Discovery of carbon-rich Miras in the Galactic bulge

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ABSTRACT
Only one carbon-rich (C-rich, hereinafter) Mira variable has so far been suggested as a member of the Galactic bulge and this is in a symbiotic system. Here we describe a method for selecting C-rich candidates from an infrared colour-colour diagram, \((J−K_s)\) vs \(([9]−[18])\). Follow-up low-resolution spectroscopy resulted in the detection of 8 C-rich Mira variables from a sample of 36 candidates towards the Galactic bulge. Our near-infrared photometry indicates that two of these, including the known symbiotic, are closer than the main body of the bulge while a third is a known foreground object. Of the 5 bulge members, one shows He i and [O ii] emission and is possibly another symbiotic star. Our method is useful for identifying rare C-rich stars in the Galactic bulge and elsewhere. The age of these C-rich stars and the evolutionary process which produced them remain uncertain. They could be old and the products of either binary mass transfer or mergers, i.e. the descendants of blue stragglers, but we cannot rule out the possibility that they belong to a small in-situ population of metal-poor intermediate age (< 5 Gyr) stars in the bulge or that they have been accreted from a dwarf galaxy.

Key words: Galaxy: bulge – stars: carbon

1 INTRODUCTION
Work in recent years on the Galactic bulge has shown that it is complex, consisting of stars with a range of chemical compositions, ages and distributions (e.g., Ness & Freeman 2016; McWilliam 2016; Catchpole et al. 2016). It is striking that although Mira variables are common in the bulge only one carbon-rich Mira has been suggested as a possible bulge member, and that is in a symbiotic system (Miszalski, Mikołajewska, & Udalski 2013). However, a small number of giant carbon-rich stars have been found in the Galactic bulge (Azzopardi et al. 1991; Tyson & Rich 1991) and their nature will be considered below.

Miras are long period \((P ≥ 100\) days), large amplitude variables lying at the top of the asymptotic giant branch (AGB). Kinematic and other studies (Feast & Whitelock 2000; Feast 2008; Menzies et al. 2011) indicate that the Mira pulsation period is a good indicator of age and initial mass, and theoretical evolutionary models of single low to intermediate mass stars are consistent with this (Vassiliadis & Wood 1993). Miras are separated into two major groups according to their surface chemistry: oxygen-rich and carbon-rich (hereinafter, O-rich and C-rich, respectively). In addition to CO molecules which are present in the atmospheres of stars in both groups, O-rich stars, which have \(C/O< 1\), show molecules such as \(H_2O\), TiO and SiO whereas C-rich stars, with \(C/O> 1\), show molecules such as \(C_2\) and CN. Stars born from material of normal composition have more oxygen than carbon, but thermal pulses in shell-burning AGB stars can dredge up carbon produced in the interior to the surface, thereby making them C-rich. The ages and initial metallicities of stars will determine whether they become C-rich or not, and this third dredge-up path will produce C-rich stars aged at around 0.5–5 Gyr (Mouhcine & Lançon 2003; Marigo et al. 2008).

As regards C-rich stars generally, several other methods of production are possible. The giant and subgiant C-rich CH stars and Barium stars are in long period binary systems and are believed to have atmospheres polluted by a companion which has passed through the
AGB phase (McClure & Woodsworth 1990, and references therein). Cool dwarf C-rich stars have been found in significant numbers. Although they are not all now in binary systems, they must have been paired with a much more massive star at some stage in their evolution (Green & Margon 1994; Totten, Irwin, & Whitelock 2000; Green 2013; Plant et al. 2016). Various paths for the formation of CEMP stars (carbon-enriched metal poor stars) are discussed by Beers & Christlieb (2005). Binary interaction has been suggested for R type stars (Izzard, Jeffery, & Lattanzio 2007) and for the Azzopardi bulge C-rich stars (Azzopardi, Lequeux, & Rebeiro 1988; Whitelock 1993; Ng 1997), while a binary merge has been suggested for a C-rich Mira in a globular cluster (Feast, Menzies, & Whitelock 2013).

Cole & Weinberg (2002) assumed that stars in the bulge with \((J - K) > 2\) were C-rich. However, because mass-losing O-rich AGB stars can also be very red (e.g., Wood, Hабing, & McGregor 1998; Ojha et al. 2007), particularly in metal-rich environments, this is clearly not a sufficient condition for identifying C-rich stars in the bulge (Utenthaler et al. 2015; Catchpole et al. 2016). The present paper reports the discovery of C-rich Miras in the bulge based on a new method using infrared colours to select candidates and also on follow-up spectroscopy. We also briefly discuss the nature of these stars and their possible relationship to the Azzopardi C-rich stars.

2 SPECTROSCOPIC OBSERVATIONS

2.1 Target selection

We use the \((J - K)\) and \(([9] - [18])\) colours to identify candidate C-rich stars (Ishihara et al. 2010). C-rich and O-rich stars, especially those with thick circumstellar dust shells, tend to show different colour trends in these bands. As summarised by Ita et al. (2010), dusty C-rich stars often show the SiC emission band at 11.3 \(\mu m\) within the \([9]\) band in addition to a continuum excess due to amorphous carbon dust, while dusty O-rich stars have the silicate bands within 9.8 and 18 \(\mu m\) (Lançon & Wood 2000; Loiill, Lançon, & Jørgensen 2001; Wright et al. 2009). In the near-infrared bands, C-rich AGB stars have strong \(C_2\) and CN bands in \(J\), whilst there are no correspondingly strong bands in \(K\), which, unlike the \(K\) band, is minimally affected by the strong CO band longward of 2.29 \(\mu m\). In contrast, for O-rich AGB stars, strong \(H_2O\) absorption has a large impact on both \(J\) and \(K\) magnitudes while \(TiO\) and \(VO\) bands affect \(J\). These features at least give a qualitative explanation for the different locations of C-rich and O-rich Miras.

As the primary list of Miras towards the bulge we used the catalogue by Sozzyński et al. (2013) which contains 6528 Miras, together with more than 230,000 other types of long-period variable as a result of the third phase of Optical Gravitational Lensing Experiment (OGLE). During the first and mid-infrared colours are taken from the 2MASS (Skrutskie et al. 2006) and AKARI (Ishihara et al. 2010) surveys, respectively. Among the OGLE-III Miras, we found that 4148 objects have both of the required colours, and we identified 66 candidates that fall in the region expected for C-rich stars (Fig. 1, region E). We observed 33 of them, listed in Table 1, as we describe below.

![Figure 1. Colour-colour diagram, \((J - K)\) vs \(([9] - [18])\), for OGLE-III Miras in the bulge indicated by grey dots and for our spectroscopic targets. Those found to be C-rich and O-rich are indicated by filled circles and open squares, respectively, while crosses indicate those that were not observed or were unclassified. Error bars for \([9] - [18]\) colours are given for targets that we describe in this work. Panels (a) and (b) use 2MASS and IRSF near-infrared colours, respectively, except for three objects whose \(J - K\) colours are taken from Catchpole et al. (2016) in panel (b). The regions E and F are defined by Ishihara et al. (2011) and host mainly C-rich and O-rich stars, respectively.

We added a few targets from the catalogue of Catchpole et al. (2016), which is based on \(JHKL\) photometry (our numbers 06, 07, and 33). We combined their \(J - K\) colours (without system transformation) with the \(AKARI\) \([9] - [18]\) colours from the catalog by Ishihara et al. (2010) for identifying them as C-rich candidates. Object No. 06 (IRAS 17446–4048) was already identified as C-rich based on its IRAS/LRS spectrum (Groenewegen, de Jong, & Baas 1993); it is also listed in the General Catalog of Galactic Carbon stars (Alksnis et al. 2001).

When we cross correlate the variable catalogues (Sozzyński et al. 2013; Catchpole et al. 2016) with the photometric ones (2MASS and \(AKARI\)), we used a relatively large radius, \(5''\), in order to avoid missing any C-rich stars whose positions got somehow disturbed by error. Nevertheless, every target we observed has good positional matches in the 2MASS and \(AKARI\) catalogues within \(2.5''\) (mostly
within 0.5″ of a 2MASS counterpart and within 1.5″ of an AKARI counterpart). Miras almost always dominate other nearby stars in the infrared and the cross-correlation with infrared catalogues is straightforward.

It should be noted that the interstellar reddening can affect our target selection. Although the OGLE-III survey regions (selected for their I-band survey) are expected to be less affected by the interstellar reddening than the Galactic mid-plane, in some regions AV reaches 6 mag (see e.g. Nataf et al. 2016b), which corresponds to ~0.8 mag in EJ−K. Considering that the effect of the reddening is larger in the near infrared than in the mid infrared, this may give offsets on the colour-colour diagram which bring some objects near the boundary from the region F (for O-rich) to E (for C-rich). We have not corrected the photometry of the selected candidates for interstellar reddening (in Fig. 1) although this might possibly be done in an approximate way using nearby giants. Again, the priority of our target selection was to include as many C-rich candidates as possible.

### 2.2 Observations and data analysis

For this programme we used the SpUpNIC spectrograph (Crause et al. 2016) on the SAAO 1.9 m telescope at Sutherland. Because the Miras are all very red, we installed the GR8 grating with a resolving power of 1200 to cover the wavelength range from 5600 to 9200 Å. With a slit width corresponding to 2.1 arcsec, this gave spectra with a resolution of about 8 Å. Conditions were rarely photometric throughout the one week’s observing run, 13–19 July, 2016, and the Moon was near full, resulting often in high sky backgrounds.

The spectra were bias-corrected and flat-fielded in the usual way, and IRAF routines were used to calibrate the spectra in wavelength. For some objects, close companions coupled with relatively poor seeing made extraction of the target spectra difficult. While the SpUpNIC usually reads out images with 2 pixels binned (in the spatial direction), we observed the object No. 05 without this binning to maximise chance of separating it from a much brighter M-type companion. No attempt has been made to flux-correct the spectra.

### 2.3 Results

Spectra for 32 targets (Table 1) were of sufficient quality for further analysis. That for No. 8 is of low quality but a tentative classification seems plausible. A further three targets (Nos. 34, 35, and 36) were either too faint or too badly blended to be useful, so they are not included in the following discussion.

Figs. 2 and 3 show the spectra for C-rich and O-rich Miras respectively. The spectra in Fig. 2 clearly show the sequential vibrational bands of CN, 2-0, 3-1, and 4-2, between 7780 and 8400 Å (Wyckoff 1970). No. 08 has a relatively bright close companion that, together with seeing and bright sky background, made it difficult to extract the spectrum, resulting in a poor signal-to-noise ratio. There is no evidence of TiO bands and it is probably a C-rich star based on the appearance of the spectrum in the region around the CN bands. The spectra in Fig. 3, in contrast, are characterized by strong TiO bands at 8194 and 8430 Å together with TiO bands longward of 7667 Å beside the telluric A band at around 7594 Å (Wyckoff 1970; Lançon & Wood 2000). We thus gave the classification as listed in Table 1, seven C-rich, one probably C-rich and 25 O-rich Miras.

In Fig. 2, our spectrum of No. 01 is similar to that shown by Miszalski et al. (2013) who identify the star (H1-45) as a symbiotic.

![Table 1](image)

| No. | Object | I (°) | b (°) | UT (in 2016) | Exp (s) | Type |
|-----|--------|------|------|-------------|--------|------|
| 01  | 149402 | +2.0186 | -2.0559 | 7/13 19:24 | 420 C |      |
| 02  | 145820 | -2.7870 | -4.7249 | 7/14 22:37 | 2400 C |      |
| 03  | 056745 | -0.3282 | -1.2751 | 7/13 22:09 | 600 C |      |
| 04  | 169921 | -0.1137 | -3.7556 | 7/13 21:03 | 600 C |      |
| 05  | 189627 | +2.4710 | -2.9176 | 7/14 20:23 | 1200 C |      |
| 06  | C16CC1 | -9.9378 | -6.5831 | 7/18 18:38 | 300 C |      |
| 07  | C16CC3 | +7.3177 | -8.9058 | 7/18 18:54 | 600 C |      |
| 08  | 230835 | +7.1745 | -4.7850 | 7/17 01:07 | 1200 C |      |
| 09  | 194902 | +2.2482 | -3.2756 | 7/15 00:39 | 300 M |      |
| 10  | 013404 | +0.1418 | 2.5743 | 7/13 20:17 | 420 M |      |
| 11  | 031232 | +3.9599 | 2.3630 | 7/15 00:51 | 300 M |      |
| 12  | 030924 | +4.7764 | 2.4548 | 7/18 18:23 | 300 M |      |
| 13  | 039561 | +5.3812 | 2.7934 | 7/19 16:00 | 300 M |      |
| 14  | 110786 | -2.3417 | -3.5774 | 7/13 20:40 | 300 M |      |
| 15  | 122034 | -1.8007 | -3.5504 | 7/16 23:35 | 300 M |      |
| 16  | 127293 | +0.2527 | -2.5135 | 7/17 18:55 | 300 M |      |
| 17  | 131690 | -0.3688 | -2.9776 | 7/17 20:07 | 300 M |      |
| 18  | 133170 | +0.1915 | -2.6888 | 7/19 00:06 | 300 M |      |
| 19  | 170446 | +1.8618 | -2.6492 | 7/15 00:22 | 300 M |      |
| 20  | 188857 | +0.0420 | -4.2511 | 7/15 00:08 | 300 M |      |
| 21  | 195036 | +1.8849 | -3.4856 | 7/16 23:55 | 300 M |      |
| 22  | 195810 | +2.0728 | -3.4196 | 7/13 23:04 | 600 M |      |
| 23  | 214635 | +5.1753 | -2.6767 | 7/17 01:45 | 300 M |      |
| 24  | 216952 | -0.1630 | -5.7607 | 7/17 00:13 | 1200 M |      |
| 25  | 230250 | +6.9510 | -4.2590 | 7/16 21:18 | 120 M |      |
| 26  | 072723 | -0.2513 | -1.5968 | 7/14 18:19 | 900 M |      |
| 27  | 076743 | +0.5344 | -1.2234 | 7/15 21:38 | 600 M |      |
| 28  | 110674 | -0.9474 | -2.7629 | 7/19 00:27 | 300 M |      |
| 29  | 216273 | +2.4655 | -4.2839 | 7/16 20:12 | 600 M |      |
| 30  | 194903 | -0.2322 | -4.6589 | 7/16 22:01 | 600 M |      |
| 31  | 168224 | +0.9524 | -3.1055 | 7/17 20:23 | 300 M |      |
| 32  | 132552 | +1.2480 | -2.0630 | 7/16 19:33 | 1200 M |      |
| 33  | C16CC5 | +5.7962 | -7.9836 | 7/18 19:16 | 600 M |      |
| 34  | 082471 | -0.3249 | -1.8431 | 7/15 22:38 | 600 M |      |
| 35  | 151973 | +1.4302 | -2.4562 | 7/15 01:29 | 300 M |      |
| 36  | 179847 | +0.8947 | -3.3470 | 7/13 23:28 | 600 M |      |

† No. 1 is the C-rich star (H1-45) identified by Miszalski et al. (2013) as a symbiotic.
Figure 2. Spectra of C-rich Miras. The telluric absorption features, the strongest of which are due to O$_2$ 6867 Å (B band), H$_2$O 7164 Å and O$_2$ 7594 Å (A band), are shown as shaded vertical bands. The spectrum of No. 8 has a rather low signal-to-noise ratio as illustrated by the grey curve, but the black curve after smoothing shows the similarity to the other spectra.

Figure 3. Same as Fig. 2 but for O-rich Miras.

3 FOLLOW-UP PHOTOMETRY AND DISTANCES

3.1 New photometric data

We used the 1.4-m Infrared Survey Facility at Sutherland, with the SIRIUS near-infrared camera (Nagashima et al. 1999; Nagayama et al. 2003), to estimate mean magnitudes of our targets. We observed each target for 6–9 epochs between 2015 June and 2016 August. For No. 36, we obtained 18 measurements in each band, but we used two different integration times and so there are pairs of measurements close in time at each epoch. Fig. 4 plots phased light curves of C-rich Miras in JHK$_s$ in addition to the ones in the OGLE I band. The third-order Fourier series,

$$m(t) = m_0 + \sum_{i=1}^{3} A_i \cos \left(2\pi t/P + \phi_i \right)$$  \hspace{1cm} (1)

was fitted for the I band, and it was adjusted to fit the light curves in JHK$_s$ with changing the mean ($m_0$), total amplitude, and maximum phase. The amplitudes of our C-rich objects are larger than 1 mag, which is typical for C-rich Miras (Whitelock et al. 2006). The derived means are compared with the simple averages of N measurements in Table 2. The 2MASS magnitudes, crosses in Fig. 4, were not considered when the amplitudes were scaled and tend to be offset from the fitted curves (see the next paragraph). Although our photometric data show relatively large gaps in phase, the light curves seem to give reasonable estimates of mean. For the six C-rich Miras in Fig. 4, the difference between the two kinds of mean is estimated to be approximately $-0.1(\pm 0.2)$ mag in each of the JHK$_s$. This suggests that our estimates of mean are as good as 0.2 mag. The mean magnitudes from the fitted light curves are used in the following, but the difference between two kinds of means does not affect the conclusions. For the three objects from Catchpole et al. (2016), we adopt the published JHK magnitudes which are averages of two measurements in most cases.

It is worthwhile to give some further comments on the light curves of our C-rich Miras. The OGLE-III I-band light curves of the C-rich Miras are plotted in Fig. 5 when available. All of them show cycle-to-cycle variations except No. 02 for which the time coverage is very short. It is known that C-rich Miras tend to show such variations more often than O-rich ones (Whitelock et al. 2003, 2006). The fact that the 2MASS points in Fig. 4 are not aligned with the IRSF light curves may be explained by such variations since the 2MASS photometry was obtained over 15 years ago.

For two objects, Nos. 03 and 08, the fitted curves show large offsets in phase between the I-band and JHK$_s$-band ones in Fig. 4. The long time interval between the OGLE-III datasets and our photometry, ~10 years, makes it difficult to discuss such offsets, they can be understood as follows. No. 03 shows a large fluctuation in the I-band light curve and some cycles seem to show unphased trends. The OGLE-III light curve of No. 08 covers less than two cycles (Fig. 5) and seems to show a variation between the two minima. The period and phase may have significant errors which produce the inconsistency in phase between the two datasets.

As presented in Fig. 1, all eight C-rich stars fall in the region E although the large errors in [9] – [18] make it hard
Figure 4. Phased light curves of C-rich Miras. Black, blue, green, and red points indicate photometric measurements in $I$, $J$, $H$, and $K_s$. The cross symbols mark 2MASS magnitudes. The fitted light curves are drawn for each band. The width of a $I$-band curve corresponds to the standard deviation of the photometric points around the fitted curve, while the widths of the curves for other bands correspond to that of the $I$ band but scaled according to the difference in amplitudes. The filled and dashed horizontal lines indicate the mean magnitude for a fitted curve and the simple average of the photometric points, respectively.

to be sure of their precise locations in this diagram. On the other hand, many of the candidates are found to be actually O-rich, especially among those near the boundary between the regions E and F (Fig. 1). In fact, our follow-up photometry suggests that there were biases in the 2MASS $J - K_s$ colours that we used for the targets selection. This may be due to colour variations during a cycle; the 2MASS magnitudes were single-epoch values. Some O-rich stars could have been included in our C-rich candidates due to the interstellar reddening as mentioned in Section 2.1.

It should be pointed out that there are clearly O-rich stars with $J - K_s$ colours significantly larger than 2 mag. There are such red stars among our spectroscopic O-rich samples, and a number of objects among the OGLE-III bulge Miras have similarly large $J - K_s$ and are located in the region F. These are probably O-rich objects with thick circumstellar dust shells. The $J - K_s$ colour is not sufficient to select C-rich stars.

3.2 Colour-magnitude diagram

Fig. 6 shows the colour-magnitude diagram of our target Miras. OGLE Miras in the LMC (Soszyński et al. 2009) are compared after a vertical offset corresponding to the approximate difference in distance modulus, $\Delta \mu_0 = 4$ mag, between the bulge and the LMC. The line-of-sight depth of the bulge is much larger than that of the LMC and the colours and magnitudes of the bulge stars are affected by interstellar extinction, while the LMC Miras have small interstellar reddenings. The very bright Mira is No. 06 which was classified as a C-rich star based on its IRAS/LRS spectrum (Groenewegen, de Jong, & Baas 1993). This is obviously a foreground object. Whitelock et al. (2006) estimated its distance as 1.40 kpc and foreground extinction, $A_V = 0.80$ mag. The other C-rich Miras indicated by filled circles are scattered around a sequence roughly expected for such objects at around the distance of the bulge. Two of them look slightly brighter than the other Miras, and one somewhat fainter; we discuss their distances further below.

The C-rich stars from Azzopardi et al. (1988, 1991) are also shown in Fig. 6. These are faint for evolved C-rich AGB stars at the distance of the bulge as previously known (e.g. Azzopardi et al. 1988; Whitelock 1993; Ng 1997). The faint C-rich stars in the Sculptor dwarf spheroidal (Menzies et al. 2011) have $M_{K_s} < -5.1$, which would give $K_s < 9.5$ at the distance of the Galactic bulge. All of the bulge Azzopardi
The star symbol in Fig. 5 indicates X-ray emission makes it particularly interesting and suggests that it is a binary source.

In Fig. 6, the O-rich Miras we observed are indicated by open squares, and most of them are significantly bluer than the C-rich targets. This suggests that the latter have intrinsically larger $J - K$ as expected. Compared to the O-rich Miras in the LMC (grey dots in Fig. 6), our sample of O-rich Miras are redder, presumably due to the combined effect of circumstellar and interstellar dust, and at around the bright end of the LMC distribution. Fig. 7 shows that the spectroscopic targets we selected are biased towards longer periods which explains the higher luminosities.

### 3.3 Distances

Estimating accurate distances to the C-rich Miras is not straightforward. It is known that reddish C-rich Miras appear fainter than predicted by the near-infrared period-luminosity relation for bluer Miras. The deviation from the relation is correlated with the colour in a quadratic manner (Ita & Matsunaga 2011); such a correlation can be used for correcting the luminosities and estimating the distances. However, Miras towards the bulge are also reddened by interstellar dust. The interstellar extinction is represented by the total-to-selective extinction ratio, $A_K/E_{J-K} = 0.494$ (Nishiyama et al. 2006), which is different from the quadratic form of the deviation from the period-luminosity relation. These two effects are mixed and difficult to separate.

Here we consider the Wesenheit index, $W_{JK} = K_s - 0.5(J - K_s)$, to make approximate corrections for the reddening and dimming. The coefficient 0.5 is close to the total-to-selective extinction ratio and, to some extent, the ratio between the colour and the deviation from the period-luminosity relation, and thus $W_{JK}$ is insensitive to both reddening and the interstellar-type correction.
reddening effects. Fig. 8 plots the same objects, except non-Miras as in Fig. 6 on the log \( P - W_{J}K_{s} \) diagram. Besides the clearly foreground object, No. 06, two stars (Nos. 01 and 03) are distinctly brighter than the others. They are also bright in Fig. 6. This suggests that the latter two are also foreground objects. Although it is difficult to estimate their distances as mentioned above, they can be located at ~5 kpc from the Sun considering that they look brighter than the bulk of other Miras by approximately 1 mag. This is around the short end of the distance estimated by Miszalski et al. (2013) for the symbiotic star No. 01. Those authors also discussed the star’s possible membership of the extended bar-like Galactic bulge, which we cannot rule out. The fact that star No. 08 appears to be more than the bulk of the bulge stars may be an indication that we are simply observing the large spread of the bulge in the line of sight or it may indicate that this star is undergoing an obscuration event of the type common in C-rich Miras (Whitelock et al. 2006). Future tests of bulge membership should be based on kinematic measurements, both radial velocities from infrared high-resolution spectroscopy and proper motion, e.g. based on Gaia and/or the VVV (VISTA Variables in the Via Lactea) survey (Libralato et al. 2015).

The colours and magnitudes of the other four C-rich Miras, Nos. 02, 04, 05 and 07, are consistent with what we ex-
errors can increase the number of false positive candidates as discussed in Section 3. In a stellar system like the Galactic bulge where O-rich objects are dominant, it is hard to isolate individual C-rich objects. Nevertheless, this method has proved useful enough to find the new C-rich Miras in the bulge. As discussed in Section 3.1, C-rich Miras tend to show cycle-to-cycle variations (Fig. 5). The combination of light curve behaviour and the position in the \((J - K_s)\)-(\([9] - [18]\)) diagram, or just the light curve behaviour alone, might be a good diagnostic for selecting candidate C-rich Miras.

4.2 The origin of C-rich Miras in the bulge

The origin of the bulge C-rich Miras is difficult to establish. We consider three possibilities below.

The five C-rich Miras (Nos. 03-05, 07, and 08) are, within the uncertainties, in the bulge. They have periods between 373 and 512 days, and are not obviously interacting binaries. If they have evolved from isolated stars they are of intermediate age, 0.5-3 Gyr, according to the correlation between age and period for C-rich Miras (Feast, Whitelock, & Menzies 2006). This would imply the existence of a small population of intermediate age stars with low metallicities, or at least low oxygen abundances. The presence of intermediate age stars in the bulge has long been suspected, e.g. from the presence there of longer period O-rich Miras and related objects (see Catchpole et al. 2016; Nataf 2016a for reviews, and among others on this general topic, van Loon et al. 2003; Groenewegen & Blommaert 2005). However, at a time when a case was being made for an entirely old bulge, it was suggested that these variables could be merged binaries (Renzini & Greggio 1990). More recently evidence has been found for relatively metal-rich dwarfs with ages of ~ 5 Gyr or younger (Bensby et al. 2013; Haywood et al. 2016). and for stars (of unknown age) with \(\alpha\)-element abundances below the general bulge \(\alpha\)-Fe correlation (Recio-Blanco et al. 2017). This serves to illustrate the complexity of the bulge population and further exploration of this point is beyond the scope of this work. If our C-rich Miras are intermediate age stars, this would be the first demonstration that a (small) intermediate age population exists in the bulge with the correct mass, metallicity, and oxygen abundances to produce C-rich stars in the AGB dredge-up process.

However, older stars can produce more massive, potentially C-rich, progeny through either a mass transfer or a merger process. The C-rich Mira in the globular cluster Lynga 7 (Feast et al. 2013), with a pulsation period of 551 days, is an example of a merger; the authors argued that the current mass of that Mira was about twice what was expected for a single Mira in that cluster. Such stars could be the descendants of blue stragglers, several of which have been clearly identified in the bulge (Clarkson et al. 2011). It may also be that the Azzopardi C-rich stars are the giant branch and/or AGB predecessors of the C-rich Miras.

The two Miras likely in binary systems (Nos. 01 and 02, considering their symbiotic nature) also have long periods, 416 and 600 days, suggesting that they are binary mergers, i.e. these were once triple systems, or that they have accreted most of the mass of their companions. It is beyond the scope of this paper to discuss the theoretical implications of this in terms of stellar evolution or dynamics. It is certainly notable that two out of the six C-rich Miras that are in or very near the bulge are binary. Furthermore, the demonstration by Pietrzyński et al. (2012), that a bulge binary system involved an RR Lyr-like star with a mass of only 0.26 \(M_\odot\), shows that extreme mass transfer events, of the type that would be required to produce long period C-rich Miras, do occur.

A third alternative is that these C-rich Miras have been accreted from a merging dwarf galaxy with a composition similar to that of the Sagittarius dwarf galaxy, which contains numerous C-rich Miras in its core and in its tidal stream (Whitelock, Irwin, & Catchpole 1996; Law & Majewski 2016).

The merged binary scenario, or at least the scenario in which one star accretes most of the mass of a companion, is marginally preferred for the origin of these Miras, simply because mass-transfer binaries are found in the bulge and quite possibly become C-rich stars on the AGB. However, in a very large and heterogeneous population such as the bulge it is impossible to be definitive about the origins of a small group of stars. Identification of more C-rich stars and studies of their kinematics and distribution will shed light on the problem. An abundances analysis would help a great deal, but that is not practical for these very cool stars with extended and dynamic atmospheres.

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