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DEFINITIVE DETECTION OF THERMALLY PULSING ASYMPTOTIC GIANT STAR FEATURES IN NEAR-INFRARED SPECTRA OF THE NUCLEAR REGION OF NEARBY GALAXIES

Rogério Riffel[1], Rachel E. Mason[2], Alberto Rodríguez-Ardila[3], Luis C. Ho[4,5], Lucimara P. Martins [6], Rogemar A. Riffel [7], Paulina Lira [8], Omaira Gonzalez Martin [9,17], Daniel Ruschel-Dutra [1,9], Almudena Alonso-Herrero[10], Helene Flohic[11], Richard M. McDermid[2,12,16], Cristina Ramos Almeida[9,17], Ricardo P. Schiavon[2,13], Karun Thanjavur[14] and Claudia Winge[15]

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ABSTRACT

We report the detection of absorption features associated with thermally pulsing asymptotic giant stars in high signal-to-noise ratio near-infrared (NIR) spectra of the nuclear region of 12 nearby galaxies. The features detected in some or all of the galaxies are the TiO (0.843 μm and 0.886 μm), VO (1.048 μm and 1.45 μm), CN (1.1 μm and 1.4 μm), H_2O (1.4 μm and 1.9 μm) and CO (1.6 μm and 2.2 μm) bands. The C_2 (1.17 μm and 1.76 μm) bands are generally weak or absent, although C_2 (1.76 μm) may be weakly present in the mean galaxy spectrum. A deep feature near 0.93 μm, likely caused by CN, TiO and/or ZrO, is also detected in all objects. This is the first time such a large number of these features are reported simultaneously in individual galaxies. Fitting a combination of stellar spectra to the mean spectrum suggests that a significant fraction of the stellar light of these galaxies comes from evolved stars with luminosity class I to III. Comparison with evolutionary population synthesis models shows that models based on empirical libraries that predict relatively strong NIR features provide a more accurate description of the data. However, neither of the models tested in this Letter accurately reproduces all of the features observed in the spectra.

Subject headings: galaxies: bulges – galaxies: near-infrared – galaxies: stellar content – stars: AGB

1. INTRODUCTION

Studying the unresolved stellar content of galaxies generally involves disentangling the various components contributing to the spectral energy distribution (SED), fitting a combination of simple stellar populations (SSPs) to derive information about age, metallicity, and star formation history. The first use of the near-infrared (NIR; $\sim$ 0.8–2.5 μm) dates back more than thirty years, when Frogel et al. (1975) and Rieke et al. (1980), for example, detected the 2.3 μm CO bands in elliptical galaxies, NGC 253, and M 82. Other groups have since used this spectral region to study galaxy stellar populations, with methods based on the 1.6 μm and 2.3 μm ^{12}CO bands (e.g. Origlia, Moorwood & Oliva 1993; Oliva et al. 1995; Lançon et al. 2001; Alonso-Herrero et al. 2000, and references therein) or broad band photometry (e.g. Moorwood & Glass 1982; Hunt et al. 2003). More recently, individual NIR windows (e.g. Davies et al. 2009; Ramos Almeida et al. 2006, 2009) or the whole NIR (Riffel et al. 2008, 2009, 2010a, 2011; Storchi-Bergmann et al. 2012; Martins et al. 2010, 2013b) have been used to investigate the stellar content of galaxies.

A galaxy's stellar population can be determined by mixing SSPs with different ages and metallicities to find the best match to the absorption line spectrum. Since NIR spectra of star clusters covering the range of age and metallicity expected in galaxies are not yet available in the literature (Riffel et al. 2011), evolutionary population synthesis (EPS) models are commonly used to describe the stellar population. However, we are far from a complete understanding of certain stellar evolutionary phases that strongly affect the calculated spectrum of the SSPs (Charlot et al. 1996; Maraston 1998). The largest source of discrepancy between different SSP models in the NIR is the treatment of the Thermally-Pulsing Asymptotic Giant Branch (TP-AGB) phase (Maraston 1998, 2005; Marigo et al. 2008; Conroy et al. 2013; Conroy & Gunn 2010; Kriek et al. 2010; Zibetti et al. 2013; Noël et al. 2013). This is the last part of the evolution of interme-

[1] Departamento de Astronomia, Universidade Federal do Rio Grande do Sul. Av. Bento Gonçalves 9500, Porto Alegre, RS, Brazil.riffel@ufrgs.br
[2] Gemini Observatory, Northern Operations Center, 670 N. A'ohoku Place, Hilo, HI 96720, USA
[3] Laboratório Nacional de Astrofísica - Rua dos Estados Unidos 154, Bairro das Nações . CEP 37504-364, Itajubá, MG, Brazil.
[4] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
[5] The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[6] NAT - Universidade Cruzeiro do Sul, Rua Galvão Bueno, 868, São Paulo, SP, Brazil
[7] Universidade Federal de Santa Maria, Departamento de Física/CCNE, 97105-900, Santa Maria, RS, Brazil
[8] Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile.
[9] Instituto de Astrofísica de Canarias, Calle Vía Láctea, s/n, E-38205, La Laguna, Tenerife, Spain
[10] Instituto de Fisica de Cantabria, CSIC-UC, 39005 Santander, Spain
[11] University of the Pacific, Department of Physics, 3601 Pacific Avenue, Stockton, CA 95211, USA
[12] Australian Astronomical Observatory, PO Box 296, Epping, NSW 1710, Australia.
[13] Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park 146 Brownlow Hill, Liverpool L3 5RF, United Kingdom.
[14] University of Victoria (UVic), Victoria, Canada.
[15] Gemini Observatory, Southern Operations Center, c/o AURA, Casilla 603, La Serena, Chile
[16] Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia
[17] Departamento de Astrofísica, Universidad de La Laguna, E-38205, La Laguna, Tenerife, Spain

diate mass stars (M$\lesssim$ 6M$\odot$), occurring for ages between ~300 Myr and ~2 Gyr (for reviews, see Maraston 2005; Zibetti et al. 2013). A proper treatment of this phase is highly desirable since it impacts a range of measurements, including mass-to-light ratios and stellar masses (van der Wel et al. 2006; Maraston et al. 2006; Melbourne et al. 2012; Tonini et al. 2009; Chisari & Kelson 2012; Girardi et al. 2013).

In contrast to "classical" EPS models, such as those of by Bruzual & Charlot (2003, hereafter BC03), the models of Maraston (2005) and Maraston & Strömbäck (2011, hereafter M05/M11) predict the presence of strong NIR molecular features like TiO (0.843 μm, 0.886 μm), CN (1.1 μm, 1.4 μm), C_2 (1.17 μm, 1.76 μm), H_2O (1.4 μm, 1.9 μm) and CO (1.6 μm, 2.2 μm). Detection of these features would clearly show the fingerprints left by TP-AGB stars on the integrated spectrum. The 1.1 μm CN band has been detected in galaxies (Riffel et al. 2007; Ramos Almeida et al. 2009; Martins et al. 2013b) and in Magellanic Cloud globular clusters (Lyubenova et al. 2010, 2012), and the various models have been the subject of many studies. For example, Riffel et al. (2011) show that M05 models are able to reproduce the equivalent widths observed in about half of their sample of Galactic globular clusters for the right input ages and metallicities. Conversely, Zibetti et al. (2013) do not detect the TP-AGB spectral features predicted by M05 in their spectra of post-starburst galaxies at z~0.2.

In this Letter we report the detection of TP-AGB molecular features in NIR spectra of 12 nearby galaxies. The molecular bands detected include CN (1.1 μm, 1.4 μm), CO (~1.6 μm, ~2.2 μm), H_2O (~1.4 μm, ~1.9 μm), VO (1.048 μm, 1.45 μm) and TiO (0.843 μm, 0.886 μm). We also detect a feature at ~0.93 μm which is probably due to a blend of CN, TiO, and ZrO bands. A tentative detection of a C_2 (1.76 μm) bandhead in the mean spectrum of the whole sample is also reported. While some of these bands have been detected in previous work, the novelty of this study is the simultaneous detection of many features over a wide range of wavelengths. The dry atmospheric conditions of Mauna Kea have allowed us to obtain high signal-to-noise ratio (S/N) spectra of local Universe objects including coverage of wavelength ranges not usually accessible from the ground, resulting in the detection of even rather subtle stellar absorption features arising in the galaxies.

2. DATA

The galaxies discussed in this Letter are a subset of those observed for the Palomar XD project (Mason et al. in prep). That program aims to acquire high-quality NIR spectra of active galactic nuclei (AGN) in the Palomar survey of nearby galaxies (Ho et al. 1995, 1997), using the Gemini Near-Infrared Spectrograph (GNIRS) on the Gemini North telescope. The parent sample contains AGN covering a wide range in luminosity and accretion rate. Of these, 12 objects were selected for this study on the basis of high S/N spectra, a strong stellar continuum, weak or undetectable AGN emission, and good cancellation of the strong telluric absorption bands around 1.4 and 1.9 μm. **The subsample was specifically chosen to illustrate the presence and detectability of the widely-debated TP-AGB star features in high-quality data.**

The spectra were obtained using GNIRS' cross-dispersed mode, which provides simultaneous spectral coverage from ~0.8-2.5 μm. The 0.3″ slit was used, providing R~1200, and was orientated at the mean parallactic angle at the time of the observations. The observations were executed in queue mode[18] and the observing condition criteria allowed for observations to be taken with thin cirrus and seeing $\lesssim 1''$. The data were reduced using standard procedures, described in Mason et al. (in prep).

Some stellar features of interest are located in regions of poor atmospheric transmission, in which the telluric cancellation process (dividing by a slightly shifted and scaled spectrum of an A star observed near in time and airmass) may leave artefacts in the spectrum. For instance, the 0.93 μm feature lies close to telluric H_2O absorption at ~0.95 μm. The reality of this feature was verified in two ways. First, the shifting and scaling applied to the standard star were adjusted, while verifying that the strength and profile of the feature were not significantly affected. Second, a standard star spectrum was reduced using the same procedure applied to the galaxies, showing that no similar feature was produced in the resulting spectrum (Fig. 1). A similar procedure was applied to the H_2O absorption regions, indicating that the broad H_2O bands apparent in some objects are not artefacts from the data reduction but true stellar features.

The Palomar XD sample spans a wide range of Hubble types (see Fig. 1) and is composed mainly of low luminosity AGN, specifically low-ionization nuclear emission region galaxies (LINERs) and weak Seyferts. The weak AGN continuum of the sources selected for this Letter ($39.5 < \log L_X < 41.9$ erg s^{-1}) allows a detailed study of the stellar population properties of the host galaxies. The continuum shape of the spectra is characteristic of an evolved stellar population (although some dusty objects like NGC 3718 show a decrease in flux at short wavelengths due to extinction), and in any case the effect of the AGN continuum would be to weaken the stellar features and make them more difficult to detect. The 0.3″ slit width corresponds to 40 pc at the median distance of the sample (24 Mpc; 10 < D < 92 Mpc).

3. RESULTS

The individual spectra are shown in Fig. 1. The CN (1.1 μm, 1.4 μm) and CO (1.6 μm, 2.23 μm) bands are clearly detected in the majority of sources. We also detect the H_2O 1.4 μm band in a significant fraction of them. These features are present in the IRTF atlas of cool stars (Rayner et al. 2009; Cushing et al. 2005, see their Fig. 7 to 34), and many are predicted by M05 (their figures 14, 15). Comparing the GNIRS spectra to the IRTF library shows that, besides the bands in the M05 models, we also detect VO bands at 1.048 μm and 1.453 μm. TiO bands at 0.843 μm and 0.886 μm are also evident in the spectra of NGC 2832, NGC 4594, and perhaps others. A broad feature ranging between ~0.93 – 0.95 μm is also detected, but the identity of the carrier is uncertain. Among the candidates are bands due to CN, TiO, and ZrO, which are all strong in the spectra of cool giants (Rayner et al. 2009).

As the spectra of the 12 galaxies are rather similar in

[18] Programs GN-2012B-Q-80, GN-2013A-Q-16

continuum and emission line properties (Fig. 1), we averaged them to construct a mean spectrum with very high S/N. The spectra were normalized to unity at 1.223 μm before computing the mean value of the fluxes, pixel-by-pixel. The mean spectrum (Fig. 2) allows us to perform a robust, quantitative analysis of the common features. We carry out a stellar population synthesis on the mean spectrum using the STARLIGHT spectral synthesis code (Cid Fernandes et al. 2004, 2005a,b; Asari et al. 2007) following Riffel et al. (2009), using three different approaches to define the base set of spectra used by the code. First, we use the EPS models of M11, which consist of theoretical SSPs covering 12 ages ($t = 0.01$, 0.03, 0.05, 0.1, 0.3, 0.5, 0.7, 1, 2, 5, 9 and 13 Gyr) at solar metallicity - *M11 approach*. Second, we use theoretical SSPs from Bruzual & Charlot (2003) with the same ages and metallicity as above - *BC03 approach*. Third, we use a base composed **of all the** 210 dereddened stars (spectral types F–S/C, F being the hottest available) in the IRTF spectral library (Rayner et al. 2009; Cushing et al. 2005) - *stars approach*. **The observations were degraded to the model resolution before fitting (Riffel et al. 2008; Martins et al. 2013b). The broad absorption bands are, however, relatively unaffected by this procedure.**

The results are presented in Fig. 2, where we show in the top panels a zoom of the mean spectrum (black), and the best fit with the *Stars*, *M11* and *BC03* approaches. In the middle panels we show the residuals of the subtraction of the fits from the mean spectrum, and in the bottom panels the contributions of the different components to the fit as well as the reduced χ^2 and the percentage of deviation (adev).

It is clear from Figs. 1 and 2 that besides the well-known CO bands, the most prominent band in the spectra is the 0.93 μm feature. This feature may be due to a combination of CN (red system, $\Delta v = v'' - v' = -1$), TiO (ϵ system, $\Delta v = -1$), and possibly ZrO. The 0.886 μm band due to the δ system of TiO ($\Delta v = 0$) is detected in most of the spectra. Depending on the spectral coverage, the $\Delta v = 0$ bandheads of the ϵ system of TiO are also detected in those objects, blended with the well-known Calcium triplet lines.

Almost as strong as the 0.93 μm feature is the CN band at 1.1 μm, first detected in an extragalactic source by Riffel et al. (2007). The CN band at 1.4 μm has only been detected in NGC 4102 (Martins et al. 2013a). According to Maraston (2005), these bands are strong in TP-AGB stars, whose contribution to the integrated light peaks at intermediate ages. In contrast, these CN bands were not detected by Zibetti et al. (2013) in their study of 16 post-starburst galaxies, suggesting that TP-AGB stars do not greatly affect the stellar spectrum of that type of galaxy. The CN 1.4μm band falls in a region of poor atmospheric transmission and is therefore difficult to detect in low-redshift extragalactic sources. Thanks to the the dry conditions under which these data were obtained, though, we detect the 1.4 μm CN band in almost all the galaxies (Fig. 1).

The C_2 lines are weak or absent in the individual galaxy spectra but the 1.76 μm band shows up in the mean spectrum. We also detect the H_2O absorption at 1.4 μm in almost all sources, while the 1.8 μm band seems to be visible only in some of the galaxies (NGC 2655, NGC 2768, NGC 3147, NGC 4548 and NGC 5850).

Comparing Fig. 1 with Fig. 8 of Cushing et al. (2005) shows that the VO bands at 1.048 μm and 1.453 μm, which are due to M III stars, are detected in many of the galaxies in our sample. To our knowledge, this is the first time that these bands have been reported in galaxies.

Fig. 2 suggests that the features observed in the individual galaxies are real, since they clearly appear in the mean spectrum. **The galaxies are at different redshifts, so when they are shifted to the rest frame to create the mean spectrum, any systematic effects are shifted to different positions and will therefore tend to cancel out or be weakened in the mean spectrum. Additionally, (i) reducing a standard star using the same procedures results in a very clean spectrum with few telluric line residuals (Fig. 1), and (ii)** we can fit the observed absorption spectrum very well using the IRTF library. The *stars approach* allows us to get a rough idea of the stars typically contributing to the integrated light of galaxies in the NIR. Those are predominantly cool giants and dwarfs, which are responsible for the spectral features detected in the galaxy data.

4. DISCUSSION

The fits of the mean spectrum with the stellar library (*stars approach*) suggest that a significant fraction of the NIR features of these galaxies is due to evolved stars (luminosity class I to III). This is supported by the presence of strong molecular bands in the mean spectrum. However, an unexpectedly high fraction of **the dwarf star HD 145675 (K0V) is found**. This is probably because the stellar library only contains evolved stars which have relatively deep absorption features, so to find the best fit STARLIGHT dilutes these deep bands of the evolved stars through inclusion of a strong contribution by the spectrum of a K0V star, which essentially has only atomic absorption features. **This result is further supported by the fact that when we remove this star,** STARLIGHT **finds the best fit by splitting the contribution among other dwarf stars (G, M and K), while the evolved stars contribution remains almost the same**. By the same token, a very large contribution by S stars is found, which is surprising and possibly reflects an incomplete representation of stars in different stellar phases and metallicities in the input library.

Several absorption bands are qualitatively reproduced in the M11 model fit, notably those of CN and CO. These bands are weaker or absent in the BC03 model fit, which is partly, but not entirely, due to the fact that these models have lower resolution ($R = \sim 200$, as compared to $R = 500$ in M11 models). While the observed VO and TiO bands, as well as the 0.93 μm feature are poorly reproduced by the model fits, the possible weak C_2 1.76 μm band is in agreement with the M11 model fit shown in Fig. 2.

Fitting the mean spectrum with the M11 models results almost exclusively in intermediate age and old SSPs (Fig. 2). With the BC03 models, though, the STARLIGHT code includes a young ($\sim 10^7$ yr) component and requires only a very small fraction of old SSPs. This is probably because the BC03 models do not have deep NIR CN bands so that STARLIGHT attempts to fit the 1.1 μm CN

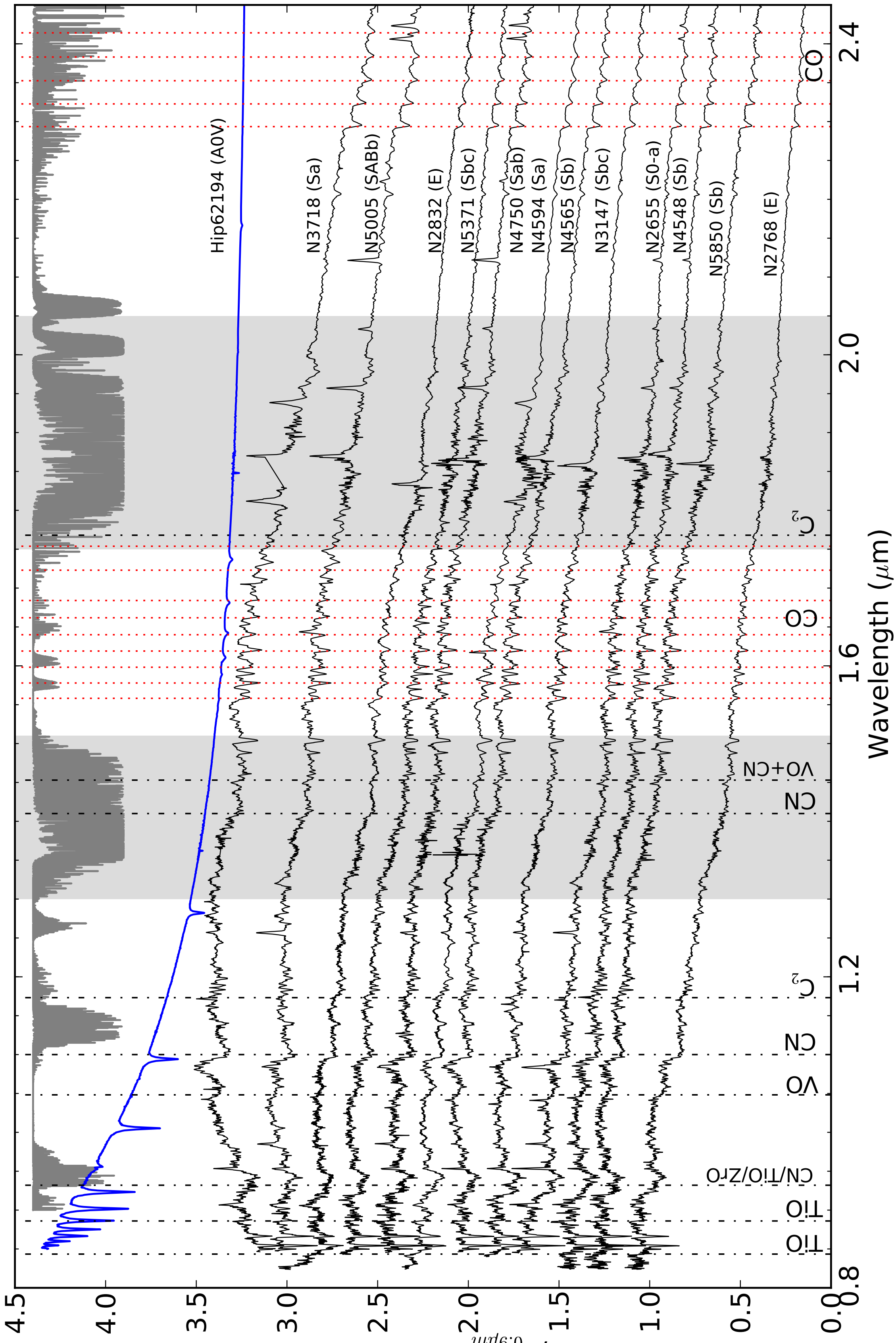

FIG. 1.— Rest frame spectra of the galaxy sample showing absorption bands due to intermediate-age stars. Shaded regions indicate broad, stellar H_2O molecular bands, while dotted lines denote the CO bands. Other molecular bands are labeled in the bottom panels. Hubble types are from HyperLeda (Paturel et al. 2003). A Mauna Kea atmospheric transmission spectrum for 1 mm H_2O and 1 airmass is also shown (gray), along with the spectrum of an A0 star (blue) reduced in the same manner as the galaxy data. Because of the small redshifts of the galaxies, the telluric features/residuals in the A0 star and atmospheric spectra do not correspond precisely to those in the galaxy data.

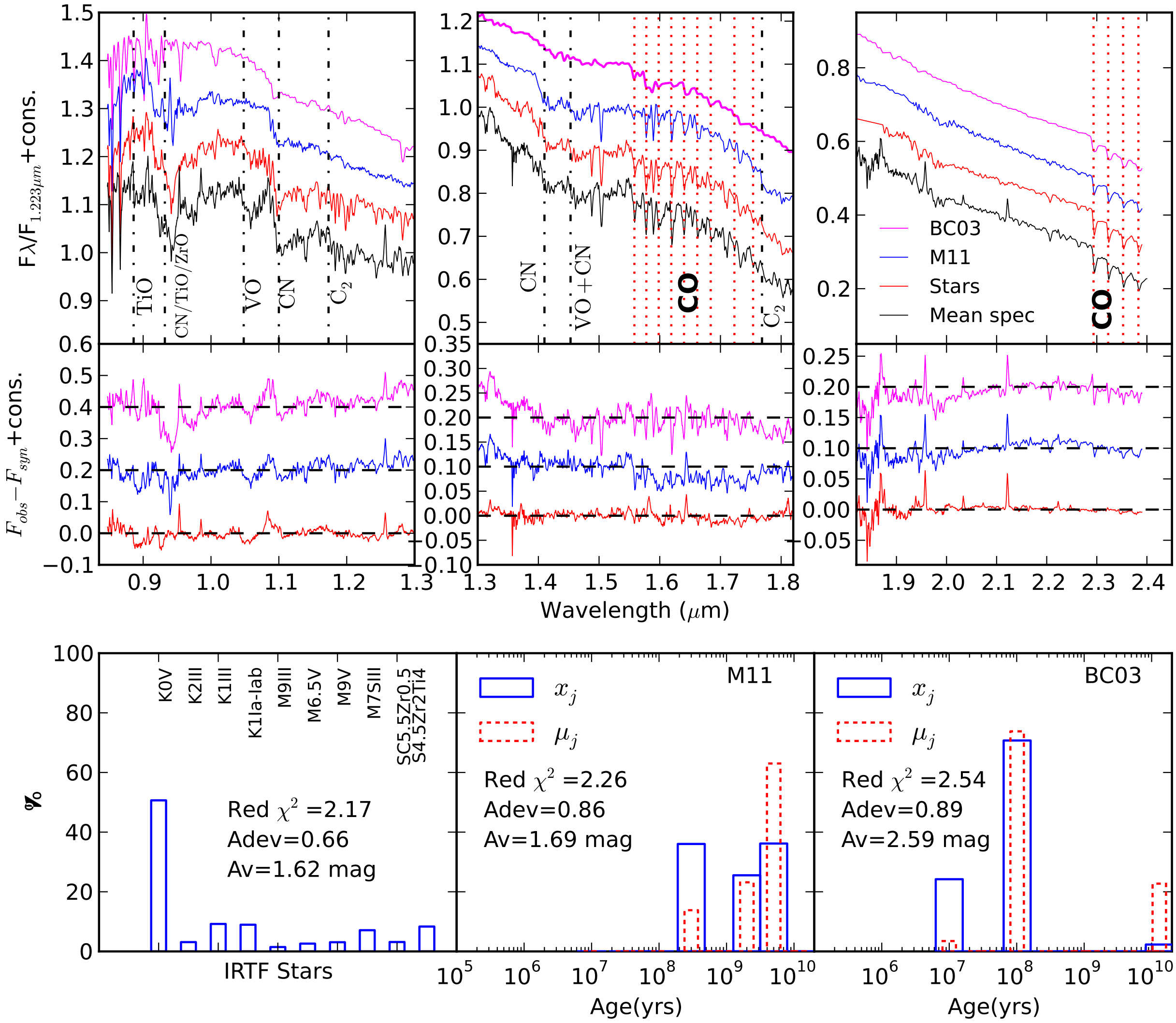

Fig. 2.— Top: high SNR mean spectrum (black), along with EPS fits using (lowest to highest) the IRTF stars, M11 and BC03 models. Middle: the difference between the mean spectrum and its fits, following the same order as in the top. Bottom: synthesis results from these three methods. x_j denotes light fractions and μ_j denotes mass fractions. Stars spectral types are taken from Cushing et al. (2005); Rayner et al. (2009). The goodness of the fits **and Av** are on the labels, see Cid Fernandes et al. (2005a) for more details.

band with Paγ. If such a young component were genuinely present, we would expect to require a significant fraction of F stars (the hottest available in the IRTF library) when fitting the mean spectrum with the stellar library, which is not the case. **Furthermore, when we remove the $\leq$100 Myr components from the BC03 approach, the best fit is achieved with $\sim$ 35% of the light due to the 1 Gyr and $\sim$ 65% due to the 2 Gyr components, however, with a much poorer fit ($\chi^2 \sim 100$).**

Since the relative band strengths depend on metallicity (M05), we also tried fitting the mean spectrum with BC03 and M05 models with three non-solar metallicities (the M11 models include only solar metallicity for this wavelength range). Similar ages to those derived from the original analysis were obtained in all cases.

The galaxies in our sample have similar spectral shapes, thus, their intrinsic reddening is similar. The mean spectrum has an average reddening which is treated by STARLIGHT **as a free parameter. The visual extinctions derived with** ***Stars*** **and** ***M11*** **are very similar (Fig. 2) , while for** ***BC03*** **a larger value is required (to compensate for the spectral shape of the younger populations fitted). The goal of this work is to show the general behavior of model predictions when trying to reproduce the stellar absorption features, which are only weakly affected by extinction (e.g. Riffel et al. 2011). A more in depth analysis of the stellar populations of the individual galaxies, including a detailed discussion of reddening effects, is deferred to future work (Riffel et al., in prep).**

5. FINAL REMARKS

The high-S/N GNIRS spectra presented in this Letter clearly show the NIR absorption features of CN, VO, H_2O and CO that are present in the spectra of thermally pulsing asymptotic giant stars. Another feature characteristic of cool giants is detected at 0.93 μm, and is probably due to a blend of CN, TiO, and possibly ZrO. After comparing the mean spectrum of the 12 individual galaxies with observed stellar spectra (Cushing et al. 2005; Rayner et al. 2009), the M11 "enhanced TP-AGB models" and the BC03 models, we find that the relatively strong molecular features predicted by the M11 models provide a good fit to the galaxy spectra, indicating the presence of intermediate age stellar populations in these galaxies.

Recent EPS models reproduce qualitatively well most absorption features of the galaxy NIR spectra, but issues related to both incompleteness of the stellar libraries and uncertainties in the the theoretical treatment of AGB and TP-AGB stellar phases prevent us from pursuing a more detailed quantitative analysis at this stage. A more precise determination of the ages and metallicities of the stellar populations of the individual galaxies will be the subject of a future paper, where we will perform an in-depth analysis on the basis of a wider range of stellar population synthesis models and model parameters.

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