Fingerprints of Stellar Populations in the Near-Infrared: An Optimised Set of Spectral Indices in the \textit{JHK}-Bands

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\section*{ABSTRACT}

Stellar population studies provide unique clues to constrain galaxy formation models. So far, detailed studies based on absorption line strengths have mainly focused on the optical spectral range although many diagnostic features are present in other spectral windows. In particular, the near-infrared (NIR) can provide a wealth of information about stars, such as evolved giants, that have less evident optical signatures. Due to significant advances in NIR instrumentation and extension of spectral libraries and stellar population synthesis (SPS) models to this domain, it is now possible to perform in-depth studies of spectral features in the NIR to a high level of precision. In the present work, taking advantage of state-of-the-art SPS models covering the NIR spectral range, we introduce a new set of NIR indices constructed to be maximally sensitive to the main stellar population parameters, namely age, metallicity and initial mass function (IMF). We fully characterize the new indices against these parameters as well as their sensitivity to individual elemental abundance variations, velocity dispersion broadening, wavelength shifts, signal-to-noise ratio and flux calibration. We also present, for the first time, a method to ensure that the analysis of spectral indices is not affected by sky contamination, which is a major challenge when dealing with NIR spectroscopy. Moreover, we discuss two main applications: (i) the ability of some NIR spectral indices to constrain the shape of the low-mass IMF and (ii) current issues in the analysis of NIR spectral indices for future developments of SPS modelling.

\textbf{Key words:} infrared: galaxies – galaxies: stellar content

\section*{1 INTRODUCTION}

Understanding the evolutionary history of galaxies has shed light on many physical processes such as supernova explosions and gamma-ray burst events, evolution and merger of supermassive black holes, dust formation and destruction, stellar dynamics, interstellar medium enrichment and even histories of planet formation. Hence, a better picture of galaxy formation and evolution is beneficial to many other areas of astrophysics. One way to achieve this goal is by studying the stellar content of galaxies since it provides valuable information on different star formation episodes in a galaxy and its chemical evolution.

Spectroscopy-based studies of the stellar population content of galaxies are based on the comparison between evolutionary stellar population synthesis (SPS) models and data. This comparison can be made by using either line-strength fitting (e.g. Worthey et al. 1994; Vazdekis et al. 1997; Trager et al. 2000; Thomas et al. 2005; Gallazzi et al. 2008; Riffel et al. 2008; Graves et al. 2009; La Barbera et al. 2013; Spiniello et al. 2014; Martín-Navarro et al. 2015a,b; Martín-Navarro et al. 2015c; La Barbera et al. 2015; La Barbera et al. 2016; La Barbera et al. 2017; Rosani et al. 2018; La Barbera et al. 2019; Ferreras et al. 2019; Salvador-Rusíñol et al. 2019, 2021), full spectral fitting (e.g. Vazdekis 1999; Vazdekis & Arimoto 1999; Riffel et al. 2009, 2010; Conroy & van Dokkum 2012; Ferré-Mateu et al. 2013; La Barbera et al. 2014; Choi et al. 2014; van Dokkum et al. 2017), or full index fitting (FIF) (Martín-Navarro et al. 2019) methods. In the line-strength approach, the stellar population parameters of galaxies are determined by fitting the pseudo-equivalent width of spectral indices, while in full spectral fitting, fluxes at different wavelengths are fitted simultaneously. The FIF is a new approach, and it uses index definitions to normalize the continuum and then fits pixels within the feature. Each method has its own advantages and drawbacks. For example, the advantage of using line-strength indices is that the focus is given only to relatively narrow and well characterized spectral regions particularly sensitive to relevant stellar population parameters. However, this
advantage is achieved with a lot of information from all pixels in the spectrum and also in the spectral shape of the feature. Moreover, in line-strength fitting, the absorption line-strengths are measured with respect to pseudo-continua, which in reality are blends of several element species. Therefore, variation of an index may be due to a combination of variations in the feature itself and to variations in the pseudo-continua, which are due to different stellar population parameters. On the other hand, spectral fitting can use the entire measured signal rather than partial information encoded in the spectral indices. This approach involves many free parameters, not necessarily well constrained, and demands much higher model accuracy. It assumes, ideally, that model predictions are ‘perfect’, and all systematics from data reduction are fully under control. The advantage of the hybrid approach (FIF) is that it focuses on narrow spectral regions, as in the line-strength method, trying to maximize the information we can extract from the spectrum in those regions.

Although the information about the properties of a stellar population is distributed over the entire spectrum, this information is highly redundant. Hence, regardless of the technique of fitting models to data, it is important to have a system of spectral indices, in order to extract relevant information required for the stellar population analysis. So far, detailed analysis of the spectral absorption features in the spectrum of galaxies has been concentrated mainly on the optical wavelengths. Diagnostics of the stellar content of galaxies have been identified and well-characterized thanks to high-quality empirical spectral libraries in the optical SPS models (e.g. Worthey et al. 1994; Vazdekis et al. 1996; Vazdekis 1999; Bruzual & Charlot 2003; Thomas et al. 2003; Le Borgne et al. 2004; Maraston 2005; Vazdekis et al. 2010; Maraston & Strömbäck 2011; Conroy & van Dokkum 2012; Vazdekis et al. 2012; Vazdekis et al. 2016; Conroy et al. 2018; Maraston et al. 2020). The Lick IDS instrument dependent system of indices (Worthey et al. 1994) and its flux-scaled LIS version (Vazdekis et al. 2010) is the most widely used set of indices in the optical that contains the definition (wavelength limits) of these diagnostic features.

Due to the challenges of spectroscopy with ground-based telescopes in wavelengths beyond 9000 Å, the near-infrared (NIR) range has been relatively unexplored. The background radiation is significant, and absorption from the Earth’s atmosphere is strong in the NIR. These effects make observational strategies and data reduction in the NIR domain complicated. However, spectroscopy at NIR wavelengths has the advantage of probing optically-obscured regions of galaxies. Moreover, cool evolved stars such as short-lived red supergiants (in very young populations ~ 10 Myr) and thermally-pulsating asymptotic giant branch (TP-AGB) stars (in intermediate-age populations 0.1-2 Gyr) or red giant branch stars (in old stellar populations) make a strong contribution to the total flux of galaxies in the NIR. However, the NIR domain has lower sensitivity to the young stellar component of galaxies that dominate the optical part of the spectrum. Hence, NIR spectroscopy allows the degeneracy between multiple stellar populations to be broken, providing information complementary to the optical range.

Owing to the advent of NIR instrumentation, it has recently become possible to measure absorption features in the NIR with the accuracy required for stellar population studies. In parallel to the development of NIR instruments, theoretical and empirical spectral libraries have been extended to this window (IRTF Rayner et al. (2009), XSL Gonneau et al. (2020)) and used as a basis for the population synthesis models in the NIR (Maraston (2005), Conroy & van Dokkum (2012), Meneses-Goytia et al. (2015), E-MILES Röck et al. (2015); Vazdekis et al. (2016); Röck et al. (2016), A-LIST Ashok et al. (2021)). Unlike in the optical range, there is no homogeneous, optimized and fully characterized set of indices, covering the J-, H- and K-bands, to compare the predictions of spectral synthesis models to observations. In the last two decades, several studies have attempted to utilise NIR absorption features in the study of stellar populations. These studies have either identified new spectral indices or modified previous definitions, based on different criteria. In many cases only a narrow spectral window was covered. For example, Frogel et al. (2001) modified some of the wavelength intervals of only three spectral indices at the end of the K-band (Na, Ca, and CO), Ivanov et al. (2004) defined new indices for atomic lines and also adopted previous definitions for some indices in the H- and K-bands. Silva et al. (2008) considered velocity broadening of galaxy spectra and optimised the definitions of Fe i and Mg i absorptions at the red end of the K-band. Mármol-Queraltó et al. (2008) optimised the CO index at 2.3 μm. CvD12 supplemented the blue Lick indices with new indices in the NIR to constrain the number of low mass stars in the spectrum of galaxies. Röck (2015) proposed a homogeneous set of indices in the NIR. The author re-defined a number of indices in the J-, H- and K-bands based on E-MILES SPS models and characterised them as a function of age, metallicity and IMF slope. Riffel et al. (2019) presented new definitions for the NIR absorption features, taking into account the location of the most common emission lines detected in active galaxies. Cesetti et al. (2013) and Morelli et al. (2020) presented an extensive study of absorption features in the I, J, Y, H, K and L windows. They optimised the definition of indices to be sensitive to physical stellar parameters, i.e. $T_{\text{eff}},[\text{Fe/H}]$, and log(g) and they characterized the dependence of their indices on velocity dispersion broadening. However, these studies lacked an optimization, relevant stellar population parameters wise, and full characterization of each index (see below). Moreover, the existence of various definitions for the same absorption in the literature makes the comparison of results from different studies far from trivial. For these reasons, in the present work, we provide a new set of optimized NIR indices, fully characterized for stellar population analysis. The indices are characterized not only with respect to the main physical properties of galaxies, namely age, metallicity and stellar initial mass function (IMF) but also with respect to the effect of elemental abundance ratios, velocity dispersion, wavelength shifts, signal-to-noise ratio (SNR), flux calibration and the contamination from sky emission/absorption lines. For the first time, we also describe a procedure to select indices that can be robustly used for stellar population analysis in the NIR.

The layout of the paper is the following. In Sect. 2, we present the method to identify the most sensitive absorption features to a particular stellar population parameter (age, metallicity and IMF). The procedure to define spectral indices is described in Sect. 3, while a thorough characterization of the indices is provided in Sect. 4. In Sect. 5, we describe practical applications of our newly defined indices. The paper closes with a summary in Sect. 6.

2 ABSORPTION IDENTIFICATION

We aim to determine which absorptions in the NIR spectra of unresolved populations could be of interest for studying their stellar content. Simple stellar population (SSP) spectra provide us with a flexible tool for such kind of analysis. In this work, we used E-MILES SSPs (Vazdekis et al. 2016) which adopt the IRTF stellar library (Cushing et al. 2005; Rayner et al. 2009) in the NIR. The E-MILES SSPs cover a wide range of ages, from 1 to 14 Gyr (1 to 17.78 Gyr), and metallicity between -0.35 to +0.26 dex (-0.4
to +0.22 dex), for models based on BaSTI isochrones (Pietrinferni et al. 2004) (Padova00 isochrones (Girardi et al. 2000)). They are computed for a variety of IMFs, including both single power-law (unimodal) and low-mass tapered (bimodal) IMF, whose slope $\Gamma$ and $\Gamma_p$, respectively, increases as the IMF becomes more enriched in dwarfs relative to giant stars (i.e. more bottom-heavy compared to a Kroupa-like distribution, see Vazdekis et al. (1996, 1997), for details). To identify the most sensitive spectral features to a given stellar population parameter, we computed "response functions" of SSP models to age, metallicity and IMF slope, respectively. Each response is obtained by dividing a given SSP spectrum to a reference model. For the response to age, we divided two SSPs of solar metallicity and Kroupa-like IMF with different ages, i.e. 12 and 2 Gyr, respectively. To obtain the metallicity response function, we divided SSP spectra with the same IMF (Kroupa-like) and the same age (12 Gyr) but with $[\text{M}/\text{H}] = +0.15$ and -0.25 dex, respectively. Finally, for the IMF sensitivity, we divided an SSP with bottom-heavy bimodal IMF (slope $\Gamma_p = 3$; which is typical for the central regions of massive early-type galaxies (ETGs), see La Barbera et al. (2013)) by an SSP with Kroupa-like IMF. Both models have solar metallicity and 12 Gyr age. All SSPs used to compute response functions are base models (see, e.g., Vazdekis et al. (2015)), computed with BaSTI isochrones and broadened to $\sigma = 360$ km s$^{-1}$.

To create response functions to a given parameter, we removed the effect of different continuum shapes between different SSPs, by fitting second-degree splines to the SSPS ratios. The sensitivities obtained in this way, provide us with useful visual guidelines for identifying potential proxies. In the top panel of each plot in Fig. 1, we show the SSPs response functions. The red, green and purple lines show age, metallicity and IMF sensitivities, respectively. The upper and lower black lines, around each response function, show ±1% sensitivities.

As our reference spectrum in defining NIR indices, we used an SSP of solar metallicity, Kroupa-like IMF and 12 Gyr age. This spectrum is shown with a thick black line in the bottom panels of each plot in Fig. 1. In the same panels, we also show (arbitrarily rescaled) sky emission lines in pink and telluric absorption lines in dark blue (both obtained by the ESO SkyCalc tool (Noll et al. 2012; Jones et al. 2013)).

By looking at the SSP spectral ratios, we find regions that are more sensitive to a given stellar population parameter. In order to identify which atomic/molecular species are responsible for the corresponding absorption features in the reference spectrum, we proceed as follows. Since the IRTF library is used to build up the E-MILES models in the NIR, we used the prominent Arcturus atomic lines identified in this library (table 7 of Rayner et al. (2009)). Moreover, we used molecular band identifications in the IRTF library from table 10 of Rayner et al. (2009). We also made use of M-dwarf absorption features which are identified as IMF-sensitive features in Lagattuta et al. (2017), as well as line lists from Klei mann & Hall (1986). Appendix A shows a zoom in of each index and indicates identified element species.

Figure 1 shows that the bluest part of the J-Band contains CN and FeH absorptions at about 9000 – 10000 Å. The sensitivities around 11000 – 12000 Å show rises and dips with variable strength, corresponding to CN, Na I, Fe I and Mg I features, respectively. Pa β and Al I are also indicated with a peak and a dip, respectively, in both age and IMF sensitivities. CO molecular absorptions at about 15000 – 17000 Å are the most prominent features in $H$-band. The CN molecules and metallic species such as Mg I and Al I are also present in the $H$-band. In the $K$-band, the sensitivity of IMF shows high peaks beyond 23000 Å corresponding to CO band heads. Ca I lines correspond to the dips in sensitivities in the bluest part of the $K$-band. Sensitivity to metallicity is almost flat in the entire NIR spectral range.

3 OPTIMISED INDEX DEFINITION

To define a key set of spectral indices in the NIR, we use a Lick-style index definition, where each index consists of a central bandpass enclosing the feature, as well as a blue and red pseudo-continuum bandpasses at either side of the feature. The SSP response functions provide us with a useful tool to define optimised central wavelengths and pseudo-continuum bands with respect to stellar population parameters. Indeed, we included the peak of sensitivities for selecting central bandpass of indices if associated with an absorption. For defining spectral indices, we also take into account several criteria, as described in the following.

Atmospheric absorption is a severe challenge in the NIR, as several indices are affected by telluric lines. The strongest atmospheric absorptions in the NIR are water vapour features, while atmospheric transmission is also affected by $O_2$, $CO_2$ and $CH_4$. Sky emission lines, especially in the $H$-band, are another source of concern when studying NIR spectral features. We tried not to include strong telluric absorption and sky emission lines in the wavelength range of the index definition; however, it was almost unavoidable. Note that we are aided in this task by the E-MILES models, which are fed with empirical stellar spectra. Hence, our effort to define indices with minimum contamination from sky lines helps to obtain clean SSP model predictions (as the models are based on the spectra of nearby stars), as well as measure clean indices for galaxies at redshift $z \sim 0$. Since the effect of sky residuals might be confused with that of stellar population parameters, in Sect. 4.8 we also introduce a more general methodology to recognize indices that cannot be used when analysing a given set of galaxy spectra in the NIR.

In order to have indices that are robust against systematic effects arising in the flux calibration, the wavelength range involved should be quite narrow. Hence, we tried not to put pseudo-continuum bands very far apart from the absorption feature. Indeed, 65% of our indices are less than 300 Å wide. This means that most of our indices are robust against flux calibration with uncertainties affecting wavelength scales of (typically) ~300 Å.

Absorption features broaden due to galaxy velocity dispersion or instrumental resolution. Line-strength might be affected if the pseudo-continua overlaps with the feature bandpass (Vazdekis & Arimoto 1999; Vazdekis 2001). To ensure that pseudo-continua are not going to be contaminated by the smeared absorption feature, we have defined sideband limits to be at least 10 Å far from the central band.

The widths of bandpasses were chosen to minimise the effect of typical galaxy velocity dispersions on the line-strengths. As the bandpasses become narrower, the sensitivity of the index to velocity dispersion becomes generally higher, but the bandpass width should not be too broad; since it can be affected by metallic lines. In order to be conservative, we put a minimum width of 10 Å for bandpasses, since narrower definitions might be sensitive to the Poissonian noise at scales shorter than velocity dispersion (Cardiel et al. 1998).

We changed the position of central and pseudo-continua band-

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1 This is a conservative choice as it is the typical velocity dispersion of highest mass galaxies, corresponding to the "maximum" smoothing one might have when studying unresolved stellar populations.
Figure 1. The plots show J- (top), H- (middle), and K- (bottom) band spectral regions, respectively. The top panel of each spectral region shows the flux ratios obtained by dividing two models that differ only in the adopted parameter (age, metallicity and IMF slope; plotted with red, green, and purple colours (see the inset in the bottom plot)). Grey and orange bands represent absorption and continuum bandpasses, for each index definition, overplotted on a spectrum of E-MILES SSP model (black). A scaled telluric absorption spectrum (dark blue) and sky emission spectrum (pink) is shown to better highlight clear sky regions (see the inset in the upper plot).
passes or modified their widths on trial index definitions until optimizing the definition of indices to the above requirements. We defined spectral indices as presented in Table 1. At the effective resolutions imposed by galaxy dynamics, none of these atomic and molecular lines is contributed by a single element. Column 8 reports the elements whose absorption were found to contribute to the given feature, with the feature name (Col. 1) coming from what we identified as the possible main contributor to the absorption. Columns 2 to 7 show the limiting wavelengths of bandpasses. All wavelengths in this paper are quoted in the air system. Some of these indices were already defined and studied in other works (e.g. Na$1.14$, Mg$1.50$, Na$2.21$, CO$2.30$, etc.). In this paper, we redefined and optimised them according to our criteria. Appendix A compares all the definitions of the same feature that we found in the literature.

Figure 1 shows our newly defined indices. The grey and orange mark the bandpasses of the features and their adjacent pseudo-continua, respectively.

4 CHARACTERIZATION OF INDICES

Spectral population synthesis allows us to measure absorption features of SSP models with given metallicity, age, stellar IMF, and elemental abundance. In this section, we utilize base E-MILES models, as well as Conroy & van Dokkum (2012) (hereafter CvD12) models to study the behaviour of our new set of spectral indices extensively. Since E-MILES models do not include the effect of individual abundance ratios, we use CvD12 models to evaluate the sensitivity of indices to individual abundance variations, while relying on E-MILES SSPs to characterize the dependence of the indices on the main stellar populations parameters (age, metallicity, and IMF slope). The use of SSP models does not only allow us to characterize spectral indices as a function of population parameters but also characterize their sensitivity to the Doppler broadening, SNR requirements, as well as wavelength shifts due to, e.g., kinematic rotation, recessional velocity and uncertainties due to wavelength calibration, as detailed in the following.

4.1 Index behaviour as a function of age, metallicity and IMF

The characterization of the line-strength indices defined in this work is shown in Figs. 2 to 6. The panels in Col. ‘a’ of all figures show the sensitivity of indices to age. The indices are measured on the four different sets of base E-MILES models: Two sets of models with bimodal IMF of slope 1.3, which is representative of the Milky Way IMF, with solar and super-solar metallicities (green and black solid lines) and two other sets of models with bimodal IMF of slope 3.0, representative of bottom-heavy IMF in massive galaxies, with solar and super-solar metallicities (green and black dashed lines). Each set of models span a range in age from 1 to 14 Gyr. These panels show that indices redward 15000 Å stay almost flat for ages greater than 2 Gyr. Exceptions are calcium indices and the sodium index in $K$-band. Comparing green and black colours shows that the dependence of NIR indices on age does not change with metallicity. Only for bottom-heavy models and old ages, the CN0.93, CN1.42 and CN1.46 indices show some differences in time evolution for different metallicities. It is also noteworthy to mention that the line-strength of Pa$\beta$ index at 1.28 $\mu$m (Fig. 3) drops sharply with age for populations younger than 2 Gyr. The comparison of solid lines with dashed ones reveals that except Al$1.67$ in $H$-band, indices in the NIR have a mild to significant dependence on IMF. For instance, the larger line-strengths of CO and CN indices in SSPs with IMF slope of 1.3 (solid lines) with respect to SSPs with IMF slope of 3.0 (dashed lines) are noticeable.

The AGB evolutionary phase has essential contributions to the NIR light of stellar populations with intermediate age. According to Maraston (2005), this phase is dominated by the TP-AGB stars. They show that inclusion of the TP-AGB stars in the modelling of 0.3 $\leq t \leq$ 2 Gyr stellar populations has a substantial impact not only on the absolute flux but also on the absorption features such as CN, C$_2$, H$_2$O and CO$_2$. Therefore, the peak at around 2 Gyr in the CN0.93, CN1.10, CN1.42 and CN1.46 indices in Col. ‘a’ of Figs. 2 and 3 is an indicator of intermediate-age stellar populations in the integrated light of galaxies. The first detection of the CN molecular band at $\sim$11000 Å was reported by Riffel et al. (2007) in a sample of Seyfert galaxies, implying the presence of recent star formation episodes in these systems.

The panels in Col. ‘b’ of Figs. 2 to 6 show the line-strengths of NIR indices as a function of metallicity, for E-MILES SSPs with a fixed Kroupa-like IMF, and young (2 Gyr; blue lines) and old (12 Gyr; red lines) populations. The total metallicity in each set of spectra varies from -0.35 to +0.26 dex. According to these panels, CN indices in J- and H-bands are the most sensitive ones to the metallicity. FeH0.99, Al$1.31$, CO1.60, CO1.64 and Ca1.95 show a very mild trend with metallicity. The strength of CN0.93 decreases rapidly from solar to super-solar metallicity. CN indices, Na$1.14$, Pa$\beta1.28$ and CO indices in K-band have different sensitivity to metallicity when comparing young to old populations (i.e. comparing blue to red lines), while other indices do not change significantly. Note that the line-strength of most of the indices varies in a non-linear way with metallicity for [M/H] $\geq$ +0.06 dex, especially in young populations (solid blue lines). For instance, in Fig. 3, for young populations (blue line), Pa$\beta1.28$ decreases as a function of total metallicity in the range $-0.25 \leq [M/H] \leq 0.06$, but then it increases and goes down again at the highest [M/H].

In Col. ‘c’ of Figs. 2 to 6, we keep the metallicity constant (at solar value), for two ages of 2 Gyr (blue line) and 12 Gyr (red line), respectively, and vary the slope of the bimodal IMF from 0.3 to 3.5 (x-axis). A general decrease of all CO features towards bottom-heavy IMFs can be seen. Ca1.95, Ca1.99a and Ca1.99b indices change by $\sim$1 Å between an SSP of $\Gamma_b=3.0$ and $\Gamma_b=3.5$, compared to $\sim$0.4 Å for Ca1.99c and Ca2.26. Note that most of the NIR indices can be used to determine the IMF slope of populations with a steeper IMF than the Kroupa-like one, without any degeneracy between IMF and age/metallicity. For instance, the line-strength of CO1.64, in Col. ‘c’ of Fig. 4, changes from $\sim$3 Å to $\sim$2.2 Å for an old population when IMF slope varies from 1.3 to 3.5. According to Col. ‘b’, the minimum index value that can be derived by varying total metallicity from +0.26 to -0.35 dex, is $\sim$2.8 Å. This means that index values less than $\sim$2.8 Å can be only obtained for a bottom-heavy distribution. However, one should always consider how indices respond to abundance ratios; for many NIR indices (e.g. FeH0.99, Na$1.14$, Mg$1.18$, Mg$1.50$, Na$2.21$, Fe$2.24$) the change due to elemental abundances (Col. ‘d’) is comparable to
Some indices are strongly sensitive to a given parameter. For example, Pa β1.28 is much more sensitive to the age than metallicity or IMF. Both NIR sodium indices, Al i1.31, Mg i1.50, calcium indices in the K-band and most of CO indices are strongly sensitive to IMF. Some indices are also significantly sensitive to more than one parameter. For instance, CN indices are sensitive to age, but also to metallicity and IMF.

Since the line strength indices, which we have discussed here, show different sensitivities to age, metallicity, IMF slope and elemental abundances, in principle it should be possible to break degeneracies between these parameters by employing an appropriate combination of indices. However, as we will see in Sect. 5, this task is hampered by current limitations of SSP models in the NIR spectral range.

### Table 1. Definition of spectral indices

| Index   | λ_blue1 | λ_blue2 | λ_centre1 | λ_centre2 | λ_red1 | λ_red2 | Absorber(s) |
|---------|---------|---------|-----------|-----------|---------|---------|-------------|
| CN0.93  | 9040.0  | 9070.0  | 9138.0    | 9465.0    | 9500.0  | 9530.0  | CN/ZrO/TiO/Si/Fe/Mg/Cr |
| FeH0.99 | 9830.0  | 9860.0  | 9880.0    | 9935.0    | 9955.0  | 9980.0  | FeH/Fe/TiO |
| CN1.10  | 10845.0 | 10860.0 | 10920.0   | 11012.0   | 11124.0 | 11170.0 | CN/Mg/Si/Fe/Fe/Ni |
| Na i1.14| 11305.0 | 11325.0 | 11362.0   | 11420.0   | 11453.0 | 11480.0 | Na/Cr/Fe |
| Fe i1.16| 11540.0 | 11570.0 | 11593.0   | 11640.0   | 11705.0 | 11740.0 | Fe/Si/Fe/Fe |
| Mg i1.18| 11705.0 | 11740.0 | 11810.0   | 11850.0   | 11905.0 | 11935.0 | Mg/Fe/Fe |
| Pa β1.28| 12760.0 | 12780.0 | 12790.0   | 12845.0   | 12855.0 | 12875.0 | Paβ/Fe/Ti/Fe/Ca |
| Al i1.31| 13045.0 | 13075.0 | 13105.0   | 13160.0   | 13170.0 | 13195.0 | Al/Fe/Fe |
| CN i1.42| 14015.0 | 14050.0 | 14070.0   | 14250.0   | 14315.0 | 14350.0 | CN |
| CN i1.46| 14460.0 | 14485.0 | 14500.0   | 14750.0   | 14800.0 | 14840.0 | CN/VO |
| Mg i1.50| 14935.0 | 14985.0 | 15005.0   | 15044.0   | 15097.0 | 15120.0 | Mg/Fe |
| CO i1.56| 15445.0 | 15485.0 | 15545.0   | 15620.0   | 15640.0 | 15670.0 | 12CO/Fe/Si/Ti/Fe/Ni |
| CO i1.58| 15705.0 | 15735.0 | 15750.0   | 15810.0   | 15835.0 | 15860.0 | 12CO/Fe/Mg |
| CO i1.60| 15920.0 | 15950.0 | 15970.0   | 16020.0   | 16045.0 | 16120.0 | 12CO/Fe |
| CO i1.64| 16330.0 | 16355.0 | 16370.0   | 16634.0   | 16680.0 | 16800.0 | 12CO/Fe/Si |
| CO i1.66| 16565.0 | 16585.0 | 16600.0   | 16680.0   | 16780.0 | 16800.0 | 12CO/Fe/Si |
| Al i1.67| 16650.0 | 1685.0  | 16710.0   | 16770.0   | 16780.0 | 16800.0 | Al/Fe |
| CO i1.68| 16780.0 | 16800.0 | 16815.0   | 16890.0   | 16905.0 | 16945.0 | 12CO/Si/Fe/Ni |
| Ca i1.95| 19350.0 | 19385.0 | 19405.0   | 19530.0   | 19545.0 | 19580.0 | Ca/Mg/Si/Fe |
| Ca i1.99a| 19660.0 | 19695.0 | 19730.0   | 19800.0   | 20005.0 | 20090.0 | Ca/Fe/Fe |
| Ca i1.99b| 19660.0 | 19695.0 | 19830.0   | 19885.0   | 20005.0 | 20090.0 | Ca/Fe/Fe |
| Na i2.21| 21930.0 | 21975.0 | 22025.0   | 22114.0   | 22130.0 | 22185.0 | Na/Si/Sc |
| Fe ii2.24| 22315.0 | 22350.0 | 22360.0   | 22480.0   | 22500.0 | 22545.0 | Fe/Ti |
| Ca ii2.26| 22500.0 | 22545.0 | 22590.0   | 22680.0   | 22715.0 | 22765.0 | Ca |
| CO ii2.30| 22850.0 | 22895.0 | 22915.0   | 23170.0   | 23340.0 | 23425.0 | 12CO |
| CO ii2.32| 23090.0 | 23170.0 | 23190.0   | 23300.0   | 23340.0 | 23425.0 | 12CO |
| CO ii2.35| 23340.0 | 23425.0 | 23440.0   | 23630.0   | 23660.0 | 23710.0 | 12CO |

### 4.2 Abundance ratio effects

Panels in Col. ‘d’ of Figs. 2 to 6, plot the effect of element-by-element abundance changes on spectral indices, based on CvD12 SSP models. The changes are represented by vertical lines that start from a fiducial model of 13.5 Gyr, solar abundance and Chabrier IMF (dotted horizontal line), reaching index values for models with given elemental enhancement, as labeled at bottom of Col. ‘d’. Notice that the lines show relative changes in index value as E-MILES and CvD12 models differ in absolute values for many line-strengths. According to CvD12 models, Ca i1.95 and Ca i1.99b show a strong dependence on [C/Fe]. Fe indices are expected to have some sensitivity to the abundance of α-elements. All CN indices response strongly to variations of C, N and α. The variation in α for CN indices mostly comes from oxygen. The exception is CN1.46 which does not change with [O/Fe]; rather it varies with [Mg/Fe]. The Paβ index at 1.28 μm shows a mild dependency on titanium abundance. This is due to contamination of the central bandpass with Ti i lines (see panel ‘c’ of Fig. A1). All CO indices have a strong depen-
dependence on carbon abundance, but CO1.60 and CO1.68 show a mild dependence on [Mg/Fe] too.

4.3 Index dependence on the velocity dispersion and resolution

Since galaxies have intrinsic velocity broadening due to their velocity dispersion, it is important to test how line-strengths are affected by line broadening. This is also important to take into account the effect of instrumental resolution. Ideally, one would like to have indicators that are insensitive to variations in \( \sigma \), such as those due to uncertainties in velocity dispersion measurements. The dependence of line-strength indices on velocity dispersion is quantified in Col. ‘e’ of Figs. 2 to 6. To this effect, we have convolved base E-MILES SSPs to different velocity dispersions in steps of 50 km s\(^{-1}\) from 100 to 400 km s\(^{-1}\). The four fiducial models that we used have an age of 12 Gyr, two different metallicities and two different bimodal IMF slopes. The trends for SSPs with bimodal IMF of slope 1.3 are shown with solid lines, for solar (green) and super-solar (black) metallicities, respectively. For a bottom-heavy IMF with slope 3.0, the same trends are shown with dashed lines. The panels show that the dependence on \( \sigma \) of broad molecular indices, such as CO and CN indices, is (as expected) barely noticeable. The line-strength of K-band indices shows a significant change with \( \sigma \), but for most of the indices, for \( \sigma < 200 \text{ km s}^{-1}\) (low- and intermediate-mass galaxy regime) the change in index-strength is modest. FeH0.99 is practically insensitive to velocity dispersion up to 400 km s\(^{-1}\). Almost all indices do not change their sensitivity to broadening with metallicity and IMF slope variations (comparing green and black colours, dashed and solid lines, respectively). Notice that, in most cases, the index-strength decreases with \( \sigma \) above 200 km s\(^{-1}\).

4.4 Wavelength shifts and uncertainties

Wavelength shifts due to galaxy internal rotational velocity, recessional velocity or uncertainties in wavelength calibration, can lead to variation in the measured index value. To evaluate these effects, we shifted a representative E-MILES SSP spectrum of age 12 Gyr, [M/H] = 0.06 and \( \Gamma_b = 1.3 \) to radial velocities of \( \pm 200 \text{ km s}^{-1}\) in steps of 4 km s\(^{-1}\). The index measurements as a function of radial velocity are shown in Col. ‘f’ of Figs. 2 to 6. According to these plots, some indices such as FeH0.99 in J-, MgI1.50 in H- and NaI2.21 in K-band require a rather careful wavelength calibration as they are very sensitive to radial velocity uncertainties (the required accuracy for those sensitive indices is provided in the plots). The same applies also to, e.g., the CO1.56 index in the H-band. In fact, an uncertainty greater than 48 km s\(^{-1}\) in radial velocity implies variations in the CO1.56 index comparable to those for a varying IMF, hence making the index not useful for an IMF analysis.

4.5 Signal-to-noise ratio effects

Figures 2 to 6 also show the sensitivity of spectral indices to SNR. The error bars in Col. ‘g’ show the average uncertainties on index measurements for a simulated set of E-MILES spectra with SNRs in the range of 30 to 1000 \( \text{ Å}^{-1}\). The reference spectrum (horizontal black line) used to simulate the effect of different SNRs has an age of 12 Gyr, solar metallicity and bimodal IMF of slope 1.3. The error bars can be used to establish the required SNR to differentiate between two values of a given parameter with a given spectral index. For instance, in the case of FeH0.99 (Fig. 2), the SNR per angstrom required to differentiate between a Kroupa-like IMF and \( \Gamma_b = 3.5 \) IMF is 200 \( \text{ Å}^{-1}\). For most of the indices, a SNR ~ 100 \( \text{ Å}^{-1}\) is needed to differentiate between a Kroupa-like IMF and a bottom-heavy IMF. In general, for indices covering a wider wavelength range, the required SNR is less demanding. For instance, for CO2.32 and CO2.35, a spectrum with SNR of 30 \( \text{ Å}^{-1}\) would be sufficient to distinguish between a metal-poor population ([M/H]=−0.25) and a metal-rich one ([M/H]=+0.15).

Table 2. Impact of flux calibration on line-strength indices. Columns 1 and 4 give the name of indices sorted by increasing width. The width of each index (\( \Delta \lambda_{\text{red}} – \Delta \lambda_{\text{blue}} \)) is provided inCols. 2 and 5. The fractional change on indices value when removing continuum is given inCols. 3 and 6.

| Index         | Width  | \( \Delta \lambda \) (%) | Index         | Width  | \( \Delta \lambda \) (%) |
|---------------|--------|---------------------------|---------------|--------|---------------------------|
| (Å)           | (Å)    |                           | (Å)           | (Å)    |                           |
| Pab1.28       | 115.0  | 0.2                       | CO1.66        | 235.0  | 2.1                       |
| FeH0.99       | 150.0  | 7.4                       | All1.67       | 235.0  | 2.9                       |
| All1.31       | 150.0  | 0.3                       | NaI2.21       | 255.0  | 0.0                       |
| CO1.58        | 155.0  | 0.4                       | CaI2.26       | 265.0  | 0.4                       |
| CO1.68        | 165.0  | 1.4                       | CO2.30        | 320.0  | 17.5                      |
| NaI1.14       | 175.0  | 0.4                       | CN1.10        | 325.0  | 7.2                       |
| CO1.64        | 175.0  | 0.1                       | CO2.32        | 335.0  | 4.1                       |
| MgI1.50       | 185.0  | 0.4                       | CN1.42        | 335.0  | 11.5                      |
| CO1.60        | 200.0  | 0.3                       | CO2.35        | 370.0  | 27.1                      |
| FeI1.16       | 200.0  | 0.5                       | CN1.46        | 380.0  | 4.1                       |
| CO1.56        | 225.0  | 0.7                       | CaI1.99b      | 430.0  | 5.8                       |
| FeI2.24       | 230.0  | 0.3                       | CaI1.99a      | 430.0  | 2.9                       |
| MgI1.18       | 230.0  | 0.0                       | CaI1.99c      | 430.0  | 5.6                       |
| CalI1.95      | 230.0  | 0.0                       | CN0.93        | 490.0  | 4.8                       |

NIR spectral Indices
Figure 2. Model predictions of line-strength indices, defined in this work, as a function of age (panels in Col. 'a'), metallicity (Col. 'b'), IMF slope (Col. 'c'), elemental abundance ratios (Col. 'd'), velocity dispersion (Col. 'e'), radial velocity (Col. 'f') and SNR (Col. 'g'). All plots are based on E-MILES models with BaSTI evolutionary tracks, but those in Col. 'd', where we used CvD12 SSPs to estimate the effect of elemental abundance variations. (Panels 'a') Different colors correspond to different metallicity, i.e. [M/H] = +0.06 (green) and [M/H] = +0.26 (black). Models with a Kroupa-like IMF are shown as solid lines while models with a bottom-heavy IMF ($\Gamma_b = 3.0$) are shown as dashed lines. (Panels 'b') The blue lines are model predictions for young populations with an age 2 Gyr while the red lines correspond to old (12 Gyr) populations. (Panels 'c') Blue and red lines are predictions for young (2 Gyr) and old (12 Gyr) populations, respectively. (Panels 'd') The vertical lines show the variation of a given line-strength for variations of different elemental abundances, [X/Fe]'s, shown with different colours. (Panels 'e') Different colors correspond to different metallicities, i.e. [M/H] = +0.06 (green) and [M/H] = +0.26 (black), respectively. Models with a Kroupa-like IMF are shown as solid lines while models with a bottom-heavy IMF ($\Gamma_b = 3.0$) are shown as dashed lines. (Panels 'f') The orange line shows index measurements on a reference E-MILES SSP spectrum shifted to a given radial velocity, $\Delta v_r$. (Panels 'g') The error bars show the average uncertainties on index values as a function of S/N.
Figure 3. same as Fig. 2.
Figure 4. same as Fig. 2
Figure 5. same as Fig. 2
Figure 6. same as Fig. 2
4.6 Index sensitivity to flux calibration

Following Vazdekis & Arimoto (1999), we studied potential systematic effects on line-strengths due to flux calibration by first measuring indices on an E-MILES SSP spectrum (i.e. flux-calibrated) and then on a continuum subtracted one. In Cols. 3 and 6 of Table 2, we show, for each index, the fractional change (in percent) due to continuum subtraction. The width of each index (from the bluest to the reddest end of the pseudo-continua) is shown in Cols. 2 and 5 of the table. Indices are sorted by increasing width to illustrate a general trend of increasing fractional change with increasing index width. However, we notice that the trend is not linear. For instance, the fractional change of Ca\_i.99a which is 430 Å wide is similar to that of CO1.66 and Al\_i.67 whose definitions span less than 300 Å. Indices involving wavelength ranges narrower than 300 Å have negligible (mostly less than 1%) fractional changes, except for FeH0.99.

4.7 Observed wavelengths of indices as a function of redshift

The wavelengths of spectral indices in Table 1 are given in the rest-frame; with increasing redshift, the indices shift to redder wavelengths and might fall in regions with prominent telluric absorption features. Figure 7 shows the observed wavelengths, defining each index bandpasses, as a function of redshift. The grey shaded area corresponds to indices’ central bandpass, while the orange ones correspond to the pseudo-continua bandpasses. The indices are indicated on top of the figure. In the right panel, we show atmospheric transmission and indicate the strongest absorptions (transparency less than 10%) with horizontal dark blue lines in the left panel. This plot should help the user to identify the best redshift ranges for studying specific spectral indices, or identify potentially useful spectral indices in a given observed-frame window. For instance, redshift ranges of 0.3 < \( \frac{z}{0.6} \) and 0.8 < \( \frac{z}{1.25} \), are not suitable for studying CN0.93 and FeH0.99 indices, as in these redshift ranges, both indices are severely contaminated by atmospheric absorption.

As another example, if a spectrograph has a spectral coverage from 9000 to 14000 Å, according to Fig. 7, Pa\_\( \beta \)1.28, and Al\_i.31 can be observed up to \( z \sim 0.05 \), CN1.10, Na\_i.14, Fe\_i.16, and Mg\_i.18 up to \( z \sim 0.15 \), while CN0.93 and FeH0.99 up to \( z \sim 0.5 \).

This figure also shows that it is possible to perform a stellar population analysis including at least three of the newly defined indices (i.e. CN0.93, FeH0.99, and CN1.10) out to \( z \sim 1.2 \). Moreover, none of the NIR indices will fall within the J and H bands for \( z > 1 \).
### Observed Bandpasses of Spectral Indices as a Function of Redshift

The grey and orange shaded areas correspond to the central and pseudo-continua bandpasses of each index, respectively. The right panel shows a telluric absorption spectrum, with strongest absorption lines (transmission of less than 10%) being overplotted by horizontal dark blue lines in the left panel.

| Redshift | Observed Wavelength ( Å) |
|----------|--------------------------|
| 0.00     | 10000                    |
| 0.25     | 12000                    |
| 0.50     | 14000                    |
| 0.75     | 16000                    |
| 1.00     | 18000                    |
| 1.25     | 20000                    |
| 1.50     | 22000                    |
| 1.75     | 24000                    |

**Figure 7.** Observed bandpasses of spectral indices as a function of redshift. The grey and orange shaded areas correspond to the central and pseudo-continua bandpasses of each index, respectively. The right panel shows a telluric absorption spectrum, with strongest absorption lines (transmission of less than 10%) being overplotted by horizontal dark blue lines in the left panel.
4.8 Reliability of measured indices in the NIR

For defining wavelength limits of NIR indices, we tried to avoid as much as possible rest-frame regions affected by sky contamination. This ensures that when measuring indices on stellar population models, one should have clean estimates. However, depending on the redshift of galaxies, their rest-frame indices can be actually affected by sky emission and telluric lines. This can lead to deriving unreliable stellar population parameters. To avoid systematic effects due to sky contamination or other potential sources of uncertainty (e.g. bad pixels and cosmic rays), we provide a general prescription to assess the robustness of each index analysis.

To this aim, we tried to establish the maximum percentage of affected pixels in a spectral range of an index for which a reliable index estimate is still possible. In practice, one may consider as affected pixels those for which the residual of any kind of correction is just at, or above, the noise level. To address the problem, we used an E-MILES SSP as our reference spectrum and removed a given percent of pixels randomly (from 1% to 80%) within either the blue pseudo-continuum, or feature, or red pseudo-continuum bandpasses, respectively. The reason for doing so is that, in principle, whether the affected pixels reside in the pseudo-continua or the feature, it affects the line-strength differently. For each index, the process was repeated 1000 times, and the index-line-strength was measured for each iteration. To be conservative, for each bandpass, we saved the maximum change in the line-strength with respect to that of the reference spectrum. This maximum variation might correspond, for instance, to the case where adjacent pixels in a given bandpass have to be masked out because of, e.g., the poor subtraction of blended sky lines. We performed this procedure on spectra with various resolutions from 60 to 360 km s\(^{-1}\). Moreover, we considered the effect of SNR by using two sets of spectra with signal-to-noise ratios of 100 and 50 per Angstrom, respectively.

Figure 8 shows the results for the CN1.10 index as an example. Solid lines in the upper panel show the changes in the index measurement as a function of the fraction of removed pixels within blue pseudo-continuum bandpass (blue), feature bandpass (black) and red pseudo-continuum bandpass (red) with shaded areas indicating the effect of varying velocity dispersion for spectra with SNR=100 (50) Å\(^{-1}\) (upper panel). The lower panel shows the variation of stellar population parameters that correspond to the change of index values due to the masking of pixels within the index bandpasses. The changes in stellar population parameters are computed with respect to a reference spectrum with age 12 Gyr, [M/H]=0.06, and \(\Gamma_b = 1.3\), and are normalized to range of stellar populations parameters of intermediate-mass and massive ETGs (see the text). Shaded areas, in both the upper and lower panels, show the effect of varying the velocity dispersion of the spectra from 60 to 360 km s\(^{-1}\). For a spectrum with SNR=100 Å\(^{-1}\), assuming a maximum relative variation of \(\pm 0.5\) for stellar population parameters, the lower panel shows that the fraction of masked pixels has to remain lower than 25%, 25%, and 45%, to obtain acceptable estimates of age, metallicity, and IMF, respectively. For a smaller SNR this fraction is smaller as described in the text.

![Figure 8](image.png)

**Figure 8.** Effect of removing a given percentage of pixels within blue (blue solid (dotted) line), feature (black solid (dotted) line) and red (red solid (dotted) line) bandpasses on the line-strength of CN1.10 index for a spectrum with SNR=100 (50) Å\(^{-1}\) (upper panel). The lower panel shows the variation of stellar population parameters that correspond to the change of index values due to the masking of pixels within the index bandpasses. The changes in stellar population parameters are computed with respect to a reference spectrum with age 12 Gyr, [M/H]=0.06, and \(\Gamma_b = 1.3\), and are normalized to range of stellar populations parameters of intermediate-mass and massive ETGs (see the text). Shaded areas, in both the upper and lower panels, show the effect of varying the velocity dispersion of the spectra from 60 to 360 km s\(^{-1}\). For a spectrum with SNR=100 Å\(^{-1}\), assuming a maximum relative variation of \(\pm 0.5\) for stellar population parameters, the lower panel shows that the fraction of masked pixels has to remain lower than 25%, 25%, and 45%, to obtain acceptable estimates of age, metallicity, and IMF, respectively. For a smaller SNR this fraction is smaller as described in the text.
that it can be performed on any sample of galaxies at any redshift. Also, it is relatively general in such a way that it takes into account not only the effect of pixels contaminated because of uncertainties due to sky subtraction or telluric correction, but also because of any other issue deriving from data reduction. Moreover, the same approach could also be implemented to characterize other sets of indices, e.g. in the UV and optical spectral ranges, as when studying high redshift galaxies, the UV/optical features are redshifted to the NIR and thus are unavoidably plagued by sky contaminations. Overall, we suggest using our approach as a standard procedure in the analysis of (NIR) spectral features.

5 EXAMPLE APPLICATIONS

We discuss here some applications of our newly defined indices to the study of unresolved stellar populations. To this effect, we rely on E-MILES and CvD12 spectral synthesis models, selecting samples of ETGs from the literature. The selected samples cover a range of morphological types (from ellipticals to spirals), velocity dispersions (from ~30 to ~360 km s⁻¹) and environments (field and cluster).

5.1 Galaxy samples

- La Barbera et al. (2019): The sample consists of seven nearby massive ETGs (σ integrated > 300 km s⁻¹) selected from SPIDER survey (La Barbera et al. 2010) and SDSS DR7 (Abazajian et al. 2009). Most of these galaxies are brightest cluster galaxies, while two of them are satellites (XSG2 and XSG7). The high-quality spectra were obtained with the X-Shooter multi-wavelength medium resolution slit echelle spectrograph (Vernet et al. 2011) at the ESO Very Large Telescope (VLT). The NIR part of the spectra covers a wavelength range from 9800 to 25000 Å with a resolution power of ~5500, which allows an accurate correction of sky lines. All galaxy spectra have SNR above 100 Å⁻¹. For our study, we used galaxy spectra for the innermost radial bins defined in La Barbera et al. (2019), as their quality and SNR is highest. In addition to the spectra of individual galaxies, we also used a stacked spectrum for all seven galaxies.

- François et al. (2019): The sample consists of 14 bright nearby galaxies ranging from ellipticals to spirals along the Hubble sequence. The authors observed the galaxies from the optical to the NIR (3000–24800 Å), using the X-Shooter spectrograph (Guinouard et al. 2020) at the ESO-VLT on Paranal (Chile). They obtained the NIR(3000–24800 Å), using the X-Shooter spectrograph (Guinouard et al. 2020) at the ESO-VLT on Paranal (Chile). They obtained the NIR spectra with a resolution power between R = 17000–23700 Å with a resolving power of R ≈ 2900. The velocity dispersion of this sample spans a range between 128 to 222 km s⁻¹.

- Márkim-Queraltó et al. (2008): The sample consists of twelve elliptical and SO field galaxies and their spectra were obtained with the ISAAC NIR imaging spectrometer at the ESO-VLT. The instrumental configuration was the same as in Silva et al. (2008) in order to allow a direct comparison of the two samples. The lowest velocity dispersion in this sample is 59 km s⁻¹, while the highest one is 305 km s⁻¹.

We convolved the spectra of La Barbera et al. (2019)’s galaxy sample to σ = 360 km s⁻¹, as this is an upper limit to the individual velocity dispersions of galaxies in different samples. The reduced spectra of galaxies in the François et al. (2019) and Baldwin et al. (2018) samples are publicly available. While the spectra of François et al. (2019) are rest-frame, we have used the Heliocentric velocities provided in Table 1 of Baldwin et al. (2018) to shift their galaxy spectra to the rest-frame. Both samples are flux calibrated, and we only needed to convolve their spectra out to σ = 360 km s⁻¹. The reduced spectra of Silva et al. (2008) and Márkim-Queraltó et al. (2008) samples are the same as those used by Röck et al. (2017), who corrected them to restframe, and convolved to a common resolution of σ = 360 km s⁻¹. Note that the spectra in these samples are extracted within ~1 R eff except for galaxies in François et al. (2019) which are extracted within < 0.3 R eff. As all spectra correspond to galaxy central regions, we do not expect a significant aperture bias in our derived results.

5.2 Constraining the shape of the low-mass end of the IMF

Assuming a given shape for the IMF affects the derivation of several observable properties of galaxies, such as mass-to-light ratios and star formation rates. Therefore, the IMF plays a fundamental role in understanding galaxy evolution mechanisms. The difficulty in measuring the low-mass end of the IMF is that variations in the number of low-mass stars (which dominate the mass budget of ETGs) imply only little changes in the integrated light of old stellar populations. According to La Barbera et al. (2013), although IMF-sensitive indices in the optical can constrain the mass fraction of low-mass stars expected in the IMF, they cannot be used to distinguish the functional form of the IMF. Conroy & van Dokkum (2012) proposed that the shape of the low-mass IMF in old stellar populations can be constrained by a combination of multiple IMF-sensitive indices, taking advantage of giant-sensitive features, such as TiO0.89. The work by La Barbera et al. (2016) has been the first attempt to combine TiO0.89 and the optical TiO1 and TiO2 features to separate the effect of the IMF from giant stars and abundance ratios. They found that the response of FeH absorption at 9900 Å to a low-mass tapered (bimodal) IMF is much smaller with respect to that for a unimodal (single power-law) one, helping up to constrain the IMF functional form at the very low-mass end.

As a possible application of the NIR spectral indices defined in the present work, we have tried to explore which indices can provide us with further relevant constraints on the IMF functional form. We have found that Mg indices might indeed help us to constrain the detailed shape of the IMF at intermediate masses. While performing
a detailed analysis of this point is beyond the scope of the present work, we illustrate the overall idea in Figure 9, plotting two NIR Mg i indices (MgI1.18 and MgI1.50) vs. two optical TiO indices (TiO2 and TiO0.89), measured for different stellar population models, namely E-MILES and CvD12. Since the high quality galaxy spectra from La Barbera et al. (2019) span both optical and NIR wavelengths, and have been shown to exhibit a bottom-heavy IMF ($\Gamma_b > 2.6$, in the innermost radial bins), we only used this sample in the plots. The measurement of indices on individual galaxies is shown with red points while the open red circle corresponds to the stacked spectrum. Solid orange and black arrows show the effect of a change in the slope of unimodal and bimodal IMFs on the E-MILES models from $\Gamma = 1.3$ to $\Gamma = 2.0$ and $\Gamma_b = 1.3$ to $\Gamma_b = 3.0$, respectively. Dashed black arrows show the effect of enhancement of +0.4 dex in the abundance of $\alpha$ (typical value of the sample) for both a Kroupa-like IMF and a bottom-heavy one. Light blue and yellow arrows display the effect of a change in total metallicity and age of populations with Kroupa-like IMF. They change from solar metallicity to $[\text{M/H}] = +0.26$ dex (typical metallicity of the sample) and from 11 Gyr (mean age of the sample) to 7 Gyr, respectively. CvD12 models have been used in these plots as well. The solid purple arrow shows the effect of a change of +0.3 dex in magnitude enhancement while the dashed violet arrow corresponds to the $\alpha$-enhancement of +0.2 dex. As TiO0.89 is very sensitive to the abundance of carbon, we also show the effect of enhancing carbon by +0.15 dex with a pink arrow.

While the strength of Mg i indices changes significantly by going from a Kroupa-like IMF to the bimodal IMF of slope 3 ($\Gamma_3 = 0.9\%$ for Mg i1.18 and 15.1\% for Mg i1.50), it almost does not change between a Salpeter IMF and a unimodal IMF of slope $\Gamma = 2$ (0\% for Mg i1.18 and 4.7\% for Mg i1.50). The differences due to different IMF shapes are subtle but measurable. Regarding the sensitivity of Mg i features to other stellar population properties, E-MILES models show that both Mg i1.18 and Mg i1.50 are independent of total metallicity (see the light blue arrow). According to CvD12 models, both Mg i features are sensitive to $[\alpha/\text{Fe}]$ and $[\text{Mg/Fe}]$ (dashed violet and solid purple arrows) and Mg i1.50 is sensitive to $[\text{C/Fe}]$ (solid pink arrows) as well. The dashed black arrows show the effect of $\alpha$-enhancement on both a population with Kroupa-like IMF and a population with bottom-heavy IMF. These are obtained from $\alpha$-enhanced E-MILES models (an updated version of Na-enhanced models of La Barbera et al. (2017)). The effect of $\alpha$-enhancement and bimodal IMF can be singled out in the plots of both Mg i1.18 and Mg i1.50 vs TiO0.89, as the dashed black and solid black arrows are almost orthogonal. Note that the age of E-MILES models is 11 Gyr which corresponds to the mean age of the La Barbera et al. (2019) sample while the age of CvD12 models is 13.5 Gyr. All indices are measured in EW except the TiO0.89 index, which is measured as a flux ratio. Unfortunately, the comparison of data and model predictions shows that none of the current models in Fig. 9 is able to fully match the data. However, a bimodal IMF might partly explain the high value of Mg i indices.

To understand why NIR Mg i indices can distinguish between different IMF parametrisations we have looked at the IRTF stars used to construct the models. Figure 10 shows the magnesium indices measurements on the spectra of IRTF stars as a function of their effective temperature. The type of stars (for stars cooler than 3900K) is from table 2 of Röck et al. (2015). M-dwarf stars (orange points) are the ones that correspond to the low-mass end of the IMF. These plots show that M-dwarf stars peak in strength around 3800K. According to figure 5 of Vázdekis et al. (2012) the mass of these stars is around 0.4M☉. While bimodal IMF gets flatter for stars with masses less than 0.6M☉, the unimodal IMF, keep increasing to lower masses. This means that for a unimodal IMF, the dwarf stars at ~3800K (which have the highest values of Mg i) count less than the cooler ones (which have the lowest value of Mg i). Therefore, by increasing the slope of the unimodal IMF, the overall value of Mg i does not vary significantly. However, by increasing the slope of the bimodal IMF, the number of stars with masses less than 0.6M☉, all increase with similar weight, and stars with the highest value of Mg i end up to dominate the overall absorption of Mg i.

5.3 On the need of further developments for NIR SPS modelling

We find a significant discrepancy when comparing some NIR line-strength indices from SSP models and data for ETGs. This shows
that current SPS models have difficulties at reproducing galaxy spectra in the NIR (e.g. Riffel et al. (2019)).

As a further example, in Fig. 11, we show Ca indices in the K-band measured from various samples of galaxies and compare them with predictions of E-MILES SSP models. Blue, orange, and pink colours display AGB, M-dwarf, and carbon stars, respectively. Other types of stars are represented with grey colour. In both plots, M-dwarf stars peak in strength at 3800K.

Figure 10. Dependence of NIR Mg1 spectral indices on effective temperature for IRTF stars that have been used to compute E-MILES SSP models. Blue, orange, and pink colours display AGB, M-dwarf, and carbon stars, respectively. Other types of stars are represented with grey colour. In both plots, M-dwarf stars peak in strength at 3800K.

The arrows at 13.5 Gyr mark the change in the Ca indices due to the additional contribution of the young component on top of the old one. The size of the arrow is tiny. As a result, such model is unable to fit the Ca indices of ETGs. Also the arrow points to the opposite direction than the required to match the data (with the exception of Ca1 indices). This is worth stating that, indeed, this mass fraction is higher than what expected from optical indices, such as, in particular, the Balmer lines (La Barbera et al. 2013). The yellow arrow at 10 Gyr indicates the change in the Ca1 indices due to the additional contribution of young population of age 1.5 Gyr to the underlying standard SSP model of 10 Gyr in order to study whether the predictions of such model might result into a better fit to the observed Ca1 indices. It is worth stating that, indeed, this mass fraction is higher than what expected from optical indices, such as, in particular, the Balmer lines (La Barbera et al. 2013).

The effect of increasing total metallicity from ([M/H] = +0.06) to ([M/H] = +0.15 dex, in the E-MILES model is shown by the brown arrow at 11.5 Gyr, while the effect of increasing [$\alpha$/Fe] by +0.40 dex is shown by a sky blue arrow at 12.5 Gyr. According to these arrows, an increase in metallicity does not increase the Ca1 index-strengths significantly. However, an $\alpha$-enhancement can improve the models only for the Ca2.26 index. It is worth noting that the NIR part of the E-MILES models is based on 180 stars of IRTF library which are mostly around solar metallicities and solar abundance ratios. Therefore predictions of models with super solar metallicity are less reliable (see Röck et al. (2015)), and would require stellar libraries spanning a wider metallicity range.

The arrows at 13.5 Gyr mark the change in the Ca1 indices when moving from a reference model to a CvD12 model of [Ca/Fe] = +0.15 (dark green) or [Ca/Fe] = -0.15 (light green). Note that there is an offset between predictions of the CvD12 models and E-MILES models at scaled-solar abundance with similar stellar population parameters. This could be due to differences in several modelling ingredients, such as selection of stars in (different) stellar libraries, isochrones, parameterization for the IMF and even different values for the solar metallicity (Vazdekis et al. 2015). For the present purposes, we are more interested in the relative responses of CvD12 models to variations of [Ca/Fe]. Also, notice that CvD12 models with varying abundance ratios are computed at a fixed age of 13.5
Gyr by considering a Chabrier IMF. Also, the combined effect of elemental abundances and IMF variations is not fully understood yet, as discussed in the case of Na lines by Röck et al. (2016) and La Barbera et al. (2017). In the latter, the authors developed a Na-enhanced version of E-MILES models and showed that the effect of [Na/Fe] enhancement is not linear, having a larger effect for some Na indices as the IMF slope becomes steeper. Also, while the effect of calcium abundance on the strength of calcium indices in the optical domain such as Ca\(1\,95\) and \(2.26\) \(\mu\)m is significant, according to these plots, this effect is minor/negligible on NIR Ca\(1\,95\) indices. Moreover, unlike in the optical range (see Vazdekis et al. (1997)), the NIR Ca\(1\,95\) indices are above (not below) model predictions.

Comparing the effect of IMF slope on NIR calcium indices (pink and violet lines) with the effect of abundances (blue, dark and light green arrows), shows that these lines have larger sensitivity to IMF than abundance ratios at least as far as current models seem to predict. This was first noticed by Conroy & van Dokkum (2012). Since the optical calcium indices are more sensitive to abundances than IMF, they suggested that a combination of calcium indices in the optical and NIR spectral range should be able to disentangle the degeneracy between IMF and abundance ratios.

Note also that by varying the IMF from Kroupa-like to bottom-heavy the models get significantly closer to all NIR calcium lines (as seen by comparing pink and purple lines in Fig. 11), although not enough to properly match them.

The interesting point about the behaviour of calcium indices in the NIR is that they all behave in a similar way for what concerns the mismatch to observations. Hence, any future modelling of stellar populations should be able to behave consistently among all NIR calcium lines.

It is noteworthy to mention that the discrepancy between observations and models in plots of Fig. 11 cannot be attributed to the index definition, as similar mismatch can be seen if other definitions are used for the same absorption. Baldwin et al. (2018) instead (see their fig. 17) the line-strength of the calcium absorption at 2.26 \(\mu\)m following the index definition of Frogel et al. (2001). The authors compare their sample of low-mass ETGs with predictions of various models, including E-MILES. The reason why they did not find any significant discrepancy with respect to E-MILES, is, indeed, the large scatter and error bars on observed line-strengths, making all models in the plot compatible with the data.

Fig. 11 shows that the solution from the optical line-strengths (grey line), matches the mean value of the observations (red open circles) for the Ca\(1\,95\)b and Ca\(2\,26\) indices. However, for Ca\(1\,95\)b, Ca\(1\,99a\) and Ca\(1\,99c\) indices, the optical solution does not match the data but it helps to reduce the discrepancy between model predictions and observed line-strengths, in particular for Ca\(1\,95\) and Ca\(1\,99a\). Also note that for these two indices the mismatch between the best (optical) solution and the observations is significantly smaller than the difference obtained when varying the IMF slope. In order to achieve a good match to observations, modelling of integrated stellar populations in the NIR will have to further improve, especially for what concerns the behaviour in the high metallicity regime as well as the effect of abundance ratios. Moreover, it
is important to confront in a detailed manner the models to both NIR and optical indices, to provide fully consistent solutions over a large wavelength baseline. This point will be further explored in a forthcoming paper.

6 SUMMARY

In this work, we have defined a new system of spectral indices in the NIR which are optimized and fully characterized for studying stellar population of unresolved systems.

With the aid of E-MILES stellar population models, we have obtained responses of SSP spectra to changes in age, metallicity and stellar IMF. Such responses, once associated with absorption lines, have guided us to identify features that can be used as indicators of relevant population parameters in the NIR.

We defined new NIR indices in a similar manner to the Lick system, where spectral indices are defined with a central bandpass covering the spectral feature and two other bandpasses at the red and blue sides of the feature to trace the local continuum. We defined the central bandpass of each index to encompass the maximum extent of the peak of the sensitivities around the absorption feature itself and avoid, if possible, contamination by stellar population metallic lines, telluric absorptions or sky emissions. In this way, we optimised the indices to be sensitive to the main population parameters, namely age, metallicity and IMF. Concerning continuum bandpasses, we have defined the limits in wavelength regions weakly affected by absorption features and less contaminated by telluric absorptions or sky emissions (this applies to stars and galaxies at z=0). Furthermore, the spectral bandpasses were defined as wide as possible to make them less sensitive to degradation due to the velocity dispersion or spectral resolution and also to increase the SNR of the index measurements. However, the full wavelength coverage for most indices is shorter than ~300 Å, to minimise flux calibration issues.

Depending on the redshift of galaxies, their absorption features may fall in regions not clean from telluric absorption and sky emission lines. The pixels within the index definition that have not been corrected well during the data reduction can affect the spectral index values at a level comparable to that due to variations of stellar population parameters. In order to overcome this problem, we have outlined a prescription to identify indices that can be safely measured in a given stellar population study. In this method, pixels containing substantial systematic uncertainties should be masked out before performing index measurements. If the fraction of masked pixels within the index bandpasses is less than a maximum fraction (which can be adopted depending on the specific application), which is provided in Table B1, the index can be safely used for the stellar population analysis (in particular to estimate age, [M/H], and IMF). If such constraints are not met, the index should be excluded altogether.

The present work provides the first comprehensive characteristics of NIR spectral indices. To this effect, we used base E-MILES models, as well as CvD12 models with variable abundance ratios. The analysis shows that most of the NIR indices require high SNR (~100) to obtain useful measurements.

We illustrate the potential use of the newly defined set of NIR indices with two applications to the general population of ETGs. First, we show that it is possible to constrain the shape of the IMF at low-mass end, using a combination of magnesium indices in the NIR and TiO indices in the optical. The analysis also shows that it is possible to break the degeneracy between IMF and abundance ratios.

In the second application, we confront several NIR Ca line-strengths of ETGs from the literature with predictions from SPS models. We find that predictions of models with super-solar metallicity, [α/Fe] enhanced abundance ratios, and bottom-heavy IMF provide reasonably good match to two, out of five, NIR calcium lines as measured from a stacked spectrum representative of the central regions of the most massive ETGs. On the other hand, the models underestimate the line-strengths for the remaining three calcium lines. Although the overall solution found from this analysis seems to agree with that derived from the optical range, the comparison highlights the need of improving significantly model predictions in the super-solar metallicity and non-solar abundance ratio regimes, in particular for what concerns the contribution of very cool stars, which dominate the NIR light.

The system of NIR indices presented in the present work should offer new venues to constrain the stellar population content of galaxies in the JWST era. To this effect, the plots presented here could be taken as a guide for preparing and optimizing future observations to study stellar populations based on NIR indices.

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DATA AVAILABILITY

The E-MILES SSP models are publicly available at the MILES website (http://miles.iac.es). The updated version of Na-enhanced models of La Barbera et al. (2017) are also available from the same website (under "Other predictions/data"). The Conroy & van Dokkum (2012) SSP models are available upon request to the authors (see https://scholar.harvard.edu/cconroy/projects). Observations of La Barbera et al. (2019) sample made with ESO Telescope at the Paranal Observatory under programmes ID 092.B-0378, 094.B-0747, 097.B-0229 (PI: FLB). The central spectra and stacked central spectrum are available from FLB upon request. The spectra of Baldwin et al. (2018) sample were taken using the Gemini Near-Infrared Spectrograph on the Gemini North telescope in Hawaii through observing program GN-2012A-Q-22. The reduced spectra (FTTS files) are available via https://github.com/chbalwin1/Reduced-GNIRS-Spectra. Observations of François et al. (2019) sample made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 086.B-0900(A). The reduced spectra (FTTS files) are available via http://cdarc.u-strasbg.fr/viz-bin/qcat?J/A+A/621/A60. Observations of Silva et al. (2008) sample performed at the European Southern Observatory, Cerro Paranal, Chile; ESO
**APPENDIX A: SPECTRAL WINDOWS OF THE NEW INDICES AND OTHER INDEX DEFINITIONS FROM THE LITERATURE**

In this section, we zoom into a region around each index and display atomic and molecular contributors to the index. As for some of the indices, there are multiple definitions in the literature, we compare the limits of the bandpasses in the definitions for NIR indices and discuss their trends, as well.

In Figs. A1 to A3, the spectrum of an E-MILES SSP, convolved to $\sigma = 360 \, \text{km} \, \text{s}^{-1}$, is shown in black. Sky emission lines and telluric absorption lines from Skycalc are shown in pink and dark blue, respectively. Our definition is indicated with a grey region for the central bandpass limits and in orange for pseudo-continua limits. We mark the definitions of the same feature in the literature by solid black lines for the central bandpasses and dotted blue lines as side bandpasses. The small vertical lines indicate the location of atomic and molecular absorptions identified in IRTF library, Kleinmann & Hall (1986) and Lagattuta et al. (2017) (these are present in high-resolution spectra of cool stars). In Figs. A4 to A9, we compare the sensitivity of each index definition in the literature to stellar population parameters (age, metallicity and IMF slope), elemental abundance ratios, velocity dispersion, wavelength shifts and SNR. The spectral variations due to changes in individual elemental abundances are derived from CvD12 models.

Panel ‘a’ of Fig. A1 shows two deep and broad features at the beginning of the J-band ($\sim 9200 \, \AA$ and $\sim 9400 \, \AA$). CN is the major source of continuum opacity in this wavelength range. This index is the most difficult one to define due to the presence of many atomic and molecular absorptions. Recently, Riffel et al. (2019) provided a definition for this spectral region. Since the blue pseudo-continuum in their definition is located on top of a relatively strong absorption, we decided to re-define this index. The new index defined here place the blue-continuum in a region that is not blended by any atomic line. Also, we shifted the red-continuum to the blue to decrease the wavelength range covered by the index. We modified the central bandpass of the feature as well. In the same panel, we compare our definition for the FeH absorption to the one of CvD12. The small light blue vertical line shows the position of FeH line in the high-resolution spectrum of Arcturus. According to this plot, the central bandpass limits in CvD12 definition, do not encompass this line. In our new definition we modified the feature bandpass to include it. Accordingly we changed the position of blue and red pseudo-continua to not overlap with the central bandpass limits.

Panel ‘b’ of Fig. A1, the deep and broad absorption feature at $\sim 11000 \, \AA$ corresponds to the CN. Since continuum bands are far apart in Röck (2015) and Riffel et al. (2019) definitions, we revised the definition of this index, putting the sidebands closer to the feature. It is noteworthy to mention that unlike Riffel et al. (2019)’s definition, ours does not depend on the titanium abundance (comparing Col. ‘d’ of Fig. 2 and Fig. A4). In the same panel, different definitions of the sodium absorption are shown. The sodium definition by La Barbera et al. (2017) is local, and its central bandpass is almost identical to CvD12. However, both definitions are not optimized for velocity dispersion broadening. The blue continuum in Riffel et al. (2019)’s definition is not far enough from the central bandpass and the one of Röck (2015) is placed on an absorption. In our new index, we made the central bandpass narrower, avoided sky emission at $\sim 11328 \, \AA$ and put the sidebands far enough from the feature. Fe r1.16 is the next index, in this panel. It can be seen that our definition for iron absorption avoids the strong sky emission line around 11600 \, \AA. Index trend plots in the Fig. 2 and Fig. A5 show that our definition, compared to that of Röck (2015), is more sensitive to IMF variations for both, young and old stellar populations. Moreover, the minimum SNR required for our definitions is much lower than that of Röck (2015). Mg r1.18 definition at panel ‘b’ of Fig. A1 shows that two species contribute to the absorption feature: Mg i and Ca ii. While the red pseudo-continuum is free from absorption lines, the blue pseudo-continuum is contaminated by C2 line. According to Col. ‘d’ of Fig. 3, Ca ii and C2 lines contamination do not affect the Mg r1.18 index. In fact, enhancing the [Ca/Fe] and [C/Fe] does not change significantly the Mg r1.18 line-strength.

The wavelength limits of Pa β index in panel ‘c’ of Fig. A1 clearly show the advantage of our definition with respect to that of Röck (2015); here the red pseudo-continuum is 150 \, Å far from the feature. The relative more contribution of Ti i lines, compared to Fe i and Ca i lines, in the absorption feature can explain the shallow dependence of this index on [Ti/Fe] variations (see Col. ‘d’ of Fig. 3). The red part of the same panel shows various definitions for the aluminium absorption feature. For the definition of Röck (2015), the central bandpass is wider than CvD12 and its red sideband is much wider and extends further into the red. Its blue sideband also extends further into the blue compared to CvD12 and our definitions. Figure A5 shows that the Al r1.31 definition of CvD12 is strongly dependent on the velocity dispersion broadening as it does not leave any room for broadening. This figure also shows that the index of Röck (2015) requires a higher SNR than ours. Since our definition for aluminium does not include any Ti i line, it is independent of the titanium abundance, unlike the index of Röck (2015).

Panel ‘d’ of Fig. A1 shows CN indices at the beginning of H-band: one at $\sim 14200 \, \AA$ and the other one at $\sim 14600 \, \AA$. They are located in a region with strong telluric absorptions and sky emissions. The central bandpass of CN1.46, includes contribution of VO molecule in addition to CN. Different definitions for magnesium absorption are shown in the same panel. The Mg i 1.50 feature has the central bandpass overlapping with Röck (2015), Riffel et al. (2019) and Ivanov et al. (2004) definitions, whereas the sidebandpasses are different. Our index avoids the spectral range covering Fe i metallic lines. Moreover, we avoid strong emission lines in the pseudo-continuum ranges and the central bandpass. Comparing Fig. A6 shows that our definition is more robust against $\sigma$ compared to the Ivanov et al. (2004) definition and requires significantly less SNR than Röck (2015) and Riffel et al. (2019)’s ones.

The CO1.56 index definition in panel ‘a’ of Fig. A2 shows that the central bandpass and red pseudo-continuum of the CO index at $\sim 15600 \, \AA$ is contaminated by Fe i lines. Moreover, Ti i, Si i and Ni i are other contributors to this index. While definition of Riffel et al. (2019) for CO includes Ti i in red pseudo-continuum and Fe i lines in blue-pseudo continuum, our definition is free of any lines in blue pseudo-continuum. The CO1.58 index definition in the same panel, shows that Mg i and Fe i elements are other contributors of this index. As the red pseudo-continuum in definition of Röck (2015) is $\sim 300 \, \AA$ far away from the absorption, we redefined this index by placing the central pseudo-continuum close to the CO feature. Also note that the red pseudo-continuum in definition of Röck (2015) is defined at $\sim 16000 \, \AA$ is shown in the same panel. Both definitions suffer from sky emission lines. However, the blue continuum in our index is in a region which is clean from telluric absorption lines. Moreover, since we put the blue continuum closer to the feature, the total spectral width of our CO1.60 index is smaller compared to the Riffel et al. (2019)’s one.
Definitions of CO indices at ~16400 Å and ~16600 Å are shown in panel ‘b’ of Fig. A2. Both indices are contaminated by Fe i lines but CO1.64 index is contaminated by Si i line as well. They are located in a region that is not severely contaminated by telluric absorption lines. While for CO1.66 index we could avoid strong emission lines, the contamination of CO1.64 bandpasses was unavoidable. Definition for aluminium absorption at around 16700 Å is shown in the same panel. While pseudo-continua are free from absorption lines, the central bandpass is contaminated by Fe i lines. Note that this index is clean from telluric lines. There is only one weak telluric absorption in the feature bandpass and two sky emissions are present there as well. The bandpasses of CO index at around 16800 Å is shown at the end of panel ‘b’ of Fig. A2. The index is located in region clean from telluric absorptions and our definitions avoids two strong sky emission lines at ~16900 Å and ~16950 Å, respectively. The species that contaminate this index are Fe i, Si i and Na i.

Panel ‘c’ of Fig. A2 shows our definition for calcium absorption at around 19500 Å and Cesetti et al. (2013)’s definition. The central bandpass in the index of Cesetti et al. (2013) is narrow, making it strongly dependent on the velocity dispersion broadening (see Col. ‘c’ of Fig. A7). Moreover, the pseudo-continua are far away from the feature. The same panel shows that our definition for Ca i1.99a is different from that of Conroy & van Dokkum (2012) and Cesetti et al. (2013). The latter ones have wider central bandpass and wider red pseudo-continuum, which causes strong contamination from telluric absorption lines. However, our index is much less sensitive to \( \sigma \), specially in the lower mass regime according to Col. ‘c’ of Figs. 5 and A7. The comparison of our definition for Ca i1.99b with those of CvD12 and Cesetti et al. (2013), in the same panel, shows that our central bandpass is almost identical to their definition although slightly wider, but our red sideband is much wider. According to Col. ‘e’ of Fig. A7, the CvD12 and Cesetti et al. (2013) definitions suffer from a strong dependency on \( \sigma \). The comparison of our index and Cesetti et al. (2013) definitions for Ca i1.99c (the same panel) shows that our central bandpass is wider and the blue continuum is closer to the feature.

Panel ‘d’ of Fig. A2 shows different definitions of the same feature, Na i2.21. Unlike the indices of CvD12 and La Barbera et al. (2017), we left free some space between pseudo-continua and the feature bandpasses to minimise the effects of velocity dispersion broadening as shown by their dependence against \( \sigma \) (Col. ‘e’ of Figs. 5 and A8). Our definition for iron absorption at ~22400 Å is compared with Silva et al. (2008) in the same panel. The blue pseudo-continuum in our definition is not blended with strong absorption line. Moreover, in our index the pseudo-continua are significantly closer to the feature bandpass, while the latter is wider. In the red part of panel ‘d’ of Fig. A2, we defined a modified index around the Ca i. This index is slightly different from those used by Frogel et al. (2001) and Riffel et al. (2019). Our red continuum is far enough from the central bandpass, making the index line-strength rather insensitive to velocity dispersion broadening. The new Ca i2.26 definition is promising as an IMF-sensitive feature as, unlike the other definitions in the literature is less sensitive to the titanium, carbon and oxygen abundance (see Col. ‘d’ of Fig. A8). This shows that our index is less contaminated from neighbouring strong CO absorptions.

Figure A3 shows different definitions for the first bandhead of CO in the K-band. The definition of Mármol-Queraltó et al. (2008) has two blue bandpasses. The red bandpass of Riffel et al. (2019) is far away from the absorption and is very narrow while CvD12 spectral index is local and its central bandpass is almost identical to our definition, although narrower. Finally, compared to the CvD12, our index is more robust against \( \sigma \) (see Col. ‘e’ of Figs. 6 and A9). In the same figure, we compared different definitions of CO2.32 in the literature as well. Unlike the index of Riffel et al. (2019), our definition is local, and only Na i is within the red continuum. We carefully placed the bandpasses to minimise dependence on velocity dispersion. Hence, compared to the CvD12, our definition is more robust against \( \sigma \), specially for the low and intermediate-mass galaxy regime (see Col. ‘e’ of Figs. 6 and A9). Finally, this figure compares our definition for CO at ~23540 Å with Riffel et al. (2019)’s definition. Our refined CO2.35 index has the central bandpass overlapping with their definition, whereas the continuum bandpasses are different. The blue bandpass of Riffel et al. (2019) is about 400 Å far from the absorption, and its red bandpass is narrow and touches the central bandpass, leaving no space for velocity dispersion broadening. Moreover, the required SNR for our definition is much lower than for their definition (see Col. ‘g’ of Figs. 6 and A9).
Figure A1. Zoom into the region of NIR indices defined in this work and comparison of the various definitions in the literature. The thick black line, in each panel, shows a normalised E-MILES SSP spectrum of age 12 Gyr, [M/H] = +0.06 and bimodal IMF slope of 1.3, broadened to velocity dispersion of 360 km s\(^{-1}\). The dark blue and pink lines correspond to the atmospheric transmission and sky emission spectra from ESO Skycalc tool. The small vertical lines show the position of atomic and molecular absorptions from Kleinmann & Hall (1986), IRTF library and Lagattuta et al. (2017). Grey and orange regions represent central absorption and pseudo-continua bandpasses in our definition while the corresponding bandpasses in the definitions from the literature is shown by solid black and dashed blue horizontal lines.
NIR spectral Indices

**Figure A2.** Same as Figure (A1)
Figure A3. Same as Figure (A1)
Figure A4. Model predictions of line-strength indices, defined in the literature, as a function of age (panels in Col. 'a'), metallicity (Col. 'b'), IMF slope (Col. 'c'), elemental abundance ratios (Col. 'd'), velocity dispersion (Col. 'e'), radial velocity (Col. 'f') and SNR (Col. 'g'). All plots are based on E-MILES models with BaSTI evolutionary tracks, but those in Col. 'd', where we used Circ12 SSPs to estimate the effect of elemental abundance variations. (Panels ‘a’) Different colors correspond to different metallicity, i.e. [M/H] = +0.06 (green) and [M/H] = +0.26 (black). Models with a Kroupa-like IMF are shown as solid lines while models with a bottom-heavy IMF (Γ_p = 3.0) are shown as dashed lines. (Panels ‘b’) The blue lines are model predictions for young populations with an age 2 Gyr while the red lines correspond to old (12 Gyr) populations. (Panels ‘c’) Blue and red lines are predictions for young (2 Gyr) and old (12 Gyr) populations, respectively. (Panels ‘d’) The vertical lines show the variation of a given line-strength for variations of different elemental abundances, [X/Fe]'s, shown with different colours. (Panels ‘e’) Different colors correspond to different metallicities, i.e. [M/H] = +0.06 (green) and [M/H] = +0.26 (black), respectively. Models with a Kroupa-like IMF are shown as solid lines while models with a bottom-heavy IMF (Γ_p = 3.0) are shown as dashed lines. (Panels ‘f’) The orange line shows index measurements on a reference E-MILES SSP spectrum shifted to a given radial velocity, ∆ν_r. (Panels ‘g’) The error bars show the average uncertainties on index values as a function of S/N.
Figure A5. Same as Figure (A4)
Figure A6. Same as Figure (A4)
Figure A7. Same as Figure (A4)
Figure A8. Same as Figure (A4)
Figure A9. Same as Figure (A4)
APPENDIX B: UNCERTAINTIES INDUCED BY REMOVING BAD PIXELS WITHIN THE INDEX DEFINITION

In the following, we show how index line-strengths are affected by the masking of a given fraction of pixels within each bandpass, translating these variations into changes of the main stellar population parameters involved in a stellar population analysis, such as age, metallicity, and IMF. In Table B1, we also provide, as a quick reference for the user, a more quantitative estimate of the maximum fraction of pixels with substantial systematic uncertainties that is allowed to perform a reliable stellar population analysis. We also provide below, a practical example showing how a user may benefit from the numbers provided, for each index, in Table B1.

Figs. B1 to B3 show, for all the new indices in the present work, the variation of index line-strengths when removing bad pixels within an index definition (see upper panels). In the same Figures, we also translate the above variation into relative changes of the relevant stellar population properties, plotting these relative changes as a function of the fraction of masked pixels (see lower panels). To this effect, as already detailed in Sect. 4.8, we used an E-MILES SSP with age 12 Gyr, [M/H] = +0.06 dex, and $\Gamma_b = 1.3$ as our reference model and randomly removed a percentage of the total pixels within each bandpass defining a given index, before measuring its strength. We repeated this procedure 1000 times and saved the maximum change in the index strength. For each index, in the corresponding upper panel, the changes in the index value as a function of the fraction of removed pixels (x-axis) is shown, with solid lines for spectra having SNR=100 Å$^{-1}$ and dotted lines for spectra with SNR=50 Å$^{-1}$. Blue, black and red colours correspond to removing a given percentage of pixels within the blue, feature, and red bandpasses of the index, respectively. To assess the impact of spectral resolution on the minimum fraction of pixels required to measure an index, we show the results obtained with different resolutions, from 60 to 360 km s$^{-1}$, as shaded regions. In the lower panels of the Figures, for each index, we translated the average change of index value due to the masking of a given fraction of pixels within the index bandpasses to relative changes in the main stellar population parameters, i.e. age, metallicity, and IMF. The orange, green, and pink lines show relative changes in age, metallicity, and IMF slope with respect to our reference model, respectively. For each stellar population parameter, we normalize variations by a range of value for that parameter typical for intermediate- and high-mass ETGs (i.e. age range from 2 to 12 Gyr, total metallicity from $+0.15$ to $-0.25$ dex, and IMF variation from Kroupa-like ($\Gamma_b = 1.3$) to bottom-heavy ($\Gamma_b = 3.0$)) (see, e.g., La Barbera et al. 2013). As for the upper panels, the solid and dotted lines show the results for spectra with SNR=100 Å$^{-1}$ and SNR=50 Å$^{-1}$, respectively, while the impact of spectral resolution, from 60 to 360 km s$^{-1}$, is shown with shaded area. Note that, in these plots, the upper limits are imposed by the maximum variation on the index value due to the typical stellar population variation of intermediate-mass and massive ETGs (i.e. we do not consider relative variations larger than one).

In principle, the plots in Figs. B1 to B3 should be used to assess the robustness of spectral indices against systematic uncertainties for a given galaxy sample/spectroscopic dataset. In order to facilitate the use of these plots, we have also defined a maximum fraction of masked pixels that can be allowed to use each index. We defined this fraction as the one for which the ratios of stellar population parameters changes do not exceed ±0.5. Results are reported in Table B1. Note that as mentioned in Sect. 4.8 this table should be only intended as a quick reference for the user, while different criteria can be defined based on a specific application. Column 1 in Table B1 indicates the name of indices, with SNR being given in Col. 2. Columns 3, 4, and 5 provide the maximum fraction of pixels which can be removed within the index bandpasses and do not impact our ability to derive the age, metallicity, and IMF.

As an example, we discuss the reliability of our index measurements for the sample of La Barbera et al. (2019) (see Sect. 5). For each galaxy, we identified bad pixels within each bandpass of the NIRD indices. The fractions are reported in Table B2. Since we have analyzed how Mg i 1.18 and Mg i 1.50 can help constraining the stellar IMF (see Fig. 9), we compare the estimated fraction of affected pixels with those provided in Column 5 of Table B1. The SNR of the spectra is high (> 100 Å$^{-1}$); therefore, we consider the percentages for SNR = 100 Å$^{-1}$. In case of Mg i 1.18, for a spectrum with SNR=100 Å$^{-1}$, the maximum fraction of affected pixels to constrain the IMF is (according to our criterium) 2%, within the bandpasses. According to Table B2, for XSG2, XSG6, XSG7, and XSG10, the fraction of affected pixels for Mg i 1.18 does not exceed the maximum fraction in Table B1. This shows that, to perform an IMF analysis, Mg i 1.18 index measurements are reliable for these galaxies. On the other hand, this is not the case for XSG1, XSG8, and XSG9, and therefore they were not included in the upper panels of Fig. 9. Ca i 1.95 index is reliable for analysing age and IMF slope for all galaxies in the sample but for XSG6, while it cannot be used to constrain metallicity for XSG6, XSG7, XSG9, and XSG10. Ca i 1.99a, Ca i 1.99b, and Ca i 1.99c indices fall within a clean region and none of the pixels are affected by telluric absorption or sky emission. However, for XSG8, we find that 11% of pixels in the blue bandpasses of these indices are contaminated, and thus one cannot rely on these indices to constrain metallicity of XSG8. In the case of Ca i 2.26, only for XSG6 one cannot constrain stellar population parameters, as the fraction of affected pixels within the red bandpass (5%) is higher than the maximum fractions provided in Table B1 (2% for age and metallicity and 3% for IMF).

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Figure B1. Effect of removing a given fraction of pixels within blue (blue lines), central (black lines) and red (red lines) bandpasses on the line-strength of NIR indices (upper panels). Solid and dotted lines correspond to spectra with SNR=100 and 50 Å⁻¹, respectively. In the lower panels, the changes of index values plotted in the upper panels have been transformed into relative variations of stellar population parameters, i.e. age, metallicity, and IMF slope. The changes in stellar population parameters are computed with respect to a reference spectrum with age 12 Gyr, [M/H]=0.06, and $\Gamma_b = 1.3$, and are normalized to the range of stellar populations parameters of intermediate-mass and massive ETGs. Shaded areas, in both the upper and lower panels, show the effect of varying velocity dispersion from 60 to 360 km s⁻¹.
Figure B2. Same as Figure (B1)
Figure B3. Same as Figure (B1)
**Table B1.** Maximum fraction of bad pixels within bandpass limits of spectral indices, for which it can be derived meaningful stellar population parameters. Column 1 gives the name of the indices. Column 2 indicates the SNR of the reference spectrum used to derive the fractions. Columns 3, 4, and 5 correspond to the maximum fractions of bad pixels that can be masked out within the index bandpasses to derive stellar population parameters.

| Index  | SNR (Å⁻¹) | Age (%) | Metallicity (%) | IMF (%) |
|--------|-----------|---------|-----------------|---------|
| CN0.93 | 100       | 55      | 25              | 40      |
| CN0.93 | 50        | 40      | 7               | 20      |
| FeH0.99| 100       | 2       | 2               | 2       |
| FeH0.99| 50        | 2       | 2               | 2       |
| CN1.10 | 100       | 25      | 25              | 45      |
| CN1.10 | 50        | 9       | 9               | 25      |
| NaI1.14| 100       | 2       | 2               | 4       |
| NaI1.14| 50        | 2       | 2               | 2       |
| FeI1.16| 100       | -       | 4               | 4       |
| FeI1.16| 50        | -       | 2               | 2       |
| MgI1.18| 100       | 5       | 10              | 2       |
| MgI1.18| 50        | 2       | 3               | 2       |
| PaH1.28| 100       | 4       | 2               | 2       |
| PaH1.28| 50        | 2       | 2               | 2       |
| AllI.31| 100       | 4       | 4               | 9       |
| AllI.31| 50        | 2       | 2               | 2       |
| CNI.42 | 100       | 3       | 30              | 35      |
| CNI.42 | 50        | 2       | 10              | 10      |
| CNI.46 | 100       | 2       | 10              | 20      |
| CNI.46 | 50        | 3       | 4               | 8       |
| MgI1.50| 100       | 20      | 30              | 25      |
| MgI1.50| 50        | 6       | 10              | 10      |
| COI.56 | 100       | 3       | -               | 10      |
| COI.56 | 50        | -       | -               | 4       |
| COI.58 | 100       | 2       | 5               | 8       |
| COI.58 | 50        | -       | 2               | 2       |
| COI.60 | 100       | 8       | 2               | 25      |
| COI.60 | 50        | 2       | -               | 10      |
| COI.64 | 100       | 4       | 5               | 25      |
| COI.64 | 50        | 2       | 2               | 8       |
| COI.66 | 100       | 5       | 3               | 20      |
| COI.66 | 50        | 2       | 6               | 6       |
| AllI.67| 100       | 2       | 6               | 6       |
| AllI.67| 50        | 2       | 2               | 2       |
| COI.68 | 100       | 5       | 2               | 10      |
| COI.68 | 50        | 2       | 5               |         |
| CalI.95| 100       | 3       | 3               | 10      |
| CalI.95| 50        | 2       | 2               | 9       |
| CalI.99a| 100     | 10      | 10              | 35      |
| CalI.99a| 50       | 5       | 5               | 10      |
| CalI.99b| 100      | 10      | 10              | 30      |
| CalI.99b| 50       | 4       | 3               | 10      |
| CalI.99c| 100      | 3       | 6               | 6       |
| CalI.99c| 50       | 2       | 2               | 2       |
| NaI2.21| 100       | 2       | 6               | 5       |
| NaI2.21| 50        | -       | 2               | 2       |
| FeI2.24| 100       | -       | 2               | 2       |
| FeI2.24| 50        | 2       | 2               | 2       |
| CaI2.26| 100       | 2       | 2               | 3       |
| CaI2.26| 50        | -       | -               | 2       |
| COI2.30| 100       | 45      | -               | 55      |
| COI2.30| 50        | 20      | -               | 35      |
| COI2.32| 100       | 35      | 8               | 50      |
| COI2.32| 50        | 20      | 2               | 35      |
| COI2.35| 100       | 45      | -               | 60      |
| COI2.35| 50        | 20      | -               | 35      |
Table B2. Fraction of pixels with substantial systematic uncertainties within the bandpasses of targeted indices in the spectra of La Barbera et al. (2019) sample. Column 1 gives the name of indices. Column 2 indicates the bandpass of indices. The identified fraction of affected pixels is reported in Cols. 3 to 9 for each galaxy in the sample.

| Index  | Bandpass | XSG1 (%) | XSG2 (%) | XSG6 (%) | XSG7 (%) | XSG8 (%) | XSG9 (%) | XSG10 (%) |
|--------|----------|----------|----------|----------|----------|----------|----------|-----------|
| Mg i 1.18 | blue     | 3        | 0        | 0        | 2        | 3        | 2        | 0         |
|         | feature  | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
|         | red      | 8        | 2        | 0        | 2        | 0        | 4        | 0         |
| Mg i 1.50 | blue     | 0        | 0        | 1        | 0        | 0        | 0        | 7         |
|         | feature  | 0        | 0        | 0        | 16       | 10       | 19       | 0         |
|         | red      | 0        | 0        | 0        | 0        | 0        | 0        | 25        |
| Ca ii 1.95 | blue     | 0        | 0        | 5        | 0        | 0        | 2        | 5         |
|         | feature  | 2        | 0        | 5        | 5        | 2        | 5        | 5         |
|         | red      | 0        | 0        | 13       | 0        | 3        | 3        | 0         |
| Ca ii 1.99a | blue    | 0        | 0        | 0        | 0        | 11       | 0        | 0         |
|         | feature  | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
|         | red      | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Ca ii 1.99b | blue    | 0        | 0        | 0        | 0        | 11       | 0        | 0         |
|         | feature  | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
|         | red      | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Ca ii 1.99c | blue    | 0        | 0        | 0        | 0        | 11       | 0        | 0         |
|         | feature  | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
|         | red      | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Ca ii 2.26 | blue    | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
|         | feature  | 0        | 0        | 1        | 1        | 0        | 0        | 0         |
|         | red      | 0        | 0        | 5        | 0        | 0        | 0        | 0         |