$K$ and evolutionary corrections from UV to IR

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Abstract. $K$ and evolutionary corrections are given for the E, Sa and Sc Hubble types for the $U, B, V, R, I, J, H, K$ filters of the Johnson – Bessell & Brett photometric system and the $gri$ filters of the modified Thuan & Gunn system up to the redshift $z = 3$. Their dependence on the time scale of star formation in ellipticals is investigated.

The corrections are computed according to an evolutionary synthesis model that reproduces the integrated galaxy spectrum in the range 1000-25 000 Å; such a model makes use of an infrared observed stellar library and its results are compared with nearby galaxies.

Evolving spectral energy distributions of the various Hubble types, as well as optical-IR and IR-IR colour evolution and adopted filter response functions are also given.

Key words: galaxies: evolution – galaxies: photometry – galaxies: distances and redshifts – galaxies: fundamental parameters – cosmology: miscellaneous

1. Introduction

The $K$ corrections for galaxies of different morphological types are necessary to interpret the magnitude-redshift relation, the luminosity function of galaxies and for most of the spectrophotometric studies of distant objects.

The $K$ correction is defined as the corrective term that needs to be applied to the observed magnitude in a certain band due to the effect of redshift. It does not take into account the effects of galactic evolution; when this cannot be neglected, it is necessary to apply a further correction, the evolutionary one (EC), that can be computed by using spectrophotometric models. Considering the fact that present observations reach high redshifts and progressively fainter magnitudes, establishing the connection between distant and local galaxies requires more and more often the knowledge of the galactic evolution and the use of both the corrections.

A number of authors have previously published tables of $K$ corrections (Hubble 1936; Humason et al. 1956; Oke & Sandage 1968; Schild & Oke 1971; Whitford 1971; Oke 1971; Wells 1972; Pence 1976; Ellis et al. 1977; Code & Welch 1979; Coleman et al. 1980; Frei & Gunn 1994). In most of the cases these works are limited for one of more of the following aspects: the number of photometric bands, the number of galactic types, the maximum redshift considered. Many of the papers mentioned above only deal with ellipticals, that are considered the best standard candles at high redshifts. The biggest efforts to supply an extended set of $K$ corrections have been made from Pence (1976) and Coleman et al. (1980). Pence computed the $K$ corrections for the $U, B, V, R$ filters of the Johnson system and the $R$ Sandage’s filter for the following morphological types; E/S0, Sab, Sbc, Scd, Im with a maximum redshift of 2.18. Coleman et al. (1980) found $K$ corrections in the $U, B, V, R$ bands for the bulges of M31 and M81 and for Sbc, Scd, Im with a $z_{\text{max}} = 2$. Frei & Gunn (1994) have used the energy distribution of Coleman et al. to compute the $K$ corrections at $z = 0.1, 0.2, 0.4, 0.6$ of E, Sbc, Scd and Im in five photometric systems (Johnson $UBV$, Gulixson et al. $BjRI$, Thuan and Gunn $gri$, $ugriz$ and Cousins $RI$).

These studies make use of an empirical method: with a software programme, the observed spectral energy distribution of a given morphological type (averaged over a number of objects) is redshifted. The $K$ corrections are then computed from these mean curves and using the filter transmission functions; in this case there is no need to assume a given cosmological model. With this method it is obviously not possible to compute the evolutionary corrections, for which the most direct computing method is making use of a model of spectrophotometric evolution.

Another advantage of using models instead of observations is that, in order to cover a wide range of redshift, the latter often requires the connection of observations in various spectral regions, most of the times obtained with dif-
The equation is valid:

\[ S = \frac{L}{\frac{4\pi D^2(1+z)}{4\pi D^2(1+z)}} \]

(2)

where \( D \) is the luminosity distance. Equation (2) can be written as:

\[ m_{\lambda_0} = M(\lambda_0, t_0) + 5 \log D + \text{const} \]

\[ + \left[ 2.5 \log(1 + z) + 2.5 \log \int_0^\infty E(\frac{\lambda}{1+z}, t_0)S(\lambda)d\lambda \right] \]

\[ + 2.5 \log \int_0^\infty E(\frac{\lambda}{1+z}, t_1)S(\lambda)d\lambda \]

(3)

The term in the square brackets is the \( K \) correction and the last term is the evolutionary correction. From Eq. (3) the observed magnitude \( m_{\lambda_0} \) for the band with effective wavelength \( \lambda_0 \) is equal to the sum of five terms:

a) the absolute magnitude in the same band as it would be measured in the rest frame at the epoch of observation \( t_0 \). This is indicated as \( M(\lambda_0, t_0) \) and corresponds to the numerator of the first term in the Eq. (2);

b) a term that only depends on the luminosity distance \( D \);

c) a constant term, depending only on the band used, that determines the normalization of the absolute magnitude;

d) the \( K \) correction;

e) the evolutionary EC correction.

The \( K \) correction is the difference between the observed magnitude of the galaxy of age \( t_0 \) measured at the wavelength \( \lambda_1 = \lambda_0/(1 + z) \) and the magnitude of the same galaxy of age \( t_0 \) computed at \( \lambda_0 \). Notice that \( t_0 \) is the moment of observation (\( \sim 15 \) Gyr), while \( t_1 \) is the time at which the light has been emitted. Therefore the \( K \) correction corresponds to the difference in magnitude of two objects with identical spectrum due to the redshift: it does not include in any way the intrinsic evolution of the spectrum due to the evolution of the stellar populations that contribute to it.

On the contrary, the EC correction depends on the intrinsic evolution of the spectral energy distribution (SED), being the difference between the magnitude of a galaxy of age \( t_1 \) and the same galaxy evolved (whose spectrum is different from the one of the previous galaxy) of age \( t_0 \), both computed at \( \lambda_1 \). It is therefore the difference in absolute magnitude measured in the rest frame of the galaxy at the wavelength of emission.

The sum of the \( K \) and EC corrections is the difference between the magnitude of a galaxy of age \( t_1 \) redshifted and the one of the evolved galaxy observed at the time \( t_0 \) at \( z=0 \). Both corrections are computed on the basis of models of spectrophotometric evolution, assuming a star formation history for each morphological type and having
3. The spectrophotometric model

This work makes use of an evolutionary synthesis model that reproduces the integrated spectrum of a galaxy. A description of this model is also given in Poggianti & Barbaro (1996); here the essential informations are presented.

The emission of the stellar component is computed with a modified version of the model by Barbaro & Olivi (1986, 1989 (BGOF)), that synthesizes the SED of a galaxy in the spectral range 1000-10000 Å. The BGOF model includes, besides the main sequence and the central helium burning phase, also the advanced stellar evolutionary phases such as AGB and Post-AGB. It takes into account the chemical evolution of the galaxy, therefore the contribution to the integrated spectrum of stellar populations of different metallicities. This model has been successfully employed in the studies of star clusters in the Magellanic Clouds and of elliptical galaxies (Barbaro & Olivi 1986, 1989, 1991; Barbaro 1992; Barbaro et al. 1992).

The stellar evolutionary background has not been changed, while updates have been made to the library of stellar spectra: the new Kurucz stellar atmosphere models (version 1993) have replaced the previous ones (Kurucz 1979) and the computation of the spectrum has been extended up to 25 000 Å. In the infrared region, for stars with $T_{\text{eff}} > 5500$ K Kurucz’s models (1992) have been used. For stars with lower effective temperatures the library of observed stellar spectra by Lançon-Rocca Volmerange (1992, LRV) has been employed: such spectra cover the spectral range 14500-25000 Å, with a resolution between 25 and 70 Å. The connection between the optical spectra (1000-10000 Å) and the LRV spectra has been made by means of black body curves. For each star the black body temperature has been determined by imposing that the observed spectrum is reproduced, being the SED of local ellipticals well reproduced by the models also in the UV range. Anyway the metallicities (among which oxygen and magnesium) and the iron with respect to the solar value.

Concerning the spirals, the models do not take into account the intrinsic extinction due to the presence of dust, that is expected to be progressively more significant at increasing redshifts and at decreasing effective wavelength. In some cases it will be necessary to consider a further correction for intrinsic extinction (Di Bartolomeo et al. 1995).

3.1. Comparison with nearby galaxies

In principle a first test of the model could be done by comparing the results with the observations of integrated SEDs of star clusters; good candidates are the young star clusters in the Magellanic Clouds (Barbaro & Olivi 1991). However a great dispersion in the infrared colours of these objects has been observed; such a dispersion is explained considering the stochastic fluctuations in the mass distribution of the evolved stars (Barbaro 1992). For this reason and for the uncertainty in the determination of the age and the metallicity of each cluster, the comparison has
been made with galaxies, for which the stochastic effects are expected negligible.

Table 1 presents the colours of models of age 15 Gyr of different morphological types; in the case of the elliptical, the dependence of colours from the average metallicity is shown: solar (El1, correspondent to the E model), Z=0.01 (El2) and Z=0.005 (El3). Notice that the optical-infrared colours (\((V-J), (V-H), (V-K)\)) change drastically with the Hubble type, while the IR-IR colours (\((J-H), (J-K), (H-K)\)) change slightly along the type sequence, with differences comparable to the observational uncertainty.

Observations in the near-IR have been obtained from Persson et al. (1979) for early-type galaxies in Virgo, in Coma and in the field and from Bower et al. (1992a,b) for a sample of early-type objects in Virgo and in Coma. The average galaxy colours observed by the different authors, corrected for redshift, reddening and aperture effects, are compared in Table 2 with the model results for ellipticals of various metallicities. The agreement is satisfactory.

Persson et al. corrected the colours by using Schild & Oke (1971) and Whitford (1971) \(V\)-band \(K\)-corrections; for the infrared bands, they computed the corrections using several late-type stars from Woolf et al. (1964). Bower et al. defined the \(U\) and \(V\) band \(K\) corrections from a series of template early-type galaxy SEDs, among which those of Coleman et al., and the infrared \(K\)-corrections from the SED of the K3 giant star \(\alpha\) Tau (Woolf et al. 1964). For spirals, a great dispersion in the infrared colours within the same morphological type is observed (Gavazzi & Trinchieri 1989), therefore spirals are not included in Table 2; the colours of the models for the spirals are inside the range of observed values.

Moreover the updated evolutionary synthesis model has been used successfully in the studies of galaxies at intermediate redshifts (Poggianti & Barbaro 1995, 1996).

4. Presentation of the tables and the figures

From the spectral energy distributions and from the response functions of the filters in the various bands, the \(K\) and EC corrections have been computed; they are presented in Tables 31-38. The corrections have been computed up to \(z = 3\) for the bands \(U, B, V, R, I, J, H, K\) of the Johnson’s photometric system (\(B_1\) and \(B_2\) corresponding to \(B_2\) and \(B_3\) from Buser (1978) and \(J, H, K\) from Bessel & Brett 1988) and \(gri\) of the Thuan & Gunn system (1976) as modified from Schneider et al. (1983). The \(B\) magnitude is computed considering the sum of the two filter response functions \(B_1\) and \(B_2\) divided by two. Being 1000 Å the lower limit of the wavelengths considered from the model, the \(U\) and \(B\) bands have been computed respectively up to \(z = 2\) and \(z = 2.5\).

The response function of the filters are given in Tables 39-41; it is useful to underline that, due to a typing error in Table 4 from Bessel & Brett, the definition of the \(H\) and \(K\) bands can be ambiguous. It is indispensable, in any case, to check the response function of any filter of interest; in the case of the \(K\) band, the difference between the filter here adopted and that in the figure of Bessel & Brett can give rise to errors in the corrections of 0.2 maximum.

The spectral energy distributions of the models of different Hubble types of age 15 Gyr are given in the Tables 3-5 for the E, Sa and Sc in the spectral range 1012-27000 Å. The SEDs are also presented in Fig. 1. From top to bottom (at 1000 Å) the spectra of the Sc, Sa, E2 and E are shown; it is visible that the difference between the spectra of the two ellipticals is significant only at the shortest wavelengths. The rest frame spectra of evolving SEDs of different ages are presented in Fig. 2 (E), Fig. 3 (Sa) and Fig. 4 (Sc); the ages shown are 15, 13.2, 10.6, 8.7, 7.4, 5.9, 4.3, 3.4 and 2.2 Gyr, corresponding respectively to the redshifts: 0, 0.1, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0. Such SEDs are given in Tables 6-29, from which the interested user can compute any desired property.

Considering the high metal content adopted and the observed correlation between the Mg\(_2\) index and the absolute luminosity, the elliptical model is representative of luminous objects. Due to the observed substantial variations of the ultraviolet flux with the galactic luminosity, the results presented here cannot be applied to low luminosity ellipticals (i.e. with a lower metal content) for redshifts \(\geq 0.5\). Furthermore, the differences between the two model ellipticals (\(\tau = 1\) and \(\tau = 1.4\) Gyr) appear sig-
significant starting from $z = 0.6$ (K correction) and $z = 0.20$
(EC correction) in the bluest bands.

In order to obtain the observed colour of the progenitor
galaxy of a given type of local galaxy the following relation
can be used:

\[
\text{observed colour} = \text{colour of the local corresponding}
\text{galaxy} + \text{(difference between the K corrections of the first}
\text{and the second band)} + \text{(difference between the EC}
\text{corrections of the first and the second band)}.
\]

This relation can be deduced from Eq.(3). For instance, if one wants to compute the expected observed colour (V-J) of an elliptical at $z = 1$:

\[
\text{colour of a local elliptical (V-J)} = 2.25
\]

\[
K_V = 3.42, K_J = 0.28
\]

\[
K_V - K_J = 3.14
\]

\[
\text{EC}_V = -1.87, \text{EC}_J = -0.96
\]

\[
\text{expected observed colour} = 2.25 + 3.14 - 0.91 = 4.48.
\]

Figures 5-15 show the K and EC corrections for differ-
ent bands; the sudden change in all the curves at $z = 2.5$
is due to the fact that the last two models have been com-
puted with a large redshift step (0.5). Considering the
smooth behaviour of these functions between a redshift
2.5 and 3, a smaller redshift step is not required.

Figures 16-23 show the rest frame and observer’s frame
colour evolution.

In Table 30 model $K_V$ corrections are compared with
those of Pence for negligible Galactic extinction. The dif-
fences, starting at relatively low redshift for the latest
types, are partly due to the slightly dissimilar response
functions adopted and mainly to the differences in the
SEDs. It must be stressed that two galaxies classified of
the same type on the basis of their morphological appear-
ance (spiral arms, bulge to disk ratio etc.) can have signif-
ically different spectra, indicative of unlike present
and past star formation rates. Therefore the model galactic
sequence should be interpreted as a “star formation” se-
quence, while the results found with an empirical method
will necessarily depend on the single galaxies chosen for
the sample. For this reason the comparison of the two
methods results rather difficult. Furthermore Pence him-
self defined the ultraviolet observations available to him
(preliminary OAO data) as “somewhat uncertain”, espe-
cially for E/S0. Moreover, due to the lack of ultraviolet
observations for the Sbc, Pence had to interpolate between
the types Sab and Scd. Coleman et al.’s results for bulges
are in agreement with elliptical results from Pence until
a redshift $z \approx 0.75$ in the V band. They found instead sub-
stantial differences from Pence in the $K_V$ of the elliptical
for $z > 0.3$, probably due to the UV Pence’s difficulties
mentioned above. A better agreement is obtained between
their results and the model values presented here.

5. Summary

$K$ and evolutionary corrections from UV to IR are pre-
sented for three kinds of galactic types (E, Sa and Sc) for a
number of filters in two photometric systems. Corrections
in other photometric systems are available by request (Koo-Kron $U^+, J^+, F, N$ (Koo 1985), Cousin $R, I$ (Bessell
1986), $B_J, R_F$ of Couch & Newell (1980) and 418, 502,
578, 685, 862 of the Durham group (Couch et al. 1983)).

These results are based on an evolutionary synthesis
model that successfully reproduces the colours and the
shape of the continuum of the various galactic types of
local and distant galaxies.

Spectral energy distributions of the different Hubble
types are given in a wide spectral range (1012-27000 Å)
and allow one to compute $K$ corrections for any other
photometric system.

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Table 2. Comparison models-observations for early-type galaxies; *=ellipticals only, without S0

<table>
<thead>
<tr>
<th></th>
<th>(U-V)</th>
<th>(V-K)</th>
<th>(J-K)</th>
<th>(J-H)</th>
<th>(H-K)</th>
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<td>Bower et al.:</td>
<td>Virgo</td>
<td>1.39</td>
<td>3.17</td>
<td>0.86</td>
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<tr>
<td></td>
<td>Coma</td>
<td>1.40</td>
<td>3.13</td>
<td>0.88</td>
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<tr>
<td>Persson et al.:</td>
<td>Campo</td>
<td>–</td>
<td>3.29</td>
<td>0.86</td>
<td>0.66</td>
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<tr>
<td></td>
<td>Virgo</td>
<td>–</td>
<td>3.22</td>
<td>0.86</td>
<td>0.65</td>
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<tr>
<td></td>
<td>Coma</td>
<td>–</td>
<td>3.19*</td>
<td></td>
<td></td>
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<tr>
<td>El1</td>
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<td>3.23</td>
<td>0.98</td>
<td>0.71</td>
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<td>0.79</td>
<td>0.57</td>
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Fig. 1. SEDs of 15 Gyr old models normalized at 5500 Å. From top to bottom (at 1000 Å): Sc (dotted line); Sa (short dashed line); E2 (long dashed line); E (solid line)

Fig. 2. SEDs of the elliptical model for 9 redshifts: 0, 0.1, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0
Fig. 3. SEDs of the Sa model for the same redshifts of Fig. 2

Fig. 4. SEDs of the Sc model for the same redshifts of Fig. 2
the elliptical with e-folding time 1 Gyr; the dotted line the elliptical with $\tau = 1.5$ Gyr (E2); the short dashed line refers to the Sa and the long dashed line to the Sc. In some cases the curves of the two ellipticals are superimposed and therefore indistinguishable.

**Fig. 16-23.** Rest frame and observer’s frame colour evolution: the former case is denoted by the “0” subscript. Symbols as in Figs. 2-12.