APPLICATIONS OF THE $UB_1B_2V_1G$ PHOTOMETRIC SYSTEM

M. GOLAY

Observatoire de Genève, Genève, Switzerland

Abstract. This photometric system which was described for the first time in 1963 by Golay has been in use at the Geneva Observatory since 1959. We are involved in a long term observational programme having as objective the study of cluster stars, peculiar stars and interstellar extinction. This research aims at the determination of physical parameters such as effective temperature, gravity, abundance, or those of spectral type, absolute magnitude, [Fe/H]. To permit such an analysis the photometric effects of rotation, of multiplicity and of interstellar extinction were given particular attention. Attempting to attain the above mentioned purposes, we have had to give great care to the precision of the measurements during their acquisition as also during their reduction. Finally, in view of allowing a valid comparison between observations and the theory of stellar atmospheres, particular care had to be given to the maintenance of the pass-bands and to the knowledge of their form.

We intend here to give the main bibliographical references relative to the articles which present the general properties of the system, its applications and the catalogues.

1. Pass-Bands and Catalogue

The pass-bands adopted in 1959 have been analysed by Rufener and Maeder (1971a) by means of an original method based on the observations in the 7 colours $UBVB_1B_2$ V_1G of stars whose energy distribution as a function of wavelength is particularly well known. The filters U, B and V are similar to those of the usual U, B, V system. On the other hand, the filters B_1, B_2, V_1, G have pass-bands width approximately equal to half those of filters B and V. The mean wavelengths of the system are

	U	B	V	B_1	B_2	V_1	G
λ_0 (Å)	3456	4245	5500	4024	4480	5405	5805

The response curves are given with a step of 50 Å.

About 1500 stars are published in the last edition of the catalogue prepared by Rufener (1971), and more than 2500 will be published in the next edition which is now being prepared. This catalogue will also contain 250 stars of the southern sky. The latest edition contains a table giving the standard deviations as a function of the weight published for each series of magnitude measurements made in the 7 colours. The most frequent weight is $P = 3$, which gives the following standard deviations (in thousandths of a magnitude):

σU	σB	σV	σB_1	σB_2	σV_1	σG
6.1	3.2	3.9	3.2	3.3	3.7	4.4

Ch. Fehrenbach and B. E. Westerlund (eds.), Spectral Classification and Multicolour Photometry, 145–151. *All Rights Reserved. Copyright © 1973 by the IAU.*

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

2. System of Apparent [V] Magnitudes

The next edition of the photometric catalogue will also contain the apparent [V] magnitudes. We use square brackets for the [U], [B] and [V] magnitudes or [$U-B$], [$B-V$] indices obtained with the pass-bands described above so as to distinguish them from Johnson's U, B, V, $(U-B)$, $(B-V)$ system. Actually, the [V] magnitudes are very similar to the V magnitudes. Let us point out that the two systems V and [V] are independent and that our [V] measurements do not result through the application of a transformation formula. The method used consists in treating differential magnitude measurements by the method of least squares; the resulting sequence is then reduced to the V standard scale by means of one point only ($[V]=V=5.450$ for the star HD 23288). The method and its application to the Praesepe and Pleiades clusters have been published by Rufener and Maeder (1971b). The standard deviation $\sigma_{[V]}$ for these two clusters reaches 0.006.

3. General Properties of the $UB_1B_2V_1G$ System

Here, we only mention a few of the publications devoted to the examination of our photometric system's properties. Let us begin by pointing out that the published catalogues give the 7 colours relative to colour B. In the applications, we use various indices and linear combinations of indices. These are:

$$B_2 - V_1$$
$$[d] = (U - B_1) - 1{,}430\,(B_1 - B_2) + \varepsilon d$$
$$[\Delta] = (U - B_2) - 0{,}832\,(B_2 - G) + \varepsilon\Delta$$
$$[g] = (B_1 - B_2) - 1{,}357\,(V_1 - G) + \varepsilon g$$
$$[m_2] = (B_1 - B_2) - 0{,}69\,(B_2 - V_1) + \varepsilon m\,.$$

The first 4, $[B_2-V_1]$, $[d]$, $[\Delta]$, $[g]$ are studied particularly by Golay (1972). The coefficients are chosen to obtain parameters which are weakly dependant on interstellar extinction. The corrective terms ε are there to eliminate the residual effects of interstellar extinction by relying on an approximate knowledge of the star's spectral type, of its luminosity class and of the interstellar extinction law. The parameter $[m_2]$ defined by Hauck (1968), together with $[d]$ and $[B_2-V_1]$ allows a three dimensional representation of A0 to G5 stars which gives account of effective temperature, luminosity and blocking by metallic lines. The parameters $[m_2]$ and $[g]$ measure blocking by lines situated in the interval 3800–4800 Å. The parameters $[d]$ and $[\Delta]$ measure the Balmer discontinuity, $[d]$ in a manner weakly dependant on blocking in the above mentioned interval, $[\Delta]$, on the other hand, is sensitive to the importance of this blocking. The relation between $[d]$ and $[\Delta]$ thus allows us to obtain a stellar classification in spectral type and luminosity class as well as some indications concerning certain spectral peculiarities. When we add the intrinsic colour indice $[B_2-V_1]_0$ (which is practically independant of blocking between A0 and G5) to this $[d]$ vs $[\Delta]$

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

diagram, a three dimensional representation of stars becomes possible. Figure 1 illustrates the properties of the $[d]$ vs $[\Delta]$ diagram. A great number of other diagrams can be constructed, for example $[d]$, $[g]$, $[\Delta]$, $[m_2]$ vs $[B_2 - V_1]$. The calibrations obtained for these diagrams in terms of effective temperature, [Fe/H], Mv, rotational velocity, have been published by Golay (1969). The photometric aspects of Ap, Am, AVI peculiar stars have been studied by Golay (1972) and by Hauck (1971a). Hauck (1971b) has shown that the positions of δ Scuti stars in a photometric diagram agree better with those of luminosity class IV rather than with those of Am stars. Figure 1 shows that supergiants hotter than A2 occupy a long and narrow band in the $[d]/[\Delta]$ diagram. The position of a star along this band depends on the importance of the Balmer discontinuity. On the other hand ,the $[d]$, $[\Delta]$ diagram is ambiguous for supergiants cooler than A3, wheras the $[d]$, $[B_2 - V_1]_0$ diagram allows a good separation of supergiants. Moreover, again according to Hauck and Nicollier (Goy, 1971b), the separation of hot dwarf stars with emission lines from supergiants appears clearly in $[d]$ vs $[\Delta]$.

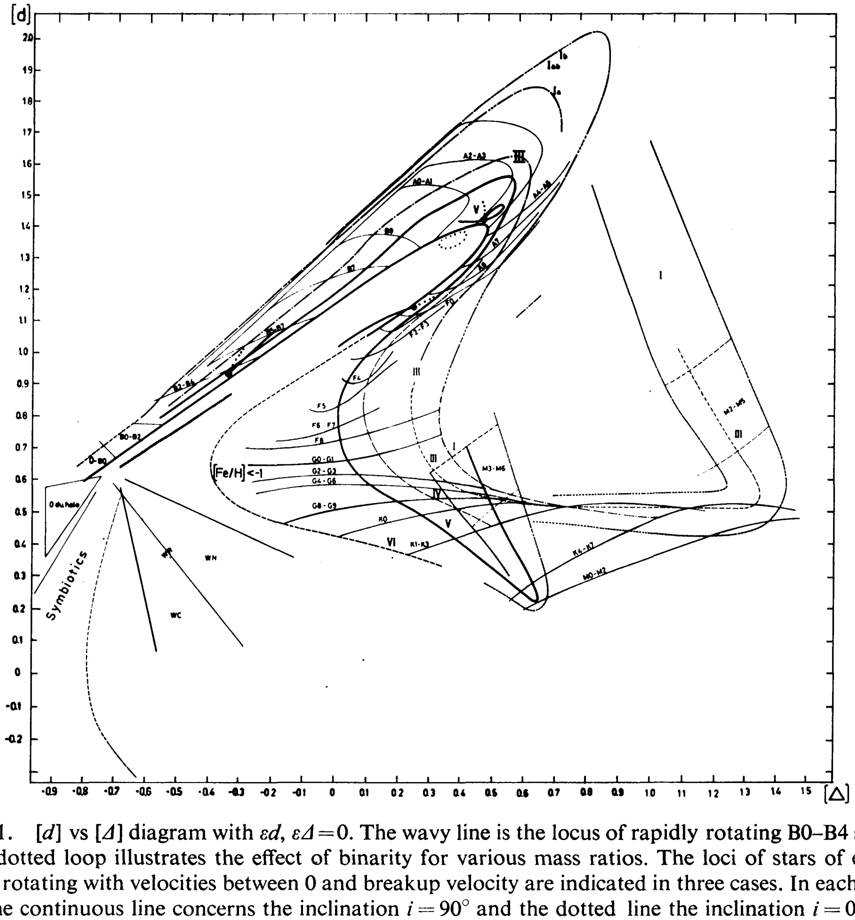

Fig. 1. $[d]$ vs $[\Delta]$ diagram with εd, $\varepsilon \Delta = 0$. The wavy line is the locus of rapidly rotating B0–B4 stars. The dotted loop illustrates the effect of binarity for various mass ratios. The loci of stars of equal mass rotating with velocities between 0 and breakup velocity are indicated in three cases. In each case the continuous line concerns the inclination $i = 90°$ and the dotted line the inclination $i = 0°$.

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

The $[d]$ vs $[\Delta]$ diagram illustrates the positions occupied by O, Wolf-Rayet, symbiotic stars. The analysis of the colours of reddened O stars and the determination of the individual interstellar extinction laws which lead to the observed values of reddening is carried out by Goy (1971a, b). The study of strongly reddened galactic clusters suggests a relationship between the density of interstellar matter and the form of the extinction law.

4. Stellar Models

In view of determining effective temperatures, gravities and abundances for F and G stars, mainly by means of information obtained in our 7 colours, Peytremann (1970) has developed stellar atmosphere models which include the opacities of metallic lines. He has computed a grid of model atmospheres with effective temperatures between 5000 K and 8500 K and gravities between $\log g = 2$ and 4.5. Various metal abundances relative to the Sun have been considered, namely $\sim 0 - 0.1 - 1$. The distribution of abundances is that of the Sun. The velocity of microturbulence was chosen equal to 2 km s^{-1}. Except for the treatment of the lines, the models are classic. The atmospheres are in radiative and convective equilibrium; the convective flux is computed with a ratio of mixing length to scale height of $l/H = 1$. These models are frequently used to analyse the various diagrams of the $UBVB_1B_2V_1G$ photometry. Other models have been used by Maeder and Peytremann to study the photometric effects of rotation. The models used are based on those of Kurucz (Harvard College Observatory) and take into account the hydrogen lines of the Balmer and Lyman series. The surface of the star is divided into several zones having each an effective temperature and a gravity: the models were established for three masses ($5M_{\odot}$, $2M_{\odot}$, 1.4 $M_{\odot}$) and 4 values of rotation (expressed in fractions of breakup velocity) $\omega = 0$, 0.5, 0.8, 0.9, 0.99. Six values of inclination were considered for each velocity. These models were compared with photometric observations of the effects of rotation (Golay, 1968) and were found to be in agreement with these for stars hotter than A7–F0 (except for the interval B0–B3). Beyond F0, it seems necessary to introduce non-uniformly rotating models. The photometric effects of rotation are illustrated in the $[d]$ vs $[\Delta]$ diagram of Figure 1. Maeder (1971) has particularly examined the effect of rotation on the age determination of 7 galactic clusters measured in the $UBVB_1B_2V_1G$ system. He has shown that neglecting rotational effects can lead to overestimations of age reaching 70%. In the same article, Maeder shows that the correcting of the colour indices $B_2 - V_1$ for effects due to rotation depends of the product $v \sin i$.

5. Stellar Classification

The $[d]$ vs $[\Delta]$ diagram of Figure 1 contains the loci of equal MK spectral type and of equal luminosity class. By considering the intrinsic colour index $(B_2 - V_1)_0$, we find that it is possible to extend this representation to cool stars (according to Grenon, 1972). Stars of MK class are distributed on a nondevelopable surface in the 3-dimensional representation $[d]$, $[\Delta]$, $(B_2 - V_1)_0$. According to Golay (1972), peculiar stars

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

lie outside this surface, either above, or below (or within the knee between B9–A9). Only those of much attenuated peculiarity are close to the surface. A fourth dimension with the indice $(V_1-G)_0$ is of great interest for the classification of cool stars. In the spectral interval O–G8, two stars having the same position in the $[d]$, $[\Delta]$, (B_2-V_1) space have also the same 'pseudo-continuum'. We call 'pseudo-continuum' the representation obtained by plotting the monochromatic magnitudes derived from the U, B, V, B_1, B_2, V_1, G, heterochromatic magnitudes as a function of the corresponding effective wavelengths. The spectral energy distribution of a star is then given by a polygonal line (the process and its application are described by Golay (1971, 1972)). The comparison of the pseudo-continua of stars reddened by interstellar matter leads to the study of the difference between extinction laws. The comparison of pseudo-continua of non reddened stars helps to locate the pass-band (or bands) coinciding with the phenomenon responsible for differing positions in the $[d]$, $[\Delta]$, (B_2-V_1) diagram. Finally, the comparison of pseudo-continua of stars of same spectral type but having different rotational velocities allows the study of photometric effects due to rotation (according to Golay (1968, 1972)). Thanks to the great number of stars measured accurately in the U, B, V, B_1, B_2, V_1, G, system, it is possible to seek out the stars for which the 6 colours relative to G do not differ by more than an arbitrary value δ. This work was first done by Golay *et al.* (1969) and is resumed for each new extension of the catalogue. The computer scans the whole catalogue and separates the stars into natural groups. This grouping has been carried out for 3 values of δ: $\delta=0.01$ mag., $\delta=0.02$ and $\delta=0.05$. It is interesting to point out for $\delta=0.01$, the stars of the same group (2 to 3 stars per group and over 100 possible groups) always have the same spectral type and the same luminosity class. The few discrepancies encountered disappeared when we got a better classification from the spectroscopists. The same applies to peculiarity, Am characteristics or peculiar lines. For Am stars, as an example, if we have access to a classification which distinguishes marginal Am stars from typically Am stars (Cowley *et al.*, 1969), stars of a given group are either all marginal or all Am. This still applies when of Cowley *et al.* (1969) add the indices *s*; all the stars of the group also share this caracteristic. When we consider $\delta=0.02$, it is clear that the groups contain a greater number of members and that the identity of spectroscopic characteristics is no longer as sharply defined as for $\delta=0.01$. When present, the Am characteristic is the one most frequently common to all stars of the group. It sometimes coexists with an Ap type. By searching in literature, it has almost always been possible to find a peculiarity for the stars of a group which contains at least one star recognized as an Ap. It then appears that the different characteristics Am, Ap, can be distinguished from stars of MK class by characteristic deviations of the pseudo-continua of at least 0.02 mag. in one, or in several colours.

Let us go back to Figure 1. We notice that the main sequence stars between B9 and A5 are widely dispersed. According to the calibration of the $[d]$ vs $[\Delta]$ diagram as described in Golay (1972) and reproduced in Golay (1971) (calibration based on models by Mihalas with blocking by hydrogen lines), this dispersion is equivalent to a dispersion in $\log g$ of 4.2 to 3.5. Photometric effects due to rotation can also be a cause

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

of dispersion in this rather complicated region of the $[d]$ vs $[\Delta]$ diagram. Such effects would nevertheless explain but half of the observed dispersion. Photometric effects of binarity of a few stars would not suffice either to explain this dispersion. A-type stars recognized as being magnetic show a dispersion of the same order (but are less uniformly distributed and seem to be more concentrated on the line of highest gravities). It still remains to be proved that the observed dispersion (which also appears in Chalonge's D, λ_1 spectrophotometry) is only an effect due to gravity which is not detectable in the MK classification.

Figure 2 illustrates the position of Am and Am: (marginal Am) stars classified by Cowley *et al.* (1969). We now see, as was not the case in the earlier spectral classifications of Am stars, that marginal metallic stars are clearly separable from typically metallic stars.

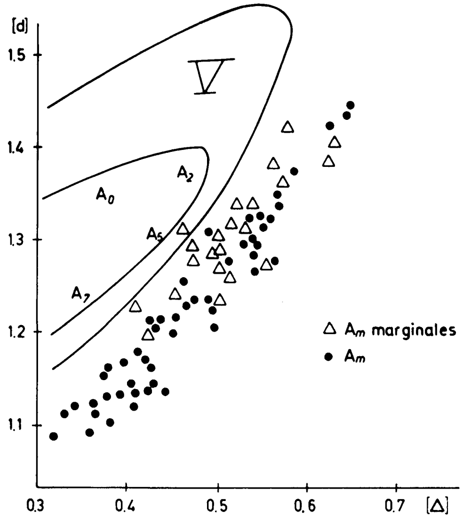

Fig. 2. [d] vs [Δ] diagram of Am stars.

6. Variability

In 10 yr of continued observations, numerous stars used as standards have been measured a great number of times. We have shown in (Golay, 1972) that the parameter $[g]$ is an indicator of absolute magnitude, for hot stars, comparable to β of the u, v, b, y, β photometry, and that $[d]$ is an indicator of temperature. The $[g]$ vs $[d]$ diagram thus appears as an Hertzsprung-Russell diagram for hot stars. Maeder and Rufener (1972) have shown that σ, the indicator of quality used by Rufener (1971) to characterize a series of measurements in 7 colours, is often unusually large for a whole group of stellar types which are situated in the hatched region of the diagram in Figure 3. This region coincides with that where the phenomenon of mass-loss is to be expected. A similar diagram can be made for cooler stars. The parameter $[d]$ is then an indicator

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press

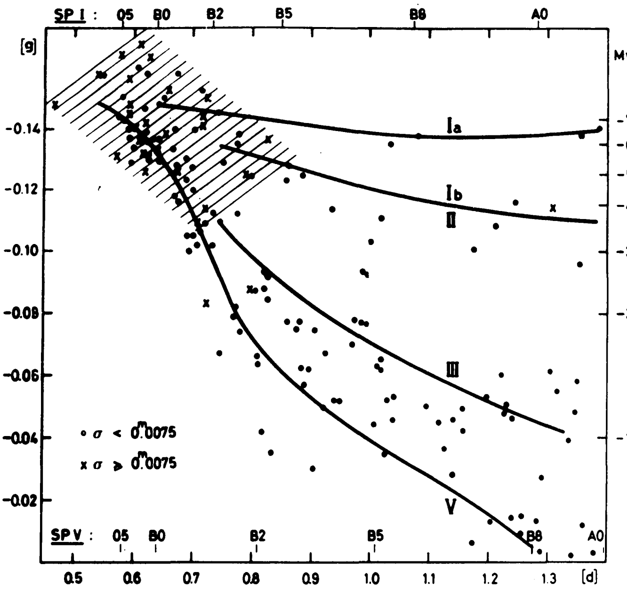

Fig. 3. [g] vs [d] diagram of hot stars. σ designates the indicator of quality of the 7 colour measurements. Figure taken from Meader and Rufener (1972).

of absolute magnitude and $(B_2 - V_1)_0$ an indicator of temperature. There also, the indicator of quality σ is distinctly more important for certain supergiants and suggests the existence of microvariability.

References

Cowley, A., Cowley, C., Jascheck, M., and Jascheck, C.: 1969, *Astron. J.* **74**, 375.

Golay, M.: 1963, *Publ. Obs. Genève* **A64**, 419.

Golay, M.: 1968, *Publ. Obs. Genève* **75**, 105.

Golay, M.: 1969, in Owen Gingerich (ed.), *Seven Color Photometry in Theory and Observation of Normal Stellar Atmospheres*, MIT Press.

Golay, M.: 1971, in L. N. Mavridis (ed.), *Structure and Evolution of the Galaxy*, D. Reidel Publishing Company, p. 34.

Golay, M.: 1972, *Vistas in Astronomy* **14**, in press.

Golay, M., Peytremann, E., and Maeder, A.: 1969, *Publ. Obs. Genève* **76**.

Goy, G.: 1971, *Publ. Obs. Genève*, **A78**.

Goy, G.: 1972, in press.

Goy, G. and Maeder, A.: 1969, *Publ. Obs. Genève* **78**.

Grenon, M.: 1972, *Obs. Genève*, in preparation.

Hauck, B.: 1968, *Publ. Obs. Genève* **75**.

Hauck, B.: 1971a, *Conferenze Dell'Osservatorio Astronomico di Milano-Merate*, Series 1, No. 12.

Hauck, B.: 1971b, *Astron. Astrophys.* **11**, 79.

Maeder, A.: 1971, *Astron. Astrophys.* **10**, 354.

Maeder, A. and Rufener, F.: 1972, *Obs. Genève*, in preparation.

Peytremann, E.: 1970, Thesis, Université de Genève.

Rufener, F.: 1971, *Astron. Astrophys. Suppl.* **3**, 181.

Rufener, F. and Maeder, A.: 1971a, *Astron. Astrophys. Suppl.* **4**, 43.

Rufener, F. and Maeder, A.: 1971b, *Publ. Obs. Genève*, **A78**.

https://doi.org/10.1017/S0074180900099216 Published online by Cambridge University Press