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Luminous carbon stars in the Magellanic Clouds*

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Abstract. We present ground-based 3 μm spectra of obscured Asymptotic Giant Branch (AGB) stars in the Magellanic Clouds (MCs). We identify the carbon stars on the basis of the 3.1 μm absorption by HCN and C_2H_2 molecules.

We show evidence for the existence of carbon stars up to the highest AGB luminosities ($M_{\rm bol} = -7$ mag, for a distance modulus to the LMC of 18.7 mag). This proves that Hot Bottom Burning (HBB) cannot, in itself, prevent massive AGB stars from becoming carbon star before leaving the AGB. It also sets an upper limit to the distance modulus of the Large Magellanic Cloud of 18.8 mag.

The equivalent width of the absorption band decreases with redder $(K-L)$ colour when the dust continuum emission becomes stronger than the photospheric emission. Carbon stars with similar $(K-L)$ appear to have equally strong 3 μm absorption in the MCs and the Milky Way. We discuss the implications for the carbon and nitrogen enrichment of the stellar photosphere of carbon stars.

Key words: Stars: carbon – circumstellar matter – Stars: mass loss – Stars: AGB and post-AGB – Magellanic Clouds – Infrared: stars

1. Introduction

As intermediate-mass stars ascend the Asymptotic Giant Branch (AGB), the combination of a convective mantle with the occurrence of thermal pulses in the interior of the star causes nuclear burning products to be transported to the photosphere of the star (3^{rd} dredge-up). It may enhance the carbon over oxygen ratio in the photosphere. When this ratio exceeds unity, a carbon star is born.

Two decades ago it was realised that in the Large Magellanic Cloud (LMC), where reliable luminosities for individual stars could be obtained, no carbon stars were known more luminous than $M_{\rm bol} \sim -6$ mag, whereas the AGB extends up to $M_{\rm bol} \sim -7$ mag (e.g. Iben 1981). This was surprising, as the lower metallicity in the LMC was thought to increase the efficiency of 3^{rd} dredge-up. Recent studies confirm the lack of optically bright carbon stars in the LMC (Costa & Frogel 1996). Three solutions were suggested: (1) high mass-loss rates yield a cut-off to the AGB evolution at $M_{\rm bol} \sim -6$ mag, (2) nuclear burning at the bottom of the convective mantle of massive AGB stars (Hot Bottom Burning, or HBB) prevents the dredge-up of carbon (Iben & Renzini 1983; Wood et al. 1983), or (3) luminous carbon stars have become obscured by their dusty circumstellar envelope (CSE). The first solution is ruled out by the detection in the LMC of Li-rich stars with luminosities between $M_{\rm bol} = -6$ and -7.2 mag (Smith et al. 1995) and AGB star luminosities in clusters in the LMC (Aaronson & Mould 1985; Westerlund et al. 1991). HBB has been commonly accepted as the solution (Boothroyd et al. 1993).

We have investigated the possibility that massive carbon stars are dust-enshrouded, by searching for obscured AGB counterparts of IRAS point sources in the LMC and SMC, (Loup et al. 1997; Zijlstra et al. 1996; van Loon et al. 1997, 1998a: papers I to IV). Chemical types could only be identified for a few stars. Hence the luminosity distributions of obscured oxygen-rich and carbon stars in the LMC are not well defined. One very luminous carbon star candidate was found in the LMC, the obscured AGB star IRAS04496−6958 (paper IV). Remarkably, Trams et al. (1999a,b) recently presented ISO spectra showing that the CSE of this object also contains an oxygen-rich dust component.

In this paper, we present ground-based L-band (3 μm) spectra of obscured AGB stars in the Magellanic Clouds. We had the opportunity to do these observations as a result of an exchange of observing time between the European Southern Observatory (ESO) and the Cerro Tololo Inter-american Observatories (CTIO). Absorption between 3.0 and 3.3 μm is due to HCN and C_2H_2 molecules in the extended atmospheres of carbon stars, whilst oxygen-rich, M-type, stars display a featureless continuum at this wavelength (Merrill & Stein, 1976a,b,c; Noguchi et al. 1977; Ridgway et al. 1978). We show the spectrum of IRAS04496−6958, confirming its carbon star nature. We also use the 3 μm spectra of other luminous obscured AGB stars in the LMC and SMC to classify them as carbon or M star. These are the first 3 μm spectra of extra-galactic stars to be presented in the literature.

* This paper is based on data obtained at the Cerro Tololo Inter-american Observatories, Chile.

Table 1. Observing log of 3 μm spectroscopy of obscured AGB stars in the Magellanic Clouds. We list IRAS and LI (Schwering & Israel 1990) designations, and alternative names. IRAS00393−7326 is a Faint Source Catalogue entry, IRAS05203−6638 is from Reid (1991). Julian Dates are $RJD = JD - 2,450,000$.

IRAS	LI	other	RJD
00393−7326			821
00554−7351	SMC0119		821
04496−6958	LMC0057		441
04498−6842	LMC0060		820
04509−6922	LMC0077		441
04553−6825	LMC0181	WOH G64	820
05003−6712	LMC0297		821
05009−6616	LMC0310		821
05112−6755	LMC0570	TRM 4	441
05128−6455	LMC1880		821
05203−6638		TRM 88	820
05291−6700	LMC1137		820
05298−6957	LMC1164		441
05300−6651	LMC1177	TRM 79	441
05329−6708	LMC1286	TRM 60	821
06028−6722	LMC1817		820

2. Observations

We used the Infra-Red Spectrometer (IRS) at the 4 m Blanco telescope at CTIO, Chile, in December 1996 and January 1998 to take L-band spectra of a sample of obscured AGB stars in the LMC (Table 1). We also included a red supergiant (RSG) in the LMC (IRAS04553−6825) and two obscured AGB stars in the SMC (IRAS00393−7326 and IRAS00554−7351).

The IRS uses a 256×256 InSb array, and is operated at the f/30 focus. The slit length is $16''$ at a spatial scale of $0.32''$ pix^{-1}. We used the 75 lines mm^{-1} grating in 1^{st} order, covering 0.33 μm (the grating is blazed at 4.65 μm). We observed with the grating centred at 3.04 and 3.34 μm to cover the spectral region between 2.87 and 3.50 μm (IRAS00393−7326 was observed with the grating centred at 3.04 μm only). The slit aperture was 0.35 mm ($0.7''$ on the sky), yielding a resolving power of $R \sim 1300$.

We performed sequences with the star alternatingly placed at either of two positions on the slit separated by $6''$ to facilitate background subtraction. The frames that were saved on disc consisted of 10 coadded frames of 2 s integration time each at 3.04 μm, and 20 coadded frames of 1 s at 3.34 μm. In December 1996 we used integration times of 3 and 1.5 s, respectively. Total on-source integration times were typically eight minutes, but observing times amount to at least five times as much. The stars of our sample represent the faintest stars of which the continuum can be detected by the IRS (8^{th} mag in L-band), and that can be acquired through a K' filter (limiting magnitude $K' \sim 12$ mag). The standard stars HR77 (ζ Tuc) for the SMC and HR2015 (δ Dor) for the LMC were observed regularly, with the star placed at five positions on the slit, separated by $3''$. Weather conditions were non-photometric, with thin cirrus passing over on the December and January 6/7 nights. Seeing was typically $1''$, 0.7 to $1''$, and 1 to $1.5''$. Atmospheric stability was least on January 7/8.

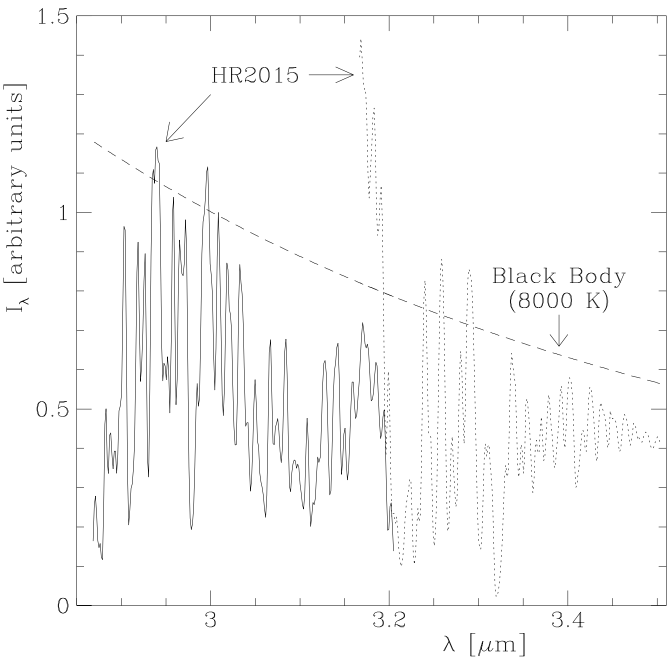

Fig. 1. Composite spectrum of the standard star HR2015, with an 8000 K blackbody for comparison. Telluric absorption is very important, leaving only half of the flux to reach the detector. The instrument response function is higher at the short-wavelength end than at the long-wavelength end, which is why the two spectral settings do not match perfectly around 3.18 μm.

A measurement of the dark current was subtracted from all frames. A measurement of the inside of the telescope dome was used to correct for pixel-to-pixel variations in the detector responsivity. Background subtraction was performed by subtracting frames with the star at different positions on the slit. Programme star spectra were divided by standard star spectra to correct for the severe absorption by telluric OH lines. The spectra were flux-calibrated by assuming L-band magnitudes of 2.797 and 3.664 mag, and effective temperatures of 7000 and 8000 K for HR0077 and HR2015, respectively. To give an idea of the importance of telluric absorption in the L-band, we show the composite spectrum of HR2015 in Fig. 1. We overplot a blackbody of 8000 K for comparison. The spectra do not match perfectly around 3.18 μm, because the instrument is more sensitive at the short- than at the long-wavelength end. Near 3.10 μm telluric absorption often reduces the measured intensity of programme stars to very low levels, introducing relatively large uncertainties. Wavelength calibration was performed by a linear fit to the positions of the many telluric lines.

We rejected pixels with flux densities more than 3-σ off the median within a running bin of 22 pixels width. The spectra were rebinned to 0.02 μm steps reducing the effective spectral resolving power to $R \sim 100$. We assigned errorbars that we derived from the spread of pixel values within the 0.02 μm bins. The long-wavelength part of the spectrum of IRAS05298−6957 is of low quality because we could not

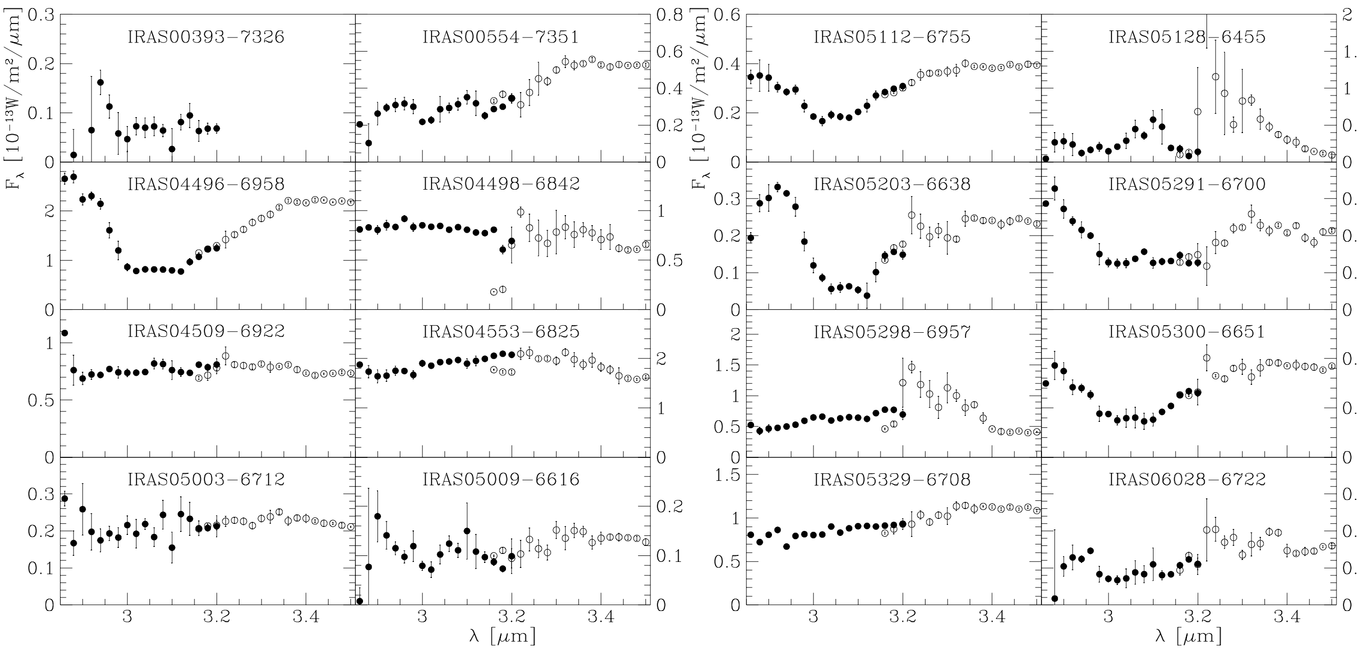

Fig. 2. 3 μm Spectra of obscured Asymptotic Giant Branch stars in the Magellanic Clouds (plus LMC red supergiant IRAS04553−6825). Absorption between 3.0 and 3.2 μm is due to HCN and C_2H_2 molecules in the extended atmospheres of carbon stars (e.g. IRAS04496−6958). Oxygen-rich (M-type) stars display a featureless continuum (e.g. IRAS04509−6922).

guide anymore in the morning twilight. The 3 μm spectra are shown in Fig. 2.

3. Results

3.1. Classification into carbon and M stars

Both SMC stars in our sample have IR colours indicative of carbon-rich dust (Groenewegen & Blommaert 1998). The drop in flux density in the spectrum of IRAS00393−7326 going from 2.94 μm to beyond 3.0 μm suggests indeed absorption by HCN and C_2H_2. The overall shape of the spectrum of IRAS00554−7351 suggests moderate absorption on a red continuum. An unpublished 3 μm spectrum of this star taken by Whitelock also confirms its carbon-rich nature (as cited by Wood et al. 1992).

IRAS04509−6922 and IRAS04553−6825 are known to have oxygen-rich photospheres from their optical spectral types: M10 (paper IV) and M7.5 (Elias et al. 1986), respectively. Maser emission from oxygen-rich molecules has been observed from IRAS04553−6825 (Wood et al. 1986; van Loon et al. 1996, 1998b), IRAS05298−6957 (Wood et al. 1992), and IRAS05329−6708 (Wood et al. 1992), indicating oxygen-rich CSEs. Their 3 μm spectra show a featureless continuum. IRAS04498−6842 and IRAS05003−6712 also have a featureless 3 μm spectrum and hence are M stars, in agreement with their IR colours (paper IV). The curvature of the spectrum of IRAS04553−6825 hints at absorption by the wings of H_2O vapour (band-head at 2.7 μm).

The other LMC stars are carbon stars. IRAS04496−6958 is the showcase of a carbon star spectrum in our sample. IRAS05203−6638 and IRAS05291−6700 also have carbon-rich CSEs according to their IR colours (paper IV), and they display very strong 3 μm absorption indeed. IR colours are not conclusive for IRAS05009−6616 (paper IV), IRAS05300−6651, and IRAS06028−6722 (paper III), but our 3 μm spectra suggest they are carbon stars. IRAS05128−6455 cannot be classified easily. Its IR colours are inconclusive (paper IV). The quality of its 3 μm spectrum is low, but the lack of flux between 3.15 and 3.20 μm, where telluric extinction is relatively weak (see Fig. 1), suggests absorption when compared to the continuum level around 3.35 μm. IRAS05112−6755 is undoubtedly a carbon star, as seen from the 3 μm spectrum. This overrules our previous and somewhat ambiguous classification as oxygen-rich (papers II & IV), explains our non-detection of OH maser emission (paper IV), and is in much better agreement with the highly evolved state of this AGB star (Wood 1998).

3.2. Strength of 3 μm absorption

We have determined the equivalent width W of the 3 μm feature. The continuum can be estimated near 2.9 and 3.3 μm, which is also the major source of uncertainty. Errors (2-σ) were estimated by measuring W for the highest and lowest continuum levels that are still compatible with the data. The results are listed in Table 2, together with the $(K-L)$ colours. The SMC photometry is from Groenewegen & Blommaert (1998).

We plot the $W_{3\mu m}$ versus the $(K-L)$ colours (Fig. 3). The scatter of the M-type stars around $W_{3\mu m} = 0$ μm gives a good impression of the accuracy of the estimates of $W_{3\mu m}$. All carbon stars are well separated from the oxygen-rich M-type stars. Despite the larger than typical error on $W_{3\mu m}$ for

Table 2. Equivalent widths of the 3 μm absorption, with 2-σ error estimates. Also listed are the bolometric magnitudes, $(K-L)$ colours, and chemical types.

IRAS	$M_{\rm bol}$	$(K-L)$	$W_{3\mu m}$	chemistry
00393−7326	-5.9	2.49	?	(carbon)
00554−7351	-6.4	2.55	0.070 ± 0.03	(carbon)
04496−6958	-7.0	1.53	0.176 ± 0.02	carbon
04498−6842	-8.4	0.89	0.011 ± 0.04	oxygen
04509−6922	-7.4	1.24	-0.008 ± 0.02	oxygen
04553−6825	-9.5	1.91	-0.023 ± 0.02	oxygen
05003−6712	-5.6	1.60	0.009 ± 0.04	oxygen
05009−6616	-6.1	2.40	0.107 ± 0.06	(carbon)
05112−6755	-6.2	3.40	0.102 ± 0.03	carbon
05128−6455	-6.5	1.96	0.091 ± 0.08	(carbon)
05203−6638	-5.7	1.80	0.166 ± 0.02	carbon
05291−6700	-5.6	1.30	0.143 ± 0.02	carbon
05298−6957	-7.8	2.76	0.004 ± 0.05	oxygen
05300−6651	-5.1	2.57	0.129 ± 0.03	carbon
05329−6708	-7.0	2.10	0.007 ± 0.04	oxygen
06028−6722	-6.4	3.10	0.089 ± 0.06	(carbon)

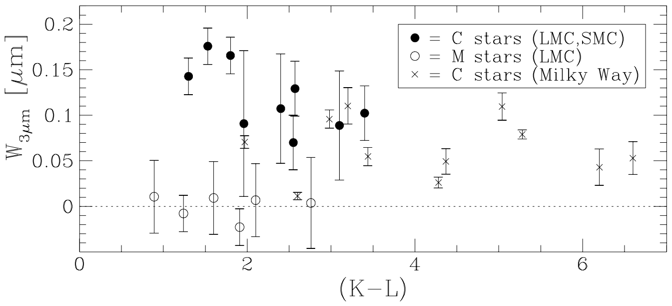

Fig. 3. Equivalent width of the 3 μm molecular absorption feature versus the $(K-L)$ colour for the carbon stars and M-type stars in our sample, and the galactic carbon star sample from Groenewegen et al. (1994). Errorbars are ± 2-σ. Carbon stars have absorption, M-type stars do not. The absorption in carbon stars decreases with redder $(K-L)$ due to the increase in circumstellar emission.

IRAS05128−6455, it is evident that it is a carbon star. We also plot equivalent widths that we measured for the galactic carbon stars from Groenewegen et al. (1994).

In the LMC, the $(K-L)$ colours of the carbon stars are redder than those of the M-type stars. As we could only take spectra of stars that were sufficiently bright in the L-band, bolometrically faint stars only entered our sample if they had red $(K-L)$ colours. The carbon stars in our sample are, on average, somewhat less luminous than the M stars. As the inner radius of the CSE scales with luminosity, at a given mass-loss rate, the CSEs of the carbon stars are optically thicker than the CSEs of the M stars.

The three bluest carbon stars show the strongest absorption feature. The absorption is formed predominantly within the dust-free inner region of the CSE. The redder carbon stars have stronger dust continuum emission, decreasing the contrast between the absorption feature and the continuum (Ridgway et al. 1983). The dust continuum emission becomes important for

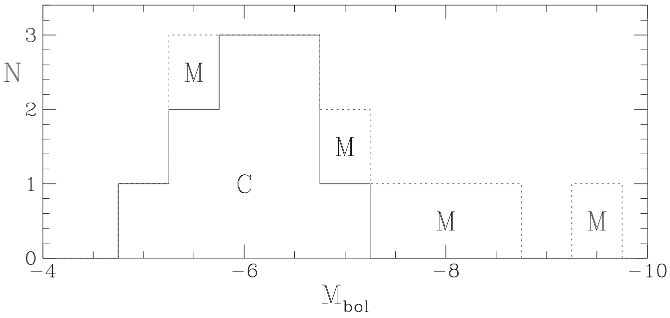

Fig. 4. Histogram of the luminosity distribution of carbon stars and M stars. Carbon stars populate the AGB up to the highest luminosities. Luminous M stars are probably red supergiants.

sources with dust optical depths corresponding to $(K-L) \gtrsim 2$ mag. This trend is prominent in our data of Magellanic Cloud stars, and matches well with the Milky Way stars of Groenewegen et al. 1994 (see also Noguchi et al. 1981, 1991).

The 3 μm absorption in the SMC source IRAS00554−7351 is relatively weak. Note that the galactic carbon star IRAS21377+5042 has $(K-L) \sim 2.6$ mag and $W_{3\mu m} \sim 0.01$ μm, which would make it indistinguishable from M-type stars with the typical signal-to-noise in our data. However, it has very blue IR colours and no molecular emission could be detected at mm wavelengths (Groenewegen et al. 1994), which makes it a highly peculiar object. It is unlikely to encounter such a star in our sample of stars.

3.3. Luminous carbon stars

In Table 2 we also list the bolometric magnitudes. We determined bolometric magnitudes for the SMC stars in the same way as for the LMC stars (papers II, III & IV) by spline fitting to the spectro-photometric energy distribution (see Whitelock et al. 1994). The accuracy of this method is ~ 0.1 mag. The near-IR photometry are single-epoch data, and time-averaged luminosities may differ from the values presented here. Bolometric amplitudes of galactic carbon stars are ~ 0.6 mag (Le Bertre 1992) and probably similar to those of galactic OH/IR stars (Le Bertre 1993), hence we expect single-epoch luminosities to be within 0.3 mag of the time-averaged luminosity. We adopt distance moduli of 18.7 and 19.1 mag for the LMC and SMC (Feast 1998). These constitute a rather long distance scale, with the average estimate for the distance moduli for the LMC and SMC being 18.55 and 18.97 mag, respectively (Walker 1998).

In Fig. 4 we plot a histogram of the luminosities of the carbon stars and M stars in our sample. We note that due to the small number of stars, and a possible bias towards carbon stars when we selected the stars, one should not over-interpret these histograms as the luminosity functions of obscured M-type and carbon stars in the MCs. However, there is no indication for a deficit in carbon stars brighter than $M_{\rm bol} = -6$ mag: carbon stars do exist up to the highest AGB luminosities: $M_{\rm bol} \sim -7$ mag. IRAS04498−6842 and IRAS05298−6957 may be luminosity enhanced due to the effects of HBB, or they may actually be red supergiants.

4. Discussion

4.1. Luminous carbon stars

Luminous carbon stars may be formed after the AGB star has become obscured by its dusty CSE. When mass loss has reduced the stellar mantle below a critical mass, HBB switches off (Boothroyd & Sackmann 1992). If such a star experiences another thermal pulse before leaving the AGB, it may become a carbon star, after all (Frost et al. 1998; Marigo et al. 1998). This scenario is consistent with our spectroscopic confirmation of luminous carbon star candidates that are dust-enshrouded as a result of their AGB mass loss. The most luminous of these, IRAS04496−6958, has an estimated $M_{\rm bol} = -7$ mag. However, we note that this object is peculiar in that it has a (minor) oxygen-rich dust component in its CSE (Trams et al. 1999a,b).

As the most luminous carbon star in the LMC is not experiencing HBB, its luminosity must not exceed the classical limit to the AGB luminosity: $M_{\rm bol} \gtrsim -7.1$ mag (Wood et al. 1983; Boothroyd & Sackmann 1992). This sets an upper limit to the distance modulus of the LMC of 18.8 mag.

4.2. Carbon and nitrogen enrichment

Differences in metallicity may be expected to affect the molecular and dust abundances in the CSEs. Yet carbon stars in the LMC and the Milky Way appear to follow the same sequence of $W_{3\mu m}$ versus $(K-L)$. We here investigate whether this can be understood.

The observed $W_{\rm observed}$ is to a good approximation a dilution factor $(1+\xi)$ smaller than the $W_\star$ in the purely photospheric spectrum:

$$W_{\rm observed} = \int \left(\frac{f_{\lambda,{\rm continuum}} - f_\lambda}{f_{\lambda,{\rm continuum}}} \right) {\rm d}\lambda = \frac{W_\star}{1+\xi} \qquad (1)$$

where the diluted flux f is given by:

$$f = F{\rm e}^{-\tau} + S\tau{\rm e}^{-\tau} \qquad (2)$$

with the photospheric flux F, dust emission source function S, and optical depth τ. We see that ξ is proportional to τ (times the ratio of $S/F_{\rm continuum}$). The difference between the observed $(K-L)$ and the photospheric $(K-L)_0$ colour is also proportional to τ. Hence, for a given $W_\star$, when the metallicity decreases, so does the optical depth of the CSE. The $(K-L)$ colour becomes bluer, and the carbon star shifts along — not away from — the $W_{3\mu m}$ versus $(K-L)$ sequence. The fact that carbon stars in the LMC and the Milky Way appear to follow the same sequence of $W_{\rm observed}$ versus $(K-L)$ therefore implies that $W_\star$ is independent of metallicity. As the 3 μm absorption is caused by HCN and C_2H_2 molecules, we now investigate how their abundances are expected to depend on metallicity.

As C_2H_2 associates at lower temperatures and gas pressures than HCN (Ridgway et al. 1978), free carbon is expected to be preferentially locked into HCN. We assume that the number of carbon atoms that are left after all oxygen is consumed in the formation of CO molecules, the free carbon abundance N(C−O), will combine with the available nitrogen atoms N(N) to form HCN molecules. The free carbon abundance is determined by the initial free carbon abundance, N_0(C−O), and the production and dredge-up of carbon during the thermal-pulsing AGB, δ(C). Likewise, the nitrogen abundance is determined by the initial nitrogen abundance, N_0(N), and the production and dredge-up of nitrogen, δ(N). The latter takes place already before the thermal-pulsing AGB, but is especially important when HBB occurs. The initial abundance is proportional to the metallicity Z. Both the free carbon and the nitrogen abundance can be written in identical form:

$$N = \alpha Z + \delta \qquad (3)$$

It is not well known what is the metallicity dependence of δ. With $Z_{\rm LMC} = \frac{1}{2} \times Z_{\rm MW}$, the HCN abundance ratio between a carbon star in the LMC and a corresponding carbon star in the Milky Way (MW) can be written as

$$\frac{N_{\rm LMC}({\rm HCN})}{N_{\rm MW}({\rm HCN})} = \frac{0.5 + \eta_{\rm LMC}}{1 + \eta_{\rm MW}} \qquad (4)$$

where the enrichment term η is given by

$$\eta = \frac{\delta}{\alpha Z_{\rm MW}} \qquad (5)$$

Initially there is more oxygen than carbon, and α(C−O) is negative. To make a carbon star, δ(C) must exceed $\mid \alpha({\rm C-O}) Z \mid$. With the same value for η(C)< -1 in the LMC and the Milky Way, Eq. 4 implies that more HCN would be produced in the LMC than in the Milky Way if the free carbon abundance limits the HCN abundance, much in the same way that it is easier to make carbon stars at lower metallicity because there is less oxygen to bind into CO. If, however, the nitrogen abundance limits the HCN abundance, then, as α(N) and thus η(N) are positive, Eq. 4 implies that less HCN will be produced in the LMC than in the Milky Way unless the nitrogen enrichment term η is larger at lower metallicity. The question now is which species is more abundant in magellanic carbon stars: nitrogen or free carbon?

The photospheric abundance of a carbon star near the end of its AGB life resembles that of the PN that will be ejected. Of the $16+15$ PNe in the LMC+SMC for which Leisy & Dennefeld (1996) measured abundances, $8+10$ have N(C−O)> 0, i.e. their progenitors left the AGB as carbon stars. All of these have N(C−O)$>$ N(N), the only exception being SMP47 in the LMC of Type I (nitrogen-enhanced). This would suggest that in the MCs, N(HCN) in carbon stars is limited by N(N), not by N(C−O). However, the PNe in the MCs are all less luminous than about 10,000 $L_\odot$, corresponding to the luminosity of the faintest carbon star in our sample. The only more luminous PN in the LMC is SMP83, which is oxygen-rich (Dopita et al. 1993). In luminous AGB stars with massive cores, HBB enhances the nitrogen abundance. This starts to be effective around $M_{\rm bol} = -6$ mag, where the optical luminosity function of carbon stars in the MCs truncates. However, when mass loss continues, HBB diminishes. Stellar evolution codes show the N/O to decrease again, whilst the C/O increases (Marigo et al. 1998). If an AGB star becomes a carbon star only after having experienced HBB, nitrogen may not be as over-abundant as observed for instance in PNe of Type I — that are usually oxygen-rich. So we cannot be sure whether our sample of magellanic carbon stars also have N(C$-$O)$>$ N(N).

Anyway, any surplus of carbon ends up in C_2H_2. Thus, all carbon contributes to the 3 μm absorption, either through HCN or C_2H_2. If this is correct, then the strength of the 3 μm absorption is determined by the free carbon abundance, no matter what the nitrogen abundance is. Hence, in analogy to Eq. 4 we expect the 3 μm absorption to be stronger in the LMC than in the Milky Way, in disagreement with our observations. If the carbon enrichment is much larger than the initial carbon abundance (η(C)$\ll -1$) the differences in 3 μm absorption strength may be too small to appreciate in our data. Alternatively, the carbon enrichment may be less at lower metallicity. Another explanation may lie in the fact that stellar photospheres are warmer at lower metallicity. The rotational bands of HCN and C_2H_2 are excited at temperatures between ~ 1000 and 1500 K (Ridgway et al. 1983), which occurs more distant to a warmer stellar photosphere. The 3 μm band strength may be weakened by this effect, canceling the expected increase in strength due to the more abundant free carbon at lower metallicity.

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Mais que muitos obrigadinhos para o anjinho Joana — Yes, I know.

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