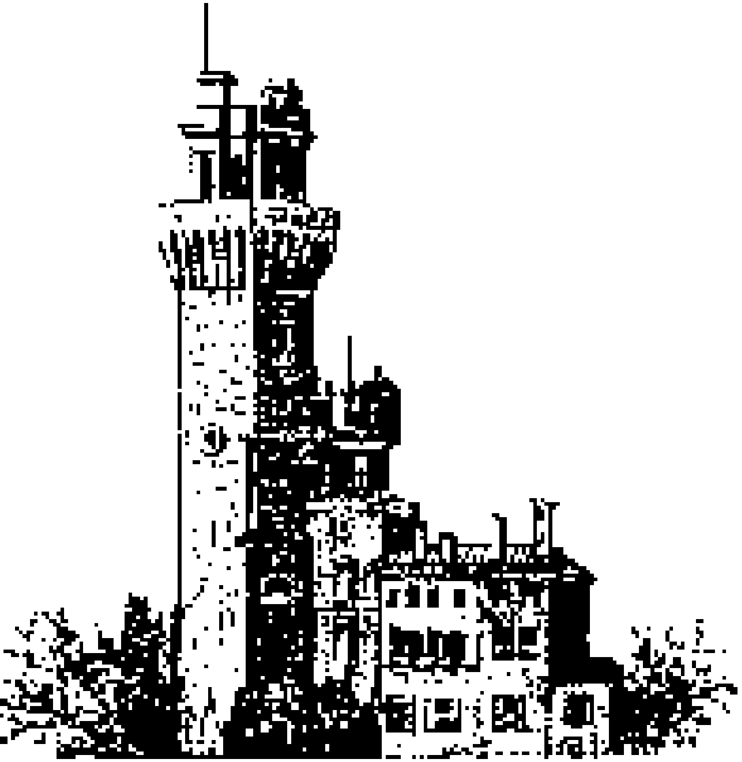

Are the Bulge C-stars related to the Sagittarius dwarf galaxy ?

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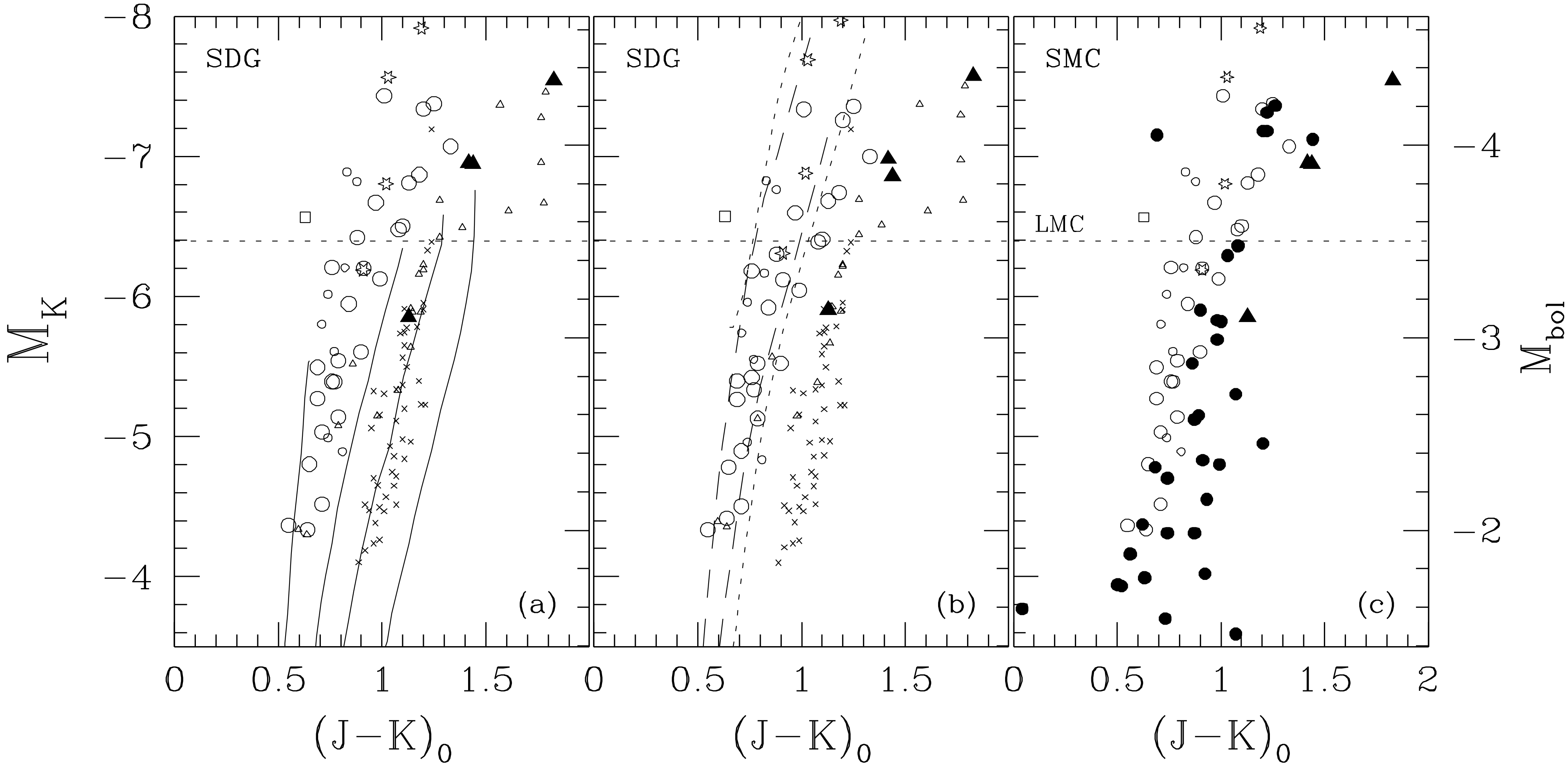

Fig. 2. Panel (**a & b**) The ALRW91 carbon stars placed at the distance of the Sagittarius dwarf galaxy (open circles; small open circles are used to indicate a larger uncertainty in the extinction adopted), together with the carbon stars from IGI95 (filled triangles). Open triangles and crosses are used for respectively the candidate carbon stars and giant branch stars of the dwarf galaxy observed by WIC96. The open square indicates the carbon stars S283 found by NS97 among the variables studied by Plaut (1971) and Wesselink (1987). The dotted horizontal line indicates the observational lower LMC limit at which carbon stars are

found, while the lower magnitude limit corresponds with the SMC limit (Azzopardi 1994). The difference between panel (**a**) and (**b**) is the method used to assign a distance to each SDG star, respectively through the unweighted least square fit or the two section line fit displayed in Fig. 1a. Panel (**c**) shows a comparison with the SMC carbon stars (Westerlund et al. 1995; filled dots).
The isochrones (Bertelli et al. 1994; only for log $T_{\rm eff} < 3.70$) displayed in the three panels are as follows: **a**) 10 Gyr RGBs for Z = 0.0004, 0.004,0.008, and 0.020; **b**) 1 and 10 Gyr AGBs for Z = 0.001 (long-dashed line) and 0.1 and 1 Gyr AGBs for Z = 0.008 (dotted line); and **c**) 5 and 10 Gyr AGBs for Z = 0.004 (dotted and solid line) and Z = 0.02 (dot-dashed and dashed line). See Sect. 3.1 for additional details about the magnitude and the colour transformations.
Note that the left vertical axes in each panel give the K-magnitude scale, while the right vertical axes indicate the M_{bol}-scale

1. ABSTRACT

Part of the mystery around the Bulge carbon stars from Azzopardi et al. (1991) is solved, when they are related to the Sagittarius dwarf galaxy. The carbon stars are in that case not metal-rich as previously thought, but they have a metallicity comparable to the LMC, with an age between 0.1 – 1 Gyr. A significant fraction of the carbon stars still have luminosities fainter than the lower LMC limit of $M_{bol} \simeq -3\overset{m}{.}5$. A similar trend is present among some of the carbon stars found in other dwarf spheroidals. At present, the TP-AGB models cannot explain the origin of carbon stars with $M_{bol} > -3\overset{m}{.}5$ through a single-star evolution scenario, even if they form immediately after entering the TP-AGB phase. Mass transfer through binary evolution is suggested as a possible scenario to explain the origin of these low luminosity carbon stars.

2. ‘Bulge’ carbon stars

Azzopardi et al. (1985, 1988) found 33 carbon stars in 8 different fields of the Galactic Bulge. Near-IR photometry and medium-low resolution spectra have been obtained for these carbon stars (Azzopardi et al. 1991, Tyson & Rich 1991, Westerlund et al. 1991).

Various studies suggest that a wide metallicity range is present in the bulge (McWilliam & Rich 1994, Ng et al. 1996 and references cited therein). According to Azzopardi et al. (1988), Tyson & Rich (1991), and Westerlund et al. (1991) the carbon stars are expected to be old, metal-rich with a mass of about 0.8 $M_\odot$ if they belong to the Bulge. However, evolutionary calculations (Boothroyd et al. 1993, Groenewegen & de Jong 1993, Groenewegen et al. 1995, Marigo et al. 1996ab) demonstrate that the initial mass of carbon stars is at least 1.2 $M_\odot$ ($t < 4$ Gyr) for $Z = 0.008$. Furthermore, the initial mass increases towards higher metallicity and decreases towards lower metallicity (Lattanzio 1989).

The Bulge carbon stars are a mystery, because they are in bolometric luminosity about $2^{m}\!.5$ too faint to be regarded as genuine AGB (Asymptotic Giant Branch) stars, if located in the metal-rich Bulge.

3. Sagittarius dwarf Galaxy

The serendipitous identification of the Sagittarius dwarf galaxy (SDG) was made by Ibata et al. (1994, 1995). It is the closest dwarf spheroidal and moves away from us at about 160 km/s. Accurate distances from RR Lyrae stars range from 22.0 – 27.3 kpc (Alcock et al. 1997; Alard 1996; Mateo et al. 1995ab, 1996; Ng & Schultheis 1997). Figure 1a, with additional distances from Sarajedini & Layden (1995) and Fahlman et al. (1996), shows that they correlate with galactic latitude.

It is generally thought that the SDG is moving towards the galactic plane (Johnston et al. 1995, Velazquez & White 1995, and Ibata et al. 1997). However, a projection of Fig. 1a on the $x - z$ plane in Fig. 1b demonstrates the contrary: *the SDG already crossed the galactic plane.* Ng & Schultheis (1997) suggested that the ‘bulge’ carbon stars could be used as a tracer for the tidal interaction between the SDG and our Galaxy. At the same time this would solve the standing question about their origin, because the difference in distance modulus between the Bulge and the SDG is about $2^{m}\!.5$.

4. ‘Bulge’ C-stars + SDG = OK ?

The possibility is analyzed that the ‘bulge’ carbon stars are related to the SDG, see Ng (1997) for full details. The photometric analysis is done together with the (candidate) carbon stars observed by Whitelock et al. (1996). All the photometry of the stars is either in- or properly transformed to the ESO system (Bouchet et al. 1991). The photometry is corrected for extinction and absolute magnitudes are obtained from the adopted SDG distance: $D(\mathrm{kpc}) = 21.83 - 0.25b$ or from the two section line shown in Fig. 1a.

Figures 2a & 2b show the colour-magnitude diagrams (CMDs) for the two adopted distance distributions. Some stars, possibly as bright as M_{bol} spanning $-6\overset{m}{.}0$ to $-7\overset{m}{.}0$, have not been displayed. A significant number of the Azzopardi et al. (1991) carbon stars are located below the LMC limit, which is the theoretical limit at which carbon stars are produced through a single star evolution scenario. On the other hand, a comparison in Fig. 2c with the SMC carbon stars (Azzopardi 1994; Westerlund et al. 1993, 1995) shows a parallel sequence. Ng (1997) argues that the SMC carbon stars constitute likely a population older than the SDG carbon stars.

In Figs. 2a & 2b isochrones from Bertelli et al. (1994) are displayed. Fig. 2a shows the RGB for an age of 10 Gyr for various metallicities and Fig. 2b shows the AGB for different age and metallicities. Figure 2a demonstrates that if one assumes a fixed age then some spread in metallicity could be present among the SDG stars. Given the uncertainties, the RGB stars likely have a metallicity of $Z \simeq 0.008$. Figure 2b demonstrates that it is difficult to distinguish 1 & 10 Gyr isochrones for the AGBs with $Z = 0.001$ from those with a 0.1 & 1 Gyr age with $Z = 0.008$.

5. Results

Figure 2a shows the presence of a ~ 10 Gyr component with $Z=0.008$. A metallicity of $Z=0.001$ would lead to contradicting results, concerning the age and chemical enrichment. A metallicity of $Z=0.008$ is within the uncertainties comparable with $[Fe/H]=-0.52\pm0.09$ obtained by Sarajedini & Layden (1995). The carbon stars reflect a recent star formation burst, while the major stellar population has an age ~ 10 Gyr. Figure 3 displays another indication for a young stellar population.

At the distance of the SDG some of the Azzopardi et al. (1991) carbon stars are located well below the tip of the RGB. Even if carbon stars can form directly after they enter the TP-AGB phase another mechanism is required for a fraction of the carbon stars, because they cannot be accounted for in the 'standard theory' of carbon stars formation in the TP-AGB phase. The sequence of carbon stars parallel to the giant branch suggest that they are either RGB or early AGB stars. The progenitors of the carbon stars might be the binary CH stars. Just like dwarf carbon stars (see Green 1997 and references cited therein), a scenario of mass transfer through binaries could be a plausible explanation (i.e. the second option considered, but not explored by Azzopardi et al. 1988) .

A binary evolution scenario would explain the $^{12}C/^{13}C$ ratio through dilution in the fully convective envelope of RGB or AGB stars, which is proportional to the time elapsed (i.e. a larger distance from the galactic disc) since the envelope is deposited on the secondary star. The NaD equivalent width and the CN line strength obtained from spectra for the carbon stars by Tyson & Rich (1991, see their Fig. 3) would support this assertion.

Summarizing:

○ The Azzopardi et al. (1991) carbon stars are likely not located in the Bulge, but are related to the SDG.

• The Azzopardi et al. (1991) carbon stars are not metal-rich and have a metallicity is about $Z=0.008$ with an age between $0.1-1$ Gyr.

• A significant number of the Azzopardi et al. (1991) carbon stars are located below the tip of the red giant branch. The origin of the carbon stars one magnitude below the red giant branch tip cannot be explained with the evolution of a TP-AGB star and likely originated through mass transfer from binary evolution.

6. Caveat

The radial velocities of the ‘bulge’ carbon stars would provide an independent verification of the photometric analysis presented here, concerning membership of the SDG. Tyson & Rich (1991) determined the radial velocities for 33 stars from the Azzopardi et al. (1991) sample. Their radial velocities would support only for a small number of stars the suggestion that the carbon stars are actually located in the SDG, while the majority of the stars are moving towards us and could be Bulge members.

The spectroscopic results related to the CN line strength and the NaD equivalent width would support membership to the SDG combined with a binary evolution scenario for these stars. Membership of the Bulge does not make sense, because there is in that case no trace of a predecessor, i.e. a brighter population of carbon stars (see Azzopardi 1994, Fig. 2). However, if both the photometric and spectroscopic analysis are correct then the Azzopardi et al. carbon stars are related to the SDG. Some stars move away from us in the same direction as the SDG, while others move towards us, away from the SDG. It is not clear if an encounter of the SDG with the galactic disc could result in the bifurcation of the radial velocity distribution for stars formed or located in the tidal tail. The numerical simulations from Johnston et al. (1995, their Fig. 10c and 10d) do show that the stars from a 1 Gyr old, tidal stream have a different radial velocity when observed at about 10° further along the orbit. But the presence of a moving group is not obvious, since its velocity distribution is not easily distinguished from halo or bulge stars.

References

Alard C., 1996, ApJ 458, L17
Alcock C., Allsman R.A., Alves D.R., et al., 1997, ApJ 474, 217
Azzopardi M., 1994, in proceedings third ESO/CTIO workshop *'The Local Group: comparative and global properties'*, , A. Layden, R.C. Smith and J. Storm (eds.), 129
Azzopardi M., Lequeux J., Rebeirot E., 1985, A&A 145, L4
Azzopardi M., Lequeux J., Robeirot E., 1988, A&A 202, L27
Azzopardi M., Lequeux J., Robeirot E., Westerlund B.E., 1991, A&AS 88, 265
Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E., 1994, A&AS 106, 275
Boothroyd A.I., Sackmann I.-J., Ahern S.C., 1993, ApJ 416, 762
Bouchet P., Manfroid J., Schmider F.X., 1991,
Fahlman G.G., Mandushev G., Richer H.B., et al., 1996, ApJ 459, L65
Green P.J., 1997, proceedings IAU symposium 177, *'The carbon star phenomenon'*, R.F. Wing (ed.), *in press* (=astro-ph/9608003)
Groenewegen M.A.T., de Jong T., 1993, A&A 267, 410
Groenewegen M.A.T., van den Hoek L.B., de Jong T., 1995, A&A 293, 381
Ibata R., Gilmore G., Irwin M.J., 1994, Nature 370, 194
Ibata R., Gilmore G., Irwin M.J., 1995, MNRAS 277, 781
Ibata R., Wyse R.F.G., Gilmore G., Irwin M.J., Suntzeff N.B., 1997, AJ 113, 635
Johnston K.V., Spergel D.N., Hernquist L., 1995, ApJ 451, 598
Lattanzio J.C., 1989, ApJ 344, L25
Lequeux J., 1990, in proceedings *'From Miras to planetary nebulae: which path for stellar evolution?'*, Montpellier (France), Sept. 4 – 7, 1989, M.-O. Mennessier and A. Omont (eds.), Editions Frontieres, 273
Marconi G., Buonanno R., Castellani M., et al. 1997, A&A *in press* (=astro-ph/9703081)
Marigo P., Bressan A., Chiosi C., 1996a, A&A 313, 545
Marigo P., Girardi L., Chiosi C., 1996b, A&A 316, L1
Mateo M., Kubiak M., Szymanski M., et al., 1995, AJ 110, 1141
Mateo M., Mirabel N., Udalski A., et al., 1996, ApJ 458, L13
McWilliam A., Rich R.M., 1994, ApJS 91, 749
Ng Y.K., 1997, A&A *accepted*
Ng Y.K., Schultheis M., 1997, A&A 123, 115
Ng Y.K., Bertelli G., Bressan A., Chiosi C., 1996, A&A 310, 711
Sarajedini A., Layden A.C., 1995, AJ 109, 1086
Tyson N., Rich R.M., 1991, ApJ 367, 547
Velazquez H., White S.D.M., 1995, MNRAS 275, L23
Westerlund B.E., Lequeux J., Azzopardi M., Robeirot E., 1991, A&A 244, 367
Westerlund B.E., Azzopardi M., Breysacher J., Robeirot E., 1993, A&A 260, L4
Westerlund B.E., Azzopardi M., Breysacher J., Robeirot E., 1995, A&A 303, 107
Whitelock P.A., Irwin M., Catchpole R.M., 1996, New Astronomy 1, 57

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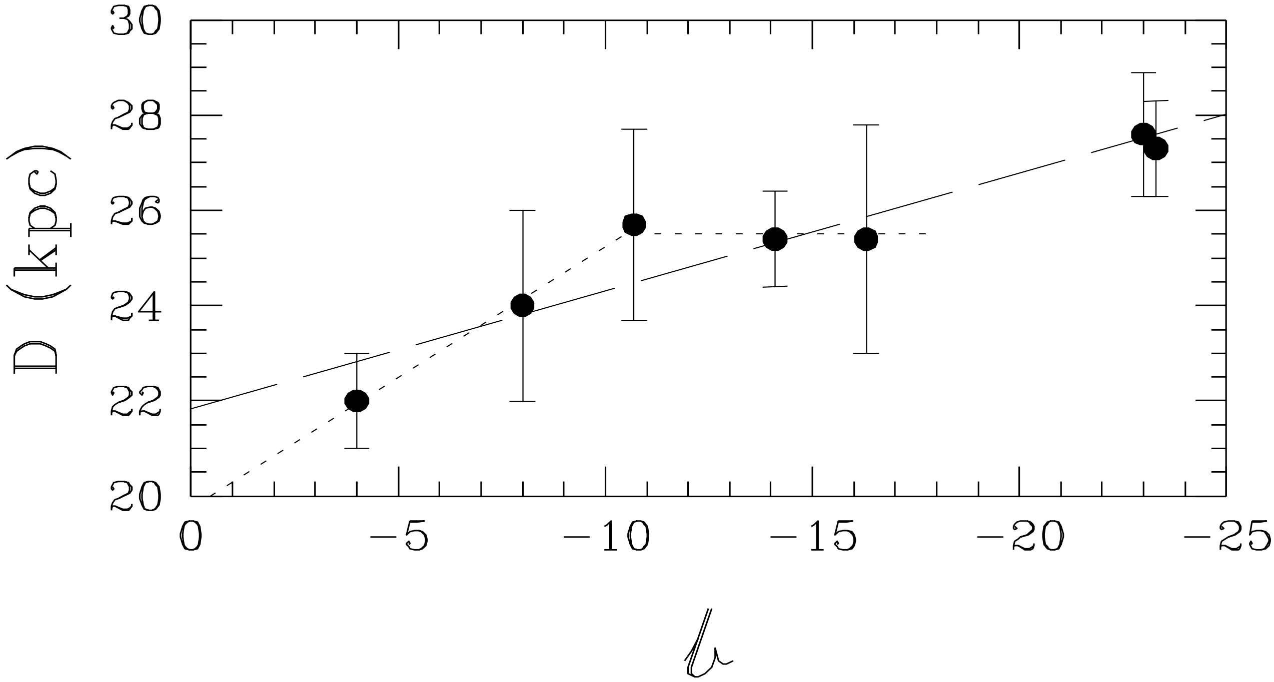

Fig. 1a. The distance of the Sagittarius dwarf galaxy determined for various galactic latitudes. The long-dashed line refers to an unweighted linear least squares fit for the points, while the dashed line shows a two section fit drawn through the points

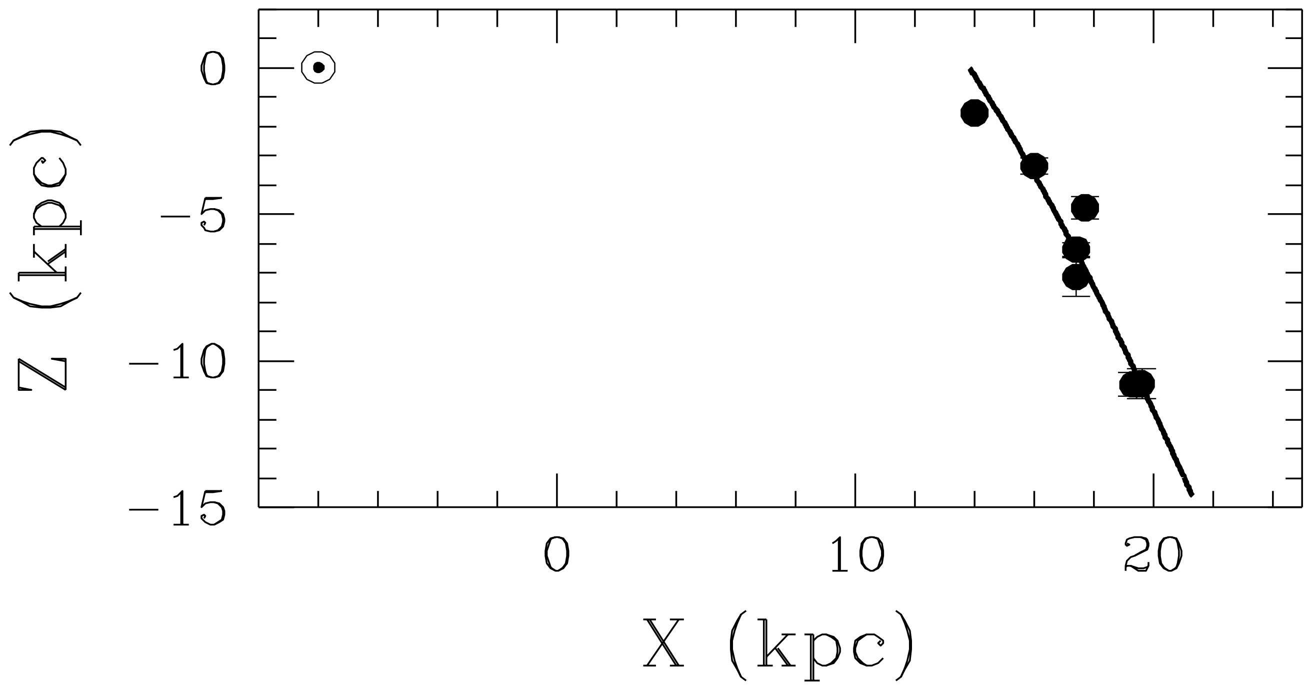

Fig. 1b. The course of the Sagittarius dwarf galaxy, projected on the $x - z$ plane. The radial velocity of the galaxy indicates that it is moving away from us. Together with the indicated course this implies that the galaxy crossed not so long ago the galactic disc. The position of the Sun is indicated by $\odot$

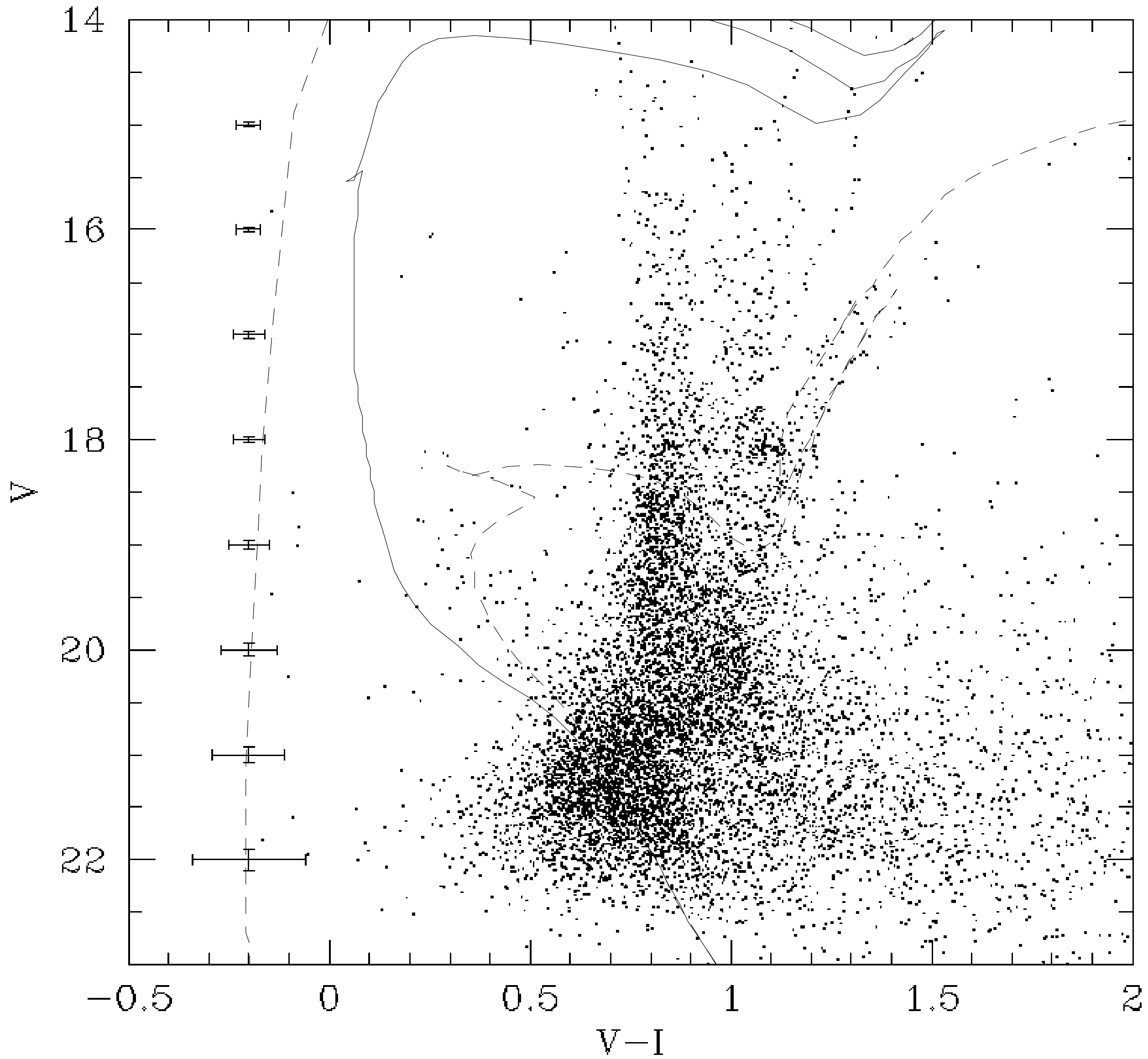

Fig. 3. CMD of SDG stars in field 1 from Marconi et al. (1997) with an overlay of Z = 0.008 isochrones of 0.1 Gyr (solid line) and 1 Gyr (dashed line) from Bertelli et al. (1994). The dashed line between (V,V–I) = ($14^{m}_{\cdot}0, 0^{m}_{\cdot}0$) and (V,V–I) = ($23^{m}_{\cdot}0, -0^{m}_{\cdot}2$) is the white dwarf cooling sequence from the 1 Gyr isochrone. An extinction of $A_V = 0^{m}_{\cdot}48$ and a distance modulus of $17^{m}_{\cdot}02$ (Mateo et al. 1995) have been adopted for the isochrones