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Letter to the Editor

How to search for AGB stars in near-IR post-starburst spectra

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Abstract. Based on evolutionary spectral synthesis models explicitly including the spectra of variable AGB stars, we select near-IR features that dentify the strong O-rich or C-rich AGB contributions to the near-IR light of post-starburst populations. AGB temperature scales and lifetimes remain major sources of uncertainties. We discuss applications and suggest massive post-starburst clusters as prime targets for observational tests.

Key words: stars: AGB and post-AGB – galaxies: star clusters – galaxies: stellar content – infrared: galaxies

1. Introduction

Population synthesis and star counts in clusters indicate that asymptotic giant branch stars (AGB stars) contribute more than 50 % of the integrated K band light of stellar populations with ages of a few 10^8 yrs, i.e. after the red supergiants have died and before the less luminous but more numerous first giant branch stars (FGB) have taken over (Bruzual & Charlot 1993, Ferraro et al. 1995). But how can one recognise AGB contributions in integrated galaxy light? While star forming regions are indicated by line emission and older starbursts by the strong CO absorption of red supergiants (e.g. at 2.3 μm), it remains a challenge to separate AGB and FGB contributions in more evolved near-IR spectra.

The AGB extends to higher luminosities and lower effective temperatures ($T_{\rm eff}$) than the FGB but the consequences on the surface brightness and near-IR colours of integrated populations are difficult to disentangle from those of inhomogeneous extinction or of the metallicity dependence of AGB evolution tracks. The way to proceed is to exploit the spectral signatures resulting from Mira-type pulsation in the later AGB stages.

Although Johnson & Méndez (1970) already observed that variable AGB stars (LPVs) display much stronger near-IR H_2O absorption bands than static giants or supergiant stars, subsequent spectrophotometric studies of cool stellar populations did

not attempt to discuss LPVs and static giants separately. Indeed, the separation was omitted until now in the stellar libraries used as input to population synthesis codes (Lançon & Rocca-Volmerange 1992, Terndrup et al. 1991, Lejeune et al. 1998). Model atmospheres confirm that the deep molecular features observed in LPVs are intimately linked to Mira-type pulsation (Bessell et al. 1989a, 1996), but the trends are not reproduced quantitatively (Mouhcine & Lançon 1998) and the model spectra are not reliable enough to be included in the libraries. The present study is therefore based on new observational spectroscopic data.

After a brief description of the updated population synthesis tool, we select near-IR narrow-band filter diagnostic plots for searches of AGB-dominated populations. Depending on the available instrumentation, the photometry can be replaced profitably by low resolution spectroscopy. We then discuss some of the now feasible and most promising applications.

2. Population synthesis models including LPV spectra

2.1. New input spectra for cool stars

The data set (Lançon & Wood 1997) consists of 140 medium resolution ($R = 1100$) near-IR spectra obtained with the cross-dispersed grisms of the camera CASPIR at the 2.3m ANU Telescope at Siding Spring (McGregor 1994) and more than 150 low resolution optical spectra (Reynolds Spectrograph, Mt Stromlo Observatory 1.9m Telescope). About 100 pairs, i.e. quasi-simultaneous observations of the same star in the two wavelength ranges, provide full wavelength coverage from 0.5 to 2.5 μm for a sample of LPVs. Carbon stars, static giants and cool supergiants are included in the set.

The data confirm that Miras produce weaker CO features than red supergiants but can display deeper and broader H_2O bands than any static star, even when their energy distribution indicates relatively warm $T_{\rm eff}$ values (≥ 3000 K). The coolest LPVs also display near-IR VO and TiO absorption bands between 1 and 1.3 μm. Carbon star spectra are dominated by CN absorption, and easily recognised by the sharp C_2 bandhead at 1.77 μm (Fig. 1B).

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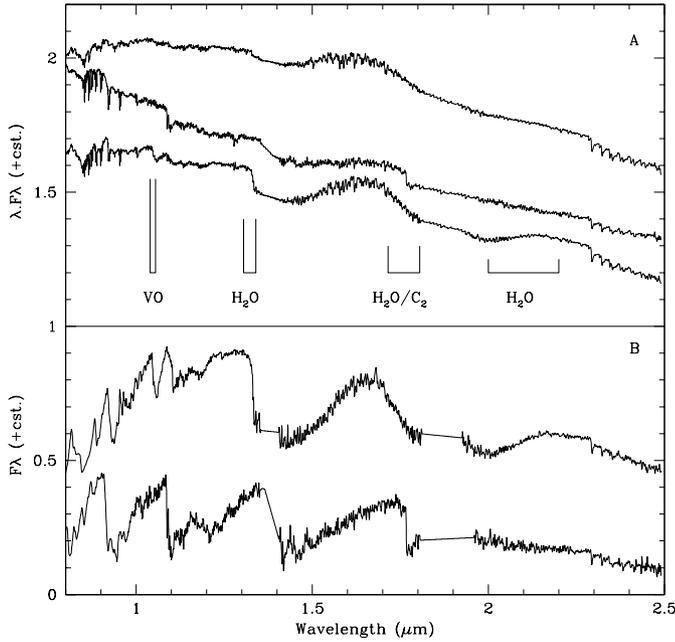⋆ Now at: NASA/GSFC, Greenbelt, MD 20771, USA

Fig. 1. A: Synthetic post-starburst spectra (instantaneous burst, Z=0.008). Bottom: t=200 Myr, LPV atmospheres remain O-rich ($\lambda F_\lambda + 1$); middle: t=200 Myr, but the dominant LPVs have become C-rich ($\lambda F_\lambda + 1.15$); top: giant dominated population (3 Gyr). Band centers/widths in nm are 1039.5/5, 1054/6, 1305/20, 1340/16, 1715/70, 1805/70, 2000/80, 2200/110. **B**: The cool mira R Phe (*top*) and the C star S Cen (*bottom*), both observed in Jan. 1996.

Fig. 2. The time evolution of selected indices. Measuring changes of a few percent in indices close to the variable telluric H_2O absorption bands (cut out in Fig. 1B) requires a dry observing site and particularly frequent observations of a reference star close to the target population.

Temperatures were assigned to instantaneous stellar spectra in two ways considered as extremes, and an intermediate scale was adopted in the synthesis calculations (unless otherwise stated). The first (and higher) scale results from the comparison with the static giant model atmospheres described in Alvarez & Plez (1998), the second from the angular diameter measurements compiled by Feast (1996). The uncertainties in LPV temperature scales are a fundamental issue that will be discussed extensively elsewhere (Mouhcine et al., in preparation).

2.2. Modelling the spectral evolution of stellar populations

The evolution of synthetic stellar populations in the HR diagram is computed with the population synthesis code PÉGASE (Fioc & Rocca-Volmerange 1997) and its extension to non-solar metallicities (Fioc 1997). Although the code is able to compute and follow the continuous chemical evolution of a galaxy, we restrict ourselves here to constant, solar ($Z = 0.02$) or Large Magellanic Cloud ($Z = 0.008$) metallicities in order to avoid additional evolution parameters and to work with AGB evolution models that have been reasonably well tested against observations. A Salpeter IMF is assumed (power law index -2.35, lower mass limit 0.1 $M_\odot$).

The stars evolve up to the early AGB along the tracks of Bressan et al. (1993) and Fagotto et al. (1994). The extensions of Fioc (1997) through the thermally pulsing AGB phase (TP-AGB) follow the prescriptions of Groenewegen et al. (1993,
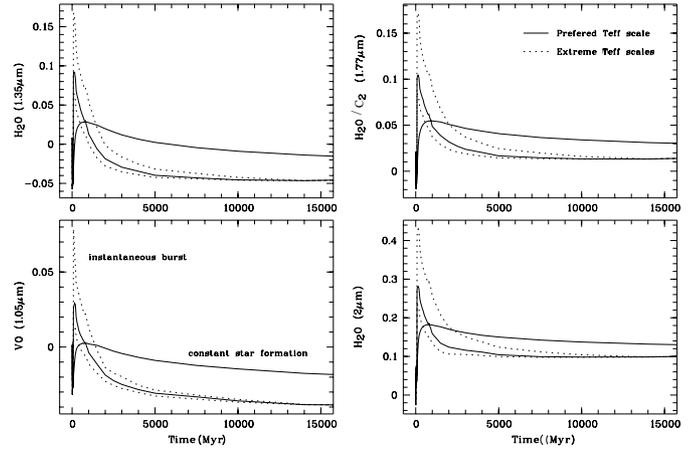
1995) with only a slight adjustment in temperature (well inside theoretical uncertainties). In the HR diagram, the resulting tracks superimpose extremely well on those of Vassiliadis & Wood (1993).

The new spectroscopic data are used in the cool, luminous regions of the HR diagram, as an addition to the colour-corrected spectral library of Lejeune et al. (1998). The LPV spectra are averaged in 0.025 wide logarithmic temperature bins (Lançon 1998). The resulting sequence displays a regular evolution with T_{eff}, both in colours and molecular band absorption indices.

## 3. Near-IR indices to search for AGB stars

Fig. 1 defines a set of filters well suited for measurements of the specific LPV features described in Sect. 2.1. For practical (observational) reasons, the passbands are chosen among those of existing filter sets whenever possible ("Wing filters", Bessell et al. 1989b; Hubble Space Telescope NICMOS filters). All indices are flux ratios expressed in magnitudes and take the value 0 for Vega.

The time evolution of the selected molecular indices at solar metallicity is shown in Fig. 2 for an instantaneous burst and for constant star formation, with the assumption that all LPVs are oxygen rich. Both H_2O and VO indices clearly identify the post-starburst period, i.e. populations with ages between 10^8 and 10^9 yrs.

The most sensitive index is the measure of H_2O at $2\,\mu m$ with respect to the K band "continuum"; it displays the largest variations with time. However, this index would fail to identify the C-rich LPVs, which may represent a significant fraction of the luminous AGB stars depending on the environment (Habing 1996). We therefore consider it essential to include the $1.77\,\mu m$ index in the observational campaigns: while it detects H_2O absorption in O-rich Miras, it has the useful property to also detect the C_2 bandhead of C-rich LPVs.

Table 1. Minimum contribution of the post-starburst allowing its unambiguous detection, for 2 extreme representations of the underlying population and 4 detection criteria (solar metallicity, Salpeter IMF, lower mass=0.1 $M_\odot$, O-rich AGB).

Selection threshold	Old 1				Old 2			
	Mass (%)	L_V(%)	L_I(%)	L_K(%)	Mass (%)	L_V(%)	L_I(%)	L_K(%)
$I_{H_2O(2\mu m)} = 0.19$	**9**	72	57	52	**11**	18	17	19
$I_{VO(1.05\mu m)} = 0.003$	**11**	78	65	60	**7**	13	12	14
$I_{H_2O+C_2(1.77\mu m)} = 0.056$	**8**	70	55	50	**5**	10	9	10
$I_{H_2O(1.35\mu m)} = 0.03$	**10**	76	62	57	**8.5**	16	14	16
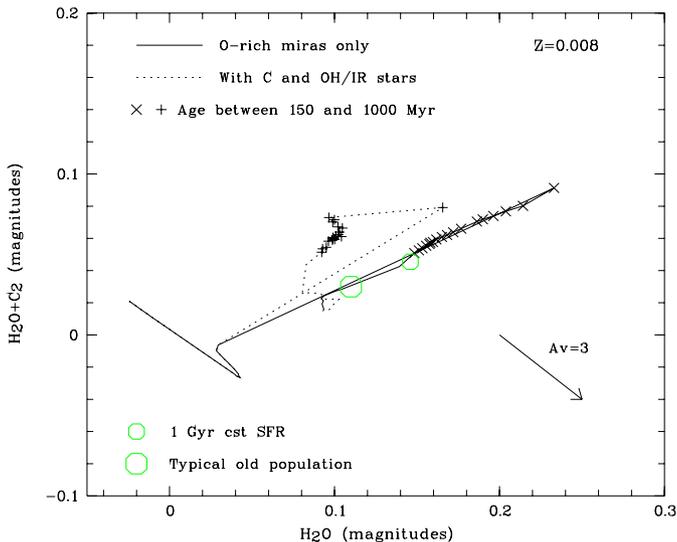
Fig. 3. Synthetic evolution in the prefered two-index diagram. The "jump" to high index values around 100 Myr takes less than 50 Myr. Circles identify plausible locations of contaminating older populations.

We have computed a sequence of models in which the LPVs become carbon rich after the fraction of the TP-AGB lifetime indicated by Groenewegen & de Jong (1993, 1994). Results are presented in the diagnostic plot in Fig. 3. The results are qualitatively independent of the prescription adopted for the O to C transition, and of the detailed filter passbands. A high 1.77 μm H_2O/C_2 index unambiguously identifies the predominance of AGB stars and thus post-starburst populations: there is no confusion with younger or older populations. The second index then indicates the chemical nature of the dominant AGB stars once they have been found.

4. Discussion and applications

The numerical model predictions are limited by the uncertainties in the TP-AGB evolution models and in the assignment of a representative spectrum to each point of the theoretical HR diagram. TP-AGB lifetimes vary by a factor of two from one author to the other (Vassiliadis & Wood 1993, Groenewegen et al. 1995, Marigo et al. 1998). Those implemented in PÉGASE are among the shortest ones: it is unlikely that the TP-AGB contributions be overestimated.

The dotted lines in Fig 2 demonstrate the sensitivity of the post-starburst AGB signatures to the combined temperature scales of the spectra and the evolutionary tracks. The situation is similar to that faced in attempts to determine red supergiant contributions from 2.3 μm CO absorption: very strong features carry a clear message, but more common lower values are not conclusive. It will be essential to test the models with simple stellar populations of known ages, before attempting to infer quantitative AGB contributions from the integrated spectra of more complex objects.

How robust are the molecular post-starburst features with respect to dilution in the light of an underlying, more evolved population?

Results are given in Table 1. Without a priori knowledge of the history of the underlying population (but assuming that it is older than ~ 2 Gyr and obeys the same stellar evolution prescription as the postburst), the unambiguous detection of a postburst via its AGB signatures requires that the observed molecular indices exceed those constantly star-forming populations can reach (cf. Fig. 2). We may consider two extreme underlying populations. "Old 1" is a 10 Gyr old instantaneous burst remnant. Its near-IR spectrum is dominated by relatively early type red giants with H_2O or VO features far below the adopted postburst detection threshold; in this case, exceeding the threshold requires a large contribution of the postburst to the integrated light. "Old 2" is the result of 2 Gyrs of constant star formation. Its spectrum is still contaminated by AGB stars, and its molecular bands are just below the adopted threshold themselves; hence, integrated indices exceeding the threshold may correspond to a much smaller contribution of the postburst to the light.

Incidentally, the mass-to-light ratios of the underlying populations compensate in such a way that a postburst detection based on the above criterion will, in both cases, imply that the postburst represents more than $\sim 10\%$ of the mass in the observed field of view.

Another hurdle to keep in mind is that TP-AGB stars, while intrinsically bright, are rare objects. At ages of a few 10^8 yrs, the stochastic fluctuations in the near-IR fluxes due to TP-AGB number fluctuations are significant (10% or more) in postburst populations containing less than about 10^6 $M_\odot$ of stars (Ferraro et al. 1996, Santos & Frogel 1997, Lançon 1998).

In summary, the ideal target populations should have ages between 10^8 and 10^9 years, and should be both massive and not too heavily diluted. Dilution can be either intrinsic, if young

and old stars are mixed efficiently (e.g. in E+A galaxies), or observational, if the spatial resolution of the data is poor. We will not discuss nearby objects here, for which high resolution imaging nowadays directly provides very complete information. Interesting spectrophotometric applications are found in their more distant counterparts or progenitors.

Many observers have drawn attention to the spatial structure of star formation in tidally induced starburst galaxies (Meurer 1995): stars form in clusters of 10^5 to 10^7 M$_\odot$, themselves associated in super-clusters (SCs). The survival of some of these clusters for more than 10^8 yrs is being investigated in relation with globular cluster formation theories. On the basis of broad band colours, Miller et al. (1997) attribute ages between 0.5 and 1 Gyr to the most massive clusters of the post-starburst galaxy NGC 7252. Our simulations indicate that AGB features should be significant in these objects, unless the prescription adopted for stellar evolution through the AGB is not relevant for starburst environments. Kroupa (1998) suggests a slightly different evolution for starburst clusters, possibly leading to dwarf elliptical galaxies. According to his dynamical arguments, about half of the clusters in an SC merge within $\sim 10^8$ yrs, forming bound objects of 10^6 to several 10^8 M$_\odot$ with radii up to a few 100 pc. Assuming a surface density of the order of 100 M$_\odot$/pc^2 for the underlying galaxy population (twice the solar neighbourhood value), the AGB signatures are again expected to show through in most of these cases. The more extended post-burst objects predicted by Kroupa may have been overlooked until now in studies based on optical surface brightness such as the NGC 7252 survey of Miller et al. (1997). The near-IR signatures of AGB stars could help us determine and understand the fate of the SCs and be used more generally in studies of the propagation of star formation in galaxies. Selected dwarf galaxies (e.g. Tol 1924-416, Östlin et al. 1998) fall in this category of studies.

Going one step "further out", Canalizo & Stockton (1997) argue that the optical spectrum of the companion galaxy of QSO PG 1700+518 ($z = 0.29$) is dominated by the emission of $\sim 10^8$ yr old stars. Objects of this type will extend our stellar evolution laboratories to the extreme environments of the vicinity of active galactic nuclei.

As we have shown, the separation between old populations dominated by red giants and younger, post-starburst populations dominated by AGB stars, based on the molecular bands discussed in this paper, opens new perspectives in the exploitation of the near-IR galaxy spectra now becoming available. Recent mid-IR simulations including the circumstellar emission of late AGB stars (Bressan et al. 1998) suggest that combined mid- and near-IR studies will be particularly helpful in solving degeneracies between the effects of stellar ages, extinction and metallicity. We note however that at the current state of knowledge the new observations, in particular those of massive post-starburst clusters, should also be seen as essential constraints on the AGB evolution models, used as input for population synthesis predictions.

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