# Basic calibrations of the photographic RGU system

## IV. Metal-poor subgiant and giant stars

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**Abstract.** We present a large grid of theoretical color-absolute magnitude and two-color diagrams in the $RGU$ photometric system. The grid comprises wide ranges of stellar ages and physical parameters, and was computed using the YALE isochrones (Demarque et al. 1996) combined with the most recent version of the *B*asel *S*tellar *L*ibrary (hereafter $BaSeL$) of color-calibrated theoretical model-atmosphere flux distributions (Lejeune et al. 2000).

The present data provide a significant expansion of vital calibrations which are required for the full analysis of the new Basel three-color high-latitude field star survey of the Galaxy (Buser et al. 1998). In particular, they bring about, for the first time, the consistent determination of metallicities and metallicity-dependent absolute magnitudes for subgiant and giant stars from observed ultraviolet excesses, $\delta(U-G)_{G-R}$, and $G-R$ colors, respectively.

**Key words:** techniques: photometric – stars: abundances – stars: late-type

## 1. Introduction

The analysis and interpretation of the photographic $RGU$ data obtained in the new Basel high-latitude field star survey of the Galaxy (Buser et al. 1998, 1999, 2000a,b) require reliable calibrations, in terms of stellar metallicity [M/H], of the color-absolute magnitude and two-color relations for all major stellar evolutionary stages and population components. However, such calibrations have only been available for solar-abundance stars of the thin disk (Buser 1978a,b; Papers I & II, respectively) and for the lower-metallicity dwarfs of the thick disk and halo (Buser & Fenkart 1990, Paper III, hereafter BF90). Thus in this paper, we provide the necessary extension to the lower-metallicity subgiant and giant stars, which have turned out to make up a non-negligible contribution to the mix of stellar populations sampled in the star count and color distributions of the

new Basel $RGU$ survey (e.g., Güngör Ak et al. 1998, Buser et al. 1999, Karatas et al. 2000).

The intended reliable – and therefore useful – calibration has eventually become feasible through significant advancements in our knowledge of stellar evolution and atmospheres which have occurred in recent years. Most importantly, a growing inventory of comprehensive libraries of theoretical isochrones and spectra have been combined and exposed to increasingly rigorous observational tests, which in turn have allowed to better assess the systematic coherence and quality of our understanding of stellar properties in significant parts of the Hertzsprung-Russell diagram. In fact, even though it must be admitted that we are still far from matching many pertinent observations by theory in sufficient quantitative detail, *qualitative agreement* has however improved to such an extent as to amply justify the propagation of current astrophysical results through the wider contexts of stellar and galactic astronomy.

This paper provides what we believe to be a reasonable justification of this optimistic view of the present state of the art. In Sect. 2, we shall briefly review the new basic data used in this work: the $BaSeL$ stellar library of color-calibrated model-atmosphere spectra, which is then used to convert the *YALE* isochrones from theoretical quantities to observables. The color-absolute magnitude and two-color diagrams of the $RGU$ photometric system are exposed in turn in Sects. 3 and 4, whence we derive the calibration of the ultraviolet excess, $\delta(U-G)_{G-R}$, in terms of stellar metallicity, [M/H]. In the final Sect. 5, results will be further discussed in view of their application and impact on the determination of the larger-scale density, luminosity, and metallicity distributions of the Galactic stellar population components from the analysis of the new Basel $RGU$ high-latitude survey data.

## 2. Basic data

### 2.1. The Basel Stellar Library
###    of theoretical model-atmosphere spectra ($BaSeL$)

$BaSeL$ (Lejeune et al. 1997, 1998) was originally constructed by combining several modern grids of model-atmosphere spec-

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tra (Kurucz 1995; Bessell et al. 1989, 1991; Fluks et al. 1994; Allard & Hauschildt 1995) into a unified library of theoretical stellar flux distributions providing almost complete coverage of wavelengths, effective temperatures $T_{eff}$, surface gravities $logg$, and metallicities [M/H] observed in Galactic stars. Apart from being uniform and comprehensive, the main innovative property of the $BaSeL$ library is that its flux spectra have been systematically calibrated against empirical color-temperature relations derived from extant $UBVRIJHKL$ photometry data.

Applications of the new library in synthetic calibrations of Washington (Lejeune & Buser 1996) and Strömgren (Lastennet et al. 1999) photometry and in calculating integrated spectra and colors of globular clusters (Lejeune 1997, Bruzual et al. 1997) demonstrate that the photometric properties of the $BaSeL$ models carry sufficient systematic accuracy to be used to advantage in statistical analyses of survey data sampling wide ranges of physical stellar properties. The translation of theoretical isochrones to the observational systems by means of the $BaSeL$ stellar library has thus been taken up as a natural next step toward this goal.

### 2.2. The YALE isochrones

In their comparative study of theoretical isochrones of globular cluster giant branches, Lejeune & Buser (1999) have shown that among several modern grids available to date, the *YALE* isochrones (Demarque et al. 1996) are the only ones which provide systematically close matches with observational data at the typical old ages ($>\sim 10$ Gyr) of interest here, at all metallicities and luminosities, and in both the Johnson-Cousins and Washington photometric systems. In particular, agreement with the spectroscopic calibration of the metallicity parameters derived from the colors of the cluster RGBs at fixed absolute magnitudes (Da Costa & Armandroff 1990, Geisler & Sarajedini 1999) is excellent.

Thus, the *YALE* isochrones, as presented in Lejeune & Buser (1999) and as used here, vindicate the anticipated internal *systematic* consistency of the $BaSeL$ library for a large range of metallicities, and hence appear to be ideally suited for the intended metallicity calibration of the $RGU$ color-absolute magnitude and two-color diagrams.

## 3. The $(M(G), G - R)$ color-absolute magnitude diagram

Synthetic photometry data have been calculated from the $BaSeL$ library spectra employing the $R$, $G$, and $U$ passband functions and the zero-point constants of the $U - G, G - R$, and $G - V$ color scales evaluated from observed spectra of main-sequence stars in Paper I. The data thus also conform to the definition of the standard-$RGU$ system as given by Buser & Fenkart in Paper III, which will serve as the basic calibration reference for the present work.

The synthetic $RGU$ data were finally applied to the *YALE* isochrones for the metallicities listed in Table 1. For each of 25 ages between 1 Gyr and 25 Gyrs, isochrones for eight metallic-
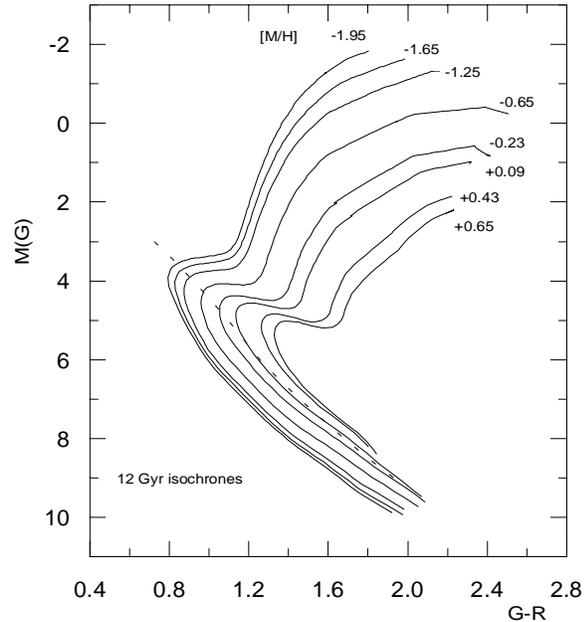


**Fig. 1.** Sample grid of 12-Gyr isochrones for different metallicities in the $(M(G), G - R)$ color-absolute magnitude diagram. The mean standard main sequence derived from observations (BF90) is plotted as a reference line (dashed).

**Table 1.** The *YALE* isochrones[1]

| Y | Z | [M/H] |
|------|--------|-------|
| 0.35 | 0.06 | +0.65 |
| 0.31 | 0.04 | +0.43 |
| 0.27 | 0.02 | +0.09 |
| 0.25 | 0.01 | -0.23 |
| 0.23 | 0.004 | -0.65 |
| 0.23 | 0.001 | -1.25 |
| 0.23 | 0.0004 | -1.65 |
| 0.23 | 0.0002 | -1.95 |

[1] For each metallicity, there are 25 isochrones for ages 1 Gyr through 25 Gyr.

ities were derived, covering all but the most extremely metal-poor or metal-rich stars observed in the Galaxy. A sample grid for an age of 12 Gyr is displayed in Fig. 1.

Several features are worth mentioning. First, there is excellent overall agreement between the slopes of the $[M/H] = +0.09$-isochrone and the standard main sequence, confirming (again) that the observed color-temperature scale is described accurately by the $G$ and $R$ passbands employed in the synthetic calculations. The remaining mismatches between the two relations are due to occasional small wiggles which are present at all metallicities and which are traceable to the original, discrete temperature calibration of the $BaSeL$ library spectra. Because this "noise" amplitude ($\sim 0.03$ mag) is in any case within the error bar of the standard relation, consistency between theory and observation is warranted. Note that the mean $RGU$ standard main sequence given by BF90 has originally been assumed to represent solar abundances (i.e., $[M/H] = 0.0$ dex), mainly because the good agreement with the model atmospheres used at
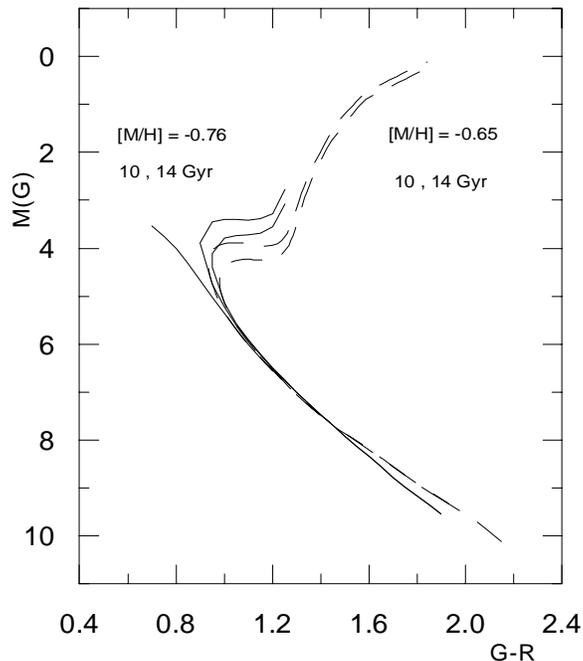
**Fig. 2.** Comparison of VandenBerg (1985) isochrones (solid lines) used by BF90 and the present *YALE* isochrones (long dashes) for similar metallicities but the same ages. While the two sets of isochrones have nearly coinciding main sequences – as should be expected for their metallicity difference of $|\Delta[M/H]| \sim 0.1$ dex –, their turnoff regions and subgiant branches differ significantly. The VandenBerg isochrones show brighter turnoff magnitudes at (slightly) bluer colors along with larger differences in absolute magnitudes between main sequence and subgiant stars of the same $G - R$ color.

the time (Buser & Kurucz 1978, 1992) did not strongly suggest a different solution. However, the BF90 standard main sequence is essentially based on transformations of the $UBV$ standard main sequence, which in turn is essentially determined by the Hyades stars (Johnson 1966). Thus, a more appropriate metallicity to be associated with either standard main sequence relation, in both $UBV$ and $RGU$, is that pertaining to the Hyades, i.e., $[M/H] = +0.08$ (Cameron 1985) – in agreement with Fig. 1, due to the improved $BaSeL$ model-atmosphere spectra. Henceforth, we shall adopt this ($[M/H] = +0.08$) rather than the solar ($[M/H] = 0.00$) value as the zero point of the dwarf–subgiant metallicity scales derived from the ultraviolet excess, $\delta(U - G)_{G-R}$, relative to the BF90 standard.

Second, differences between theoretical isochrones similar to those among the RGBs mentioned in Sect. 2.2. also seem to exist between the turnoff-subgiant regions in the present *YALE* isochrones and the VandenBerg (1985) isochrones used in the BF90 calibration paper. Fig. 2 shows a comparison for isochrones of similar metallicities at ages 10 and 14 Gyr, respectively. Although the two different sets are not immediately comparable in the same direct way as are the RGBs described by Lejeune & Buser (1999) – because the VandenBerg data were calculated for a Helium abundance Y=0.25 and were translated to $RGU$ observables via the BKLATE stellar library of Buser &

Kurucz (1992) –, these differences appear to be near the upper limit of the canonical uncertainties in current calculations of turnoff luminosities (VandenBerg et al. 1996). However, even though we probably still have to go a long way until independent determinations of globular cluster ages from isochrone fits will converge to conclusiveness, we shall adopt the present results obtained for the *YALE* isochrones, rather than the older VandenBerg data, for developping a more physically self-consistent treatment of the $RGU$ field-star survey data in this crucial area of the color-magnitude diagram.

Finally, Figs. 1 and 2 also illustrate the well-known facts that for RGB stars, the effect of stellar metallicity on both the color and the absolute magnitude is of paramount importance, whereas age effects are relatively minor or even negligible. This latter observation justifies that the metallicity calibration of the two-color diagram and its associated UV-excess parameter for giants will be set up, in Sect. 4 below, for a single (old) age, without loss of generality.

## 4. The $(U - G, G - R)$ two-color diagram and the metallicity parameter, $\delta(U - G)_{G-R,[M/H]}$

In this section, we shall first examine in some detail the morphology of the single-age (12 Gyr) isochrones in the two-color diagram. This will allow us to derive new calibrations, beyond the work of BF90, of the ultraviolet excess, $\delta(U - G)_{G-R,[M/H]}$, as a metallicity parameter for subgiants. Subsequently, we shall extend the calibration to the red giants.

### 4.1. Main sequence and subgiant stars

Fig. 3 shows a representative two-color diagram of the main sequences, turnoffs, and subgiant branches for some of the 12-Gyr isochrones displayed in Fig. 1. In each isochrone, the turnoff is the junction of the bluer main sequence (i.e., with lower $U - G$ colors) and the redder subgiant branch which, however, eventually crosses over the main sequence at redder $G - R$ colors. This pattern exhibited by the various curves clearly confirms the high metallicity sensitivity of the $U - G$ color index for either kind of stars. In fact, the ultraviolet-excess, $\delta(U - G)_{G-R,[M/H]} = (U - G)_{G-R,BF90} - (U - G)_{G-R,[M/H]}$, measured at given $G - R$ color and relative to the reference line from BF90, has been used as a metallicity parameter for deriving estimates of [M/H].

However obviously, in addition to the dependence of the ultraviolet excess on the $G-R$ color (or effective temperature) – which was accounted for by BF90 in setting up their calibration for the main sequence stars –, the relations between $\delta(U - G)_{G-R}$ and [M/H] are also *different* for dwarfs and subgiants. Differences in the ultraviolet excess which are essentially due to the lower surface gravities in subgiants, may be of order 0.1 mag and may lead, in the absence of knowledge of a star's evolutionary stage, to derived metallicities which are wrong by up to 0.5 dex.

This luminosity (or surface gravity, or evolutionary) effect is quantified in Fig. 4. From the metal-poor 12-Gyr
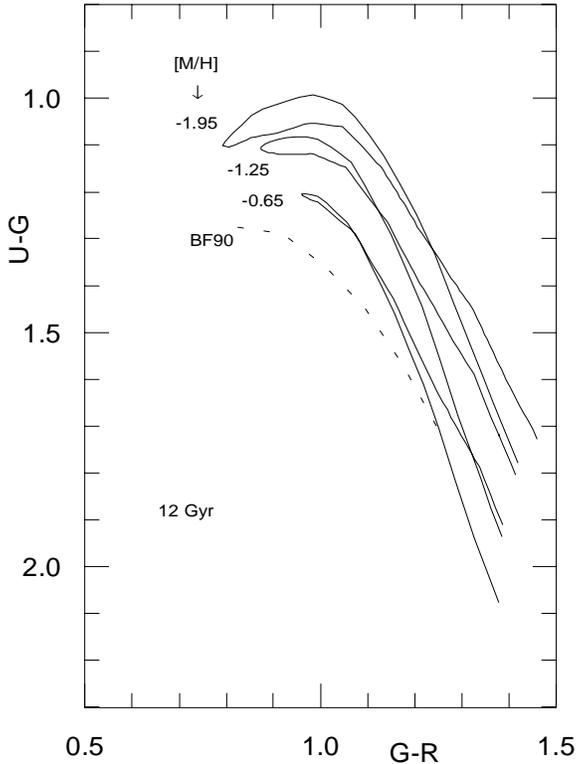
**Fig. 3.** The $U-G$, $G-R$ two-color diagram for the main sequences and the subgiant branches of 12-Gyr isochrones for different metallicities. Note that the ultraviolet excesses, $\delta(U-G)_{G-R,[M/H]}$, are different functions of [M/H] for main sequence stars and subgiants of the same age and metallicity, and are also different at the different reference colors $(G-R)$. These differences between dwarfs and subgiants are measurable on the 0.05–0.10 mag level and may imply differences in derived [M/H] of up to 0.5 dex.
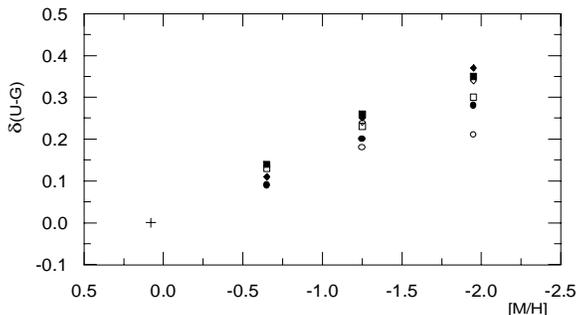


**Fig. 4.** The ultraviolet excesses, $\delta(U-G)_{G-R}$, as functions of metallicity, [M/H], for dwarfs (filled symbols) and subgiants (open symbols), respectively, derived from the metal-poor isochrones in Fig. 3 at three values of $G-R$ color: 0.9 (circles), 1.0 (squares), and 1.1 (diamonds). The cross marks the BF90 reference line at metallicity $[M/H] = +0.08$ dex.

isochrones, $\delta(U-G)_{G-R}$ have been measured for the main sequences and the subgiant branches, respectively, at $(G-R) \in \{0.9, 1.0, 1.1\}$, and have been plotted as functions of [M/H].

Note that in actual practice, diagrams similar to Figs. 3 and 4 are derived for a range of isochrone ages, according to the
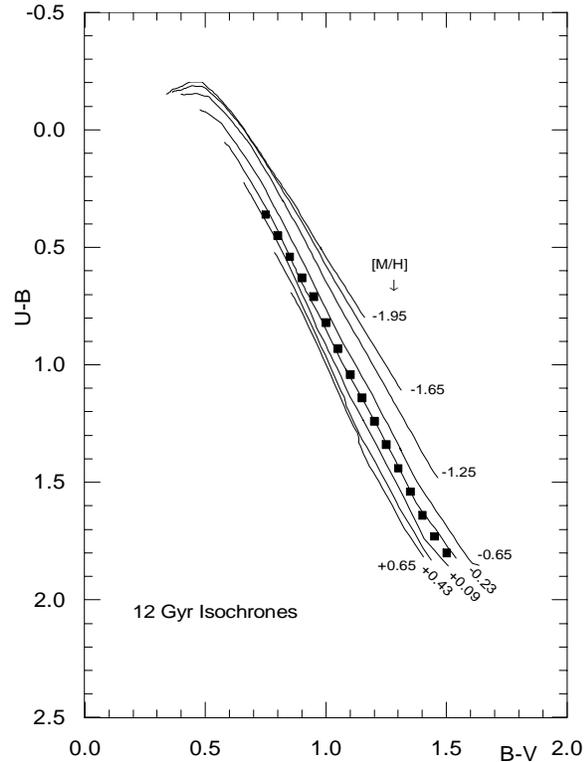


**Fig. 5.** The theoretical $U - B$, $B - V$ two-color diagram for the giant branches of 12-Gyr isochrones for different metallicities (labels). The mean two-color relation for normal Population I field giants from Buser & Kurucz (1992) is represented by the filled squares. Compare with the observational counterpart in Fig. 6.

particular morphology of the observed two-color distribution of the stars. If combined with assumptions about the luminosity functions for the different stellar population components contributing to the survey stars, both their space distribution (*via* the metallicity-dependent $(M(G), G - R)$ color-absolute magnitude calibration) and their metallicity distribution (*via* the metallicity calibration of the ultraviolet excess $\delta(U - G)_{G-R,[M/H]}$) can be derived in a statistically consistent manner.

### 4.2. Giant stars

The red giant (and subgiant) branches of the 12-Gyr isochrones are plotted in the $UBV$ two-color diagram of Fig. 5 for the full range of available metallicities, $+0.65 \geq [M/H] \geq -1.95$. This figure as well as the corresponding $(M(G), G - R)$ color-absolute magnitude diagram of Fig. 1 include only temperatures $T_{eff} > \sim 3800\,K$ but exclude models for the cooler M stars, whose photometric properties both in $UBV$ and $RGU$ still need further study before they can be used for calibration purposes on a similarly reliable confidence level. To illustrate the quality of the theoretical data, they are compared with the mean intrinsic colors of normal Population I field giants of luminosity class III derived by Buser & Kurucz (1992) from published standard-observed relations. Although in the range $0.9 <\sim B - V <\sim 1.2$ the model lines appear to have slightly too red $U - B$ colors,
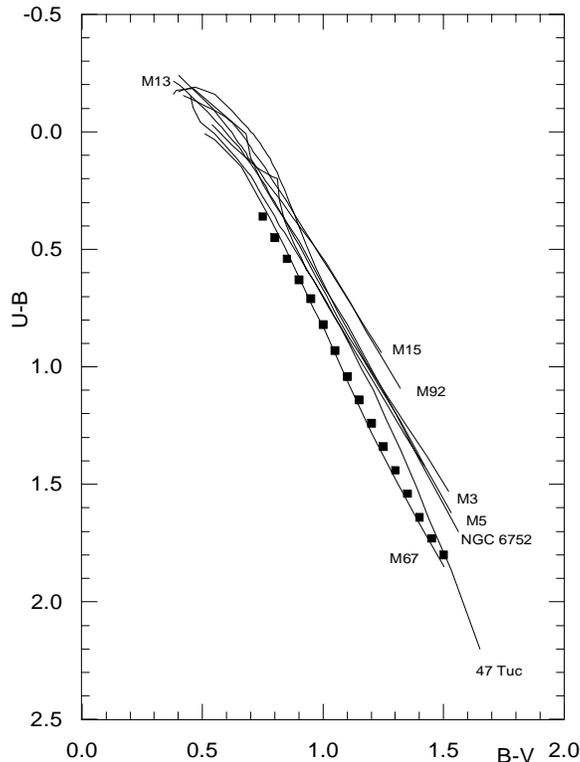
**Fig. 6.** The observed $U - B, B - V$ two-color diagram for the giant (-subgiant) branches of Galactic open and globular clusters covering a range of metallicities similar to that in Fig. 5. The mean intrinsic locus of solar-abundance field giants from Buser & Kurucz (1992) is plotted as a reference line (filled squares). Compare with the theoretical counterpart in Fig. 5.



**Fig. 7.** The $U - G, G - R$ two-color diagram for the giant branches of 12-Gyr isochrones for different metallicities (labels). The reference line (filled squares) is the same as in Figs. 5 and 6, but transformed from $UBV$ to $RGU$ *via* the transformation equations derived by Buser (1988). Extension to the bluer subgiants (filled dots) is based on synthetic $RGU$ photometry data calculated from observed spectra. Note the large amplitude of the ultraviolet excess, $\delta(U - G)_{1.6}$, measured at $G - R = 1.6$, as a function of [M/H].

or else too blue $B - V$ colors by perhaps $\sim 0.03$ mag, the overall agreement is excellent. This fact is all the more appreciable from comparison of Fig. 5 with the observed isochrones of Galactic globular clusters shown in Fig. 6, which cover the metallicity range from near solar (M67) down to $< \sim -2$. Despite the rather nonuniform shapes and separations of the observed isochrones in this $U - B, B - V$ two-color diagram[1], both the position and extent of the area occupied by them are very well reproduced by the model calculations of Fig. 5. In particular, the observed ultraviolet excess, $\delta(U - B)_{B-V=1.0}$, is closely matched by the theoretical isochrones, and thus provides a metallicity scale in good agreement with existing spectroscopic and photometric calibrations (cf. Buser & Kurucz 1992).

The $RGU$-analog to Fig. 5 is given in Fig. 7. The same line for normal Population I giants – transformed from $UBV$ *via* the bilinear equations derived by Buser (1988) and extended through the subgiant domain by direct synthetic photometry calculated from observed spectra – is again included for reference. While the similarities between the $UBV$ and $RGU$ photomet-

ric systems are obvious[2], two important differences should be pointed out. First, the agreement between theory and the observational reference is excellent for the hotter part of the diagram, $U - G < \sim 2.9$, while it deteriorates for the cooler giants, most notably at $G - R > \sim 1.8$, where the models are probably too red. This trend, which is more pronounced than the opposite trend to the blue in $UBV$ but which is also present in $V - I$, continues in an entangled manner through the M-star domain and is likely traceable to the fact that unique, or even uniform, empirical color calibrations for such stars are in any event still extremely uncertain and may even be altogether questionable, because most M stars are, indeed, variable (Lejeune et al. 1997, Schaerer & Lejeune 1999).

The second notable difference, which is of primary importance to the context of this paper and its applications, is the substantially larger amplitude of the $RGU$ ultraviolet excess, $\delta(U - G)_{G-R=1.6}$, as a function of [M/H]. The reference color, $G - R = 1.6$, is chosen such as to allow old stars on the RGB to be sampled at all metallicities (cf. Fig. 1), yet without inter-

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[1]  Incidentally, this considerable irregularity illustrates well the great difficulties in obtaining reliable *and* homogeneous UBV photometry data – both from either the extant literature or from actual new observations – that may be used to calibrate theoretical models.
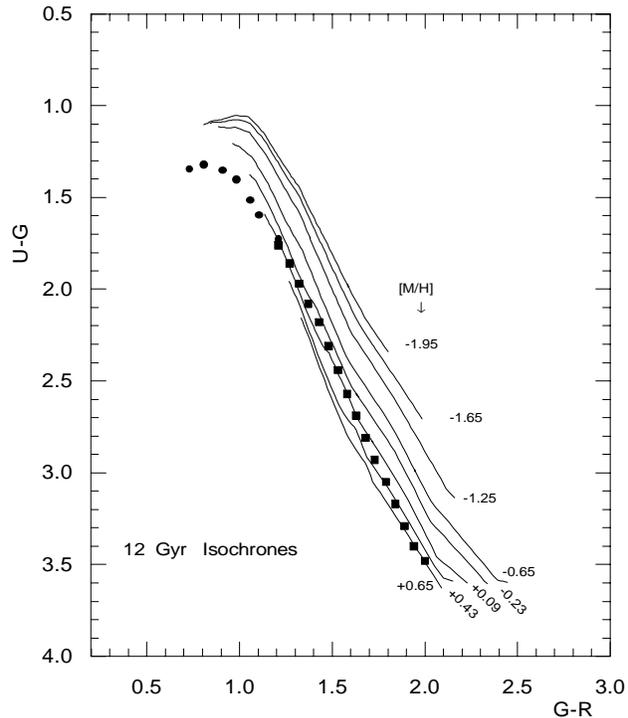
[2]  It is perhaps worth emphasizing here again that this similarity, or near-equivalence, of the two systems is crucial to the existence of well-behaved, and therefore useful, transformations that allow of an efficient *combination* of the particular performances intrinsic to either photometric system.
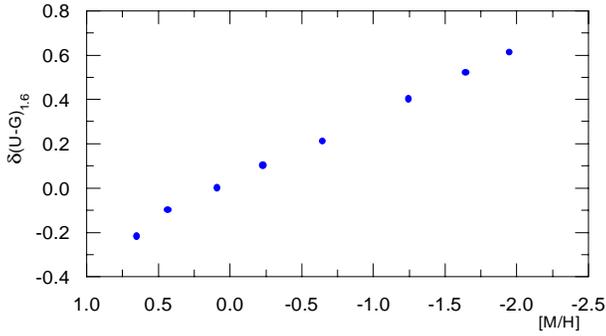
**Fig. 8.** The ultraviolet excess for giants, $\delta(U-G)_{1.6}$, as a function of metallicity, [M/H], and as derived from the 12-Gyr isochrones in Fig. 7.

ference by M-stars, whose photometric properties, as we have seen, cannot yet be modelled comprehensively and with similar confidence. As evidenced in Fig. 8, derived for the 12-Gyr isochrones relative to the standard-observed reference in Fig. 7, $\delta(U-G)_{1.6}$ rises linearly to a value near $0.6$ mag for a decrease in metallicity by 2 dex down to $[M/H] = -2$. This metallicity sensitivity is a factor 1.5 larger than for the corresponding $\delta(U-B)_{1.0}$, and may, in fact, be decisive for the success of applied (photographic) $RGU$ photometry in pinning down the metallicity distribution of the old evolved metal-poorer stellar populations in the Galaxy.

## 5. Implementation and further development

The full complement of synthetic $RGU$ and $UBV$ photometry data presented here are available for 200 $YALE$ isochrones as electronic tables. They allow of flexible multiple uses both with existing computer codes and for developping innovative analysis tools for a yet more penetrating exploitation of the observations.

At this stage, they provide significant improvements of basic input to the ongoing analysis of the observations obtained in the new Basel $RGU$ survey of the Galaxy (Buser et al. 1998). Detailed *and* comprehensive modelling of the metallicity-dependent color-absolute magnitude and two-color relations was shown to have to be developed to capabilities well superior to previous ones, if, for example, the metallicity distribution of the Galactic thick disk was to be derived to within good enough systematic accuracy to allow discrimination of formation theories (Buser et al. 1999). The capabilities which are provided by, and which are to be further developed from, the present new data may indeed prove to be strong enough to eventually satisfy this requirement.

In particular, since the present $RGU$ and $UBV$ data are based on the $BaSeL$ spectra, they will naturally share in any improvement apported by the independent further developpment of this source library. For example, a more comprehensive and systematic study of observed $UBV$ and other ultraviolet stellar data is underway (Westera et al. 1999), whose goal is to improve the accuracy of the calibration of the $BaSeL$ library spectra to

a *uniform* level of 0.02 mag at all temperatures, luminosities, and metallicities. If successful, this progress will naturally entail a corresponding improvement and further extension of the theoretical calibrations of the $RGU$ system.

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