COOL CARBON STARS IN THE GALACTIC HALO

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ABSTRACT

We briefly present an on-going survey to find AGB carbon stars in the halo. The main property of these objects is their high luminosity. In the galactic halo, about 100 such AGB C stars are known, and they are found up to a distance of $\sim$ 150 kpc. The majority, but not all, belong to the tidal stream of the Sgr dwarf galaxy. They will contribute to characterize the stellar population originating from mergers, and they will also be useful to better determine the halo total mass and its dark matter content. How Gaia will see the various types of faint high latitude C stars (AGB, RGB or dwarf type) is briefly examined.

Key words: carbon stars.

1. INTRODUCTION

There is in the Galaxy a large variety of stars with carbon-rich atmospheres. Very schematically, if just their luminosities are considered, carbon (C) stars can be evolving on the asymptotic giant branch (AGB), or they can have luminosities typical of the red giant branch (RGB), or they can have an even lower luminosity and be cool dwarfs (dC) with very low, main sequence luminosities. In fact, there are largely more than 3 types of C stars, and very detailed information can be found in the review of Wallerstein & Knapp (1998).

Faint high latitude carbon stars (FHLCs) have retained attention for a long time. They are typically fainter than R = 13, have $|b|$ larger than $\sim 30^\circ$ and are very rare. Some of them are the CH-type low-metallicity giant C stars with high radial velocities, but others are N-type AGB stars or dwarfs (dCs; see the introduction of Margon et al. (2002) and references therein).

In 1998, Totten & Irwin (1998) listed a compilation of the 48 previously known FHLCs, described in detail the reasons for searching them systematically, and reported the discovery over 6500 deg^2 of 36 new FHLCs. These new cases were primarily selected through their very red B–R colour measured on Schmidt plates and confirmed by spectroscopy. Most of these objects have R <17 and, if proved to be luminous, can probe up to $\sim$ 100 kpc. These objects deserve interest because they are potentially very good indicators of the kinematic structure of the distant halo. Accumulating a number of sources at large distances from the Galactic Centre can contribute to better knowledge of the halo dark matter, its distribution and the total mass of the Galaxy (Wilkinson & Evans 1999; Clewley et al. 2003, 2004). The N-type C stars are understood as coming from intermediate age populations and might originate from a captured satellite dwarf galaxy. With this small sample of $\sim$ 80 FHLC, Ibata et al. (2001) could trace for the first time the Stream of the Sagittarius dwarf galaxy, a large stellar structure that is spread, at least in a first approximation, as a great circle in the sky. This Stream is presently studied intensively in recent works with important consequences concerning the halo dark matter properties (Majewski et al 2003; Law et al. 2004; Helmi 2004).

Another survey for FHLC stars was published later by Christlieb et al. (2001) who found as many as 403 C stars on the Hamburg–ESO objective prism plates covering 6400 deg^2 in the South Galactic Cap. These objects were selected automatically through the detection of C_2 and CN bands in the blue-visible wavelength region (3500–5400 Å). These stars are mainly giants, with probably a small percentage of dwarfs. The faintest objects have V = 16.5 and their distances are mostly within 20 kpc with a tail up to $\sim$ 30 kpc from the Sun.

Thanks to the SLOAN survey, Margon et al. (2002) and Downes et al. (2004) discovered a total of 280 faint C stars over 3000 deg^2. These sources were first selected with photometric criteria (Krisciunas et al. 1998; Margon et al. 2002) and subsequently confirmed by follow-up spectroscopy. Downes et al. (2004) interpret their sample as a mixture of giant and dwarfs, which are not easy to discriminate when no proper motion is detected. The Sloan r magnitudes of their sample are in the range 15.6 to 20.8. Downes et al. (2004) found that 3, and perhaps 4 of their stars are members of the Draco dwarf galaxy, which is at 79 kpc (Van den Bergh 2000), and many of their objects believed to be giant (not dC) are fainter than two of the Draco stars. Therefore, the Sloan FHLCs certainly probe also at considerable distances in the halo (more than 100 kpc).

Because Gaia will be able to probe up to V $\sim$ 20.5, it will be a formidable tool to discover or to study carbon stars and especially the FHLC stars mentioned above. For example, Gaia will provide very accurate astrometry, photometry and spectra at the brightness level (V $\sim$ 17) where many FHLC have already been discovered. In particular, because the AGB C stars have an absolute magnitude of typically $M_R \approx -3$, an R-band magnitude of 15.5 puts them at 50 kpc (e.g., in the Magellanic Clouds), and R = 18 at 160 kpc. Therefore, these AGB C stars will be unique targets for Gaia.

In this context, we would like to report on a survey based on the 2MASS near-infrared photometric data base and designed to find these luminous AGB-type C stars. The first results were published in Mauron et al. (2004) and we give here a summary of more recent results.

2. A SURVEY FOR COOL AGB CARBON STARS

Our search for halo C stars follows in many aspects the work of Totten & Irwin (1998) who had selected these AGB stars through their characteristic very red colour, i.e., $B_J - R > 2.5$ on Schmidt plates. With the publication of the 2MASS catalogue, it became possible to search for these red objects by using their JHK colours, and most importantly, to do it in a homogeneous way all over the sky, except the galactic plane. First, a search based on JHK is more appropriate than with B, R bands, because the spectral energy distribution of the AGB stars peaks at NIR wavelengths. A second advantage is that AGB C stars may be dusty, and are much better seen in, for example, the K band, rather than in B or in R. Searching in the NIR is also less sensible to interstellar extinction, which is relevant if we wish to probe at $|b|$ less than 30°.

Figure 1 shows the typical colours of C stars when 2MASS JHK are used. For this diagram, we selected all carbon rich stars located at $|b| > 30°$. These objects were taken from the General Catalog of Galactic Carbon Stars of Alksnis et al. (2001), and/or in the lists of Totten & Irwin (1998) and Christlieb et al. (2001). No objects from our own survey are drawn. The threshold in galactic latitude allows any colour effect due to galactic extinction to be eliminated, but means that the majority of N-type stars located in the disc are not plotted. A few well known high latitude C stars like IRC+10216 are also not plotted because the 2MASS data are not accurate due to saturation. The diagonal straight line represents J–K = 1, roughly separating the warm RGB-type carbon star at left, and AGB cases at right. Most of the numerous warm objects come from the survey of Christlieb et al. (2001) and have approximately the same colour in H-K. Above the diagonal line, one finds mostly C stars of AGB-type. They are much rarer than RGB type, but display in this colour-colour diagram a remarkably narrow locus, with a small width of $\sim$ 0.2–0.3 mag. A very similar lane is seen when one considers the AGB C stars in the Magellanic Clouds, see, e.g., Nikolaev & Weinberg (2000).

Our survey is based on this colour property of cool halo C stars. Practically, candidate C stars are selected in the 2MASS catalogue with J–H, H–K colours such that the representative point lies within 0.15 mag from the ridge of the C star locus in Figure 1. Each candidate is then checked by interrogating the Simbad data base and looking at the POSS digitized images in order to discard interlopers, such as galaxies, known T Tauri stars, brown dwarfs, QSOs, etc. Then, follow-up spectroscopy is achieved with a resolution of $\sim$ 100 km s^{-1}. This resolution is largely sufficient to discriminate between a C-type star and an M-type star (or other type of objects). It also permits the derivation of radial velocities by correlation with C templates with a final accuracy (1σ) of about 12 km s^{-1}. More details can be found in Mauron et al. (2004)

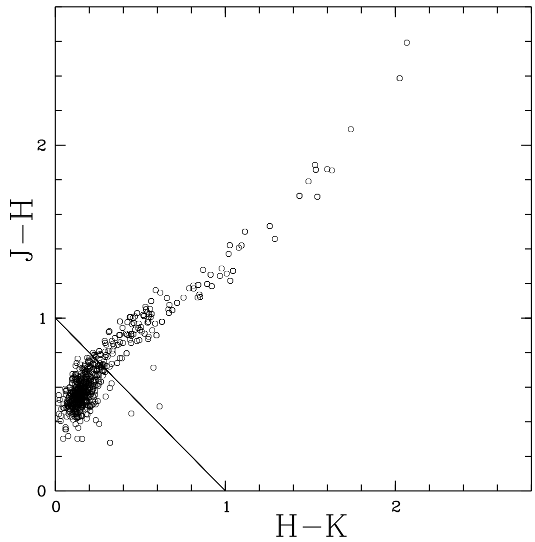

Figure 1. A 2MASS colour-colour diagram for high latitude carbon stars

Figure 2 shows the present status of the cool carbon stars in the halo (including the updated results of our survey) when a colour-magnitude diagram (K vs. J–K) is drawn. Empty circles are C stars known before our survey started. Filled squares are confirmed C stars found by us. Most of our discoveries have J–K > 1.3, because below this limit, the contamination by M-type stars is found to be very important.

It can be seen in Figure 2 that our survey strongly contributes to find cool C stars at faint K magnitudes, or, equivalently at large distances. To estimate these distances, we consider the C stars in the Large Magellanic Cloud: it is found that, depending on J–K values, their *average* K-band absolute magnitude, is between −7.5 and −8.15 if $(J–K)_0$ lies within the range 1.3 to 4. The maximum intrinsic K brightness at −8.15 is for $(J–K)_0$ = 1.9, and there is a scatter on M_K of the order of 0.3–0.4 mag. Therefore, if we consider an object with (J-K) $\sim$ 1.9 and assume that no interstellar reddening occurs, then, for K > 11, its distance is about $\sim$ 67 kpc, that is, beyond the distance of the Magellanic Clouds. Figure 2 shows that there are presently 28 AGB-type FHLC fainter than K = 11. We see also that very few objects are present above K = 12.5, but we found one case as faint as K = 13.2.

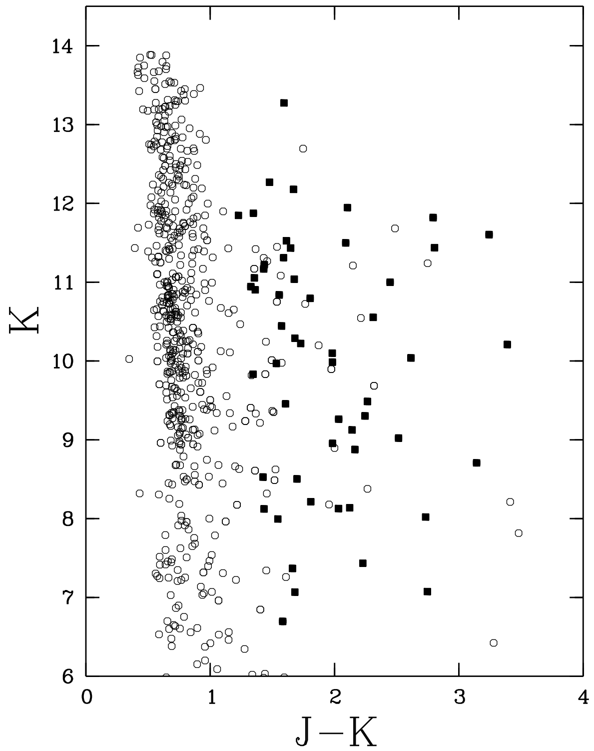

Figure 2. A 2MASS colour-magnitude diagram for high latitude carbon stars. Filled squares are new C stars.

Figures 3a and 3b show in the galactocentric XYZ system the position of all known carbon AGB stars found in the Galactic Halo. In this coordinate system, the Sun is at X = −8.5 kpc, Y=Z=0. The Z axis is towards the galactic pole. The Y axis is along the line with galactic latitude $l = +90°$. The Fornax dwarf spheroidal galaxy has been plotted to emphasize the scale: its distance to the Galactic Centre is 138 kpc (Van den Bergh 2000). The XYZ values were calculated after adopting the above mentioned distance scale based on the C stars of the Large Magellanic Clouds. The C stars belonging to the galactic disc are not plotted.

In Figure 3a, one can see very well that the majority of known C stars fall along a nearly vertical line, rather than being scattered within a spherical volume around the Galactic Centre. This line is the plane of the Sagittarius Stream viewed almost edge-on, as in Figure 7a of Majewski et al (2003). Note that a few of the halo C stars are located far away, up to $\sim$ 70 kpc, from this plane. They might possibly come either from ancient orbits of the Sgr Stream, or from tidal debris of other disrupted satellite galaxies. There are also at very negative Z values (to the South Galactic Cap) two stars located very far from the Galactic Centre but they are well within the Sgr Stream plane, and they might be the signature of extensions of this Stream.

In Figure 3b, the same objects are plotted, as if they were seen from the right in Figure 3a. Here, the location of the C stars are scattered within $\sim$ 70 kpc from the Galactic Centre with a few exceptions. The Sun is to the right of the origin at X= −8.5 kpc, Z=0. The Sagittarius dwarf

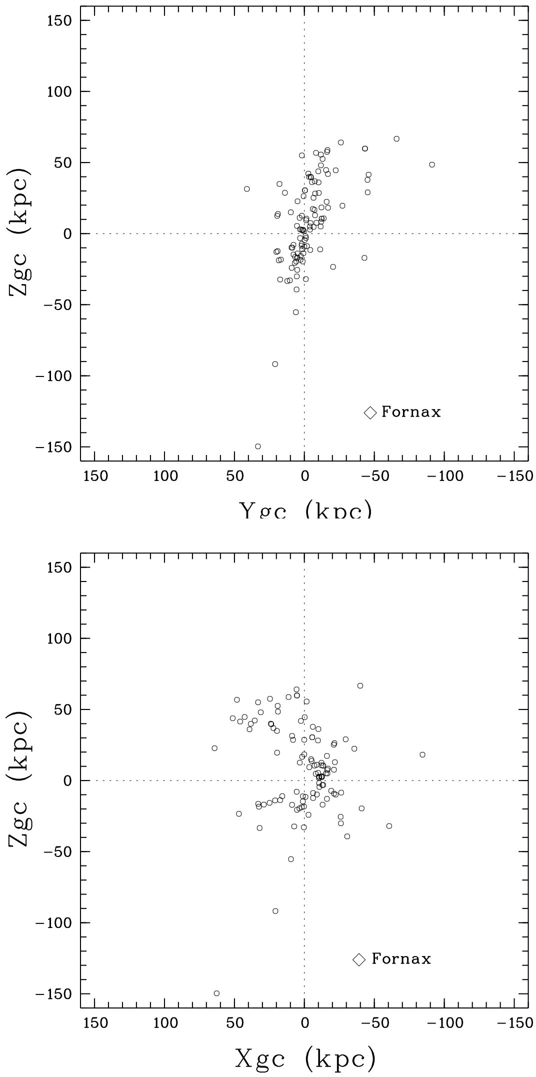

Figure 3. Plots in galactocentric XYZ of all known AGB-type C stars at $|b| > 20°$.

galaxy is at left of the origin at X= +15, Z= −6 . The absence of objects at left and right of origin near the Z=0 axis is in large part due to the difficulty of finding distant C stars near the galactic plane. Our own survey is presently limited to $|b| > 20°$, and almost all other surveys are limited to higher galactic latitudes.

3. GAIA AND THE HALO C STARS

The instrumention of Gaia will allow to have broad and narrow band photometry over a 5 year epoch for V as faint as $\sim$ 20, accurate proper motions and parallaxes (accuracy 10 μas for V=15), and usable RVS spectra for V$<$ 17.5 . These capabilities will allow a unique study of FHLCs as well as a very large number of discoveries.

Concerning the rare faint AGB-type C stars found by TI98 and our group, we estimate from our experiment that the total number of these stars $|b| > 20°$ is of the order of $\sim$ 200, with the large majority being membesr of the Sgr Stream. It is possible that, for these latitudes, nearly all of these stars will be discovered before the Gaia launch, but this will probably not be the case at lower latitudes. There are presently very few of these stars at very faint R magnitudes. Adding the lists of Totten & Irwin (1998) with our own discoveries, we find that 3 C stars have R $>$ 18 and their J–K indicate that their faint brightness is very probably due to extinction by circumstellar dust. Three not particularly red C stars have R in the range 17–18, and 9 in the range 16–17. The large majority are brighter than R=16. Therefore, Gaia will provide high accuracy broad and narrow band photometry for all of these AGB-type stars. Gaia will permit the measurement of their astrometry, their variability and the determination of a pulsation period for some objects.

Concerning the warm RGB-type C stars, it is very probable that the Gaia narrow band system will be able to determine whether a warm red giant is of M-type or C-type, and to obtain a clear separation of the warm C-stars from the rest of the oxygen-rich normal stars, as was achieved, at least in part, with the Sloan filters. We have not found in the literature any library of spectra of C stars (dC, RGB or AGB-type) with the RVS spectral domain and resolution (8480–8740 Å, $\delta\lambda/\lambda = 11\,000$), and a grid of carbon-rich RVS model spectra would be very informative. If we just scale the Christlieb sample to an area of 27000 deg^2 corresponding to $|b|$ $>$20°, about 2000 RGB-type FHLC are expected with V $<$ 16.5 . Many more stars of this type will be seen at lower latitudes due to the contribution of the disc population.

At fainter magnitudes (R$\sim$17), the dCs start to outnumber the C giants. For example, in the list of 251 SLOAN FHLC stars in Downes et al. (2004), there is a fraction of objects that could be classified by Downes et al. as G (giants) or D (dwarfs), the rest of the sample being of uncertain type. Ignoring the 3 Draco giants and 1 object already known as an AGB type star (SDSS 125149.87+013001.8), there are 16 giants, and all these giants have 15.5$<$ r $<$18.0. In contrast, there are 112 dCs, with 30 in the range 15.0 $< r <$ 18.0 and 82 in the range 18.0 $< r <$21.0 . (The Sloan r magnitude is very comparable to the Cousins R band: from the equations given by Smith et al. (2002), one finds that the Cousins R-band is R$=r'-0.04\,(g'-r')-0.14$; we have ignored here the difference between r and r', a few per cent according to Smith et al. because the Sloan giants have $(g-r)$ around 1.33, $\sigma = 0.29$, we have R $\approx r-0.2$). If we assume that about 80 per cent of the remaining 119 cases of uncertain types are dCs, then the surface density of observed dwarfs is 0.07 dC per square degree. Because of several factors of incompletness in the Sloan survey for FHLCs (Downes et al. 2004, for details), one can reasonably expect $\sim$ 0.1–0.2 dC per square degrees, or $\sim$ 4000–8000 dCs seen by Gaia. Through the measurements of parallaxes and proper motions, Gaia will discriminate dCs and distant faint halo C giants.

4. CONCLUSIONS

We have briefly summarized the present situation of surveys for FHLCs and limited our considerations to three types of C stars: AGB-type, RGB-type and dCs. We have described our programme that is designed to obtain a complete census of all halo C stars with an AGB-type, at least for $|b|$ $>$20°. Candidates for being AGB-type C stars are first selected through their JHK colours and spectroscopy is needed to discard interlopers. Many of these C stars belong to the Sgr Stream, but not all. These stars are interesting because, in complement to other populations, e.g., metal-poor giants, BHB stars, the AGB C stars can be useful to determine the halo content of dark matter and the total mass of the Galaxy. They may also be the brightest indicators of tidal debris left by an accreted satellite. The halo AGB C stars will be very well seen by Gaia, which will provide unique kinematic, photometric and spectral data.

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