The Brightest AGB Stars in the Leo I Dwarf Spheroidal Galaxy

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ABSTRACT
The first results of a study of the dwarf spheroidal galaxy, Leo I, using the new Nagoya-South African Infrared Survey Facility (IRSF) are presented. J, H, Ks observations show that most, if not all, of at least the top magnitude of the AGB in Ks is populated by carbon stars. In addition there are five very red objects which are believed to be dust enshrouded AGB stars. One of these is, remarkably, well outside the main body of the galaxy. Three of these obscured stars and five known carbon stars show variability in observations 11 months apart. One of the obscured stars has \( \Delta K_s = 0.87 \) making it highly likely that it, at least, is a Mira variable. The tip of the AGB is at \( M_{bol} \sim -5.1 \), but further variability studies are necessary to obtain a definitive value. Comparison with carbon stars, both Miras and non-Miras, in Magellanic Cloud clusters and taking into account other evidence on the ages and metallicities of Leo I populations suggests that these obscured stars belong to the youngest significant population of Leo I and have ages of \( \sim 2 \) Gyr.

Key words: galaxies: dwarf - galaxies: stellar content - stars: AGB and post-AGB - stars: variable: other - Local Group

1 INTRODUCTION
A programme has been started, using the recently commissioned Nagoya-South African 1.4m Infrared Survey Facility (IRSF) at SAAO Sutherland, to study the stellar populations, evolution and structures of Local Group galaxies. One aim of this programme is to detect long period variables (Miras and other types) in these systems and to derive their infrared light curves. The programme will necessarily take several years to complete. In the present communication we discuss the light that initial observations of the dwarf spheroidal galaxy, Leo I, throw on the AGB star population of that galaxy.

2 OBSERVATIONS
The IRSF is a 1.4-m telescope constructed and operated in terms of an agreement between SAAO and the Graduate School of Science and School of Science, Nagoya University, to carry out specialized surveys of the southern sky in the infrared. The telescope is equipped with a 3-channel camera, SIRIUS, constructed jointly by Nagoya University and the National Astronomical Observatory of Japan (Nagashima et al. 1999), that allows J, H and Ks images to be obtained simultaneously. The field of view is 7.8 arcmin square with a scale of 0.45 arcsec/pixel.

Images centred on Leo I (referred to hereafter as field A) were obtained at two epochs, 2001-01-16 and 2001-12-19, and processed by means of the standard IRSF pipeline (Nakajima, private communication). A single image comprises 10 dithered 30-s exposures. Three such sets of frames were combined to give an effective 900-s exposure in each of J, H and Ks, at both epochs. At this stage, the effective field of view is reduced to 7.2 arcmin square. Standard stars from Persson et al. (1998) were observed on each night and the results presented here are in the natural system of the SIRIUS camera, but with the zero point of the Persson et al. standards. At the first epoch, we obtained a supplementary set of images of an adjacent field (field B) centred 7 arcmin to the east of Field A. The two fields overlap by only about 20 arcsec.

Photometry was carried out on the images with the aid of DoPHOT (Schechter, Mateo & Saha 1993) used in fixed-
position mode. Since the seeing was much better at the first epoch (1.6 arcsec as opposed to 2.6 arcsec at the second epoch), the $K$ image obtained then was used as a template to measure a complete sample of stars to a limiting magnitude of about $K_s = 16.0$. The data are plotted in Figs. 1 ($K_s$ vs $(J - K_s)$) and 2 ($(J - H)$ vs $(H - K_s)$).

In the past, $E(B-V) = 0.02$, derived from Burstein and Heiles (1984) has generally been adopted for this galaxy (e.g. Lee et al. 1993). The results of Schlegel et al. (1998) suggest that a larger value (∼0.04) is appropriate. In neither case will this lead to significant reddening at JHK and we have neglected it.

2.1 Probable Field Stars

The stars lying to the blue of the main concentration of stars in Fig. 1(a) are shown as crosses there and are similarly marked in Fig. 2 (a). They are likely to be foreground field stars. This view is strengthened by the results for the adjacent field B where the stars in the almost vertical sequence are almost certainly field dwarfs. Two points (filled squares) at $(J - K_s) \sim 1.5$ in Fig. 1(a) and one in Fig. 1(b) are likely, from their colours, to be due to background galaxies. Indeed, close inspection of our images shows evidence for extended emission associated with two of them, one of which is clearly a galaxy on publicly available HST images.

2.2 The AGB sequence

Apart from the field stars discussed above and the four very red objects discussed in the next section, all the stars in field A lie on a sequence in Fig. 1(a). Objects identified as carbon stars by Azzopardi, Lequeux & Westerlund (1986 = ALW) or by Demers & Battinelli (2002 = DB) are indicated by star symbols. Photometry was obtained for 21 known or suspected carbon stars in Leo I, which account for all the stars in the ALW and DB lists except for the following: DB 4 and 8 which are seen on the edges of our frames but were not measured; DB 13 and ALW 4 and 6 which are outside our fields.

Using the bolometric corrections for carbon stars as a function of $(J - K)$ given by Frogel, Persson and Cohen (1980) and a distance modulus of 22.2 for Leo I based on the RGB tip (Lee et al. 1993), one finds that the carbon star sequence results from $M_{bol} = -4.2$ at $(J - K_s) = 0.9$ to $M_{bol} = -5.1$ at $(J - K_s) = 1.7$. However, as can be seen from work on galactic carbon stars (Whitelock 2000), the stars at the redder end of this sequence may well be Mira variables and cannot be taken as defining the upper limit of the sequence without more observations. All the stars of this sequence are AGB stars. The RGB tip is expected to be fainter than $M_{bol} = -4.0$ for any reasonable metallicities or ages (see for instance Castellani et al. 1992, Salaris & Cassisi 1998). The present results show clearly how the blue-green grism results of ALW miss the brighter carbon stars and would therefore lead to an underestimate of the brightness of the AGB tip. A similar underestimate of the AGB tip is present in V7 work (e.g. Lee et al. 1993, fig 4d). All but one of the brightest, reddest objects constituting the top of the AGB sequence appear in the DB list, and it is interesting to note that the obscured objects discussed below would, when dereddened, extend this sequence to even brighter $K_s$ magnitudes.

At the lower (bluer) end of the AGB sequence in Fig. 1(a) (which is of course determined by our adopted magnitude cut off) there is a group of objects without spectral classification. They lie mainly to the blue of the known carbon stars in Fig 2(a). It would be interesting to know whether these are O or C rich objects. A few of them may be foreground stars.

Fig 1(a) contains an object, without spectral classification, near the top of the AGB sequence with $(J - K_s) = 1.66$. In view of its position in Figs 1(a) and 2(a) it seems likely that it is also a carbon star. The fact that it was not found in the survey of DB may mean that it is a variable and was below the magnitude limit of DB at the time of their observations. The star’s colour and luminosity are similar to those expected for carbon Miras.

2.3 Obscured Objects

Four very red objects are conspicuous in Figs 1(a) and 2(a) (field A) while there is an even redder one, though it is rather fainter in $K_s$, in field B (Figs 1(b) and 2(b)). The positions and photometry of these five objects at JD 2451962.52 are listed in Table 1. Their locations in the colour-magnitude and two-colour diagrams are consistent with their being bright AGB stars obscured by circumstellar dust (see e.g. Whitelock 2000). In view of the fact that the top magnitude or more of the AGB sequence just discussed is heavily, and perhaps entirely, populated by carbon stars, it seems very likely that these obscured stars are also carbon stars. As noted by Nikolaev & Weinberg (2000) several other types of object have colours that would put them in this part of the two-colour diagram, for example, OH/IR stars and protostars. For the reasons outlined above, it seems more likely they are carbon- rather than oxygen stars, though the discussion on ages below is not significantly affected if the latter is the case. The presence of protostars of this brightness in a dwarf spheroidal galaxy would be quite remarkable.

These five stars are the most extreme examples yet found of this type of obscured object in dwarf spheroidal galaxies. The nearest comparable objects, though they are somewhat bluer($(J - K) \sim 2.4$), are the two carbon Miras that have been found in the Sagittarius dwarf spheroidal (Whitelock et al. 1999).

Table 1. Photometry and positions (equinox 2000) of 5 very red objects in the field of Leo I

| name | R.A.  | Dec  | $K_s$ | J-H  | H-K_s | J-K_s |
|------|------|-----|------|------|------|------|
| A    | 10:08:29.3 | 12:18:52 | 14.37 | 1.75 | 1.32 | 3.07 |
| B    | 10:08:27.3 | 12:18:57 | 14.45 | 1.50 | 1.08 | 2.58 |
| C    | 10:08:22.3 | 12:17:57 | 13.76 | 1.83 | 1.54 | 3.37 |
| D    | 10:08:41.3 | 12:18:08 | 14.89 | 1.44 | 1.12 | 2.56 |
| E    | 10:09:00.5 | 12:19:01 | 15.72 | 2.02 | 1.67 | 3.69 |

* We have preferred to use this distance modulus rather than the one given recently by Held et al. (2001) ($(m-M) = 22.0$) which depends on an adopted RR Lyrae absolute magnitude.
2.4 Variability

A comparison of the data from the two epochs of observation (JD 2451926.52 and 2452263.55) shows that a number of the brighter stars are variable. We list these stars in Table 2, where we give the magnitude difference between the second and first epochs, together with the standard deviation of the difference based on the internal errors of measurement as given by the DoPHOT program. Stars where variations of at least 4σ occur in two or more of the passbands are considered to be variables. Three of the obscured stars are included, together with five carbon stars: two from the ALW list, two in common between ALW and DB, and one in the DB list only. There are hints that some of the other carbon stars are also variable. Note that the obscured star C must have a very large amplitude and probably a period of at least

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Figure 1. (a) $K_s$ vs $(J-K_s)$ for Leo I centre. Crosses are probable field stars, open star symbols denote ALW carbon stars, while filled star symbols refer to DB stars not measured by ALW. Filled squares represent probable background galaxies. Variables from Table 2 are circled. (b) $K_s$ vs $(J-K_s)$ for a field 7 arcmin east of the centre of the galaxy. The nearly vertical sequence is probably due to field stars, the square is probably a field galaxy, and star E is at the lower right.

Figure 2. $(J-H)$ vs $(H-K_s)$ for (a) Leo I centre and (b) a field 7 arcmin east. Symbols as in figure 1.
Table 2. Probable variable stars

| name  | $\Delta J$ | $\sigma_J$ | $\Delta H$ | $\sigma_H$ | $\Delta K$ | $\sigma_K$ |
|-------|------------|------------|------------|------------|------------|------------|
| C     | 0.92       | 0.16       | 0.96       | 0.06       | 0.87       | 0.03       |
| ALW9  | 0.15       | 0.03       | 0.08       | 0.03       | 0.20       | 0.04       |
| B     | 0.34       | 0.09       | 0.18       | 0.04       | 0.14       | 0.03       |
| C10   | 0.22       | 0.03       | 0.15       | 0.03       | 0.14       | 0.04       |
| C06   | -0.19      | 0.02       | -0.14      | 0.02       | -0.14      | 0.03       |
| ALW16 | -0.24      | 0.03       | -0.02      | 0.03       | -0.18      | 0.04       |
| C07   | -0.28      | 0.02       | -0.16      | 0.02       | -0.24      | 0.04       |
| A     | -0.44      | 0.07       | -0.26      | 0.03       | -0.26      | 0.02       |

Obscured stars are denoted by their letters in Table 1, other stars by their DB numbers (C10 etc.) or their ALW designation.

1 year. This is consistent with the fact that stars with JHK colours similar to these stars are generally Mira variables (see Whitelock 2000, fig. 1).

3 DISCUSSION

A full discussion of the nature of the obscured stars must obviously be deferred till further variability studies have been made. Nevertheless it is of interest to draw some preliminary conclusions.

The results we have obtained are strikingly similar to those of Nishida et al. (2000) (see also Tanabé et al. 1997, 1999) who found an obscured carbon Mira in each of the intermediate age clusters, NGC 419, NGC 1783 and NGC 1978, in the Magellanic Clouds. These variables have values of $(J - K)$ (SAAO system) between 3.75 and 4.76. Thus, in colour, the obscured Leo I stars lie between the Sagittarius dwarf spheroidal Miras, mentioned above, and the LMC cluster Miras. In the Magellanic Cloud clusters the tip of the unobscured AGB is at $M_K \sim -8.4$ and $M_{bol} \sim -5.3$ (using data from Frogel et al. 1990 and distance moduli of 18.6 and 19.0 for the LMC and SMC). In Leo I the corresponding values are $-8.3$ and $-5.1$ which however remain uncertain pending full variability studies.

In the Magellanic Cloud clusters the Miras have a mean $M_K$ of $-8.0$ and $M_{bol} = -5.1$ or slightly brighter. The corresponding figures for the obscured stars in Leo I are quite uncertain both because three, and possibly all, are variable and also because the estimation of bolometric corrections for such stars from JHK colours is rather uncertain. The three obscured stars found to be variable have $M_K = -8.0$ and $M_{bol} \sim -4.9$ whilst all five obscured stars yield $M_K = -7.6$ and $M_{bol} \sim -4.6$. To derive these results for Leo I we have used a relation of $(H - K)$ to bolometric correction for carbon Miras derived by Whitelock (to be published) which includes the use of ISO data. Thus the tip of the unobscured AGB in $M_K$ and $M_{bol}$ is very similar in Leo I to that in the three Magellanic Cloud clusters. The obscured AGB may be fainter in $M_{bol}$ than the cluster Miras but that is not certain.

It is of some interest to note that if the intrinsic (underlying) colours of the five obscured stars were $(J - K) = 2.0$, they would all move to a position near the top of the AGB in $K_s$, when dereddened using the reddening law ($\Delta K \sim \Delta(J - K)$) found for the circumstellar envelope of the galactic carbon Mira R For (Feast et al. 1984).

The Magellanic Cloud clusters are estimated to have ages in the range 1.6 to 2.0 Gyr, metallicities, [Fe/H] $\sim -0.6$, and turn-off masses of $\sim 1.5M_{\odot}$. In view of the above discussion it seems likely that the Leo I obscured stars are in the same age and mass range. It is therefore interesting to note that Gallart et al (1999) suggest that major star formation in Leo I stopped about 2 Gyr ago and that a metallicity of that population as high as [Fe/H] $\sim -0.6$ is possible. The results thus suggest that the obscured stars, and the most luminous unobscured AGB stars, at least, belong to this youngest major stellar component of Leo I.

The very red star (star E) in field B is especially interesting. It is $\sim 8$ arcmin from the centre of Leo I, much further out than any of the other stars we discuss. Even the C stars outside field A, mentioned in section 2.2, are within $\sim 4.5$ arcmin of the centre. There is III in a wide area around Leo I and apparently associated with it (Blitz & Robishaw 2000). Star counts (Irwin & Hatzidimitriou 1995) show that Leo I has a tidal radius of 13 arcmin, which extends well beyond the distance of star E from the centre. However the stellar density at these distances is very low compared with that in the main body of the galaxy. Furthermore, in dwarf spheroidals the younger populations are generally more concentrated to the centre than the older ones (e.g. Harbeck et al. 2001). Thus if we have correctly interpreted this star as similar to the obscured AGB stars in field A, and hence relatively young, its position at such a large distance from the centre is remarkable. This is particularly so when it is recalled that such objects are short lived and are therefore tracers of much larger populations. Since the star has only been observed at one epoch we cannot comment on its possible variability.

4 CONCLUSIONS

We have obtained JHK$_s$ photometry of a complete sample of stars to $K_s = 16$ in a 7.2 arcmin square field centred on Leo I and in an adjacent field. This sample includes all 21 known carbon stars falling in the imaged area. Our results show that the top one magnitude or more of the AGB in $K_s$ is populated entirely or almost entirely by carbon stars. These stars form a sequence in the $K_s - (J - K_s)$ diagram and several of them are variable. In addition there are five very red stars, at least three of them variable, which from their magnitudes and colours are deduced to be AGB tip stars obscured by dust shells. They are strong candidates for Mira variability. These stars, and at least the brightest unobscured AGB stars, probably belong to the youngest and most metal rich of the significant stellar populations in Leo I. Comparison with carbon stars in Magellanic Cloud clusters suggests ages of about 2 Gyr for these stars in agreement with the age of the youngest major population in this galaxy as derived in other ways. Surprisingly, in view of the

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* Since this paper was submitted, further images have been obtained which show that star E is variable, which strengthens the assumption that it is an obscured AGB star.
fact that younger populations are generally more centrally concentrated than others in dwarf spheroidals, one of the obscured stars lies about 8 arcmin from the centre of the galaxy, compared with a tidal radius of 13 arcmin.

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