Galaxies M32 and NGC 5102 Confirm a Near-infrared Spectroscopic Chronometer

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ABSTRACT

We present near infrared (NIR) IRTF/SpeX spectra of the intermediate-age galaxy M32 and the post-starburst galaxy NGC 5102. We show that features from thermally-pulsing asymptotic giant branch (TP-AGB) and main sequence turn-off (MSTO) stars yield similar ages to those derived from optical spectra. The TP-AGB can dominate the NIR flux of a coeval stellar population between ∼0.1 and ∼2 Gyr, and the strong features of (especially C-rich) TP-AGB stars are useful chronometers in integrated light studies. Likewise, the Paschen series in MSTO stars is stongly dependent on age and is an indicator of a young stellar component in integrated spectra. We define four NIR spectroscopic indices to measure the strength of absorption features from both C-rich TP-AGB stars and hydrogen features in main sequence stars, in a preliminary effort to construct a robust chronometer that probes the contributions from stars in different evolutionary phases. By comparing the values of the indices measured in M32 and NGC 5102 to those in the Maraston (2005) stellar population synthesis models for various ages and metallicities, we show that model predictions for the ages of the nuclei of M32 and NGC 5102 agree with previous results obtained from integrated optical spectroscopy and CMD analysis of the giant branches. The indices discriminate between an intermediate age population of ∼3–4 Gyr, a younger population of $\lesssim$1 Gyr, and can also detect the signatures of very young $\lesssim$100 Myr populations.

Subject headings: galaxies: evolution — galaxies: stellar content — stars: AGB and post-AGB

1. Introduction

Integrated spectroscopy of galaxies has been performed primarily in the optical because much of the (blue) optical light comes from the well-understood main sequence turnoff stars. As one pushes into the near infrared (NIR), the integrated light of a stellar population is dominated by very

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luminous stars in later stages of stellar evolution, such as thermally pulsing asymptotic giant branch (TP-AGB) stars. Beginning with Renzini & Voli (1981) and continuing with, e.g., Frogel et al. (1990), Bressan et al. (1998), Maraston (1998), Lançon et al. (1999), Lançon & Mouhcine (2002), it has become clear that the unique features and high luminosity of TP-AGB stars profoundly affect the NIR integrated light of stellar populations. Specifically, for stellar populations with ages ∼100 Myr to ∼1 Gyr, the TP-AGB can contribute up to ∼60% of the K-band flux (depending on metallicity, see Maraston 2005). Strong molecular features, from CN, CO, C_2, and H_2O, in TP-AGB stellar atmospheres should appear in the integrated NIR spectrum of populations in this age range.

Unfortunately, relatively poorly understood processes such as mass loss, convective transport of heavy elements to the surface, and thermal pulsation influence the late stages of stellar evolution and thus predictions for the integrated spectrum. Furthermore, the ratio of C-rich to O-rich AGB stars in a population is known to depend strongly on metallicity, meaning that the contribution from TP-AGB stars can vary drastically not only with age but also composition (Mouhcine & Lançon 2003). However, observational work has constrained these effects on the integrated light of stellar populations with observations of Magellanic Cloud and Galactic clusters, and the predictive potential of NIR spectroscopic features has been demonstrated (e.g., Lançon et al. 1999; Mouhcine & Lançon 2002; Maraston 2005). In short, TP-AGB features should be traceable in galaxies whose NIR light is dominated by stars in the ∼100 Myr to ∼1 Gyr age range.

For example, Mouhcine et al. (2002) have detected the presence of TP-AGB stars in the NIR spectrum of a young star cluster in the galaxy NGC 7252, and have verified that the predicted features expected in a young population (∼300 Myr) are present in the NIR spectrum. This successful detection of TP-AGB features in NGC 7252 thus motivates additional NIR spectroscopy of bright, nearby galaxies with young populations to further test the use of NIR spectral indicators as chronometers. We also note that while light from the TP-AGB can dominate the NIR flux, the main sequence turn-off (MSTO) also contributes an appreciable amount to the integrated light, and hydrogen features (specifically the Paschen series) due to MSTO stars will be visible. To investigate the behavior of the TP-AGB and MSTO features as a function of both age and metallicity we consulted the Maraston (2005, hereafter M05) stellar population synthesis models, which include a careful treatment of the TP-AGB. In this Letter we use NIR spectra of two galaxies with very different star formation histories to test if population synthesis models of TP-AGB and MSTO features can differentiate between young and intermediate-age populations.

Because its high nuclear surface brightness and proximity allow for both high SNR spectroscopy and resolved stellar photometry of the giant branch, the intermediate age compact elliptical galaxy M32 has been extensively studied. Recent work has included integrated optical spectroscopy of the nucleus and extranuclear region out to the half-light radius R_e (del Burgo et al. 2001; Worthey 2004; Rose et al. 2005; Coelho et al. 2009), and NIR imaging of the giant branches (Davidge & Jensen 2007). These studies find that the nuclear light is dominated by an approximately solar metallicity intermediate-age population (∼3 – 4 Gyr). Because its stellar content has been constrained by several established age-dating techniques, M32 is ideal for testing other predictive techniques.

Likewise, the blue S0 galaxy NGC 5102 is close and bright enough for high SNR integrated spectroscopy plus resolved CMD analysis of its brightest stars. It is classified as a post-starburst (PSB) galaxy because its strong Balmer-line absorption and absence of emission indicates that star formation terminated recently. Studies by, e.g., Deharveng et al. (1997); Davidge (2008) have indicated that the nuclear region of NGC 5102 has undergone a termination of star formation within the past ∼10–100 Myr, after a several hundred Myr period of activity, guaranteeing that there is an appreciable young population with a mean age of a few 100 Myr. The intermediate age stars in M32 and the younger stars in NGC 5102 are a useful pairing because most of the NIR light emitted by these two galaxies comes from stars in different evolutionary stages: the younger population will be dominated by the TP-AGB and a blue MSTO, while in the intermediate age population most of the light comes from the red giant branch and an older MSTO (see Fig. 13 in M05).

In this Letter we define four age-sensitive NIR spectroscopic indices, two of which measure previously defined TP-AGB features, and two that measure Paschen series absorption lines, and compare the observed values in M32 and NGC 5102 to predictions of the M05 stellar population models. We demonstrate that the derived ages from the NIR indices agree closely with previously published ages determined from optical spectroscopy, and thus provide evidence to support the reliability of NIR spectral signatures as a useful chronometer for galaxy evolution.

2. Observations and Stellar Population Models

On the nights of 12 and 13 May 2010, we observed NGC 5102 with the SpeX spectrograph on the NASA Infrared Telescope Facility (Rayner et al. 2003). The detector is a 1024×1024 Aladdin 3 InSb array. We used the short cross-dispersed (SXD) mode, with a $0\farcs8$ slit (spectral $R = 750$) aligned with the parallactic angle. We took two ABBA object/sky sequences for a total of eight on-object exposures of 120 s each. The SXD mode simultaneously covers $\lambda\lambda 0.81-2.4$ μm, so avoids issues such as order overlap and variable sky features that plague single-order infrared spectroscopy. Standard SpeX calibrations (arc lamps and flats) were performed after the exposures, and we observed a standard A0 V star at similar airmass to remove atmospheric absorption and calibrate fluxes. The nuclear region of M32 was observed on 10 June 2010 with the same instrumental setup, number of exposures and integration time.

Spectral extraction and atmospheric correction were performed using the Spextool package, version 3.4 (Cushing et al. 2004). See Vacca et al. (2003) for a detailed description of the telluric correction process. The final spectra of six separate orders were coadded and combined, and are displayed in Figure 1, along with optical spectra.

We define four spectroscopic indices (see Table 1): two are flux ratios of narrow bands bracketing absorption breaks (1.08μm CN, 1.77μm C_2), and two are equivalent widths of hydrogen Paschen lines (1.00μm Paδ, 1.28μm Paβ+), where the "+" reminds the reader that due to the low resolution

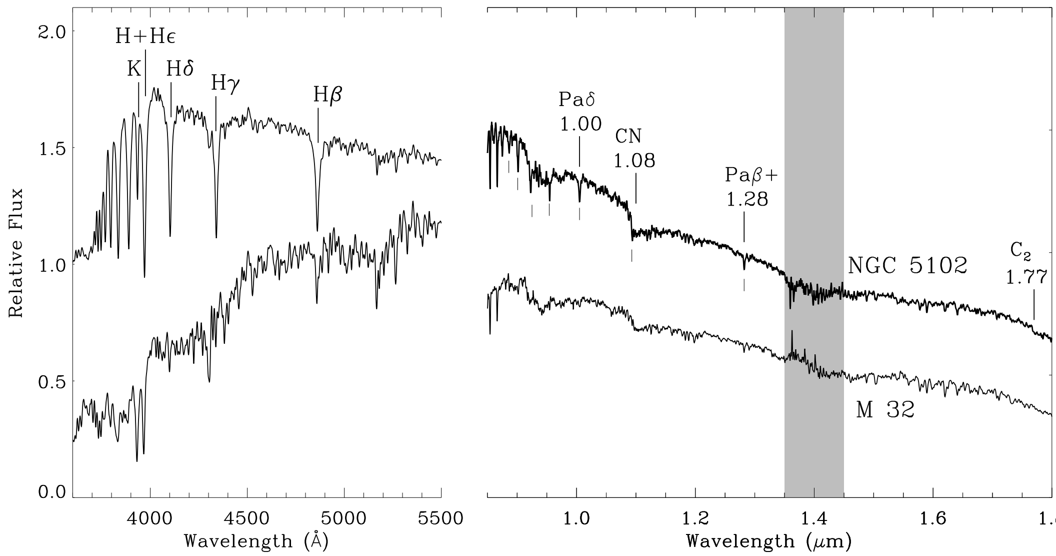

Fig. 1.— Optical (for reference) and NIR spectra of NGC 5102 and M32 are plotted. The optical spectrum of NGC 5102 is from the Goodman High Throughput Spectrograph (Clemens et al. 2004) on the 4.1 m SOAR telescope at Cerro Pachon, Chile, while the optical spectrum of M32 was taken with the FOCAS spectrograph on the 8 m Subaru telescope at Mauna Kea, Hawaii (see Rose et al. 2005). The NIR spectra were taken with the SpeX spectrograph for this paper. The region of low atmospheric transparency is shaded. The J and H bands are shown, as we have defined no indices in the K band. The Paschen series is marked with the lower ticks to illustrate the differences between the spectra. Note the stronger Balmer lines in the optical spectrum of NGC 5102 than in M32, which is also reflected in the stronger Paschen series in the NIR spectrum of NGC 5102.

Table 1. Index Definitions and Values

Feature	Band 1 (μm)	Band 2 (μm)	Line (μm)	M32	NGC 5102
1.00μm Paδ	0.997–1.000	1.012–1.015	1.002–1.011	0.84 Å	2.63 Å
1.08μm CN	1.060–1.070	1.095–1.105	–	1.10	1.20
1.28μm Paβ+	1.258–1.265	1.297–1.305	1.275–1.289	1.75 Å	2.89 Å
1.77μm C_2	1.753–1.763	1.775–1.785	–	1.06	1.11

Note. — Bandpasses used to define spectral indices. The 1.00 and 1.28 μm Paschen features are equivalent widths, while the two other indices are flux ratios of narrow bands bracketing molecular absorption breaks due to TP-AGB stars. The index values for M32 and NGC 5102 are included.

of the models, other lines are present in the Paβ equivalent width feature. The absorption breaks arise from the cool, luminous stars on the TP-AGB, while the Paschen lines are contributed by hot main sequence turnoff stars in young populations, and thus this method probes two independent stellar phases with very different physical origins (the cool, extended atmospheres of TP-AGB stars vs. the hot atmospheres of MSTO stars). An enhanced view of the spectra of M32 and NGC 5102 in the regions of the four spectral indices is shown in Figure 2. To track the dependence of these four indices on age and metallicity we have measured them in the M05 simple stellar population (SSP) models, which cover a large range in both age and metal abundance, and provide an output integrated spectrum for each age and metallicity. In all cases we have used a Kroupa initial mass function and a red horizontal branch.

3. Results

As can be seen qualitatively in Figure 1, there are clear differences between both the optical and NIR spectra of the recent PSB galaxy NGC 5102 and the intermediate-age M32. In the optical the Balmer lines are much more prominent, and the Ca II K line weaker, in NGC 5102 than in M32. Likewise, the Paschen line series and the two break features due to the TP-AGB are significantly stronger in the NIR spectrum of NGC 5102 than M32. To provide a quantitative foundation to these differences and to make a direct comparison with the predictions for spectral index behavior of the M05 models, in Figure 3 values for the four above-defined indices are plotted as a function of age for the M05 models, at four different metallicities, along with the observed values for NGC 5102 and M32. Due to the high SNR of the observed spectra, the formal (photon statistical) error bars for the NGC 5102 and M32 index values are actually smaller than the width of the plotted lines. Systematic errors due to, e.g., flat-fielding issues, subtraction of night sky emission lines, and removal of telluric features, clearly dominate the true uncertainties, and await a more detailed analysis.

It is readily seen that the two absorption break indices, as well as the Paβ+ index, first increase with increasing age as the TP-AGB becomes more prominent, and then decline at ages greater than $\sim$1 Gyr, as the RGB overtakes the TP-AGB as the dominant contributor in the NIR. The Paδ index behaves similarly, but with the index first rising and then falling more rapidly with age (at 100 Myr). The two galaxies are seen to have quite distinct SFHs; the large break indices and large Paschen index values in NGC 5102 argue for a young ($\lesssim$2 Gyr) population with appreciable flux from the TP-AGB, and from upper main sequence stars, while M32 shows little contribution from the TP-AGB or young stars.

Because both NGC 5102 and M32 must have had complicated SFHs and chemical enrichment histories, it is certainly an oversimplification to compare their integrated spectra to SSP model predictions. The derived ages are really an SSP-equivalent age (Serra & Trager 2007), in that the mean age derived from the indices is weighted by the contributions from the entire SFH of the galaxy, which tends to more heavily weight the younger, more luminous, populations. Nevertheless, we

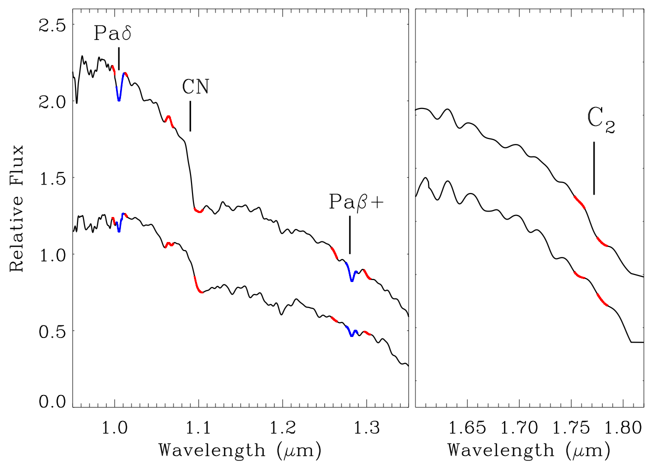

Fig. 2.— Wavelength regions of spectral indices for NGC 5102 (top) and M32 (bottom) smoothed to the resolution of the M05 models, with flux bands shown in red, and line regions in blue.

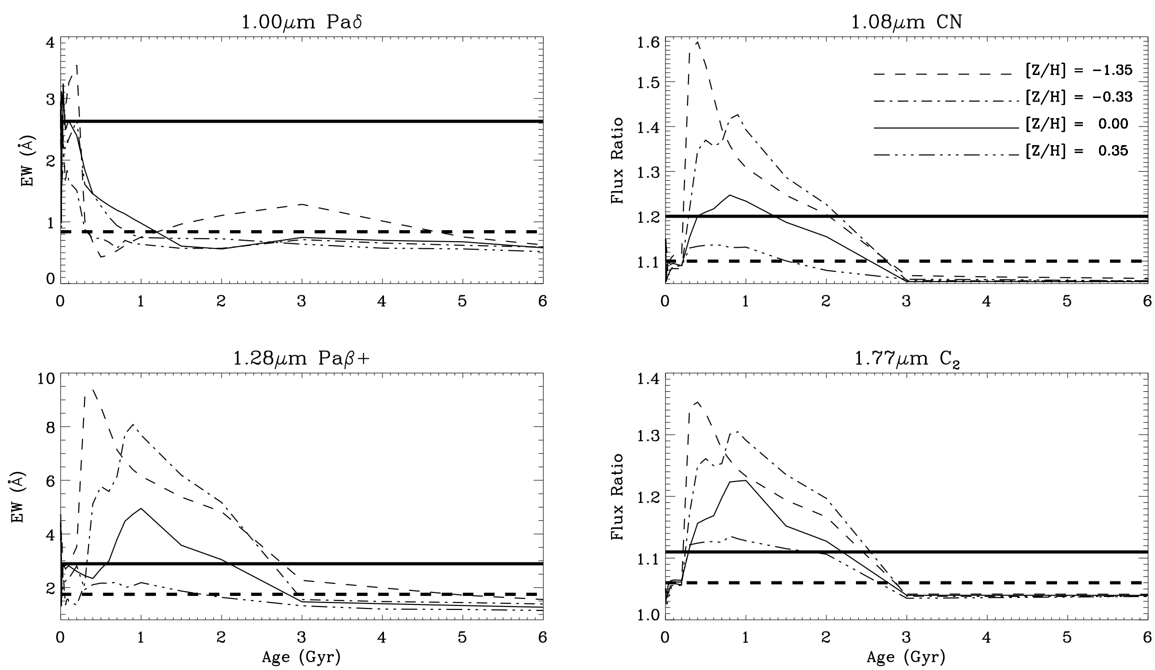

Fig. 3.— NIR spectral indices derived from the M05 models are plotted as a function of age, for four metal abundances. Thick horizontal lines denote the observed values for NGC 5102 (solid line) and for M32 (dashed line), respectively. The formal (photon statistical) error bars in the NGC 5102 and M32 indices are smaller than the thickness of the plotted lines. We note that the Paβ+ index is contaminated with other features.

can demonstrate that inferences about the SFHs of these two galaxies from the NIR spectra concur with previous results obtained at optical wavelengths. In the case of M32, the low values of all four NIR indices consistently argue for an SSP-equivalent age $\gtrsim$3 Gyr, which is in accord with the ages of $\sim$4 Gyr obtained from optical spectra by Worthey (2004) and Rose et al. (2005) for the central region; Davidge & Jensen (2007) also find an intermediate-age population in M32 based on resolved star photometry of the RGB. Coelho et al. (2009) find evidence for an old (>10 Gyr) population underlying the intermediate age population, each contributing roughly half of the optical light. The implication is that the SSP-equivalent age results from the combination of an old population, and one no older than $\sim$4 Gyr. In principle, for instance, the SSP-equivalent age of 4 Gyr could arise from the combination of a young, $\sim$1 Gyr, population superposed on the old population. However, in Rose (1994) it was found on the basis of spectral indices in the blue that any contribution from a 1 Gyr population must be very small. The NIR spectral indices for M32 plotted in Figure 3 certainly supports the conclusion from the optical indices that any contribution from a population as young as 1 Gyr must be small.

Turning now to NGC 5102, the most striking aspect of Figure 3 is the contrast between the consistently higher NIR indices in NGC 5102 and those in M32, implying that while the light of M32 is dominated by an intermediate-age population, that of NGC 5102 is dominated by a younger population in which both the TP-AGB and hot young main sequence stars make a strong contribution. The TP-AGB signature is evident in the high observed values of the 1.08μm and 1.77μm break features, while the young main sequence contribution is evident in the high value of the Paδ index at 1.00 μm and to a lesser extent the partially-contaminated Paβ+ index at 1.28 μm.

Two aspects of the behavior of the NIR indices with age and metallicity complicate their interpretation. First, as mentioned, the break indices initially rise with age at $\sim$100 Myr as the TP-AGB phase develops, then decline beyond $\sim$1 Gyr as the RGB develops. The Paschen indices behave similarly as the hydrogen lines in upper main sequence stars first strengthen and then weaken with the turnoff temperature. Thus two age solutions are possible for many index values. However, the Paδ index peaks at substantially younger ages than the other three indices, so can often lift the age degeneracy. Second, the timing and duration of the index peaks depend on metallicity. This is due in part to the strong metallicity dependence of the ratio of C-rich to O-rich AGB stars in a population: metal-poor populations will have a larger fraction of C-rich giants than their metal-rich counterparts. For NGC 5102 we can assume approximately solar metallicity, because Davidge (2008) finds that the metallicity distribution function (MDF) of its disk RGB stars peaks at [Fe/H]$\sim$-0.1, whereas Beaulieu et al. (2010) report that the young nuclear population has [Fe/H]= 0.0. The solar metallicity models in Figure 3 show that each of the observed indices for NGC 5102 is consistent with an age of $\sim$300 Myr. The shape of the absorption breaks and the 1.28μm indices yield two possible ages from any measurement, but the 1.00μm Paδ feature is sufficiently distinct in age sensitivity to distinguish between a younger and more intermediate age population, and constrains the age to $\sim$300 Myr. As mentioned, recent studies of NGC 5102 report a period of star formation lasting several hundred Myr and ending within the past $\sim$100 Myr, showing that our index values are consistent with the results from established age-dating techniques.

Our measured NIR spectral indices in M32 and NGC 5102 reinforce the importance of TP-AGB constraints on galaxy ages obtained from NIR spectra, especially when combined with features that probe the MSTO. This technique is particularly useful for distinguishing intermediate age (∼3-5 Gyr) galaxies from those dominated by a young (∼1 Gyr) population. We can further discriminate for the presence of a very young (∼100 Myr) population on the basis of the Paδ index. Hence our analysis demonstrates that NIR indices allow for a fairly complete description of age and metallicity for a range of stellar population ages that will become accessible with the large lookback times observable with the next generation IR space telescope, the *James Webb Space Telescope*. Specifically, this chronometer will aid in testing models of galaxy formation in the early universe: as a large number of high redshift galaxies are observed in the mid-IR, formation timescales can be constrained with the (restframe) NIR indices presented here. Because $z > 2$ galaxies are $\lesssim$2 Gyr old (assuming standard Λ-CDM cosmology), the TP-AGB and young main sequence turnoff will provide much of the integrated flux, and the time of their formation can be determined from the measured NIR indices.

4. Conclusion

We present an analysis of integrated NIR SpeX SXD spectra of the nuclear regions of M32 and NGC 5102, and show that mean ages determined from spectroscopic indices agree with previous studies, with the important result that this method can differentiate between young and intermediate-age populations. The indices probe contributions from two different stellar evolutionary phases, the TP-AGB and the MSTO, which effectively provides two independent chronometers. Galaxy ages are derived by comparing index values to those measured in M05 model SSPs, indicating an accurate treatment of the TP-AGB in the models. This method of defining NIR indices is the first step towards a robust NIR spectroscopic age-dating technique, which will be particularly useful when applied to high redshift spectroscopic surveys undertaken by the next generation of infrared observatories.

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