Magellanic Cloud stars with TiO bands in emission: binary post-RGB/AGB stars or young stellar objects?

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ABSTRACT

14 stars from a sample of Magellanic Cloud objects selected to have a mid-infrared flux excess have been found to also show TiO bands in emission. The mid-infrared dust emission and the TiO band emission indicate that these stars have large amounts of hot circumstellar dust and gas in close proximity to the central star. The luminosities of the sources are typically several thousand L⊙, while the effective temperatures are ~4000–8000 K which puts them bluewards of the giant branch. Such stars could be post-asymptotic giant branch (post-AGB) stars of mass ~0.4–0.8 M⊙ or pre-main-sequence stars (young stellar objects) with masses in the range ~7–19 M⊙. If the stars are pre-main-sequence stars, they are substantially cooler and younger than stars at the birth line where Galactic protostars are first supposed to become optically visible out of their molecular clouds. They should therefore be hidden in their present evolutionary state, although this problem may be overcome if asymmetries are invoked or if the reduced metallicity of the Small Magellanic Cloud and Large Magellanic Cloud compared to the Galaxy makes the circumstellar material more transparent. The second explanation for these stars is that they are post-AGB or post-red giant branch stars that have recently undergone a binary interaction when the red giant of the binary system filled its Roche lobe. Being oxygen-rich, they have gone through this process before becoming carbon stars. Most of the stars vary slowly on time-scales of 1000 d or more, suggesting a changing circumstellar environment. Apart from the slow variations, most stars also show variability with periods of tens to hundreds of days. One star shows a period that is rapidly decreasing and we speculate that this star may have accreted a large blob of gas and dust on to a disc whose orbital radius is shrinking rapidly. Another star has Cepheid-like pulsations of rapidly increasing amplitude, suggesting a rapid rate of evolution. Seven stars show quasi-periodic variability and one star has a light curve similar to that of an eclipsing binary.

Key words: stars: AGB and post-AGB – stars: emission-line, Be – stars: pre-main-sequence.

1 INTRODUCTION

As part of an optical spectral survey of post-asymptotic giant branch (post-AGB) candidates in the Magellanic Clouds (MCs), we have discovered 14 stars that show bands of the TiO molecule in emission. The post-AGB candidates were selected because they had excess mid-infrared (mid-IR) emission in their spectral energy distributions (SEDs), indicating the presence of circumstellar dust, and presumably gas.

Normal red giant or main-sequence stars with effective temperatures T eff ≥ 3800 K (the M stars) show TiO bands in absorption. However, a small number of stars have previously been found to show TiO bands in emission. Covey et al. (2011) and Hillenbrand et al. (2012) have found three nearby young stellar objects (YSOs) which show TiO bands in emission. These stars have various other emission lines, especially Hα, and Covey et al. (2011) and Hillenbrand et al. (2012) argue that their YSOs have accretion discs and that the TiO band emission comes from dense circumstellar gas with n ≥ 109 cm−3 and T ~ 1400–4000 K in the accretion disc. An earlier study by Zickgraf et al. (1989) found four Be stars in which they tentatively identified emission in the TiO bandhead at 6159 Å (our spectra of some of these Be stars, to be published elsewhere, show additional bandheads of TiO at longer wavelengths, confirming the findings of Zickgraf et al. 1989). The Be stars also show a mid-IR flux excess in their SEDs and are known to be surrounded by discs of dust and gas (e.g. Porter & Rivinius 2003). Zickgraf et al. (1989) estimate a gas density greater than ~109 cm−3 for the circumstellar gas in their stars with TiO bands in emission.
Both YSOs and Be stars which show TiO band emission have been found to also show the first overtone band of the CO molecule in emission at 2.3 μm (Zickgraf et al. 1989; Hillenbrand et al. 2012).

The common feature linking the YSOs and Be stars is a circumstellar disc and it therefore seems that a circumstellar disc of gas and dust is an essential component for the production of TiO band emission and the unusual temperature structure it requires. A common feature of binary post-AGB stars is the presence of a circumbinary disc (e.g. Van Winckel 2004; de Ruyter et al. 2006), so these stars could also potentially show TiO bands in emission. Here, we describe objects with TiO band emission in the MCs that are possible post-AGB or post-red giant branch (post-RGB) star binaries, or YSOs.

2 OBSERVATIONS AND DATA REDUCTION

Full details of the selection of objects, spectral observations, data reduction and estimation of luminosity and \( T_{\text{eff}} \) are given by Kamath, Wood & Van Winckel (2013). In brief, post-AGB candidates were selected using photometry of MC stars from the Spitzer Space Telescope surveys SAGE (Meixner et al. 2006) and SAGE-SMC (Gordon et al. 2011) combined with optical \( UBV \) photometry from Zaritsky et al. (2002) for the Small Magellanic Cloud (SMC) and Zaritsky et al. (2004) for the Large Magellanic Cloud (LMC). Candidates were selected mostly for their strong 24 μm and/or 8 μm flux excesses. Optical spectra were taken with the multi-fibre AAmega spectrograph (Smith et al. 2004) and have a resolution of \( \sim 1300 \) and a wavelength range of \( \sim 3700–8800 \) Å. A computer program was created which automatically derived \( L_{\text{bol}} \), \( T_{\text{eff}} \), \( \log g \) and \([\text{Fe/H}]\) by comparing the observed spectra to synthetic spectra from Munari et al. (2005). Given the large amount of molecular band emission superimposed on our observed spectra, additional uncertainties are associated with the parameters derived by this procedure. We therefore also made eye-estimates of the spectral type using the spectral features in the interval \( \sim 3700–4700 \) Å shown in Gray & Corbally (2009) (predominantly Balmer lines, Ca II H&K lines and the G band). \( T_{\text{eff}} \) was then computed using the \( (T_{\text{eff}}, \text{spectral type}) \) relation given by Pickles (1998). Table 1 lists these values of \( T_{\text{eff}} \) along with spectral types and the automatically derived values of \( L_{\text{bol}}, \log g \) and \([\text{Fe/H}]\). In general, the two values of \( T_{\text{eff}} \) are reasonably similar.

The luminosities of the central stars were computed in two ways. First, after removing a foreground extinction corresponding to \( E(B-V) = 0.08 \) and 0.12 (Keller & Wood 2006) for the LMC and SMC, respectively, and using the extinction law of Cardelli, Clayton & Mathis (1989), the apparent luminosity was computed by integrating under the SED made from the photometry described above, along with WISE photometry in the \( W1–W4 \) bands (Wright et al. 2010). The absolute luminosities \( L_{\text{obs}} \) were then obtained by applying distance moduli of 18.54 and 18.93 (Keller & Wood 2006) for the LMC and SMC, respectively. We also noted that the heliocentric radial velocities of all the stars (Table 1) are consistent with the membership of the MCs so the adopted distance moduli are appropriate.

For circumstellar dust that is not in a spherically symmetric distribution, \( L_{\text{obs}} \) could be either an overestimate or an underestimate. For example, in the case of a dense disc obscuring the central star but only capturing a fraction of the 4π sr of photospheric emission,

\[ L_{\text{obs}} = \frac{\text{fraction of } 4\pi \text{ sr}}{4\pi} L_{\text{eff}}. \]

<table>
<thead>
<tr>
<th>Name</th>
<th>( T_{\text{eff}} ) (K)</th>
<th>( \log g ) (cgs)</th>
<th>SpT</th>
<th>Period (d)</th>
<th>Star type</th>
<th>( L_{\text{bol}} ) (L⊙)</th>
<th>( v_{\text{hel}} ) (km s(^{-1}))</th>
<th>( E(B-V) )</th>
<th>( \delta )</th>
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<td>K2</td>
<td>5500</td>
<td>G0</td>
<td>3000</td>
<td>195</td>
<td>0.0</td>
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<td>5500</td>
<td>G0</td>
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<tr>
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<td>3000</td>
<td>195</td>
<td>0.0</td>
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</tr>
</tbody>
</table>

Notes. SpT is the eye-estimated spectral type; \( r_{\text{eff}} \) is the bolometric radius; \( \delta \) is the distance to the star. All magnitudes are the estimated evolutionary states based on \( E(B-V) \). Star type is quite uncertain (see text).
It is possible that the circumstellar extinction law is different from the interstellar extinction law, but we have not explored this possibility. For example, Cohen et al. (2004) adopt a grey circumstellar extinction law for the Red Rectangle (Cohen et al. 2004). There will also be uncertain-
ity, both cases, suggests a non-spherical distribution of circumstellar involved: a large difference between the two values, which occurs caused by asymmetry in the circumstellar dust distribution except in cases, e.g., in the bipolar post-AGB star known as the Red Rectangle (Cohen et al. 2004). There will also be uncertain-

### Results

#### 3.1 Spectral energy distributions

The observed broad-band magnitudes of the objects from $U$ to $W_4$ are given in Table 1. The SEDs corresponding to the dereddened magnitudes were derived from the estimated fluxes. The bolometric correction to $L_{\text{phot}}$ was used. The reddening was then derived by finding the value of $E(B-V)$, which minimized the sum of the squared differences between the dereddened observed and the intrinsic fluxes of the best-fitting model atmosphere. In most cases, the dereddened fluxes were close to the best-fitting model atmosphere, while in some cases, e.g., in the bipolar post-AGB star known as the Red Rectangle (Cohen et al. 2004). There will also be uncertain-

Table 2. Photometry of the objects.

<table>
<thead>
<tr>
<th>Name</th>
<th>$U$</th>
<th>$B$</th>
<th>$V$</th>
<th>$I$</th>
<th>$J$</th>
<th>$H$</th>
<th>$K$</th>
<th>$W_1$</th>
<th>$W_2$</th>
<th>$W_3$</th>
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<td>16.547</td>
<td>14.584</td>
<td>13.493</td>
<td>12.510</td>
<td>12.030</td>
<td>...</td>
<td>10.937</td>
<td>10.492</td>
<td>...</td>
</tr>
</tbody>
</table>

Figure 1. SEDs of the first six sources. The red open squares show the observed broad-band photometry, while the blue filled squares show the dereddened photometry. For wavelengths up to 1.05 \(\mu m\), the best-fitting Munari synthetic spectrum is plotted, while for longer wavelengths the low-resolution flux distribution from the corresponding atmospheric model of Castelli & Kurucz (2004) is plotted.

star embedded with the observed star, or there is another independent object coincident on the sky with the optically observed star. The object J052023.97−695423.2 has a similarly large \(L_{\text{obs}}\). For it, \(L_{\text{obs}}\) is \(\sim 2.8\) times the luminosity \(L_{\text{phot}}\). J052023.97−695423.2 has previously been classified as a high-probability YSO candidate – see Section 3.3.

3.2 Optical spectra

The full observed optical spectra for the objects studied here are shown in Fig. 3. The absolute flux values for the spectra were obtained by matching the relative fluxes of the observed spectra to the photometric \(B\), \(V\) and \(I\) values. A range of spectral types are present, from hot stars with strong Balmer absorption lines to cool stars with calcium triplet lines in absorption but no Paschen lines.

TiO band emission is prominent in all the spectra. In order to see the TiO emission better, the spectra were divided by a low-order polynomial fit to the continuum. They were then re-plotted from 6000 to 8700 Å in Fig. 4. The top panel of Fig. 4 shows the spectrum of a late M star with the position of TiO and VO absorption bands marked. It is clear that for the objects being studied here, there is TiO emission in most of the TiO bands in the spectral region shown. It is not clear that there is any VO band emission. The existence of this emission indicates the presence near the central star of molecular gas with a temperature less than \(\sim 4000\) K and with a temperature profile that increases towards the observer. The origin of this temperature structure is unclear – see Hillenbrand et al. (2012) for a discussion of possibilities.

About half the spectra also show H\(\alpha\) in emission (see Table 1 and Figs 3 and 4). The H\(\alpha\) emission in J010628.81−715204.8 and J050747.45−684351.2 shows a P Cygni profile corresponding to wind terminal velocities of approximately 430 and 350 km s\(^{-1}\), respectively. J010628.81−715204.8 also shows the calcium triplet lines in emission. The H\(\alpha\) emission lines in J005504.57−723451.1 and J052023.97−695423.2 are resolved, and their observed
Stars with TiO bands in emission

Figure 2. SEDs of the remaining eight sources.

profiles correspond to the instrumental profile convolved with Gaussian velocity distributions of standard deviation 100 and 180 km s$^{-1}$, respectively. The H$\alpha$ emission in J052023.97$-$695423.2 also has broad wings extending out to 900 km s$^{-1}$. We note that H$\alpha$ emission is common in YSOs with discs that are accreting surrounding gas (Appenzeller & Mundt 1989), but it is also common in post-AGB stars (van de Steene, Wood & van Hoof 2000).

In some stars, the [O III] 5007 Å emission line can be seen. This is most likely LMC background emission not associated with the object. Such emission is very hard to remove with a multifibre
Figure 3. The spectra of the objects showing TiO bands in emission.

spectrograph which samples the sky at random points over a $2^\circ$ field.

3.3 The stars in the Hertzsprung–Russell diagram

The stars are shown in the Hertzsprung–Russell (HR) diagram in Fig. 5 along with evolutionary tracks for pre-main-sequence (PMS) stars, normal post-main-sequence stars, and post-AGB and post-RGB stars. Both $L_{\text{obs}}$ and $L_{\text{phot}}$ values are shown. In general, these two values do not differ greatly compared to the overall spread in luminosity values, except for the two stars mentioned in Section 3.1 where the dust is most likely in a thick edge-on disc or where a second object may be contributing to $L_{\text{obs}}$, thereby making it too large.

For the range of observed luminosities, it is possible to explain the stars as either PMS stars, normal post-main-sequence stars on helium core burning loops, or post-AGB or post-RGB stars. However, given that our observed stars all have large amounts of hot circumstellar material, it is unlikely that they are in the rather quiet evolutionary stage of helium core burning. The most likely stars to have mass-loss and an IR excess in this evolutionary phase are Cepheid variables. Yet, observations of these stars in the LMC (Neilson et al. 2010) show the mid-IR excess flux at 8 $\mu$m in these stars is about 10 per cent of the photospheric continuum, whereas in the present group of objects the mid-IR excess flux at 8 $\mu$m is typically about 10 times the photospheric continuum. We therefore reject the explanation of these stars as normal post-main-sequence stars.

The other possible evolutionary states for these objects are post-AGB or post-RGB stars, or PMS stars.3 In both the post-RGB and post-AGB cases, the observed stars must have undergone a binary interaction in order for them to have left their respective giant

3 In this paper, we use the term PMS star to describe the star itself, while we use the term YSO to describe the PMS star and its surrounding dust and gas. The term post-AGB star or post-RGB star can mean either the star itself or the star and its surrounding dust and gas.
Stars with TiO bands in emission

Figure 4. The continuum-normalized spectra from 6000 to 8700 Å. Also shown is the spectrum of a late M star with the positions of band heads of the TiO and VO molecules marked. The positions of Hα, the [SII] lines at 6717 and 6731 Å, and the Ca triplet lines are also shown.

branches. For RGB stars, which have luminosities $L < 2500 L_\odot$, single-star mass-loss is insufficient to remove the H-rich envelope and produce a post-RGB star (Vassiliadis & Wood 1993). The only way large amounts of mass-loss and evolution off the RGB can occur is via binary interaction, presumably a common envelope event that leaves the binary in a tighter orbit than the original one (e.g. Han, Podsriadlowski & Eggleton 1995). For AGB stars, large amounts of mass-loss can occur either by binary interaction or, for single stars, by the very high mass-loss rate 'superwind' that terminates AGB evolution (e.g. Vassiliadis & Wood 1993). However, in the MCs, all the single stars with high mass-loss rates, at least for $\log L/L_\odot < 4.3$, are carbon stars (e.g. Blum et al. 2006; Groenewegen et al. 2007; Gordon et al. 2011). Given that the stars in the present sample are oxygen-rich because they show TiO molecules in their spectra, we believe that only binary interaction could explain a post-AGB status.

It is not easy to distinguish between post-RGB/AGB binaries and PMS stars. Both are surrounded by large amounts of circumstellar gas which is accreting (or re-accreting in the case of post-RGB/AGB stars) on to a circumstellar or circumbinary disc. However, a distinguishing feature is the gravity of the central star. We note that, at a given luminosity, the mass of a PMS star is about 15–20 times that of the corresponding post-RGB/AGB star. This leads to a difference of $\sim 1.3$ in $\log g$ between PMS stars and post-RGB/AGB stars. The errors in our $\log g$ estimates for individual stars are typically 0.5 (Kamath et al. 2013), although the presence of strong TiO emission bands in the current set of stars almost certainly increases the error. Given the expected $\log g$ difference, we can use the derived $\log g$ values in Table 1 to make a tentative assignment of PMS or post-RGB/AGB status. This evolutionary status, PMS or post-RGB/AGB, is given in Table 1. The distinction between the post-RGB and post-AGB status is based on whether $L_{\text{phot}}$ is less than or greater than, respectively, the RGB tip luminosity $L_\approx 2500 L_\odot$. We estimate that there are four post-RGB stars, two post-AGB stars and six PMS stars, the latter including the four stars hotter than
$T_{\text{eff}} = 6000\, \text{K}$. For two stars, a status could not be assigned because the estimated log $g$ was almost mid-way between the PMS and post-RGB/AGB values.

Although some of the objects in our sample have been assigned the PMS status on the basis of their gravities, there is a problem with the existence of optically-visible PMS stars in the part of the HR diagram where these objects are observed. PMS stars to the right of the ‘birth line’ shown in Fig. 5 should not be seen optically (Stahler 1985; Palla & Stahler 1990; Bernasconi & Maeder 1996; Palla & Stahler 1999) since the stars would have evolved to the birth line or beyond before the optically-thick accretion process has completed. A possible way around this would be to invoke an asymmetry in the accretion process that would allow the central star to be seen through a gap in the surrounding material (e.g. along the pole of the accretion disc). The birth line shown in Fig. 5 was computed for Galactic stars with a Galactic Population I abundance. The lower abundance in the SMC and LMC could make the circumstellar material more transparent so that PMS stars could be seen in an earlier phase of evolution. Indeed, Lamers, Beaulieu & de Wit (1999) and de Wit et al. (2005) invoked the lower metallicity of the LMC to explain the optical visibility of a group of PMS candidates in the LMC of O and B spectral type. We note that our PMS candidates are much cooler than those of Lamers et al. (1999) and de Wit et al. (2005) so that the effect of asymmetry or metallicity would need to be much more pronounced than for their stars. The evolutionary status, PMS or post-RGB/AGB, assigned here should be considered tentative.

At least one of the stars we have classified as a PMS star, J052023.97$-$695423.2, has in the past been classified consistently as a YSO, strongly suggesting a PMS status. It was observed as part of the SAGE-SPEC mid-IR spectral survey (Woods et al. 2011) and was classified as a YSO. It was found to have silicate dust emission, consistent with the oxygen-rich atmosphere that we have detected. J052023.97$-$695423.2 was also classified as a high-probability YSO in the study of Whitney et al. (2008) which used broad-band near- and mid-IR colours and luminosities to statistically separate various classes of objects.

Three of the objects show strong Li lines and several other stars show marginal detections (Fig. 6 and Table 1). Relatively strong Li lines are found in PMS stars only before the Li is destroyed by nuclear reactions in the stellar interior (e.g. Appenzeller & Mundt 1989). If this occurs when the star is convective to the surface, then the surface Li will be depleted. The PMS evolutionary tracks of Bernasconi & Maeder (1996) show that deuterium burning starts early in the evolution of stars with the luminosities observed here, at $T_{\text{eff}} \sim 5000\, \text{K}$. The stars observed to have strong Li lines (J005355.00$-$731900.9, J051516.28$-$685539.7 and...
stars that show no detectable variability (the small annual variations that can be seen in the MACHO observations for J005504.57–723451.1 are an artefact of the data reduction). These stars are shown as crosses in Fig. 5.

Most other stars show variability that is a combination of a slow long-term brightening or fading and variability with periods from 30 d to more than 3000 d. The six stars J004805.01–732543.0, J005355.00–731900.9, J05514.24–732505.3, J010628.81–715204.8, J050747.45–684351.2 and J052023.97–695423.2 all show slow variations in magnitude over intervals longer than ~1000 d, possibly due to slow changes in dust obscuration or variability in the rate of accretion.

J004805.01–732543.0 was fairly constant for the first 1500 d of observation after which it brightened by about 1 mag and exhibited an oscillation whose period decreased from ~1150 d to ~400 d over an interval of 4500 d. This oscillation is shown in Fig. 8 from JD−244 8800 = 1500 onwards after the long-term trend in magnitude was removed by fitting a fifth-order polynomial in time. The oscillation looks RV Tauri like (alternating deep and shallow minima), but it is unlikely that the interior structure of the star associated with this object could change enough on such a short time-scale that a period of pulsation could change by the observed amount. It is therefore likely that this phenomenon is associated with an accretion event in a surrounding disc, with disc viscosity causing the radius of the accreted material and orbital period to shrink rapidly. This star is shown as an open square in Fig. 5.

As well as the slow magnitude changes in J005355.00–731900.9, there is also an eclipse-like or RV Tauri-like variation with a period between deep minima of 193 d. The phased-up light curve in the interval 2000 < JD−244 8800 < 5000 is shown in Fig. 8 after the long-term trend was removed by fitting a fifth-order polynomial in time. Such a period seems too long for an RV Tauri star: Alcock et al. (1998) and Soszyński et al. (2008) find a maximum period of about 110 d for RV Tauri stars in the LMC and Soszyński et al. (2010) find a maximum period of about 100 d for RV Tauri stars in the SMC (in RV Tauri stars, the period is taken to be the time between the alternate deep minima). We suggest that J005355.00–731900.9 is a binary system with an orbital period of 193 d. This star is shown as an open triangle in Fig. 5.

J005514.24–732505.3 shows a smooth Cepheid-like light curve of increasing amplitude superimposed on the long-term variation. The period of 206 d is much longer than that of any Population II Cepheid in the MCs (Alcock et al. 1998; Soszyński et al. 2008, 2010), but the star lies close to the instability strip shown in Fig. 5 for these stars. The rapid increase in amplitude in this star suggests that it is rapidly evolving through the pulsational instability strip into a region where growth rates are larger. One problem with the interpretation of the 206 d cycle as pulsation is that when the amplitude reaches ~1 mag, the light curve maintains a sinusoidal shape rather than changing to the saw-tooth shape typical of Cepheids with this amplitude. It is possible that the 206 d variation has some other explanation such as binarity. This star is shown as a filled triangle in Fig. 5.

The stars J004843.76–735516.8, J010628.81–715204.8, J010929.79–724820.6, J050747.45–684351.2, J051516.28–685539.7, J052023.97–695423.2 and J052230.40–685923.9 display quasi-periodic variability with periods of ~30–160 d. Their periods are listed in Table 1 when they could be determined. Three of the stars are of spectral type K where semiregular variability frequently occurs in normal red giant stars but two have earlier F and G spectral types. Two of the K stars (J010929.79–724820.6 and J051516.28–685539.7) also exhibit the long secondary periods

4 VARIABILITY

Light curves from the MACHO (Alcock et al. 1992) and/or the OGLE II and OGLE III experiments (Udalski, Kubiak & Szymanski 1997; Szymanski 2005; Soszyński et al. 2009; Soszyński et al. 2011) exist for 13 of the 14 stars in our sample, and they are shown in Fig. 7.

The stars show a range of types of variability. J005504.57–723451.1 and J010324.36–723803.5 are the only stars that show no detectable variability (the small annual variations that can be seen in the MACHO observations for J005504.57–723451.1 are an artefact of the data reduction). These stars are shown as crosses in Fig. 5.

Figure 6. A small part of the spectrum of each of the stars covering the wavelength region of the Li 6708 Å and the [S ii] 6717 and 6731 Å lines. The black lines are the observed spectra and the red dotted lines are the best-fitting model spectra.

J052230.40–685923.9 have $T_{\text{eff}} < 5000$ K so the presence of the Li lines is consistent with the PMS status. In Table 1, one of these stars (J052230.40–685923.9) is considered a PMS star based on its log g value, while the other strong Li sources are a post-RGB star (J05355.00–731900.9) and a post-AGB star of low luminosity (J051516.28–685539.7, $L_{\text{phot}} = 2943 L_\odot$). Strong Li lines are a feature of AGB evolution at higher masses and luminosities ($L \gtrsim 20000 L_\odot$) where hot-bottom burning occurs (Smith & Lambert 1990), but we do not expect strong Li lines in low-luminosity RGB or AGB stars. This suggests that J005355.00–731900.9 and J051516.28–685539.7 may also be PMS stars, contradicting their post-RGB/AGB status based on log g values.
(LSPs) found in roughly one-third of variable red giants (Wood et al. 1999; Percy & Bakos 2003; Soszyński et al. 2007; Fraser, Hawley & Cook 2008). The quasi-periodic variables are shown as filled circles in Fig. 5, unless they have an LSP in which case they are shown as open circles.

The remaining star with a light curve, J051155.66$-$693020.6, has slowly brightening I and MACHO red ($M_R$) magnitudes with no evidence for other variability. It is shown as a star symbol in Fig. 5. The star with no light curve (J005529.48$-$715312.2) is shown as a filled square.

Overall, variability characteristics do not seem to help us distinguish between PMS stars and post-RGB or post-AGB stars. Of the six stars that show slow long-term variations in magnitude, three have been classified as post-RGB stars and three as PMS stars based on their estimated log $g$ values. The star with Cepheid-like variability is listed as a PMS star based on log $g$, whereas Cepheid-like variability is known to occur in Population II Cepheids (although at shorter periods) which are post-AGB or post-RGB stars. Of the stars whose quasi-periodic variations look similar to those of red giant semiregular variables, three are classified as PMS stars and two as post-RGB/AGB stars (and two have no classification based on log $g$). It is perhaps not surprising that variability characteristics are not an unambiguous pointer to the evolutionary state. Both PMS stars and post-RGB/AGB stars are expected to be surrounded...
by large amounts of circumstellar dust that is clearing so that long-
term slow changes in brightness would be expected in both cases.
Similarly, both groups of stars originate on the Hayashi track and
cross the instability strip so they might be expected to show the
same type of pulsational variability, although the PMS stars should
have shorter periods at a given luminosity because of their higher
mass.

5 INDIVIDUAL OBJECT SUMMARY

Given the various results presented above, we provide here a syn-
thesis of the properties of each object and comment on the possible
evolutionary state. As a starting point, it should be remembered that
all of these objects have both a strong mid-IR excess and TiO bands
in emission so that they all have dense, warm and dusty circumstellar
material in close proximity to the central star.

J004805.01−732543.0. The most remarkable feature of this star
is the light curve which shows a 1 mag brightening starting at
JD = 244 8800 = 1500 followed by a peak brightness around
JD = 244 8800 = 5000 and a fading thereafter (Fig. 7). During
this phase, there is an oscillation in the light curve with a period that
decreases from 1150 to 400 d. Such rapid changes in brightness and
period are most likely associated with the outer layers of the star or
the circumstellar environment. An accretion event in a circumstellar
disc is a plausible explanation. The star shows Hα emission and
this is a possible direct indicator of the existence of a circumstellar
disc. The estimated effective temperature (Teff ∼ 3849 K) and
luminosity (1960–3492 L⊙) put the star close to the low-mass giant
branch. The gravity estimate (log g = 0.0) suggests that the star is
a post-RGB star.

J004843.76−735516.8. This star has very strong TiO band emis-
sion, no Hα emission, a relatively warm temperature of 5300–
5500 K and a relatively high luminosity of 7677–10067 L⊙. The
gravity estimate (log g = 0.8) lies between that expected for a post-
AGB or a PMS star of the given Teff and L. The star shows a
quasi-periodic variability and could be classified as an SRd vari-
able because of its G0 spectral type. There is no strong evidence
favouring either the post-AGB or the PMS status.

J005355.00−731900.9. This is a cool star (Teff ∼ 4140–4250 K)
whose gravity estimate (log g ∼ 0.0) puts it in the post-RGB/AGB
class. The cool Teff, well to the right of the birth line, also favours
a post-RGB/AGB status. The two luminosity estimates put it near
the RGB tip or just above on the AGB. It has Li 6708 Å absorption
suggesting it could be a PMS star. The pointers to the PMS or post-
RGB/AGB status for this star are in conflict. The light curve has
prominent long-term variations of amplitude ∼0.6 mag as well as a
periodic component. We suggest that this star is a binary with a
period of 193 d.

J005504.57−723451.1. This is the hottest star in our sample with
(Teff ∼ 7480–8900 K), yet it still has prominent TiO emission.
It has broad Hα emission [intrinsically full width at half-maximum
(FWHM) ∼ 235 km s−1], possibly suggesting the presence of a
circumstellar disc. The star does not seem to vary. The estimated
gravity is high (log g ∼ 3), suggesting the star is a PMS star. The
luminosity of the star (L ∼ 2148–2220 L⊙) means that the stellar mass in this case is ∼8 M⊙.

J005514.24−732505.3. This object has two remarkable features.
First, its SED shows a dominant mid-IR peak and a smaller peak in
the optical, indicating a central star that is highly obscured and
seen mainly in scattered light. Secondly, the star shows a smooth,
periodic, Cepheid-like variation with a period of 206 d whose am-
plitude increases from about 0.5 to 1.3 mag over an interval of about
1500 d. The origin of the 206 d variation is probably pulsation,
although some other cause such as binarity cannot be excluded. The
luminosity of the central star is highly uncertain and the estimates
are 743 and 3486 L⊙. The star is relatively warm (Teff ∼ 6404–
6640 K) and the gravity estimate of log g = 2.5 suggests that it is a
PMS star. The luminosity estimates yield a stellar mass in the range
6–9 M⊙ in this case.

J005529.48−715312.2. This is a relatively warm star (Teff ∼
6457–7690 K) with a relatively high luminosity (L ∼ 5141–
6668 L⊙). With the estimated log g = 2.1, it appears to be a
PMS star. The luminosity estimate is consistent with a stellar mass of
∼12 M⊙ in this case. There is no light curve for this star.

J010324.36−723803.5. This is the most luminous of our objects
with L ∼ 21 757–28 384 L⊙. It also has a relatively warm effective
temperature Teff ∼ 4447–5500 K. The gravity log g = 0.0 suggests
it is a post-AGB star. This conclusion is supported by the unusu-
ally strong line observed at 6500 Å which is caused by the pair of
lines 6496.89 Å of BaII and 6498.76 Å of Ba I. The element Ba is
ally strong line observed at 6500 Å which is caused by the pair of
lines 6496.89 Å of BaII and 6498.76 Å of Ba I. The element Ba is

Figure 8. The light curves of J004805.01−732543.0 and
J005355.00−731900.9 after long-term trends have been removed in
the intervals 1500 < JD−244 8800 < 6250 and 2000 < JD−244 8800 <
5000, respectively. The light curve of J005355.00−731900.9 has been
folded with a period of 193 d. Point colours are as in Fig. 7.

Stars with TiO bands in emission 365

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lies between that of a post-AGB star and a PMS star. The light curve is typical of the semi-rigid red giants that show a primary oscillation (in this case 70–100 d) as well as an LSU (in this case 444 d). We are unable to decide between the post-AGB or PMS status for this star.

\( J050747.45 - 684351.2 \) is a low-luminosity object \((L \sim 1304 - 2068 L_\odot)\) with a warm temperature \((T_{eff} \sim 4850 - 5430 K)\). The gravity estimate \((\log g = 0.5)\) indicates that it is a post-AGB star. This object is listed as a YSO candidate by Whitney et al. (2008), although not of high probability. The light curve shows a slow variation in the mean magnitude and a very small amplitude oscillation although not of high probability. The light curve is typical of the semi-regular red giants that show a primary oscillation (in this case 70–100 d) as well as an LSU (in this case 380 d). The strong Li 6708 Å line suggests that the star may be a PMS star. This object is listed as a YSO candidate by Whitney et al. (2008), although not of high probability. The light curve shows a very slow brightening.

\( J051516.28 - 685539.7 \) is a cool star \((T_{eff} \sim 3878 K)\) of moderate luminosity \((L \sim 2943 - 3529 L_\odot)\). The gravity estimate \((\log g = 0.0)\) suggests that it is a post-AGB star. The TiO band emission is relatively weak. This object is listed as a YSO candidate by Whitney et al. (2008), although not of high probability. The light curve shows a very slow brightening.

\( J052023.97 - 695423.2 \) is a high-luminosity object dominated by the mid-IR flux, which is still rising at the longest detected wavelength of 24 μm. The star appears to be quite warm \((T_{eff} \sim 5244 K)\) and well away from the giant branch. There is a strong and broad Hα emission line of intrinsic FWHM \(\sim 424 \text{ km s}^{-1}\) and wings extending out to 900 \text{ km s}^{-1}. Like \( J055114.24 - 732505.3 \), the two luminosity estimates \((626 \text{ and } 2907 L_\odot)\) are quite different because of the dominance of the mid-IR flux. The gravity estimate \((\log g = 2.0)\) suggests the star is a PMS star. The object has previously been classified as a high-probability YSO by Whitney et al. (2008). As a PMS star, the luminosity estimates suggest a stellar mass in the range \(7 - 10 M_\odot\). The light curve shows a very brightening magnitude as well as a short period (tens of days) oscillation of low amplitude.

\( J052230.40 - 685925.9 \) is a cool star \((T_{eff} \sim 4493 K)\) of moderate luminosity \((2876 - 3375 L_\odot)\) whose gravity estimate \((\log g = 1.6)\) suggests that it is a PMS star. The strong Li 6708 Å line supports the PMS status. As a PMS star, the luminosity estimate suggests a stellar mass of \(\sim 9 M_\odot\), although this is very uncertain since such a cool star is on the steeply sloped Hayashi track. It has strong TiO band emission. The light curve shows a small-amplitude variation with a period of 46 d.

6 SUMMARY AND CONCLUSIONS

We have discovered 14 stars in the MCs that have both a mid-IR flux excess and TiO bands in emission in the optical part of the spectrum. These features suggest that the stars have dense, hot dust and gas in their immediate circumstellar environments. Effective temperatures have been estimated for the objects from the optical spectra, reddening estimates have been made and the luminosities of the central stars derived. The position of the stars in the HR diagram suggests that they are either post-AGB or post-RGB stars of mass \(\sim 0.4 - 0.8 M_\odot\) or PMS star YSOs with masses of \(\sim 7 - 19 M_\odot\). We have tentatively assigned the stars to one of these two categories based on gravity estimates for the central stars, although for two of the stars this was not possible. We estimate that there are roughly equal numbers of PMS stars and post-RGB/AGB stars in our sample of TiO emitters. Those stars that are PMS stars are in an evolutionary stage well before the birth line where Galactic PMS stars are first assumed to become optically visible. Asymmetries in circumstellar material or the lower metallicity of the SMC and LMC may allow PMS stars to be visible in early evolutionary stages before the Galactic birth line. Those that are post-RGB stars must have formed as a result of binary interaction on the RGB. Similarly, those that are post-AGB stars must have formed as a result of binary interaction on the AGB since single AGB stars in the MCs become carbon stars before they leave the AGB to become post-AGB stars, yet these stars are all oxygen-rich. A circumbinary disc is expected in binary systems that have recently interacted and such discs can explain the presence of dense warm dusty circumstellar material in post-RGB and post-AGB stars.

The light curves of a majority of the stars show gradual brightening or fading, consistent with the presence of a changing circumstellar environment. One of the stars, \( J004805.01 - 732543.0 \), shows what looks like an accretion event that causes variability with a rapidly decreasing period. The star \( J005355.00 - 731900.9 \) has a light curve suggesting that it is currently an eclipsing binary system, while the star \( J005514.24 - 732505.3 \) has Cepheid-like pulsations that are increasing rapidly in amplitude, suggesting a rapid rate of evolution. Seven of the stars show quasi-periodic variability with periods of \(\sim 30 - 160 d\).

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Stars with TiO bands in emission

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