Asymptotic giant branch stars in the Sculptor dwarf spheroidal galaxy

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ABSTRACT

JHKs photometry is presented for a 35 arcmin2 field centred on the Sculptor dwarf spheroidal galaxy. With the aid of published kinematic data definite galaxy members are identified and the width in J − K of the colour–magnitude diagram is shown to be consistent with an old population of stars with a large range in metal abundance. We identify two Asymptotic Giant Branch variables, both carbon Miras, with periods of 189 and 554 d, respectively, and discuss their ages, metallicities and mass-loss as well as their positions in the Mira period–luminosity diagram. There is evidence for a general period–age relation for Local Group Miras. The mass-loss rate for the 554-d variable, MAG29, appears to be consistent with that found for Miras of comparable period in other Local Group galaxies.

Key words: stars: AGB and post-AGB – stars: carbon – galaxies: individual: Sculptor–Local Group – galaxies: stellar content.

1 INTRODUCTION

This paper is one of a series aimed at finding and characterizing luminous Asymptotic Giant Branch (AGB) variables within Local Group galaxies; it follows similar work on Phoenix, Fornax and Leo I (Menzies et al. 2002, 2008; Whitelock et al. 2009; Menzies et al. 2010).

Sculptor was the first dwarf spheroidal galaxy to be discovered (Shapley 1938). Variable stars were found in it by Baade & Hubble (1939) and Thackeray (1950) confirmed that these were mainly RR Lyrae variables. Establishing the nature of these variables was important for Baade’s general concept of populations I and II (see letter from Baade to Thackeray 1950 March 27 in Feast 2000). Further work on the variables was carried out by van Agt (1978) and Kaluzny et al. (1995). Most of the variables are RR Lyrae stars but van Agt also discovered some red variables one of which we show below to be a Mira variable.

Carbon stars were discovered in the system by Azzopardi, Lequeux & Westerlund (1985, 1986), while Frogel et al. (1982) reported another three possible examples. In more recent times the system has been extensively studied for stellar chemical abundances (e.g. Coleman, Da Costa & Bland-Hawthorn 2005; Battaglia et al. 2008; Kirby et al. 2009) kinematics (e.g. Westfall et al. 2006; Walker, Mateo & Olszewski 2009) and star formation rate (Hurley-Keller 2000).

Sculptor is believed to contain a predominantly old population but with a small population of age ~2 Gyr and less (Revaz et al. 2009, especially their fig. 13). Work by various authors has shown that there is a large range in [Fe/H]. Kirby et al. (2009) found a mean value of ~ −1.58 and an asymmetric tail extending out to ~ −3.0. There is evidence of a metallicity gradient in the galaxy with the more metal strong stars preferentially concentrated to the centre (see Tolstoy et al. 2004; Westfall et al. 2006; Kirby et al. 2009; Walker et al. 2009).

2 OBSERVATIONS

Observations were made with the SIRIUS camera on the Japanese–South African Infrared Survey Facility (IRSF) at SAAO, Sutherland. The camera produces simultaneous J, H and KS images covering an approximately 7.2 × 7.2 arcmin2 field (after dithering) with a scale of 0.45 arcsec pix−1. Images were obtained on a 5 × 5 grid centred on the nominal centre of the galaxy, 01:00:06, −33:44:13 (2000.0) (van Agt 1978). With overlaps between adjacent fields, the area observed was approximately 35 arcmin2. An additional field was included later to allow one of the carbon stars (ALW1) to be observed.

Images were obtained at 25 epochs spread over 4 yr in the central nine fields, and between 16 and 20 epochs in the remaining fields. In each field, 10 dithered frames were combined after flat-fielding and dark and sky subtraction. Exposure times were either 30 or 20 s for each frame, depending on the seeing and on the brightness of the sky in the KS band. Photometry was performed using DOPHOT (Schechter, Mateo & Saha 1993) in ‘fixed-position’ mode, using the...
best-seeing $H$-band image in each field as templates. Aladin was used to correct the coordinate system on each template and RA and Dec. were determined for each measured star. This allowed a cross-correlation to be made with the 2MASS catalogue (Cutri et al. 2003), and photometric zero points were determined by comparison of our photometry with that of 2MASS. In each field, stars in common with the 2MASS catalogue with photometric quality A in each colour were identified and the IRSF zero-point was adjusted to match that of 2MASS. The mean number of common stars per field was 12 and the mean standard deviation over all fields of the differences between IRSF and 2MASS are 0.04 mag in $J$ and 0.06 mag in $K_S$. No account was taken of possible colour transformations, such as in Kato et al. (2007). Those transformations were derived using highly reddened objects to define the red end and it is not obvious that the same transformations will apply to carbon stars.

3 COLOUR–MAGNITUDE AND COLOUR–COLOUR DIAGRAMS

Fig. 1 shows the $K_S - (J - K_S)$ diagram and Fig. 2 the $(J - H) - (H - K_S)$ diagram for all the stars discussed in this paper. Mean magnitudes from all epochs are used in the plots.

Following the interpretation of the similar diagram for the Fornax dwarf spheroidal, the main features of Fig. 1 are a well defined red giant branch (RGB) with a tip near $K = 13.5$ mag; bluer stars of all magnitudes which are likely foreground stars; a few stars above the TRGB which are likely foreground stars, though some might be AGB members; two bright red variables; unresolved background galaxies with $J - K_S \sim 1.5$ mag extending from $K_S \sim 16.0$ mag to fainter magnitudes.

Bellazzini (2008) gives a relation between $M_K$ and $(J - K)$ for the tip of the red giant branch (TRGB) which is shown as a line in Fig. 1, assuming a distance modulus of 19.46 mag and adjusted for consistency with an Large Magellanic Cloud (LMC) distance modulus of 18.39 mag. It is interesting to note that, apart from the variables, all the C stars lie below the TRGB. Three stars with [Fe/H] < −3.4 are shown in the figure, and their details are listed in Table 1 for convenience.

We have found only two periodic red variables in Sculptor; one is our catalogue number 12002, found to be variable by van Agt (1978) and catalogued as V544. The other is newly discovered (our 3001), and was found to be a C star, designated MAG29, in a survey of 2MASS red stars by Mauron et al. (2004). The light curves are shown in Fig. 3. Following Whitelock et al. (2006) we classify them both as Mira variables, because they are periodic and have amplitudes $\Delta K > 0.4$ mag; MAG29 has a period of 554 d and V544 a period of 189 d. There is some evidence for long-term variations in the MAG29 light curve, but with only about two cycles covered by our observations it is difficult to comment constructively on this point; more data are required.

Of the eight carbon stars identified by Azzopardi et al. (1986), six fall in the area of our survey. In a study of late-type stars in Sculptor, Frogel et al. (1982) find two definite C stars (in common with Azzopardi et al.) and three possible ones, which however were not confirmed by Richer & Westerlund (1983). Our data for the variables and C stars are given in Table 1.

The distribution on the sky of the stars included in the colour–magnitude diagram is illustrated in Fig. 4.

4 MEMBERSHIP AND METALLICITY

Babusiaux, Gilmore & Irwin (2005) have drawn attention to the considerable breadth in the infrared of Sculptor’s giant branch. They deduce a range of 0.75 dex in [Fe/H] on the basis of fits of Padova theoretical isochrones for a fixed age to the $K_S$, $V - K_S$ colour–magnitude diagram. Since then, a number of kinematic and membership studies have been conducted, some of which also
Table 1. Red variables, Carbon stars and very metal-poor stars in Sculptor.

| $\alpha$ (equinox 2000.0) | $\delta$ | ScI# | $J$ | $H$ | $K_S$ | $J - K_S$ | Other name | Membership | Ref. | Note |
|--------------------------|---------|------|-----|-----|------|-----------|------------|------------|------|------|
| Variables                |         |      |     |     |      |           |            |            |      |      |
| 00:59:53.8               | −33:38:31 | 3001  | 14.35 | 12.94 | 11.44 | 2.91 | MAG29 | 1 |
| 00:59:58.9               | −33:28:35 | 12002 | 13.78 | 12.90 | 12.38 | 1.40 | V544, ALW3 | 2,3 |
| Carbon stars             |         |      |     |     |      |           |            |            |      |      |
| 00:58:36.1               | −33:40:26 | 26010 | 14.67 | 13.99 | 13.72 | 0.95 | ALW1 | Y | C | 3 |
| 01:00:10.4               | −33:51:00 | 7010  | 15.28 | 14.61 | 14.38 | 0.89 | ALW2 | Y | C | 3 |
| 01:00:10.7               | −33:40:58 | 1023  | 14.95 | 14.33 | 14.05 | 0.90 | ALW4, FBMC12 | Y | W | 3,4 |
| 01:00:20.7               | −33:45:18 | 1003  | 14.60 | 13.93 | 13.66 | 0.94 | ALW5, FBMC4 | Y | S | 3,4 |
| 01:00:27.4               | −33:53:04 | 8008  | 15.03 | 14.36 | 14.17 | 0.87 | ALW6 | 3 |
| 00:58:27.1               | −34:01:19 | 14.50 | 13.77 | 13.57 | 0.93 | ALW7 | Y | C | 3,5 |
| 00:58:30.7               | −33:28:40 | 15.20 | 14.73 | 14.37 | 0.83 | ALW8 | Y | W | 3,5 |
| Metal-poor stars         |         |      |     |     |      |           |            |            |      |      |
| 01:00:47.8               | −34:41:03 | 2030  | 16.46 | 15.89 | 15.83 | 0.63 | S1020549 | Y | S | K | 6 |
| 01:00:05.0               | −34:01:17 | 20028 | 16.48 | 15.94 | 15.92 | 0.56 | Scl07-49 | Y | Wa | 6 |
| 01:00:01.1               | −33:59:21 | 20034 | 16.86 | 16.31 | 16.30 | 0.56 | Scl07-50 | Y | We | 6 |

Note.
(1) MAG29 is 2MASS00595367–3338308. It is a C star according to Mauron et al. (2004) MAG29 has a peak-to-peak $K$ amplitude of 0.87 mag.
(2) V544 from van Agt (1978). Peak-to-peak $K$ amplitude 0.42 mag.
(3) ALW numbers from Azzopardi et al. (1986). Note ALW2 and ALW3 are reversed in Azzopardi et al. (1985).
(4) FBMC numbers from Frogel et al. (1982).
(5) 2MASS data for ALW7 (J00582732–3401186) and ALW 8 (J00583082–3328401) outside our field.
(6) [Fe/H]: −3.81 (Scl2030) (Frebel, Kirby & Simon 2010); −3.48 (Scl20034), −3.96 (Scl20028) (Tafelmeyer et al. 2010). Member (Y) according to Coleman et al. (2005): C; Schweitzer et al. (1995): S; Walker et al. (2009): Wa; Westfall et al. (2006): We.

Figure 3. $K_S$ light curves of (bottom panel) MAG29 and (top panel) V544 phased with periods 554 and 189 d, respectively, and arbitrary epoch of JD 2450000. For MAG29 filled circles (black) show first pulsation cycle, triangles (magenta) show second cycle, squares (cyan) show third cycle. For V544, these same symbols show the first, second, third pairs of cycles, respectively.

determine metallicities for individual stars. We use these new results to investigate the star formation history of Sculptor further.

A proper-motion study covering 1177 stars within a 7.25 arcmin radius of the Sculptor centre was conducted by Schweitzer et al. (1995). Our limiting magnitude is significantly brighter than theirs, but we have observed 407 star in common with their presumably unbiased selection, including 381 member stars.

Coleman et al. (2005) conducted a wide-area (10 deg² centred on the galaxy) photometric and spectroscopic survey of Sculptor...
with a view to mapping the outer structure of the galaxy. The $V$, $V-I$ colour–magnitude diagram was used to select likely members. Velocities were determined from the spectra and the equivalent width of two Ca ii triplet lines used to determine [Fe/H] on the Zinn & West (1984) metallicity scale. Data were only published for members, of which 84 are in common with our photometry.

Another wide-area investigation was conducted by Westfall et al. (2006), this time employing Washington $M, T2 + DDO51$ photometry to isolate likely members. Their final catalogue contains 179 stars (157 velocity members) of which 113 are in common with our catalogue. No metallicity information was provided.

Sculptor was included in a velocity survey of four Local Group dwarf spheroidals by Walker et al. (2009). The area covered extends well beyond our survey fields, and a total of 1541 stars with velocities and line strength information are catalogued. These were selected on the basis of their positions within a box drawn on a $V$, $V-I$ colour–magnitude diagram. The bright limit appears to lie well below the tip of TRGB. Our survey has 762 stars in common with Walker et al., including 729 members.

In a large-scale survey of abundances in Sculptor, Kirby et al. (2009) catalogue [Fe/H] values based on Ca ii triplet measurements for 388 stars which were selected from the Westfall et al. (2006) paper. Only radial-velocity members are listed, but the underlying sample is subject to the same selection criteria as in the Westfall et al. study. Kirby et al. show that their abundances are in good agreement with those derived from high-resolution spectra by Battaglia et al. (2008).

Finally, in a paper aimed at comparing Ca ii triplet and high-resolution spectroscopy of Sculptor stars, Battaglia et al. (2008) catalogue 93 stars, all of which are in common with our survey. They show that Ca ii triplet abundances calibrated with respect to globular cluster [Fe/H] data give a reliable measure of metal abundance for members of Sculptor.

Taking all of these surveys together, we find 952 definite members and 48 non-members in our sample, with a further 796 stars of unknown status. Our final $JHK_s$ data, with membership status, are listed in Table 2. The coordinates are as determined by us, and the column labelled ‘Scl#’ refers to our internal numbers for the stars measured.

The $K_s, J - K_s$ colour–magnitude diagram is shown in Fig. 5, with the definite members marked in green, and definite non-members in magenta. Given the biases in the catalogues referred

### Table 2. $JHK_s$ for stars in Sculptor.

| $\alpha$ (equinox 2000.0) | $\delta$ | Scl# | $J$ | $H$ | $K_s$ | $J-K_s$ | Membership ref. |
|--------------------------|---------|------|-----|-----|-------|---------|-----------------|
| 00:58:15.7               | −33:40:27 | 26060 | 17.32 | 16.77 | 16.77 | 0.56    | Wa             |
| 00:58:19.5               | −33:43:00 | 26038 | 16.66 | 16.05 | 16.03 | 0.63    | Wa We          |
| 00:58:29.7               | −33:38:22 | 26064 | 17.29 | 16.68 | 16.64 | 0.66    | Wa             |
| 00:58:33.7               | −33:40:42 | 26043 | 17.25 | 16.63 | 16.62 | 0.63    | Wa             |
| 00:58:33.7               | −33:43:18 | 26013 | 15.15 | 14.48 | 14.34 | 0.81    | C We           |
| 00:58:38.0               | −33:43:03 | 26055 | 17.41 | 16.87 | 16.74 | 0.66    | Wa             |
| 00:58:39.2               | −33:43:14 | 26054 | 17.35 | 16.83 | 16.74 | 0.62    | Wa             |
| 00:58:40.8               | −33:39:44 | 26044 | 17.17 | 16.58 | 16.54 | 0.63    | Wa             |
| 00:58:43.1               | −33:43:34 | 26036 | 16.79 | 16.24 | 16.14 | 0.65    | Wa             |
| 00:58:43.4               | −33:35:59 | 15035 | 16.67 | 16.11 | 16.03 | 0.63    | Wa C           |
| 00:58:44.0               | −33:41:45 | 16086 | 17.09 | 16.55 | 16.43 | 0.66    | Wa             |
| 00:58:44.7               | −33:41:56 | 16006 | 14.66 | 14.00 | 13.88 | 0.78    | We             |
| 00:58:44.7               | −33:30:49 | 14018 | 16.31 | 15.74 | 15.61 | 0.70    | Wa We          |
| 00:58:45.5               | −33:38:02 | 15026 | 16.73 | 16.19 | 16.16 | 0.57    | Wa             |
| 00:58:45.6               | −33:35:10 | 15059 | 17.61 | 17.16 | 17.09 | 0.52    | Wa             |

**Note.**

Membership references: Battaglia et al. (2008): B; Coleman et al. (2005): C; Kirby et al. (2009): K; Schweitzer et al. (1995): S; Walker et al. (2009): Wa; Westfall et al. (2006): We.

This is a partial table to indicate the format and contents. The full table including definite members and non-members, as well as stars with unknown status is available with the online version of the paper – see Supporting Information.

Figure 5. Colour–magnitude diagram for Sculptor with symbols as in Fig. 1. The line shows the expected position of the tip of the red giant branch assuming a distance modulus of 19.46 mag (see text). Definite proper motion or radial velocity members are overplotted as green dots, while non-members are shown as magenta open squares.
to above, too much should not be read into the distribution of stars with \( K_S \) magnitude, especially at the bright end where AGB stars, if any, have probably been discriminated against. The sloping line indicates where the tip of TRGB is expected to be (Bellazzini 2008) for a range of \( J - K_S \) magnitudes as proxies for metal abundance.

It is noteworthy that some of the ‘definite’ members lie some distance from the giant branch in Fig. 5 on the blue side. There are three outliers more than 0.1 mag bluer than the blue edge of the giant branch. Three stars from the Schweitzer et al. (1995) catalogue, our numbers 1017, 2034 and 9033, have probabilities of membership of 0.61, 0.90 and 0.78, respectively. They all lie in a part of the \( J - H, H - K \) diagram that suggests they are most likely field stars, but it would be worth checking on this. On the red side, star 7082 is about 0.2 mag redder than the red edge of the giant branch, but is a member according to Walker et al. (2009).

We have already alluded to the good agreement between the Kirby et al. (2009) and Battaglia et al. (2008) metallicities. The same applies to the Coleman et al. (2005) results, once they have been converted to the Carretta & Gratton (1997) scale. This is illustrated in Fig. 6(a). Walker et al. (2009) measured equivalent widths for several Fe and Mg absorption lines in their spectra. They calibrated these with respect to globular cluster abundances to give [Fe/H] for the Sculptor stars. They cautioned against the use of these as absolute abundances since in two other Local Group galaxies, abundances derived from Fe and Mg lines in this way gave rise to significantly narrower ranges than did those derived from the Ca ii triplet. We find the same result for stars we have in common with both Kirby et al. (2009) and Walker et al. (2009) as shown in Fig. 6(b).

We have determined the mean \( J - K_S \) as a function of \( K_S \) for the giant branch members and have divided them into two groups, redder or bluer than the mean. Using the metallicities from Coleman et al. (2005), Kirby et al. (2009) and Battaglia et al. (2008) we find a mean [Fe/H] of \(-1.48\) for 193 giants on the red side, and [Fe/H] of \(-1.81\) for 184 giants on the blue side. The two distributions are relatively broad and overlap, but the large range of abundances across the giant branch is clear.

In Fig. 7 we show the colour–magnitude diagram for the members and C stars (MAG29 is off the red edge). Superposed on the plot are isochrones (Marigo et al. 2008) for populations of age 12.7 Gyr and metal abundances, [Fe/H] = \(-1.76\) (blue) and \(-1.4\) (red), to illustrate that the width of the giant branch can be explained this way. Each isochrone has two parts, the rightmost one representing stars on the RGB, and the other the stars on the AGB.

The presence of two very red Miras, both carbon stars, indicates that there must be an intermediate age population in Sculptor as well as the old population (see Section 6). It is puzzling that the other carbon stars lie below the expected TRGB in the colour–magnitude diagram. However, Revaz et al. (2009) have found evidence for a population of age \( \sim 2 \) Gyr. In Fig. 8 we show an isochrone for a 2 Gyr population and [Fe/H] \( \sim -1.1 \) superposed on the colour–magnitude diagram of members. The section of the isochrone marked in black shows where the C/O ratio exceed 1.0, which suggests that carbon stars can be produced in the region of the diagram where they are
observed if such a young relatively metal-rich population exists in Sculptor.

5 MIRAS AND THE DISTANCE TO SCULPTOR

Table 3 lists various estimates of the distance to Sculptor. The distances of the two carbon-rich Miras are based on the $K$ and/or $M_{bol}$ period–luminosity (PL) relations:

$$M_K = -3.52 [\log P - 2.38] - 7.24$$

(1)

from Whitelock, Feast & van Leeuwen (2008), and

$$M_{bol} = -3.31 [\log P - 2.5] - 4.271$$

(2)

from Whitelock et al. (2009).

Both these relations were derived from carbon-rich Miras in the LMC and assume a modulus of 18.39 mag obtained from a classical Cepheid distance scale based on parallaxes of Galactic Cepheids and with a metallicity correction applied to the LMC Cepheid results (van Leeuwen et al. 2007). In the case of the 554-d Mira only the $M_{bol}$ result is listed. In view of the redness of the star ($J - K = 2.89$) mag we anticipate significant circumstellar absorption at $K$ and indeed the apparent distance modulus given using equation (2) is 0.4 mag greater than the $M_{bol}$ modulus. In the case of the 189-d variable, equation (1) gives a modulus of 19.20 mag and equation (2) a modulus of 19.18 mag. Data for Sculptor RR Lyraes in $K$ were taken from Pietrzyński et al. (2008). The $V$ data for the Sculptor RR Lyraes are from Kaluzny et al. (1995). A reddening of $E(B - V) = 0.018$ mag from Schlegel, Finkbeiner & Davies (1998) is adopted (see Pietrzyński et al. 2008). The derivation of the PL($K$) and $M(V)$–[Fe/H] relations used is discussed by Feast (2010). The table also gives the LMC moduli obtained using the same relations. A recent discussion of the TRGB distance scale (Feast 2011) gives a distance modulus of 19.43 mag for the LMC and 19.50 mag for Sculptor (van Loon et al. 2003) its age is $\sim 1.0$ Gyr. It is likely that there will be a range in periods at a given age. How large this is is not precisely known. The cluster NGC 1978 (age $\sim 2$ Gyr; Milone et al. 2009) contains two carbon-rich Miras for which Kamath et al. (2010) give periods of 376 and 458 d, while Nishida et al. give 491 d for the second star. In NGC 419 there are also two Miras (periods 488 and 738 d (Kamath et al 2010) for the first of which Nishida et al. give a period of 526 d). The mean age of this cluster is $\sim 1.5$ Gyr though there appears to have been an extended period of star formation in it (Rubele, Kerber & Girardi 2010), which seems a common phenomenon in intermediate age clusters in the Magellanic Clouds (Milone et al. 2009). A more detailed discussion of the evolution of AGB variables will be given elsewhere, but it will be clear that Mira variables with periods $\sim 200$ d and lying on the PL relations with $M_{bol} \sim -3.6$ mag are far below the RGB tip of clusters such as NGC1978 and must presumably have evolved from lower mass (older) stars.

Table 4 lists the periods of the Miras in the four Local Group galaxies we have so far studied. All these Miras are known to be, or are very likely to be carbon rich. We can now ask how consistent these Miras are with the Local Group results with the period–age correlation just described.

Consider first the long period Miras ($\sim 400$–$550$ d). These imply a significant population of a few Gyr age in all the systems. This is consistent with other evidence for Phoenix, Leo I and Fornax.

In Phoenix there is evidence of significant star formation in the age range 1–5 Gyr (see, e.g. Young et al. 2007, Fig. 6) and a lower rate between 5 and 10 Gyr. In Leo I the star formation rate is relatively high in this same age range (e.g. Dolphin 2002, fig. 15). In Fornax, too, there is significant star formation in this age range (e.g. Coleman & de Jong 2000, Fig. 7). The case of Sculptor is particularly interesting in that it is frequently said to have only a very old population. Nevertheless, the

6 AGES OF CARBON-RICH MIRAS

Mira variables have considerable potential both as Galactic and extragalactic distance indicators and as indicators of the age of stellar systems. Our work on dwarf spheroidals of the Local Group allows us to test Mira PL relations for possible metallicity dependence and to check whether our results are consistent with an period–age relation.

For oxygen-rich Miras the evidence (summarized by Feast 2009) indicates that periods increase with decreasing age and increasing initial mass, from $\sim 150$ d at an age of $\sim 12$ Gyr to 450 d at $\sim 3$ Gyr and OH/IR Miras with periods $\sim 1000$ d are even younger. A broadly similar trend of period with age is found amongst the longer period carbon-rich Miras. Thus Galactic kinematics (Feast, Whitelock & Menzies 2006) indicates an age of $\sim 1.8$ Gyr for carbon-rich Miras of period $\sim 520$ d with some indication of an increasing period with decreasing age. There is a Mira with a period of 450 d in NGC 1783 for which Milone et al. (2009) give an age of $\sim 1.5$ Gyr, and if a carbon-rich Mira of period 680 d is a member of an LMC cluster (van Loon et al. 2003) its age is $\sim 1.0$ Gyr. It is likely that there will be a range in periods at a given age. How large this is is not precisely known. The cluster NGC 1978 (age $\sim 2$ Gyr; Milone et al. 2009) contains two carbon-rich Miras for which Kamath et al. (2010) give periods of 376 and 458 d, while Nishida et al. give 491 d for the second star. In NGC 419 there are also two Miras (periods 488 and 738 d (Kamath et al 2010) for the first of which Nishida et al. give a period of 526 d). The mean age of this cluster is $\sim 1.5$ Gyr though there appears to have been an extended period of star formation in it (Rubele, Kerber & Girardi 2010), which seems a common phenomenon in intermediate age clusters in the Magellanic Clouds (Milone et al. 2009). A more detailed discussion of the evolution of AGB variables will be given elsewhere, but it will be clear that Mira variables with periods $\sim 200$ d and lying on the PL relations with $M_{bol} \sim -3.6$ mag are far below the RGB tip of clusters such as NGC1978 and must presumably have evolved from lower mass (older) stars.

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| Table 3. Distance modulus determinations for Sculptor. |
| Method     | Sculptor | LMC   |
|------------|----------|-------|
| 554 d C Mira ($M_{bol}$) | 19.57    | (18.39) |
| 189 d C Mira ($M_{bol}/M_K$) | 19.19    | (18.39) |
| RR Lyraes ($K$) | 19.37    | 18.37  |
| RR Lyraes ($V$) | 19.46    | 18.38  |
| TRGB($V$) | 19.46    | (18.39) |

| Table 4. Metal abundances in Local Group galaxies. |
| Galaxy | [Fe/H] | Mira periods (d) |
|--------|--------|------------------|
| Phoenix | $-1.37$–$-1.8$ (old population) | 425 |
| Leo I   | $-1.4$ | 158, 180, 191, 252, 283, 336, 523 |
| Fornax  | $-0.9$ (–2.0 to $-0.4$) | 215, 258, 267, 280, 350, 400, 470 |
| Sculptor | $-1.6$ (14 Gyr) to $-1.2$ (4 Gyr) | 189, 554 |
presence of a 554-d carbon-rich Mira indicates a significant population of age $\sim 1$–2 Gyr. Interestingly, the model of Revaz et al. (2009, fig. 13) does in fact show a small population in the 0–2 Gyr age range. Earlier work (Tolstoy et al. 2001, fig. 14) had this population at $\sim 4$ Gyr.

In both Leo I and Fornax there has been significant star formation over the whole period, 1–12 Gyr. Thus, the range of Mira periods found in these galaxies is expected if period depends on age. This does not itself establish an age–period relation. However, as was previously pointed out (Menzies et al. 2010) two of the Leo I Miras fall in the outer parts of the galaxy where, as shown by Mateo, Olszewski & Walker (2008), stars on the extended AGB are rare and where the main stellar population is older than in the inner parts. These two stars have periods of 191 and 283 d and are among the shorter period stars as we would expect for an older population.

Sculptor is particularly interesting in this regard. Although, as we have just seen, the presence of a 554-d Mira is consistent with the small $\sim 1$ Gyr population of the model, there is no evidence of an intermediate population between that and the main population at $\sim 10$ Gyr and older. Since the evidence points against a carbon-rich Mira of 189-d period belonging to a young population we must assign it to this old population.

Carbon stars in the Galactic halo are considered to be either intermediate age stars belonging to infalling streams or else old, low-mass objects in binaries that have acquired their carbon from an initially more massive companion. This latter mechanism is reasonable since only a relatively low percentage of halo giants are carbon rich. This does not seem to be a viable explanation for the short period carbon-rich Miras in the dwarf spheroidals unless there are undetected short-period oxygen-rich Miras in them, which is very unlikely. Evolutionary models of low-mass stars do not usually produce carbon stars (e.g. Iben & Renzini 1983). The exact details of the mass and metallicity at which carbon stars do form depend on the models and we note that recent work (e.g. Karakas 2010; Suda & Fujimoto 2010) suggests that low-mass stars with low metallicity may become carbon rich.

It is also of interest to note that whereas the intermediate age 554-d Mira is centrally located in Sculptor, the old 189 d one is outside the main concentration of stars in the galaxy. A similar Mira in Phoenix, with period 425 d, is only about 1.3 arcmin from the centre of that galaxy, compared with the overall extent of about 8.7 arcmin (van der Rydt, Demers & Kunkel 1991).

The relative numbers of Miras in the various galaxies is roughly what we might expect from the total luminosities of the galaxies and estimates of the age distribution of their stars. Thus, data in Amorisco & Evans (2011) suggest the total luminosities of Fornax and Leo I are $14 \pm 4$ and $3.4 \pm 1.1$ in units of $10^6$ solar luminosities and both have had ongoing star formation from early times until quite recently. However, the intermediate age population is relatively stronger compared to the very old population in Leo I than in Fornax (e.g. Dolphin 2002, fig. 15; Revaz et al. 2009, fig. 13). Thus the roughly equal number of Miras is understandable. Sculptor is less luminous ($\sim 1.4 \pm 0.6$ in the same units,) while Phoenix has a similar luminosity, and one expects fewer Miras in these galaxies. Both have a dominant old population and another increase in star formation later [$\lesssim 5$ Gyr in the case of Phoenix, $\lesssim 2$ Gyr in the case of Sculptor (Young et al. 2007; Revaz et al. 2009), though with the old population being relatively stronger in the case of Sculptor. Within the constraints of small number statistics these results for Miras in Local Group galaxies are consistent with a general period–age relation for Miras and the known properties of the galaxies.

7 CARBON-RICH MIRAS: METALLICITIES, MASS-LOSS AND LUMINOSITIES

The extent to which AGB stars produce dust at low metallicities is of importance among other things for an understanding of dust formation in the early universe.

There is a general expectation that, other things being equal, the dust production in oxygen-rich AGB stars will decrease with decreasing metallicity since the amount of available material will decrease. In AGB carbon stars, however, this restriction does not necessarily apply since fresh carbon is transported to the stellar atmosphere by dredge-up. Tests of these expectations using observations in the Galaxy and the Magellanic Clouds have not been entirely conclusive (see Sloan et al. 2008; van Loon et al. 2008). Nevertheless, this and our other papers on dwarf spheroidals have shown the presence of carbon Miras with thick dust shells in metal-poor systems. Furthermore, Sloan et al. (2009) have used Spitzer Space Telescope spectra to deduce that Sculptor MAG29 is producing significant amounts of dust and have suggested on this basis that evolved low-metallicity stars may make a significant contribution to dust production in the early Universe.

Our present discovery that this star is a long-period Mira allows us to further discuss this matter together with our work on Miras in other dwarf spheroidals. On the basis of the discussion of the last section, MAG29, with a period of 554 d, will be a member of the younger population in Sculptor. This has a mean metallicity of [Fe/H] $\sim -1.4$ (Tolstoy et al.). This star is similar to the longest period Mira in Leo I, with a period of 523 d, and is thus of similar age. Gullieuszik et al. (2009) find from Ca ii triplet observations of red giants that Leo I has a rather small dispersion in metal abundance, with [M/H] = $-1.2$, which they take as equivalent to [Fe/H] = $-1.4$ and thus similar to that inferred for MAG29. We have already shown (Menzies et al. 2010) that this star has a significant dust shell since, whilst it fits an $M_{bol} - \log P$ relation, it is too faint, due to shell absorption, for a $K - \log P$ relation. The difference between the apparent moduli for the $K$ and $M_{bol}$ relations gives an indication of the optical depth of the shell. For the Leo I star it is 0.8 mag whereas for MAG29 it is 0.4 mag indicating a thicker shell in the case of the Leo I Mira. There are other Miras in both Leo I and Fornax with similar thick shells indicating high mass-loss. Evidently MAG29 is not particularly exceptional in this regard.

It is worth noting that in comparing mass-loss rates in different stellar systems it is important to consider similar types of objects. At least in the case of oxygen-rich Miras the mean mass-loss rate is a function of both luminosity (i.e. period) and pulsation amplitude (White洛克, Feast & Pottasch 1987).

Groenewegen, Lançon & Marescaux (2009) have drawn attention to the great strength of the 1.53-µm band of C$_2$H$_2$ (acetylene) band in MAG29. Sloan et al. have discussed the bands of this molecule at 7.5 and 13.7 µm in MAG29 and connect their strength with the low metallicity. The 1.53-µm band is known from the work of Joyce (1998) to vary strongly with pulsation phase in the 421-d carbon-rich Mira V Cyg and comparing his results with the AAVSO light curve shows it to be very strong near minimum light. Our infrared light curves show that MAG29 was near maximum light when the data of both Groenewegen et al. and Sloan et al. were obtained implying unusual strength compared with stars so far observed in this region. However, we might expect it to be of similar strength in long-period, dust-enshrouded Miras in other Local Group systems. It is thus clear that carbon-rich Miras can produce significant amounts of dust in metal-poor systems. However, it is important to realize that the carbon-rich Miras in the dwarf spheroidals we have discussed...
are, judging from their periods ($\lesssim500\text{d}$), too old ($\sim1\text{ Gyr}$) and of too low initial mass ($\sim2\text{M}_\odot$) to be directly relevant to the early Universe. At the metallicities of our Galaxy or the LMC, Miras with intermediate initial masses and ages of relevance for the early Universe (periods $\gtrsim1000\text{d}$) are not carbon rich. This is attributed to Hot Bottom Burning which turns the carbon into nitrogen. Nevertheless, theory (e.g. Karakas 2010) suggests that at much lower metallicities, intermediate mass AGB stars do have C/O $>1$ and will thus be carbon stars.

8 CONCLUSIONS

Infrared monitoring of Sculptor over a 4-yr period has led to the following results.

(1) A comparison with spectroscopically measured abundances shows that the width of the giant branch is primarily due to a metallicity spread with extreme metal poor stars ([Fe/H] $<-3.4$) on the extreme blue side of the branch.

(2) Apart from the two variables discovered, the known carbon stars in the galaxy all lie below the TRGB. This contrasts with the situation in other dwarf spheroidal galaxies. However, an isochrone with [Fe/H] $\approx -1.1$ and an age of 2 Gyr (Marigo et al. 2008) has an abundance ratio C/O $>1$ extending down to the luminosities of these stars.

(3) Two carbon-rich Miras are present in Sculptor and give a mean distance modulus of 19.38 mag based on an LMC modulus of 18.39 mag.

(4) A general discussion of the relation of Mira periods to age, together with other evidence leads to the conclusion that the 554-d period Mira in Sculptor belongs to the small population with an age of $\sim2\text{ Gyr}$ whilst the 189-d Mira belongs to the dominant population of age $\sim10\text{ Gyr}$.

(5) The 554-d Mira is identical with the star MAG29 which has been previously discussed from Spitzer Space Telescope spectra as a low-metallicity star with heavy mass-loss. Using our previous work we find that there are several carbon-rich Miras in other metal-poor dwarf spheriodals with similarly thick circumstellar shells. Whilst this appears to strengthen the suggestion of Sloan et al. (2009) that low-metallicity carbon stars could make a significant contribution to dust formation in the early Universe, this depends on whether young, high-mass AGB stars can become carbon rich.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 2. JHK_s for stars in Sculptor.

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