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The Carbon Star Population in the Fornax Dwarf Spheroidal Galaxy Revisited

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Abstract. Our systematic searches for carbon stars in the Fornax dwarf spheroidal galaxy at the Canada-France-Hawaii Telescope have led to more than a doubling of the number of carbon stars known in this system, to 104. Furthermore, low-luminosity carbon stars resembling those we had previously found in the Small Magellanic Cloud have been identified in this system. We review the carbon star surveys carried out in the Fornax dwarf and present our main results. The Fornax carbon star population is compared to those of other Galactic halo dwarf systems.

1. Introduction

Red giant stars are valuable objects for the study of the morphology, stellar evolution, and kinematics of galaxies. The ratio of carbon (C) stars to late-type M stars, and possibly the faint end of the C star luminosity function, is sensitive to the metallicity of the parent system. Consequently, a number of extensive surveys for C stars have been carried out in the Magellanic Clouds and the dwarf spheroidals in the Galactic halo. Of special interest, Fornax provides an unrivalled opportunity to get the entire C star luminosity function for an extragalactic system, since now the census of these objects can be considered as complete. Their substantial, but not too large, number (about a hundred) makes possible near-infrared JHK photometric observations for the majority of them.

2. C Star Identification in the Fornax Dwarf Spheroidal Galaxy

The first indication that Fornax possesses a wide giant branch reminiscent of that of ω Centauri was given by Demers et al. (1979). Extensive iris photometry of a pair of B, V plates obtained with the CTIO 1.5-m reflector led Demers &

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Kunkel (1979, hereafter DK) to identify 66 very red stars and to suggest that the redder ones would be C stars. Indeed, vidicon spectra obtained at the CTIO 4-m telescope by Aaronson & Mould (1980) of seven objects, selected in the full colour range of the very red star sample found by DK, revealed the presence of the first five proven C stars in the Fornax dwarf spheroidal and induced these authors to claim that "for $B-V$ greater than ~ 2.1, the giant branch of Fornax may consist entirely of C stars". Subsequent transmission grating slitless spectroscopy studies were to confirm this assertion.

2.1. Early Near-Infrared Spectroscopic Surveys

A near-infrared low-dispersion spectroscopic survey for late-type stars in the Fornax system was carried out at the prime focus of the CTIO 4-m telescope by Blanco & McCarthy (Frogel et al. 1982), using a grism (2350 Å mm^{-1} dispersion at the atmospheric A band) in combination with Kodak IV-N plates and a Schott RG 695 filter. In a circular field (23 arcmin diameter) covering the Fornax central regions, 34 cool stars were found including 25 very probable C stars.

Concurrently, Westerlund (1979) using the same grism observing technique (1700 Å mm^{-1} dispersion at 7300 Å), with the Gascoigne correctors at the prime focus of the ESO 3.6-m telescope, reported the discovery of 69 red stars in Fornax, including several C star candidates, in three circular fields of 16 arcmin diameter (see also Richer & Westerlund 1983). Combining this search for late-type stars with that of Blanco & McCarthy (both surveys having about the same magnitude limit of $I \approx 17.5$) led Westerlund et al. (1987) to take the census of 46 possible C stars in the field of the Fornax dwarf spheroidal, between 23 and 27 of them belonging to the DK list of very red giants, the carbon star nature of three of them (DK 22, DK 46 and DK 60) having previously been spectroscopically confirmed by Aaronson & Mould (1980).

Our subsequent observations of the majority of the C star candidates listed by Westerlund et al. (1987), using various ESO telescopes and spectrographs, reduced the total number of C stars found by the near-infrared grism surveys in the Fornax system to 42. The carbon star nature of four of them (BM 21≡DK 28, BM 23≡ DK 29, BM 24 and DK 10) was not confirmed. Note that stars BM 23 and BM 24 are classified M1 and S4/3 by Aaronson & Mould (1980) and Lundgren (1990), respectively. Also, long slit and multislit spectroscopy of a sample of red stars selected from the Westerlund observing material, by Lundgren (1990) with the ESO Faint Object Spectrograph and Camera (EFOSC) mounted on the 3.6-m reflector, resulted in the detection of two additional C stars. Adding two more C stars (DK 2 and DK 7), but not the Ctm (continuum) star (DK 6) – all three lying outside the boundaries of the near-infrared grism surveys and classified by Aaronson & Mould (1980) – the total number of field C stars known in the Fornax system reached 46, not taking into consideration our blue-green low-resolution slitless spectroscopic surveys.

2.2. CFHT Blue-Green Spectroscopic Surveys

Within the framework of our C star Galactic halo dwarf spheroidal surveys (Azzopardi et al. 1985, 1986), two plates (one square degree field of view), centred on the accepted centre of the Fornax galaxy, were obtained by Lequeux and Azzopardi. We used the Canada-France-Hawaii Telescope (CFHT) equipped with the wide-field corrector and the blue-green grens giving 2000 Å mm^{-1} dispersion. We adopted the Swan C_2 bands at 4737 and 5165 Å for C star selection criteria, an observing technique pioneered by Sanduleak & Philip (1977). Combined use of the IIIa-J emulsion with a Schott GG 435 filter, by restricting the instrumental spectral domain to 4350–5300 Å, allowed us to constrain the image crowding satisfactorily. Close inspection of the plates led to the identification of several C star candidates whose carbon star nature was afterwards confirmed by medium-resolution spectroscopy carried out with ESO instruments. This survey resulted in 29 new C stars, 12 of them lying inside the boundaries of the previous near-infrared grism surveys.

By the end of 1994, the C star population of the Fornax galaxy was revisited by Muratorio and Azzopardi with the CFHT, using the same observing method. The Multi-Object Spectrograph (MOS) was used in the slitless spectroscopy mode, equipped with the 2048×2048 15 μm pixel Loral 3 CCD camera, giving 0.31 arcsec resolution per pixel. This time the dispersion was provided by a prism (800 Å mm^{-1} dispersion) – in order to avoid the images of the different orders given, for the brighter stars, by the low-dispersion transmission gratings – while the useful spectral range was selected through an interference filter having a 1025 Å bandwidth centred at 4850 Å. In five 1200 s slightly overlapping frames ($10' \times 10'$ each) a number of new C star candidates were found, both by scrutinising the slitless spectroscopic frames and using a semi-automatic procedure developed in the Munich Image Data Analysis System (MIDAS) environment (see Muratorio & Azzopardi 1994). Subsequent multi-object medium-resolution spectroscopy with the Meudon ESO Fiber Object Spectrograph (MEFOS) at the ESO 3.6-m reflector yielded 29 additional C stars, missed by the previous photographic transmission grating searches owing to their faintness.

In spite of the unfavourable declination ($\delta = -30°$) of Fornax for the Mauna Kea site, our grens/prism observations have more than doubled the number of carbon stars known in this system. This is mainly due to the high image quality provided by the CFHT – which is essential for slitless spectroscopy – but also to the detection method used, based on the C_2 band feature recognition. As a matter of fact, more often than not, the strength of the Swan C_2 bands more than compensates the loss of flux in the blue-green spectral domain, even for late C stars (see the discussion section). Actually, one can consider the C star census in the Fornax galaxy virtually complete, at least within the limits of the CFHT MOS survey.

3. C Star Population in the Fornax Dwarf Spheroidal Galaxy

With 104 identified objects, the Fornax system contains by far the largest number of C stars known among the Galactic halo dwarf spheroidal galaxies. Table 1 gives an up to date census of C stars identified in these systems as well as the estimated total number of C stars in the Magellanic Clouds, for comparison. According to Aaronson et al. (1983) and Aaronson & Mould (1985), it is interesting to compare the normalized C star number $\log N_{C,L} \equiv \log N_C + M_V/2.5$ as a function of parent system luminosity in Galactic halo dwarfs (Table 2). Adopted absolute visual magnitudes come from Irwin & Hatzidimitriou (1995).

Note that the logarithm of this number is near or equal to −3.3 for most of these systems except for Leo II, Draco and Carina where it is larger.

Table 1. Carbon stars in Galactic halo systems.

System	n_C[a]	N_C[b]	*references*[c]
LMC		11000	1,2
SMC		3060	3,4
Fornax	104	≈120	5
Leo I	19		6
Carina	11	11	5,6
Sculptor	8		6
Leo II	8	8	5,6
Draco	4		6
Ursa Minor	1		6
Sextans	0		7
Sagittarius	≥31		8,9,10
Galactic Bulge	34		11

[a] Number of C stars known in the system

[b] Possible total number of C stars in the system

[c] References:

(1) Blanco & McCarthy (1983)
(2) Blanco & McCarthy (1990)
(3) Rebeirot, Azzopardi & Westerlund (1993)
(4) Morgan & Hatzidimitriou (1995)
(5) Azzopardi et al. (in preparation)
(6) Azzopardi, Lequeux & Westerlund (1986)
(7) Irwin, Bunclark, Bridgeland & McMahon (1990)
(8) Ibata, Gilmore & Irwin (1995)
(9) Whitelock, Irwin & Catchpole (1996)
(10) Ng & Schultheis (1997)
(11) Azzopardi, Lequeux, Rebeirot & Westerlund (1991)

Near-infrared *JHK* photometry of ≈ 87% of the Fornax system C star population, mainly carried out by us with IRAC 2 mounted on the ESO/MPI 2.2m telescope, resulted in the obtaining of a virtually complete C star luminosity function. The absolute bolometric magnitudes, derived by the method of Wood et al. (1983), allowed us to point out the existence of low-luminosity objects as faint as $M_{\rm bol} \simeq -1.2$, assuming for the Fornax dwarf absorption-free distance modulus $(m - M)_0 = 21.0$. These objects resemble the ones we identified in the Small Magellanic Cloud (SMC). In addition, the Fornax C stars so far examined spectroscopically by us appear to show a wide range in carbon-band strength as well as a variation in $^{12}C/^{13}C$ ratio, similar to what we have seen in the SMC (Westerlund et al. 1992, 1995) and in many ways in the Galactic Bulge (Westerlund et al. 1991).

Our discovery of low-luminosity C stars in two slightly metal-poor galaxies corroborates the theoretical predictions about the dependence of mean C star luminosity on metallicity, leading to the expectation that, for two systems with similar star-formation histories (i.e., similar initial stellar mass functions and star formation rates), the mean luminosity of C stars would be lower in the

Table 2. Normalized carbon star number as a function of parent system luminosity in Galactic halo dwarfs.

System	N_C[a]	$-M_V$[b]	$-\log N_{C,L}$[c]
LMC	11000	18.4	3.3
SMC	3060	16.7	3.2
Fornax	104	13.0	3.2
Leo I	19	11.5	3.3
Sculptor	8	10.7	3.4
Leo II	8	9.6	2.9
Carina	11	8.6	2.4
Ursa Minor	1	8.4	3.4
Draco	4	8.3	2.7

[a]Total number of C stars known in the system

[b]Adopted absolute visual magnitude for the system according to Irwin & Hatzidimitriou (1995)

[c]$\log N_{C,L} \equiv \log N_C + M_V/2.5$: C star number normalized to parent system luminosity according to Aaronson, Olszewski, & Hodge (1983) and Aaronson & Mould (1985)

system with lower metallicity. As a matter of fact, given two stars of equal mass but different metallicities, the metal-poor one will become a C star at a lower luminosity than the metal-rich one since less carbon has to be dredged up to the surface to get C/O>1.

Low-luminosity C star formation is still debated. A number of possible processes to produce these objects have been proposed (see for instance Westerlund et al. 1991, 1992, 1995 and van Eck et al. (1998), as well as the comment by Lloyd Evans in the discussion section). If low-luminosity C stars are formed by mass transfer in binary systems, the faint ends of the C star luminosity functions determined for the SMC and the Fornax dwarf would be questionable since they should not be typical of the intrinsic luminosity of the fainter objects but dependent of the observational magnitude limits. Further studies of the C star luminosity function of the nearer extragalactic systems (especially the Large Magellanic Cloud) are required in order to confirm the possible correlation between the mean luminosity of C stars and the metallicity of the parent system, and to understand better how the various C star formation processes produce carbon stars over so wide a range of luminosity.

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Discussion

Pritchet: There exist surveys of C stars in more distant galaxies. Is it possible to plot the results of these surveys on your figure showing normalized C star numbers according to luminosities?

Azzopardi: Certainly this would be possible and very interesting provided that the C star census for those galaxies is sufficiently complete. Unfortunately, this condition is not as yet met for any galaxy beyond the Galactic halo systems.

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Kerschbaum: With your C_2 band search technique you are biased towards "blue" C stars. You probably miss all mass-losing stars!

Azzopardi: As shown by Westerlund et al. (1986) and McCarthy (1987), comparing the SMC C star survey by Blanco et al. (1980) with that of Rebeirot et al. (1993), our detection technique is more sensitive to the bluer C stars including classical R-, CH-, Ba II- and J-type stars than the near-infrared method (search for CN-band blends) which favours the redder and cooler C stars of the classical N-type. Hence concerning the detection in the visible domain of the few bluest and reddest C stars, these two survey techniques are basically complementary. However, both miss many C stars, among the most luminous ones, with strong stellar winds responsible for high mass-loss rates, which can only be detected at infrared or radio wavelengths and will most likely be found by the 2MASS and/or the DENIS observations, for instance.

Armandroff: I was interested in the normalized C star number density for Leo I, which looks quite typical. Given the large intermediate-age population in this galaxy, I am surprised that the C star density is not higher. Can you please comment on this?

Azzopardi: With only 19 C stars, Leo I nevertheless contains, after Fornax, the larger number of these objects known among the Galactic halo dwarf spheroidals. However, its normalized C star number ($\log N_{\mathrm{C},L} = -3.3$) as a function of parent system luminosity is comparable to the values obtained for most of the other Galactic halo systems, for instance the LMC (see Table 2). Deeper C star surveys than the photographic slitless spectroscopic one by Azzopardi et al. (1986) could reveal fainter C stars. Note that this kind of search may be impeded by the proximity of the bright star Regulus which anyhow makes the Leo I observations difficult.

Whitelock: Do you have a near-infrared two-colour diagram of the Fornax C stars? Can you comment on the presence of red AGB C stars in Fornax?

Azzopardi: I have this kind of diagram but not here to be displayed, unfortunately. For the Fornax C star sample with available JHK photometry, $J-K$ ranges from 0.7 to 1.6 and $H-K$ from -0.12 to 0.90. As shown for the SMC (see Westerlund et al. 1995 and papers quoted therein), the possible trend for metal-poor galaxies to easily form low-luminosity and relatively blue C stars does not prevent the presence in these systems of C stars with colours similar to those of red AGB C stars found in more metal-rich galaxies.

Lloyd Evans: There must be at least three processes to produce carbon stars over the wide range of luminosity which you find: 1) The third dredge-up operates in thermally-pulsing AGB stars brighter than about $M_{\mathrm{bol}} \approx -4$. Most of the carbon stars in the Magellanic Cloud clusters of intermediate age may be accounted for in this way; 2) The binary mechanism proposed for the CH stars. This may face difficulty in accounting for the enhanced ^{13}C of many CH stars; 3) The unknown mechanism which accounts for the R stars other than CH stars, which are not binaries according to McClure.

Azzopardi: Thank you for your comment.