Massive Stellar Clusters
ASP Conference Series, Vol. ????, 2000
A. Lançon, and C. Boily eds.

Asymptotic Giant Branch Stars in Interacting Galaxy Globular Clusters

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Abstract. We present new modelling of the spectrophotometric properties of intermediate age stellar populations in the near-infrared (NIR). We take into account the evolutionary and spectroscopic properties of the Asymptotic Giant Branch (AGB) stars which dominate the integrated NIR emission of those populations. The predictions of spectrophotometric narrow-band molecular indices require the use of an effective temperature – colour (or spectrum) calibration for AGB stars; synthetic indices show a strong dependence upon this calibration.

Preliminary results of NIR observations of a supermassive 500 Myr old stellar cluster in the prototypical merger remnant NGC 7252 are presented. The spectra are indeed consistent with intermediate age models dominated by light from AGB stars, a significant fraction of which may be carbon rich. Implications for the stellar inputs used in the modelling of intermediate age stellar populations and their NIR emission are discussed.

1. Introduction

Space and ground based observations have shown that the star formation in starburst regions appears to be biased toward compact clusters. This process seems to be common to all galaxy types: merging galaxies (NGC 3597: Lutz 1991, NGC 1275: Holtzman et al. 1992, NGC 4038/39 Whitmore et al. 1999), starburst galaxies (NGC 1705: Meurer et al. 1992, M82: Gallagher & Smith 1999, Smith & Gallagher, this volume), dwarf galaxies (Henize 2-10: Conti & Vacca 1994, ESO338-IG04, Östlin et al. 1998) and even barred galaxies (NGC 1097: Barth et al. 1995). Colours, luminosities and spatial properties of those clusters are consistent with their being globular clusters with effective radii of a few parsecs (Schweizer 1999).

It is established that the AGB stars are the principal contributors to the near infrared (NIR) luminosity of intermediate age stellar populations\(^1\) (Persson et al. 1983). The AGB evolutionary phase translates into major changes of the HR diagram properties of stellar populations over small time scales. Traditionally, the spectroscopic diagnostic tools that are used in the NIR for age dating are principally based on CO bands (2.3 μm) or broad-band colours. The accuracy of those methods is questionable. After the disappearance of massive supergiants

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\(^1\)We define intermediate age populations as those having ages between $10^8$ and $10^9$ yr.
that display very deep CO bands, it becomes hard to discriminate between AGB stellar populations and the red giant branch (RGB) stellar populations on the basis of CO bands only. Changes in the NIR colours are ambiguous because of degeneracies with the effects of metallicity and extinction. Evidence for strong colour changes due to the AGB stars is found principally in observations of the Magellanic Cloud globular clusters. However, the spectrophotometry of those clusters is affected by large stochastic fluctuations due to the small numbers of luminous cool stars. The interpretation of those observations is not very secure and larger samples (not available in the LMC) are required.

Recently, Lançon et al. (1999) have proposed new diagnostic tools to identify the intermediate age populations using other molecular absorption bands than the CO bands. They distinguish between the oxygen rich and carbon rich AGB stars contributing to the NIR light of post-starburst populations based on the spectroscopic features of the AGB stars that are absent in the RGB star spectra.

2. Intermediate Age Stellar Populations in the NIR: Modelling and Uncertainties

The synthesis of stellar populations and their emission is initially based on the code PÉGASE (Fioc & Rocca-Volmerange 1997, Fioc 1997), with considerable adjustments to allow for changes in all the AGB-related inputs. In this section we present the main features of the modified models.

From the main sequence and up to the Early-AGB phase we use the tracks of the Padova group (Bressan et al. 1993, Fagotto et al. 1994). The physical processes controlling the detail of the evolution along the thermally pulsing AGB (TP-AGB) are complex (e.g. Iben & Renzini 1983). Models are still affected by a large degree of uncertainty and are still a matter of debate (Habing 1996, Olofsson 1999). Full calculations of AGB stars (internal structure, evolution, pulsation-stimulated mass loss) for a large grid of initial masses and metallicities are still missing in the literature (see Vassiliadis & Wood 1993 for 6 initial masses at solar and LMC metallicities). In this context, the so-called synthetic evolution models based on analytical formula derived from full numerical calculations provide an ideal tool to study evolutionary and chemical aspects of TP-AGB stars (Iben & Truran 1978, Renzini & Voli 1981, Groenewegen & de Jong 1993, Marigo et al. 1996, Wagenhuber & Groenewegen 1998). They make it possible to model, in a simple but relatively complete way, the complex interplay between the many relevant physical processes that together rule TP-AGB life. They allow us to cover a large grid of parameters and to reproduce the basic observational constraints obtained mostly from Magellanic Cloud and Milky Way observations. We have chosen to model TP-AGB evolution with such a synthetic code, including: (1) Mass loss, with winds reaching the superwind regime with final rates as high as \(10^{-4} M_\odot \text{ yr}^{-1}\) (we investigate the prescriptions of various authors, but do not currently include any explicit metallicity dependence; the implicit dependance through effective temperature and luminosity remains). Winds play a dominant role in determining the lifetime and the extent of nuclear processing in TP-AGB stars. (2) The third dredge-up phenomenon which is responsible for the formation of carbon-rich stars characterized by very red
colours (especially in J-K) and peculiar spectral features. Dredge-up also affects the core mass–luminosity relation. (3) Hot bottom burning, which affects the evolution of massive stars ($M_{ZAMS} \geq 3-4 M_\odot$ for solar metallicity) preventing the formation of carbon-rich stars from the progenitors of massive core stars and drastically reducing the lifetime of those stars, which reduce their contribution to the integrated (particularly the NIR) light of a population. We assume the TP-AGB phase to be complete either by the total ejection of the envelope, or when the core mass has reached the Chandrasekhar limit ($\sim 1.4 M_\odot$). In contrast to other synthesis models for the spectrophotometric evolution of stellar populations, the evolution of the chemical types of the stars along the TP-AGB is followed here as a result of the competition between all those processes. The values of the free parameters of the synthetic AGB star evolution models are, as a starting point, taken from the literature (Groenewegen & de Jong 1993, Marigo et al. 1996).

In addition to the thermal pulses, occurring on a time scale of the order of $10^4 - 10^5$ years, the AGB stars exhibit another type of variation: the Mira-like pulsation, with a time scale of the order of $10^2 - 10^3$ days. Those pulsations lead to large effective temperature shifts and have strong effects on the NIR spectral features of upper AGB stars. The latter display stronger and deeper molecular bands than any static giant or supergiant. The relevant molecules are H$_2$O, TiO and VO for oxygen-rich stars, CN and C$_2$ for carbon-rich stars. Those spectral particularities give us the possibility to recognise TP-AGB stars from RGB stars. They are the basis of our strategy to look for intermediate age populations, and for dating the stellar populations (Mouchcine & Lançon 1999, Lançon 1999). Introducing the mechanical Mira-like pulsations explicitly in the calculations of the evolutionary tracks is impossible due to the different time scales of the two effects. This effect is included in our calculations via a new stellar spectral library. Although the libraries of stellar spectra available in the literature include various spectral types, they do not include variable stars yet. To overcome this problem, we have constructed a new extension designed specially for our applications. The library relies on suitable averaging procedures over a large data set of NIR spectra of cool AGB stars with various periods (Lançon & Wood, submitted). The innovative aspect of this library is that it includes spectra of objects at different evolutionary stages along the AGB: M stars, carbon rich stars, OH/IR stars and C/IR stars. To assign effective temperatures to the stars in our spectral library is a difficult task. To be conservative, we have used two different effective temperature scales for the variable AGB stars. The first one is based on a large grid of static giant atmosphere models (Plez 1999) and fits to the whole spectral energy distribution of instantaneous stellar spectra without special care to the special spectral signatures of variable stars. The second one is established using angular diameter measurements and IR photometry of late-type stars for a mixed sample of mostly Mira-type stars by Feast (1996). The second scale is steeper than the first one. This means that when the first scale is used to relate the theoretical plane to the observational plane, the very late type spectra (spectra with very pronounced signatures) are assigned a relatively high temperature and get used frequently in comparison to the case when Feast’s temperature scale is used. This effect is clearly shown in Fig. 1 where the temporal evolution of two molecular indices is plotted.
3. NGC 7252 Massive Cluster

One of the best systems where to study supermassive clusters is the prototypical merger remnant NGC 7252. Using ground based observations, Schweizer (1982) identified many very luminous point-like sources in this galaxy. Whitmore et al. (1993) and Miller et al. (1997) performed Hubble Space Telescope UBVI observations and confirmed these sources to be globular clusters. They estimated that the most luminous (massive) ones have ages between 0.1 and 1 Gyr and masses of up to $10^8 M_\odot$. Such systems not only represent an excellent laboratory to study the impact of galaxy interactions on the star and cluster formation; to us, the massive clusters are ideal systems to test the theoretical predictions for the evolution of spectrophotometric features dominated by rare bright stars, which suffer from stochastic fluctuations in smaller populations (e.g. Lançon & Mouhcine, this volume). The general advantage of observing globular clusters comes from the fact that they contain (in general) a single stellar population, homogeneous in age and chemical composition.

In order to investigate the above questions, we have selected the most luminous cluster of NGC 7252, cluster W3. Schweizer & Seitzer (1998, hereafter SS98) have recently obtained ultraviolet-to-visual spectra of W3. The most striking features are the dominating strong Balmer absorption lines and the blue continuum, indicative of A-type main-sequence stars. The spectra do not show any strong emission lines, indicating that the system is not very young (age higher than 0.1 Gyr). Based on comparisons between the observed and modelled spectra, they derive for this cluster an age of about 0.5 Gyr and near-solar metallicity.

We have observed W3 with the infrared imager and spectrometer SOFI on the ESO New Technology Telescope in August 1999. SOFI has a field-of-view of $\sim 5' \times 5'$ and a pixel size of 0.292". The total spectroscopic exposure time was about 2.5 hours both in the blue wavelength range (0.9 to 1.61 $\mu$m) and in the red wavelength range (1.6 to 2.5 $\mu$m). Our spectra have a resolution of $R \simeq 1000$ and a signal-to-noise ratio in the range of 30-35 (note that the seeing

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**Figure 1.** Evolution of selected molecular indices in the NIR for solar metallicity for an instantaneous burst and for constant star formation with the assumption that all AGB stars remain oxygen-rich. Dot-dashed lines: the two extreme $T_{\text{eff}}$ scales described in the text; solid and dotted: an intermediate scale.
rarely dropped below 1″). The observations were reduced following standard procedures using IRAF software.

To fit the NIR observed W3 spectra, we have used an early version of the population synthesis models presented in Sect. 2, with the assumptions of instantaneous star formation and a standard Salpeter IMF extending from 0.1 to 120 M⊙. We have adopted the age and the metallicity derived by SS98 and have tested the two effective temperature scales for AGB star spectra described in Sect. 2.

The comparison between the models and the W3 data strongly argues against a dominant contribution of the O-rich TP-AGB stars with the deepest molecular features, i.e. against the warmer temperature scale based on static models. The steeper, cooler scale provides satisfactory agreement with the data.

Although the NGC 7252 clusters are said to have a quasi-solar metallicity, we have compared the W3 data with a model at LMC metallicity, in which, as a consequence of Groenewegen & de Jong’s (1993) relative C-rich and O-rich TP-AGB lifetimes, carbon stars dominate at 0.5 Gyr. The agreement with the shape of the features is better than with the solar metallicity models, in which C-stars currently provide an insignificant flux contribution. These may be the first direct observations of carbon stars at more than 50 Mpc. In any case, it confirms that the inclusion of C-star formation processes in spectrophotometric evolution models, as discussed in Sect. 2, is relevant. More detail will be given in a forthcoming paper.

4. Conclusions

The use of massive globular clusters in merging galaxy remnants gives us the opportunity to overcome the stochastic fluctuations affecting the NIR spectrophotometric properties of the intermediate age population due to the small number of bright AGB stars and to test, both qualitatively and quantitatively, the population synthesis models. We have observed the most massive cluster of NGC 7252 in the NIR. These observations allow us to report the first observations of a stellar population dominated by AGB stars beyond the Local Group.

Comparisons with our model cluster spectra lead us to argue that the use of an effective temperature scale calibrated on static giant branch stars for TP-AGB stars is, at best, questionable. The observed spectrum is more consistent with model cluster spectra calculated using an effective temperature scale calibrated on LPV stars. The good fit obtained when a significant fraction of the 500 Myr old TP-AGB stars are carbon rich shows the importance of taking surface abundance evolution into account in models for the spectroscopic evolution of intermediate age populations.

Acknowledgments. It is a pleasure to acknowledge the fruitful collaboration with M. Fioc, M. Groenewegen, C. Leitherer and D. Silva at various steps of this work.

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Discussion

B. Miller: If spectra are unavailable, are JHK integral magnitudes also useful discriminators of your models? Are there other useful NIR bandpasses? How small do the uncertainties in the colors need to be?

M. Mouhcine: Some near-IR colours, in particularly H-K, do get particularly red in intermediate age populations in our models; however, there are dangerous degeneracies with effects of dust and metallicity, for example in the J-H versus H-K plane. Being able to determine these independently is at least as important as good photometric accuracy. How red the colours become also strongly depends on the T\textsubscript{eff} scale adopted for the TP-AGB star spectra; we believe that calibrations on more extended cluster samples than just those of the LMC are needed before NIR colours become a reliable age dating tool. Searching for spectrophotometric features due to stellar pulsation has the advantage of avoiding ambiguities.

G. Meurer: Maybe narrow band filters could be used in the IR to isolate spectral features, and thus observe many clusters at once.

M. Mouhcine: This is exactly the observational strategy that we have proposed to discriminate between the intermediate-age populations dominated by the AGB stars and the other stellar populations (Lançon et al. 1998). It is based on observations on different narrow bands. But as shown in the graph, the evolution of the molecular indices depends strongly on different stellar parameters and, again, must be calibrated using simple burst populations before it can be used in more complex stellar populations. In addition, since the relevant features are rather close to telluric absorption bands and since good relative photometry is needed, we still tend to prefer low resolution, broad wavelength coverage spectroscopic methods at the moment.