A Photometric System for Metallicity Mapping in Galaxies

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Abstract.
A new photometric system suitable for deep, precise and quick metallicity mapping in galaxies is proposed. We find a linear correlation between our metallicity index and the $Mg_{2}$ index for stellar, globular cluster, and early-type galaxy spectra, and model spectral energy distributions of the simple stellar populations.

Keywords: galaxy, metallicity, photometry

1. Introduction

To understand how galaxies are formed and evolve we need to investigate their stellar populations and to derive their main parameters such as metallicity and age. During the last decade determination of the metallicity has been performed using spectroscopic approach in particular, by measuring the prominent absorption feature around 518 nm, the so called $Mg_{2}$ index (Burstein et al. 1984). It was shown that $Mg_{2}$ is a good metallicity indicator for globular clusters. This feature has been also measured extensively by many authors for ellipticals (see Trager et al. 1998 and references therein). Different theoretical approaches also show that this feature is a function of metallicity (e.g., Mould 1978; Barbuy 1994; Casuso et al. 1996). However spectroscopic observations are strongly limited by the large telescope time consumption because of a high signal to noise ratio ($S/N$) requirement. This is why most of the studies deal with the innermost regions of the galaxies and only a few attempts to reach the galaxy effective radius were made (e.g. Saglia et al. 1993). Another limitation arises from the fact that the observations are performed via long-slit spectroscopy, thus lacking a possibility to map the galaxies. Such maps are crucial for full understanding of the spatial distribution of metallicity within a galaxy and thus for constraining the galaxy formation models. Spectroscopic
mapping was attempted by Peletier et al. (1999) using Integral Field Spectroscopy. However this study is restricted to the very innermost regions of bright nearby galaxies. An alternative way is to use three well tuned narrow-band filters for \(Mg\) feature and continuum on the both sides of it (Beauchamp & Hardy 1997). However, this system is rather telescope time consuming. The main purpose of this work is to define and investigate a new photometric system suitable for the efficient mapping of the \(Mg\) (518 nm) feature.

2. Definition of the Photometric System

A photometric system suitable for an accurate and quick mapping of the metallicity in galaxies should satisfy the following requirements: possess linear relation of a photometric index with the well defined spectroscopic metallicity indicator; allows wide coverage in radial velocity (\(v_{\text{rad}}\)) with a single set of filters; maintains high stability of the response and precision of measurement; is robust against the influence of the galaxy’s internal radial velocity; retains homogeneity of the parameters over the whole field. Taking into account these requirements we have designed a new photometric system which is composed of two filters: narrow-band \((W1, \delta \lambda = 8 \text{ nm})\) and wide-band \((W2, \delta \lambda = 45 \text{ nm})\), both centered at 519 nm. The present configuration is optimized for the observations with \(v_{\text{rad}}\) ranging from \(-500\) to \(\sim 2000\) \(\text{km/s}\). However, this system could be extended to higher \(v_{\text{rad}}\) if a new narrow-band filter with redshifted central wavelength is added. In the present investigation we limit ourselves with a theoretical set of filters which, for the sake of simplicity, have rectangular transmission function. An application of the transmission curves of real filters would not affect the main conclusions of this work, but generality of the discussion would be lost.

The color index \(W\) is defined as follows:

\[
W = (W1 - W2) + C, \tag{1}
\]

where \(W1, W2\) and \(C\) are defined as:

\[
W1 = -2.5 \lg \left( \int_{\lambda_2}^{\lambda_3} F(\lambda) \, d\lambda \right) \tag{2}
\]

\[
W2 = -2.5 \lg \left( \int_{\lambda_1}^{\lambda_4} F(\lambda) \, d\lambda \right) \tag{3}
\]
Figure 1. $Mg_1$ and $Mg_2$ vs. $W$ for a) stars, b) galaxies & globular clusters, c) galaxy models.

$$C = -2.5 \log \left( \frac{\lambda_4 - \lambda_1}{\lambda_3 - \lambda_2} \right),$$  \hspace{1cm} (4)

$F(\lambda)$ - is the spectral energy distribution, $\lambda_1, \lambda_4$ are the bluest and reddest wavelengths of $W2$ respectively, while $\lambda_2, \lambda_3$ are wavelength limits for $W1$. We designed the filter $W2$ to be wide enough, while allowing to avoid $H\beta$ at its blue side and the atmospheric lines at its red side. The filter $W1$ has been designed to cover as large $v_{rad}$ interval as possible and to allow a plausible photometric dynamical range for $W$. However, we neglected the influence of the emission line OIII at 500.7 nm because our main targets are early type galaxies. A redefinition of the index $W$ for late type galaxies is easy and works well but then only a small range of radial velocities can be covered using one set of filters. These obviously contradicting conditions restricted the number of possible solutions for the definition of the final system.

Figure 1 shows the main properties of the new system. Panels (a,b,c) demonstrate a strong relation of the photometric index $W$ with the spectroscopic indices $Mg_1$ and $Mg_2$ (as defined in Worthey et al. 1994). All these indicators are (and should be) measured employing only the flux-calibrated spectra. We used the stellar sample of Jones (1997) ($\sim 600$ stars), the spectra of globular clusters (Covino et al. 1995) and galaxies (Gorgas et al. 1997), the galaxy templates and individual spectra (types $E - Sb$) from Kinney et al. (1996), and the single-age single-metallicity models (SSPs) (Vazdekis 1999). We find a linear relation between $W$ and $Mg_2$. However, $Mg_1$ (shown in Fig. 1) and $Mg_6$ (Worthey et al. 1994) exhibit a non linear behavior with $W$, and therefore cannot be simply applied for a calibration of $W$ because a nonlinear transformation to the standard system would be required.

3. Properties of the System

Figure 2 shows a behavior of the index $W$ for the SSPs when definition of the filters $W1$ and $W2$ is varied within a range of an achievable manufacturing accuracy. Panel (a) demonstrates the changes of $W$ when $\delta \lambda$ and $\lambda_0$ characterizing $W2$ are varied, while keeping constant the parameters of the filter $W1$. Panel (b) shows the changes of $W$ when parameters of the filter $W1$ are varied, while for $W2$ they remain standard. From Figure 2 we learn that the linearity is independent on
Figure 2. The index $W$ vs. $Mg_2$ for different definitions of the filters. The parameters of the filters $W2$ & $W1$ are changed in the panels a) and b) respectively.

Figure 3. The index $W$ vs. $Mg_2$ for different recessional velocities applied to the galaxy models. Filter set is standard.

the precise definition of the filters, and the required corrections for the analyzed cases are rather small. Therefore the proposed system is quite robust against small changes of the main characteristics of the filters.

Since galaxies have different radial velocities we should study the stability of the system response against the spectrum shift and constrain the range of $v_{rad}$ where the standard system is applicable. Figure 3 shows $W$ versus $Mg_2$ for the spectra of SSPs redshifted assuming various $v_{rad}$. We do not see significant deviations except for $v_{rad} = 3000$ km/s. Once again only small linear correction factors should be applied to $W$ allowing an accurate transformation to the standard system. We see that the strongest correlation is for $v_{rad} \sim 1000$ km/s, the value for which the system was optimized.

The observing run must include observation of several standard stars (or, even better, standard fields) with $Mg_2$ values determined accurately from flux-calibrated spectra. The correction for the atmospheric extinction and all data reduction steps dealing with CCD camera’s and filter’s distortions should be carefully performed. The standard stars, SSP models and availability of galaxy radial velocity determination will warrant an accurate transformation to the standard system at $v_{rad} = 0$ km/s. The dependence of the transmission curves of real filters on temperature and focal ratio of the telescope should also be taken into account.

4. Advantages and Disadvantages of the New System

The main advantages of the newly introduced photometric system are: a strong linear relation with respect to the spectroscopic index $Mg_2$; large range of $v_{rad}$ covered by one set of filters; efficiency to reach high $S/N$ within short exposure times. A strong linear relation of $W$ with $Mg_2$ ensures an accurate transformation of the observations to the standard system, independent on the galaxy radial velocities up to $v_{rad} \sim 2000$ km/s. The system could be easily reproduced at any observatory if adequate calibration stars are observed. The stability of the system within a wide range of $v_{rad}$ is also very important for observations of the galaxies possessing a large internal radial velocity differences. In addition, we see a great advantage in having a large field
of view which is limited only by the CCD and filter dimensions, and the image scale in the focal plane of telescope.

Unfortunately, narrow photometric dynamical range of $W$ requires very accurate correction for the atmospheric extinction, high photometric precision of the data, and precise transformation to the standard system. Additional limitation of the system in present definition is its applicability for the analysis of early type ($E - Sb$) galaxies only.

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Stars

Mg\textsubscript{1}, Mg\textsubscript{2}

Galaxies

Mg\textsubscript{1}, Mg\textsubscript{2}

Globulars

Mg\textsubscript{1}, Mg\textsubscript{2}

Galaxy models

Mg\textsubscript{1}, Mg\textsubscript{2}
W2
- Standard
+ Blue shift 3 nm
× Red shift 3 nm
• Width 40 nm
○ Width 50 nm

W1
○ Standard
+ Blue shift 1 nm
× Red shift 1 nm
• Width 7 nm
○ Width 9 nm

Mg$_2$
