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A possible scientific case study for the future NIR spectrograph with IRAIT ⋆

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Abstract. The atmospheric conditions in Antarctica for astronomical observations in the infrared are outstanding. The project to install a 0.8 m infrared telescope (IRAIT) in the base Dome C, to be exploited by Italian and French scientific teams, is aimed at making use of these extraordinary observation conditions. Here, we study the viability of a scientific case that could be performed with this telescope using an infrared spectrograph, namely a study of the $^{12}C/^{13}C$ ratio in AGB stars (O-rich & C-rich). The actual value of this isotopic ratio gives valuable information about the nucleosynthetic and mixing processes occurring within stars. Currently, there is some controversy concerning the typical (average) value of this ratio in carbon-rich and oxygen-rich AGB stars. The large isotopic splitting existing between ^{12}CO and ^{13}CO lines around 2.3 microns, and the fact that this spectral region is not very crowded, offers the opportunity to determine this isotopic ratio more accurately than from atomic or molecular features placed at optical wavelengths. For atmosphere parameters typical of AGB stars, we compute synthetic spectra of this molecular band simulating different spectral resolutions to determine the minimum resolution needed to successfully perform this study. Two Spanish institutions have recently expressed interest in joining the European astronomical team at Dome C and possibly in obtaining a low resolution infrared spectrograph for IRAIT.

Key words. AGB stars – nucleosynthesis – abundances

1. Introduction

Recent site testing experiments at Dome C have revealed the fantastic quality of its sky for astronomical observations, particularly for near and mid-infrared wavelengths (Burton et al. 2000; see also Storey et al. in this Conference). For instance, a comparison of background sky brightness in the three near infrared bands K, L and M with respect to other sites considered good for astronomical observations on the Earth, show gains ranging from a factor of twenty to over one hundred. Moreover, the transparency of the sky at Dome C in the mid infrared wavelengths (i.e. at

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$\sim$ 20 μm) is better than anywhere else. The recent development of the infrastructure at the Concordia base exploited by Italy and France, will make it possible to site a permanent astronomical observatory there to make use of these outstanding observation conditions. The IRAIT (Infrared Antarctic Italian Telescope) project could be the first astronomical facility installed in Dome C. This project seeks to install a 0.8 m telescope dedicated mainly to near and mid infrared observations that could also serve as the cornerstone of other astronomical facilities to be installed in the near future, making Dome C a real International Antarctic Observatory. Initially, IRAIT will be equipped with a camera for mid infrared ($\sim$ 8 $-$ 30 μm) imaging as the first light instrument. The telescope and camera are currently in the testing phase at the Coloti Observatory (Perugia, Italy) and are scheduled to be delivered to Dome C during the Antarctic summer of 2004-05. Very recently, two Spanish institutions (Universidad de Granada and Institut d'Estudis Espacials de Catalunya (CSIC-UPC)) expressed their interest in joining the scientific teams (Italian and French) involved in the IRAIT project. As a real contribution to this project, the Spanish teams could participate in the following areas: i) the design and ultimate construction of a (definitive) enclosure for IRAIT at Dome C, ii) the building of the wobbling mirror system necessary for infrared observations and/or iii) the study and building of a second generation instrument, namely a camera or spectrograph (or both) for near infrared (1 $-$ 4 μm) imaging and/or spectroscopy. Here, we present a scientific case study that might be undertaken with this second instrument and IRAIT at Dome C: the study of the ^{12}C/^{13}C ratio in a large sample of AGB stars, both in the Milky Way and in the nearby external galaxies.

2. The ^{12}C/^{13}C ratio in AGB stars

The Asymptotic Giant Branch (AGB) stars represent the final phase of the evolution of stars in the mass range $1 \lesssim M/M_\odot \lesssim 8$. The structure of an AGB giant is characterised by a degenerate CO core, by two shells (of H and He) burning alternatively, and by an extended convective envelope. In the HR diagram, these stars lie close to the brightest part of the Hayashi line. Schwarzschild & Härm (1965) showed at an early stage that thermal instabilities in the He-shell (thermal pulses, TP) occur periodically during the advanced phases of AGB evolution. During a TP the whole region between the H shell and the He shell (called "the He intershell") becomes convective. After each TP, the convective envelope penetrates downward dredging-up material previously exposed to incomplete He-burning conditions. This phenomenon is called *third dredge up* (TDU), and its main consequence is the increase in the carbon content in the envelope so that, eventually, the C/O ratio can exceed unity and the star becomes a *carbon star*. Thus, the carbon content in the envelope is expected to increase during the spectral sequence M$\rightarrow$MS$\rightarrow$S$\rightarrow$SC$\rightarrow$C, stars of spectral class C showing C/O$>$ 1 (see e.g. Iben & Renzini 1983; Smith & Lambert 1990). Therefore, the ^{12}C/^{13}C ratio in the envelope is expected to increase during the AGB phase from the values reached during the previous phases of evolution (i.e. from a typical value of ^{12}C/^{13}C$\sim$ 20 in the red giant branch phase after the first dredge-up). However, exceptions to this figure exist. In AGB stars of intermediate mass (M $\geq$ 4 M$_\odot$) this isotopic ratio can again be reduced if the bottom of the convective envelope is hot enough (T$\geq 20 \times 10^6$ K) to partially activate the CN cycle. In this case, the operation of this *hot bottom burning* (HBB) can even prevent the formation of a carbon star, keeping the C/O ratio below unity and reducing the carbon isotopic ratio to near the CN-cycle equilibrium value. Indeed, many of the most luminous (and, thus, presumably massive) AGB stars in the Galaxy and in the Magellanic Clouds are O-rich stars instead of C-rich objects, showing very low isotopic ratios, ^{12}C/^{13}C$\sim$ 4 (e.g. Smith et

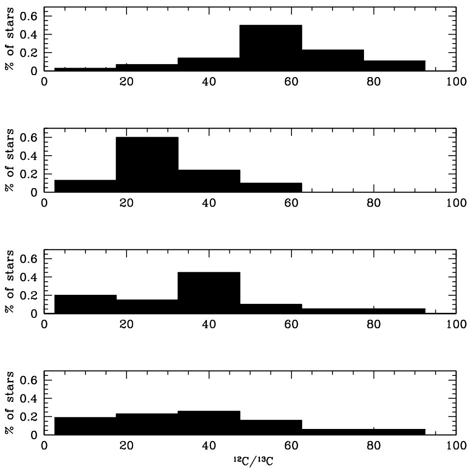

Fig. 1. The $^{12}C/^{13}C$ ratio in galactic carbon stars. From up to down: Lambert et al. (1986), Ohnaka & Tsuji (1996), Schöier & Olofsson (2000) and Abia et al. (2002). The box size is 10.

al. 1995). In low mass AGB stars (M$\leq$ 3 $M_\odot$), the bottom of the envelope is not hot enough to develop HBB, and therefore large isotopic ratios ($^{12}C/^{13}C > 40$) are expected as well as the formation of a carbon star. However, observations indicate that this is not always the case.

During the last few years, several groups have derived the carbon isotopic ratio in carbon stars. The main results of these studies are shown in Figure 1. Lambert et al. (1986) derived this ratio in a sample of galactic carbon stars from CN lines in the near infrared (1.9-2.3 μm). They found typically $^{12}C/^{13}C$ ratios larger than about 40, which was in agreement with theoretical expectations. Some of the stars in the sample showed very low ratios ($3-10$), but most of these stars are classified as carbon stars of spectral type J, a type of carbon star which could be the consequence of a different evolutionary path from that followed by the normal C(N) carbon stars (Lorentz-Martin 1986). However, Ohnaka & Tsuji (1996) from a larger sample of stars, found typically lower ratios (see Figure 1), peaking at around 30, in contrast with the previous figure. These low values, in principle, cannot be understood on the basis of the standard stellar models on the AGB phase. Two very recent works (Schöier & Olofsson 2000; Abia et al. 2002), have found $^{12}C/^{13}C$ ratios in between the values found by Lambert et al. (1986) and Ohnaka & Tusji (1986) (see Figure 1), adding more confusion to the situation. Indeed, part of the discrepancy between the different works might be of a spectroscopic origin. For instance, Ohnaka & Tsuji and Abia et al. derived the $^{12}C/^{13}C$ ratio from CN lines in a very crowded spectral region, where many of the ^{12}CN lines are, in fact, saturated. On the other hand, Schöier & Olofsson determined this isotopic ratio from CO absorptions at submillimetric and millimetric wavelengths in the circumstellar envelope formed around the AGB star. It is not clear whether the circumstellar isotopic ratio might represent those in the photosphere since part of the carbon isotopes could be differentially depleted in the dust and grains formed in the cool circumstellar envelope. Also, differences in the model atmospheres for carbon stars used by the different authors certainly play a role in this controversy. However, even taking into account all of these possible sources of uncertainty, when comparing the data from different studies and the error bars in the measured ratios, there are still a considerable number of carbon stars with low $^{12}C/^{13}C$ ratios that cannot be explained. In fact, Abia et al. (2001) showed that even considering the existence of an extra-mixing mechanism (as many RGB stars seem to indicate, e.g. Gilroy & Brown 1991) during the previous phases of evolution, capable of reducing the carbon isotopic ratio to values as low as $\sim$ 10 after the first dredge-up, it is impossible to obtain $^{12}C/^{13}C$ below $\sim$ 40 for any stellar mass model. This is a very important result since, if confirmed, it could also indicate the existence of an extra-mixing mechanism on the AGB phase, preferably in AGB stars of low mass. This non-standard

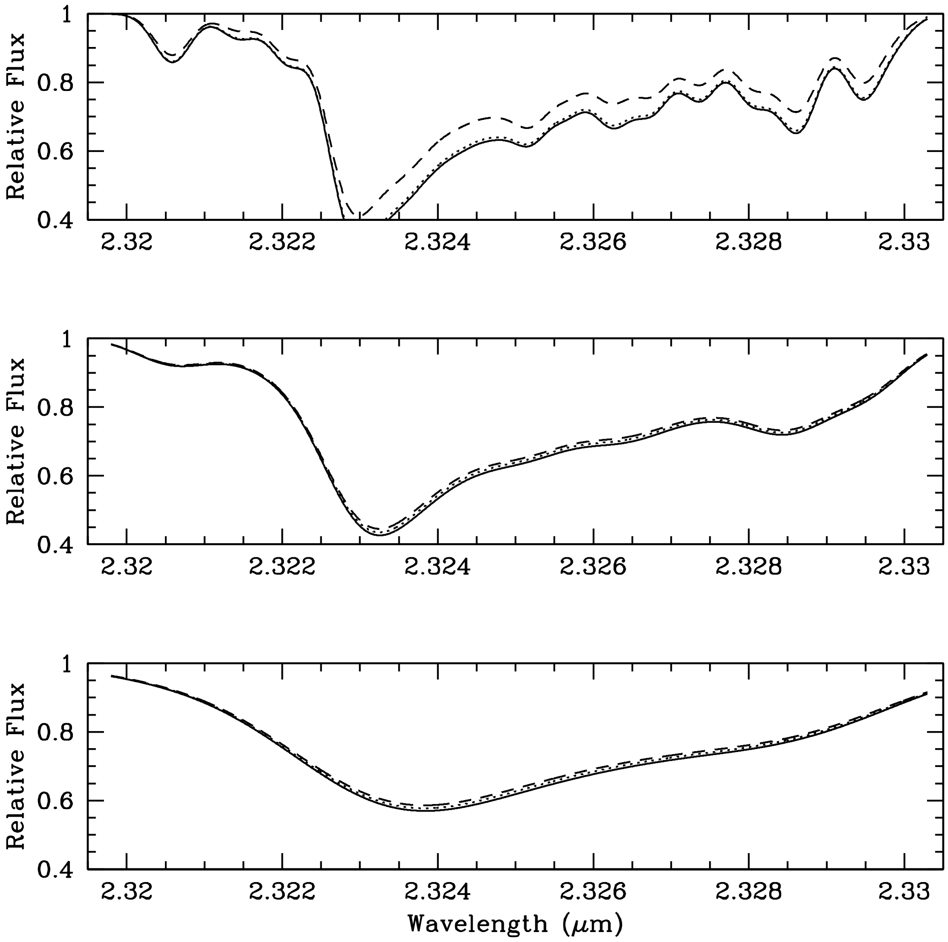

Fig. 2. Theoretical spectra of the CO band for different ^{12}C abundance A(^{12}C)= 8.66, 8.56 and 8.46 simulating different resolving power R. From up to down: $R \sim$ 3000, 1500 and 600. The top panel shows and extra case (long dashed line) computed with A(^{12}C) = 8.16.

mixing mechanism could also explain other chemical anomalies observed in AGB stars (Wasserburg et al. 1995; Nollet et al. 2003).

3. The ^{12}C/^{13}C ratio with IRAIT

¿From the above, it is obviously important to derive accurate carbon isotopic ratios in a large sample of carbon stars. To do this, it is necessary to have a spectroscopic tool that is free of the analysis problems quoted above. This tool could be the ^{13}CO(3-1) and ^{12}CO(2-0) molecular band absorptions at 2.374 μm. There are several advantages to this: a) The isotopic splitting between the ^{12}CO and ^{13}CO lines is very large, and thus it is not necessary to have a high spectral resolution. b) CO lines

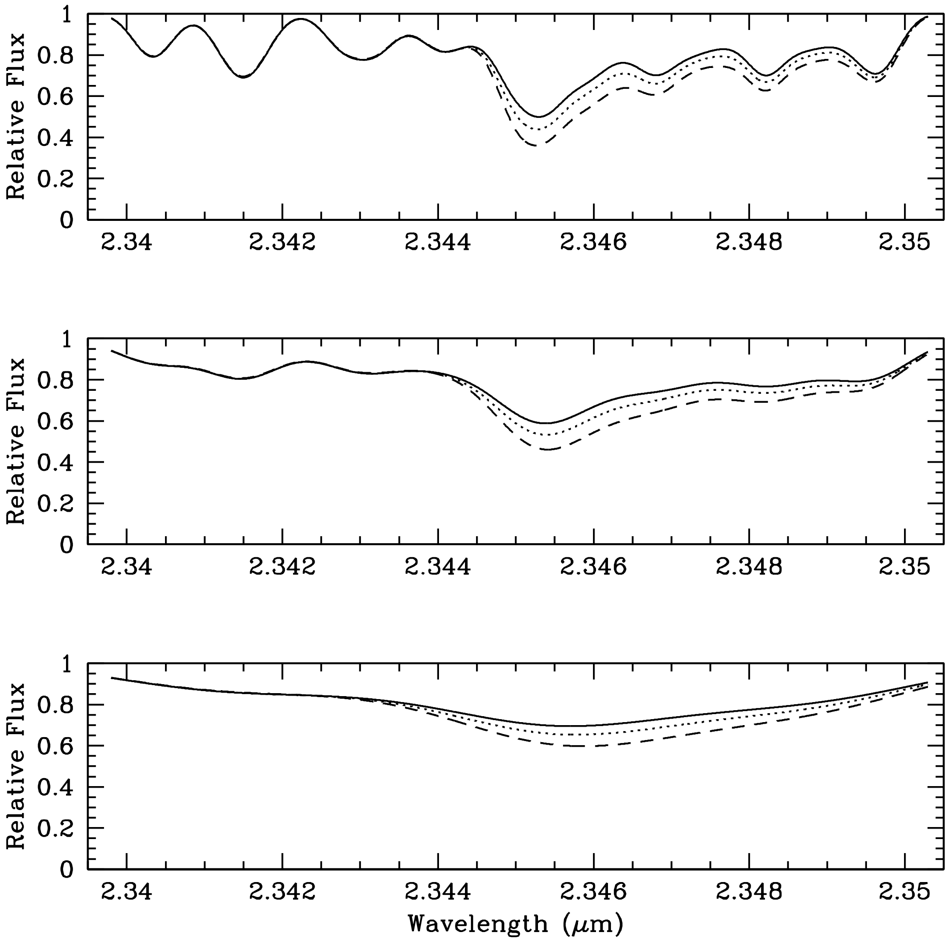

Fig. 3. As Figure 2 for different $^{12}C/^{13}C$ ratios: 89, 30 and 6, simulating different resolving power R. From up to down: $R \sim 3000, 1500$ and 600.

in this molecular band are not saturated in C-rich or O-rich AGB stars. c) Carbon abundances and isotopic ratios can be derived independently of the nitrogen abundance, unlike that from CN lines. In the latter case, a nitrogen abundance must be estimated in advance. The nitrogen content in the envelope is modified during the AGB phase and the previous evolution of the star. d) Finally, AGB stars are very bright at 2.374 μm (the K band); from observations of AGB stars in the Magellanic Clouds, these stars have $<M_K> \sim -8$ (e.g. Frogel, Persson and Cohen 1980). This would make spectroscopic observations of AGB stars in the Magellanic Clouds possible with a medium size telescope such as IRAIT without very long exposure times. In order to design a near infrared spectrograph for IRAIT we must, nevertheless, take into account several limitations. First, IRAIT is planned to be installed inside an

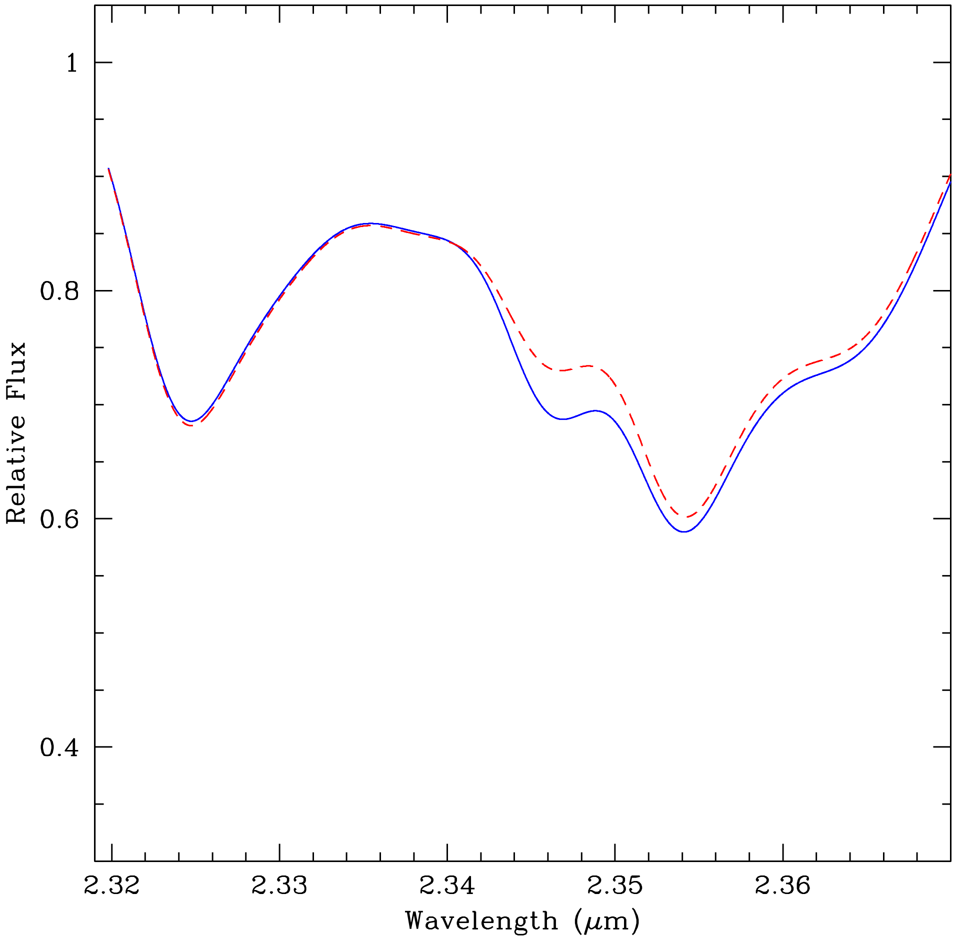

Fig. 4. The full CO band at $R \sim 600$ for two different $^{12}C/^{13}C$ ratios: 30 and 6, and a total carbon abundance of 8.62. Even with this low spectral resolution, the difference between both theoretical spectra is clearly appreciated. Still, it would be possible to estimate the $^{12}C/^{13}C$ ratios in a large sample of AGB stars with IRAIT and a NIR spectrograph.

ISO standard container (see Tosti et al. at this Conference). This limits the available space for astronomical instruments. Second, due to the space limitations, the distance between the primary mirror and the telescope fork will be greatly reduced, and thus the available space for a focal plane instrument will be limited, too (the possibility of the Nastmyth focus configuration must be considered). All this clearly limits the actual size of the instrumentation to be used with IRAIT. Since, as a general rule for spectrographs, the higher the spectral resolution desired the larger the size of the spectrograph, it is necessary to address the question of the minimum resolving power (R= $\lambda/\Delta\lambda$) required to estimate the $^{12}C/^{13}C$ ratio from the CO band at 2.3 μm. We attempt to answer this question by computing theoretical synthetic spectra in this wavelength range for the atmosphere parameters typical of carbon stars. Then, we convolve the synthetic spectra using Gaussian functions with different FWMH (sigma) values to simulate the final spectral resolution achieved depending on the spectrograph performance. Figure 2 shows synthetic spectra computed in the range $\lambda 2.32-2.33$ μm where the CO band is most sensitive to variations in the total carbon abundance (i.e. ^{12}C and ^{13}C). The spectra are computed using the stellar parameters T_{eff} = 2850 K, log g = 0.0, [Fe/H] = 0.0, C/O = 1.1, $^{12}C/^{13}C$ = 40 and ξ = 2.2 kms^{-1}; these are typical parameters for carbon stars of the galactic disk (see e.g. Lambert et al. 1986). For each spectral resolution case (the R value), the spectra are computed for three different values of total carbon abundance, namely A(^{12}C) = $8.66, 8.56$ and 8.46. From this Figure, it is obvious that theoretical spectra are not very sensitive to small changes in the total carbon abundance. There must be a variation by an important amount in the carbon abundance ($\sim$ 0.5 dex, A(^{12}C)=8.16, the long dashed line in the $R \sim 3000$ case), for there to be appreciable differences in the theoretical spectra. We conclude, therefore, that even with a moderate resolution spectrograph, carbon abundances cannot be derived with accuracy from this CO band, although a first estimate can always be made. However, this figure is quite different concerning the derivation of the $^{12}C/^{13}C$ ratio. Figure 3 shows synthetic spectra in the range $\lambda 2.34 - 2.35$ μm, where the CO band is most sensitive to ^{13}C abundance variations. For the same spectral resolution cases as in Figure 2, synthetic spectra computed with $^{12}C/^{13}C = 89, 30$ and 6 are shown. It is now clear that even in the low resolution case ($R \sim 600$), differences by $\sim 5-10\%$ in the relative flux exist, which can be easily detected observationally. The same conclusion is obtained when computing similar spectra for O-rich AGB stars and/or for AGB stars with lower metallicity, for instance [Fe/H] ~ -0.8, which would simulate an AGB star belonging to the Magellanic Clouds. Thus, this spectral region in the near infrared constitutes a promising tool to derive the carbon isotopic ratio in AGB stars.

4. Conclusions

Probably the most important limitation to the minimum spectral resolution required is determined by the continuum location in the spectrum. As can be seen from Figure 4, where the full CO band is represented, in the case $R \sim 600$ the continuum position is lost, thus impeding the determination of accurate isotopic ratios. One could therefore conclude that the minimum resolution required would be around $R_{min} \sim 1000$, although this would depend on the specific scientific goals to be achieved with the spectrograph. For instance, with such a low resolution spectrograph one could study the $^{12}C/^{13}C$ ratio in a large sample of AGB stars, identifying those having larger ^{13}CO absorptions and later deriving the carbon isotopic ratio more accurately using larger telescopes than IRAIT and a near infrared spectrograph with better performance. Alternatively, many other scientific cases not requiring very large spectral resolutions are possible with a low resolution spectrograph and IRAIT: spectroscopy of planetary nebulae, detection of very low mass stars, brown dwarfs and/or planets, studies of ultra-luminous infrared galaxies etc.

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