparent g^* magnitudes of A-type stars, for which they adopted $M_{g^*} = 1.0$ (these A stars are a mixture of blue horizontal branch and blue stragglers; see Ibata et al. 2001b for more details). Using this absolute magnitude and the NIR distances of Table 5, we derived a corresponding g_{A-type}^* for each of our program stars. This g_{A-type}^* is the apparent magnitude of an imaginary A-type population if it were present at the distance of the C star. We then compared for each star α , δ , v_{helio} and g_{A-type}^* with those of the model stream in Fig. 1 of Ibata et al. (2001a). This comparison, and therefore establishing the membership to the stream, is difficult for several objects, especially when i) uncertainties on distance or, equivalently, on g_{A-type}^* are taken into account; and/or ii) the object is located in a region where the model stream presents a relatively low density of particles (in the α , δ , v_{helio} and g_{A-type}^* space). As a check, we also used the more recent work of

Martinez-Delgado et al. (2004) by considering their diagrams showing δ , v_{helio} , and d as a function of α . Our final best estimates for membership are indicated in Table 5 by “yes” or “no”, with a “.” sign for particularly uncertain cases.

The result is that of the 28 FHLC found in this survey, 15 are found in the Sgr Stream, as indicated by “yes” in Table 5. It is also found that several distant C stars are not in the Sgr Stream, like #4, #7 and #11. Finding about half of our sample in the Sgr stream is comparable to the results of Ibata et al. (2001b) based on the APM and previously known C stars. The same fraction is derived if only objects with $|b| > 30^\circ$ are considered. Figure 3 shows indeed that our stars are not randomly distributed in the high latitude caps, with for example no case at $\delta < -40$ degrees.

An interesting question is whether calculating distances of these high latitude C stars with the 0.5-mag more luminous LMC C star templates (instead of the Sgr C templates that we assumed here) would change the number of stars found in the Stream. The exercise described above provided us with a weak indication that a smaller number of stars would be found to be Stream members. But this question should advantageously be reconsidered with a larger sample, e.g. at least all presently known distant FHLC stars, and not only the new objects presented here. Settling this question properly, i.e. by taking into account quantitatively and statistically the various experimental and model errors, is beyond the goal of this paper.

Our spectroscopic survey is not yet complete and only involved candidates originating from the 2MASS 2nd Incremental Release which covers $\sim$ half of the sky (see e.g. Ibata et al. 2002), so that only supplementary observations will permit a complete census and a more detailed view of the spatial location of these near-infrared selected AGB C stars in the halo.

6. Summary and concluding remarks

In this work, we have described the first results of a survey for discovering new cool C stars in the high latitude sky. The survey is based on the exploitation of the 2MASS catalogue in its Second Incremental release. Candidates were first selected by requiring their $J - H$, $H - K_s$ colours to be similar to those of already known N-type C stars in the halo, and further examined by sample cleaning, e.g. through appearance on the POSS plates and presence in existing catalogues of galactic and extragalactic objects. This selection process gave us a list of ~ 200 best candidates, and for about half of them spectroscopy could be secured at ESO and OHP. We found 28 cool halo C stars: 27 objects are new; one was rediscovered erroneously (FBS 1056+399). In addition, we also found one new C star in Fornax, and one in Sculptor.

The spectra of these C stars show in half of the cases $H\alpha$ in emission. Also, about $2/3$ of our objects could be observed between 6000 and 7000 Å (at ESO), and for all of them, the spectral energy distribution is clearly rising toward the red. These properties suggest that we are finding, at least in a large proportion, C stars with a N-type classification, i.e. *luminous pulsating* AGB objects.

Fig. 3. Aitoff map showing the location of objects in the sky. The dashed line is a great circle with pole at galactic coordinates $l = 274^\circ$, $b = -14^\circ$. (Majewski et al. 2003) and this very schematically represents the Sgr orbit (see Fig. 8 of Ibata et al. 2001b for a much more detailed view). All halo C stars have been labelled with their ranks as in Table 2. The last two objects (#29 and #30) in the direction of Sculptor and in Fornax are the small squares with labels S and F, respectively, seen at lower right of the map.

Radial velocities could be determined by cross-correlation with templates observed with the same instrumentation, yielding velocities accurate to $\sim 12 \text{ km s}^{-1}$ (1σ).

A surprising fact was to find that 8 of these presumably N-type distant stars had small but measurable proper motion measurements in the recent USNO B1.0 catalogue. After analysing the properties of our sample, with either a statistical approach or through consideration of individual objects, we came to the conclusion that these proper motion measurements are very intriguing and that the studied objects are much more probably true distant AGB stars than close dCs with unusual brightnesses, colours and kinematics. Yet, this point clearly deserves further study.

Under the assumption of AGB type for the totality of our sample, the analysis of photometric data have allowed us to estimate distances in the range 10 to 80 kpc from the Sun, the distance scale being based on the 26 Sgr C stars of Whitelock et al. (1999). Then, consideration of position and radial velocities resulted in ultimately finding about half of our sample in the Sagittarius stream.

In the future, it would be extremely valuable to monitor all these stars in the NIR, as has been achieved by Feast, Whitelock and collaborators for various galactic or Local Group AGB samples (e.g. Whitelock et al. 2003 and refs. therein). This would permit the AGB classification of variable objects to be ascertained, and to infer very accurate distances for most objects by using the period-luminosity relation.

Our survey is also far from complete: only half of our 200 best candidates were confirmed spectroscopically, and the 2MASS 2nd Incremental Release which we utilised only covers about half of the sky at $|b|$ larger than $\sim 25^\circ$, and we found 27 new halo C stars. It will be interesting to see if, with the same criteria, an additional ~ 80 of these cool objects can still be discovered despite the continuing succession of systematic surveys. Enlarging the sample of distant C stars may help to further clarify the characteristics the Sgr stream, but also to gain a clearer view of the “background” C stars population (not in Sgr stream) and its origin. It will also be a challenge to search for cases at fainter magnitudes and/or lower galactic latitudes. Exploring the invaluable 2MASS database for these luminous tracers will increase our knowledge on the halo properties, its stellar populations and the merging history of our Galaxy.

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Online Material

Appendix A: Spectra

Spectra obtained at ESO have a domain of 5800–8400 Å, and those made at OHP have a domain of 5700–6600 Å. The ordinates are fluxes in $\text{erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$, after dividing these fluxes by convenient factors given in the captions. Photometric calibration was achieved with at least one spectrophotometric standard star observed for each run. No correction was made for atmospheric extinction or slit losses. The absolute scale of these fluxes is therefore of poor accuracy, $\sim$ a factor of 2 (note also that probably all objects are variable), but the flux scale from wavelength to wavelength was found to be much better ($\sim 20\%$) by comparing spectra of stars observed several times. The strong feature at $\sim 7600 \text{ Å}$ is the O_2 telluric absorption band. Some ESO spectra are affected by imperfect correction of CCD fringes above $\sim 8000 \text{ Å}$.

Fig. A.1. Spectra of objects 01, 04, 07 and 11. In all these graphs, fluxes in ordinates are in $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$. Fluxes were divided by factors 1.5×10^{-14} , 1.4×10^{-15} , 0.9×10^{-14} and 0.6×10^{-15} for objects 01, 04, 07 and 11, respectively.

Fig. A.2. Spectra of objects 12, 13, 16, and 17, for which fluxes were divided by factors 0.23×10^{-14} , 0.4×10^{-14} , 0.47×10^{-14} and 0.35×10^{-14} , respectively.

Fig.A.3. Spectra of objects 18, 19, 20, and 21, for which fluxes were divided by factors 0.22×10^{-15} , 0.30×10^{-14} , 0.60×10^{-13} and 0.27×10^{-14} , respectively.

Fig. A.4. Spectra of objects 22, 23, 24, and 25, for which fluxes were divided by factors 5.5×10^{-15} , 6.5×10^{-15} , 4.5×10^{-14} and 1.1×10^{-14} , respectively.

Fig. A.5. Spectra of objects 26, 27 and 28, for which fluxes were divided by factors 0.32×10^{-14} , 0.23×10^{-13} and 0.45×10^{-14} , respectively.

Fig. A.6. Spectra of objects 29 and 30, for which fluxes were divided by factors 0.55×10^{-15} , 0.40×10^{-15} , respectively.

Fig. A.7. Spectra obtained at OHP of objects 02, 03, 05 and 06, for which fluxes in ordinates in $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$ were divided by factors 4.7×10^{-14} , 0.90×10^{-14} , 0.57×10^{-13} and 0.10×10^{-12} , respectively.

Fig. A.8. Spectra obtained of objects 07, 08, 09 and 10, for which fluxes were divided by factors 0.65×10^{-14} , 1.90×10^{-14} , 0.70×10^{-14} and 1.2×10^{-15} , respectively.

Fig. A.9. Spectra of objects 14 and 15, for which fluxes were divided by factors 1.30×10^{-14} and 0.55×10^{-14} , respectively.