Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
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The End: Witnessing the Death of Extreme Carbon Stars

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Abstract. A small number of the sample of 184 carbon stars in the Magellanic Clouds show signs that they are in the act of evolving off of the asymptotic giant branch. Most carbon stars grow progressively redder in all infrared colors and develop stronger pulsation amplitudes as their circumstellar dust shells become optically thicker. The reddest sources, however, have unexpectedly low pulsation amplitudes, and some even show blue excesses that could point to deviations from spherical symmetry as they eject the last of their envelopes. Previously, all dusty carbon-rich AGB stars have been labeled "extreme," but that term should be reserved for the truly extreme carbon stars. These objects may well hold the clues needed to disentangle what actually happens when a star ejects the last of its envelope and evolves off of the AGB.

Keywords. infrared: stars, stars: carbon stars: AGB and post-AGB, Magellanic Clouds

1. Introduction

Before the *Spitzer Space Telescope* ended the cryogenic portion of its mission, the Infrared Spectrograph (IRS) observed a total of 184 carbon stars in the Large and Small Magellanic Clouds (LMC and SMC). The spectra were obtained in several observing programs, each with its own scientific objectives. Despite these differences, the spectral and photometric properties of the sample reveal the multiple evolutionary phases through which carbon stars pass before they shed their envelopes and leave the asymptotic giant branch (AGB; Sloan et al. 2016).

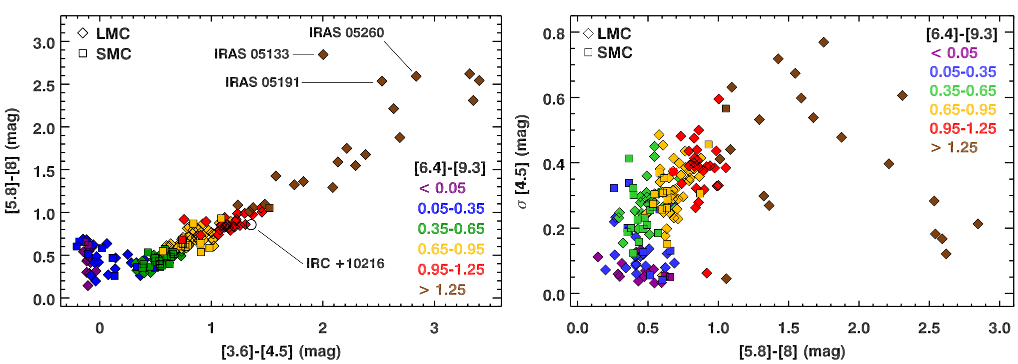

Figure 1. Left: A color-color plot of the IRS sample of Magellanic carbon stars using photometry from *Spitzer* and *WISE*. The data are coded by their [6.4]−[9.3] color, which is determined from their spectra and is a good proxy for the amount of dust. See the text for more on the labeled objects. **Right:** Variability, as measured by the standard deviation of *Spitzer* and *WISE* data at 4.5 and 4.6 μm, vs. [5.8]−[8] color. Both plots are adapted from Sloan et al. (2016).

Figure 1 shows the trends followed by the Magellanic carbon stars and how the reddest stars break those trends. Because carbon stars grow redder consistently in all near- and mid-infrared colors as the amount of circumstellar dust increases, they generally occupy a tight sequence in any infrared color-color space. However, some of the reddest carbon stars in the sample from the IRS (in the [5.8]−[8] color) have an excess at 3.6 μm which pulls them away from the sequence. Generally, more dust and redder colors are associated with stronger pulsation amplitudes, but in the IRS sample, the peak amplitude occurs at [5.8]−[8] $\sim$ 1.5. For redder objects, *more* dust is associated with *weaker* amplitudes. This behavior led Sloan et al. (2016) to hypothesize that the reddest Magellanic carbon stars observed by the IRS may have ejected their envelopes and be developing asymmetries in their circumstellar dust shells as they evolve off of the AGB.

2. The dusty AGB

Gruendl et al. (2008) first identified the reddest carbon stars in the LMC photometrically, initially describing them as *extremely red objects*, or EROs. When spectra from *Spitzer* revealed their carbon-rich nature, they could be more properly referred to as *extreme carbon stars*. Their circumstellar dust shells are so optically thick, the SiC dust emission feature normally seen at $\sim$11.5 μm can appear in absorption, much like extreme carbon stars identified in the Galaxy (e.g. Speck et al. 1997, 2009, Pitman et al. 2007). Describing these objects as "extreme" reflects their rarity, with fewer than 20 or so known in either the LMC or the Galaxy, and none in the SMC.

However, another class of far more numerous objects has also been labeled "extreme," which confuses matters. Blum et al. (2006), noting a change in slope in the near-infrared color-magnitude diagram of the LMC at a $J-[3.6]$ color $\sim$ 3.1, identified all stars to the red as *extreme AGB*.

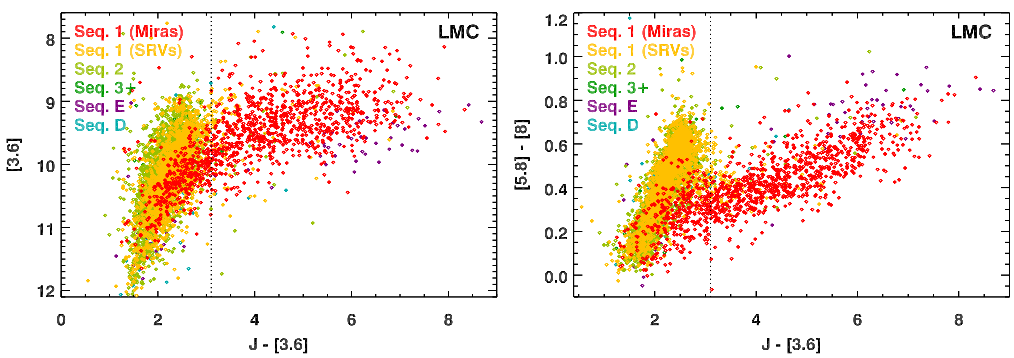

Figure 2. Left: A color-magnitude diagram of carbon stars in the OGLE-III survey (Soszyński et al. 2009), coded by their OGLE-III variability type and pulsation sequence. **Right:** The same carbon-rich sample in color-color space. The vertical line at $J-[3.6]$ = 3.1 marks the boundary of the extreme AGB as defined by Blum et al. (2006).

The two panels of Figure 2 plot all of the carbon-rich Miras and semi-regular variables identified in the LMC in the OGLE-III survey (Soszyński et al. 2009) for which we have found near- and mid-infrared photometry. The data are coded by their location on a period-luminosity diagram (see Fig. 1 by Sloan 2017), using the sequences defined by Fraser et al. (2005). Sequences 1, 2, and 3 refer to the fundamental mode, first overtone, and possibly higher overtones, respectively.

Both panels in Figure 2 show that a $J-[3.6]$ color of 3.1 forms a reasonable boundary between two sequences, with most of the semi-regular variables, no matter their pulsation mode, to the blue. Carbon stars with redder colors are almost always Miras. While both Miras and semi-regulars can pulsate in the fundamental mode, the Miras as defined by OGLE-III have stronger pulsation amplitudes. As explained by Sloan et al. (2015), different mechanisms produce the reddening along the two sequences. The sequence on the left can be described as the *molecular* sequence because increasing absorption from C_3 molecules at 5 μm leads to redder [5.8]−[8] colors. Stars on this sequence are pulsating at amplitudes too low to drive significant mass loss, and they have little circumstellar dust. The sequence to the right, previously referred to as the extreme AGB, is better described as the *dusty* sequence (or "D-AGB") because these stars have substantial mass-loss rates, and increasing amounts of circumstellar dust drives their reddening.

3. The dying carbon stars

We wish to draw attention to the population of objects more extreme than the dusty AGB. For comparison, Figure 1 (left) includes IRC +10216, in many ways the prototypical extreme carbon star in the Galaxy. This object was discovered in the Two-Micron Sky Survey (Neugebauer & Leighton 1969), but it did not stand out until it was found to be the brightest object outside the Solar System in the mid infrared (Becklin et al. 1969). Its thick dust shell gives it a $J-[3.6]$ color $\sim$ 10.7, which is off-scale in Figure 2, and yet the shell is still not thick enough to put SiC in absorption.

The location of IRC +10216 in the color-color diagram in Figure 1 is informative. Despite its optically thick dust shell, it is still a member of the main population of dusty carbon stars and to the blue of the break in the population density at [5.8]−[8] $\sim$ 1. Some caution is warranted with the population statistics of the IRS sample of Magellanic carbon stars, because it inherits the biases of the observing programs that contributed to it. Nonetheless, this break appears to be real. It would most likely be even more substantial in a less biased photometric sample, because Gruendl et al. (2008) targeted the majority of extreme carbon stars in the LMC. No comparable objects have been found in the SMC (Srinivasan et al. 2016). All of these arguments point to the extreme carbon stars, with their various indications of a highly evolved state and a possible departure from the AGB, as a special class of objects.

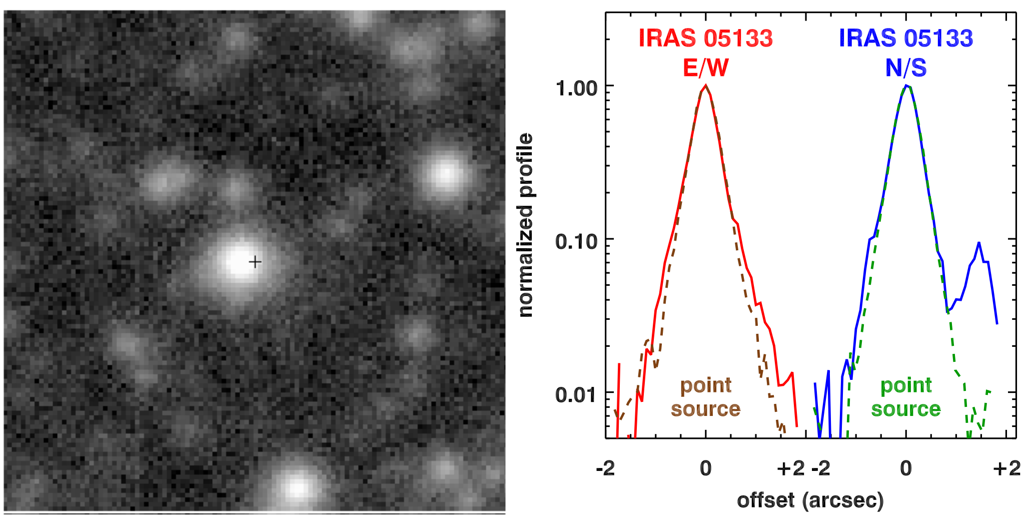

Figure 3. Left: An *I*-band image of IRAS 05133−6937 from the SOAR Adaptive Module (SAM) covering 10" × 10". The cross marks the infrared position of the source (Sloan et al. (2016)), which is 0.26" from the center of the *I*-band source. **Right:** Profiles of IRAS 05133 showing a low-contrast halo (solid lines) compared to a nominal point source (dashed lines).

Given the many unanswered questions about the final moments of stellar evolution, these extreme carbon stars require further study. We have started that follow-up process. Figure 1 (left) marks the three objects with the greatest excess emission at 3.6 μm. IRAS 05133−6937 has the strongest excess. Our preliminary analysis of *I*-band imaging with the SOAR Adaptive Module (SAM) reveals a source with an apparent low-contrast halo, possibly as a result of scattering from light escaping from the dust shell, as Figure 3 illustrates.

The other two sources marked in Figure 1 tell a more complex story. Both IRAS 05260−7010 and IRAS 05191−6936 are accompanied by a naked star ∼0.9” to the south, as previously noted by Gruendl et al. (2008). The *I*-band SOAR images show only the neighbors; the infrared sources are undetected. These neighbors raise the possibility that pollution in the beam of the *Spitzer* photometry could explain the excess at 3.6 μm. Our investigation of the *Spitzer* images at 3.6 and 4.5 μm reveals no indication that contamination at 3.6 μm is responsible, but we cannot yet draw a definitive conclusion.

These initial findings are the result of just one night observing with a 4-m telescope, and further work is needed to better understand the behavior of these extreme carbon stars. They are likely to be our window into the poorly understood processes driving the final moments of a star’s lifetime on the AGB.

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Discussion

KWOK: One of the defining spectral characteristics of galactic extreme carbon stars is the presence of acetylene. However acetylene is not present in all your LMC examples. Would you care of comment on the presence of acetylene as a property of extreme carbon stars?

SLOAN: The acetylene bands at 7.5 and 13.7 μm appear in most spectra. The 13.7 μm band is almost always present, even in optically thick dust shells, which tells us that it does not originate in the stellar photosphere.