OBSERVED STELLAR ENERGY DISTRIBUTIONS FOR SYNTHETIC PHOTOMETRY

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ABSTRACT. *Observed stellar energy distributions are used in synthetic photometry to evaluate the accuracy of the response functions and to determine the transformation coefficients. The characteristics required of a catalog of energy distributions to be used for synthetic photometry are discussed, and the catalogs found in the literature are reviewed.*

1. INTRODUCTION

Synthetic photometry is a powerful technique for calibrating and evaluating the performance of photometric systems, evaluating model stellar atmospheres, and for doing photometry using spectral data when direct measurements do not exist or are impossible. The key is in having response functions for each filter-detector-optical train combination which accurately describe the behavior of the photometer at the telescope. Once the response functions have been determined, their correctness may be evaluated by calculating synthetic colors using observed energy distributions for representative objects of the correct type, and comparing the calculated color with observed ones. Additionally, when the response functions are used, one requires transformation coefficients to calculate magnitudes and colors in the photometric system from the "instrumental" ones. These transformation coefficients are best determined from synthetic photometry of well-determined observed energy distributions.

2. CHARACTERISTICS OF ENERGY DISTRIBUTIONS FOR SYNTHETIC PHOTOMETRY

Three characteristics of the energy distributions will be considered here: a) their systematic accuracy; b) their need to be continuous,

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and c) their membership in a catalog covering a suitable range of spectral types, luminosity clases, and so forth. The degree of success of the use of observed energy distributions to evaluate response functions is determined by their systematic accuracy. The precision of each resolution element is, of itself, not so important if the passband being integrated includes enough resolution elements. The systematic accuracy of the energy distributions is determined by: a) the relative spectrophotmetry (instrumental effects, observing technique, stability of atmospheric transparency), b) the accuracy with which the atmospheric extinction is determined (the importance of which is determined by the spread in airmass between program and standard stars), and c) the systematic accuracy of the energy distributions of the standard stars. In the past, the measurement of energy distributions sufficiently free of systematic errors for this purpose has been difficult because of the use of sequential photoelectric "scanners". These instruments are very sensitive to changes in the sky transparency during a scan. Also, they are so slow that the temptation (and, indeed the practice) is to slight the measurement of standard stars and extinction. These problems are ameliorated by the use of array detectors such as reticons and CCD's on low-dispersion spectrometers. Firstly, because all wavelengths are measured at the same time, the problem of transparency changes during a scan disappears. Secondly, they are usually so much faster that one has less difficulty doing justice to standard stars and extinction measurements. On the other hand, there is the temptation (and again, indeed, the practice) to assume that if you only want colors, and if the extinction of clouds is gray (probably true, for thin clouds), that you can safely observe when the sky is not photometric. This may not be true because of a changing background which is significant compared to the stars. In any case, the other principles of good photometry apply: the program and standard stars must be measured at as nearly the same airmass as possible, and as the spread in airmass increases, the atmospheric extinction must be increasingly well determined. Care must be taken when the background varies with time (moonlight or twilight).

Another characteristic which must be considered is that the energy distributions must be continuous. This may seem obvious, but it is worth noting because a major part of the better-quality energy distributions to be found in the literature are not continuous. The data are given for lists of wavelengths the same as, or similar to, that used by Oke (1964), which is a set of wavelengths chosen to measure the continuum in early-type stars. The adoption of this set of wavelengths was given impetus by the absolute calibrations of Vega by Hayes (1970) and by Oke and Schild (1970). Catalogs of energy distributions, reduced to the absolute calibration of Vega by Hayes and Latham (1975) have been published by Breger (1976) and by Ardeberg and Virdefors (1980). Other worthwhile data have been published since the latter catalog. Among these data may be found some of excellent photometric quality. Catalogs of data taken at the Oke wavelength sets, or at other non-continuous wavelength sets, will not be discussed further here because they do not sample the line blocking fully.

In addition to needing to be continuous and having good photometric quality, the catalog of energy distributions to be used for synthetic photometry must include the full range of spectral types, luminosity classes, metallicity, and reddening that the photometric system was designed to cover. Ideally, the catalog of energy distributions will include the standard stars of the system; in practice, this is rarely the case. If too narrow a range of spectral type, or other relevant parameter, is covered, there is the danger that the transformation equations will be biased by any non-linearities present, or by observational errors.

Finally, and obviously, all of the stars for which energy distributions are known must be well-measured in the photometric system to be investigated. Although this criterion is an obvious one, it is so rarely met that substitute measures have often been taken. Because many of the energy distributions in the literature have, until recently, been measured in the Oke wavelength set, or something similar, and many of the stars have not had good photometric measures, even in the UBV system, energy distributions for *mean* main-sequence spectral types have been constructed using whatever data for energy distributions and blocking coefficients could be found. An often-used example are the "Vilnius" energy distributions (Straizys and Sviderskiene 1972). For these mean spectral types one is tempted to use the mean colors for the type. The obvious disadvantage of this approach is that the group of stars whose energy distributions contribute to that for a given mean type will, in general, not be the same group which contributes to the mean color. Further, the data contributing to the mean energy distributions have been so sparse that energy distributions have been used without careful consideration being given to uniformity in metallicity, small differences in luminosity, and photometric homogeneity. Nevertheless, the Vilnius energy distributions have been used with success to evaluate response functions of the UBV and RGU systems (Hayes 1975; Buser 1978a, b; Buser and Kurucz 1978). Catalogs of energy distributions for mean types will not, with one exception, be discussed further here.

3. CATALOGS OF CONTINUOUS ENERGY DISTRIBUTIONS

In this section several recent catalogs of stellar energy distributions will be discussed. These catalogs have the following useful characteristics: a) they are continuous energy distributions, b) they cover usefully large wavelength ranges, c) they include relatively large numbers of stars (except for one case), and d) they include stars covering a wide range in spectral types (again, with one exception). The catalogs are listed in Table I. Three of them were constructed with the intention of providing catalogs of spectra which could be used for the synthesis of the spectra of stellar systems, such as galaxies. The result of this objective is that they cover a wide range of representative types; the disadvantage is that, in all three

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cases, the photometric quality of the data was considered to be of secondary importance. Further, the existence of photometric observations, or the quality of such observations, was not of the highest importance. Please note, that this critique of these catalogs reflects judgements formed with synthetic photometry in mind; in all three cases, the approach taken and the results achieved appear to be quite appropriate to the original objective of the program.

The Gunn and Stryker (1983) catalog was made using the multichannel spectrometer on the 5-m telescope on Palomar Mtn. The results are continuous spectra covering a wide wavelength range with step sizes of 10A in the blue and 20A in the red; the bandpasses are 20A in the blue and 40A in the red. The stars range in brightness from V = 2.5 to 12.8, covering a wide range in spectral type for both giants and dwarfs of roughly solar metallicity. Some observations were made during twilight or other non-photometric conditions; many stars had to be attenuated by masking the telescope or using neutral-density filters. Mean extinction coefficients were used; signal-to-noise ratios were low at the blue end of the spectra of very red stars and at the red end of very blue stars. Reddening corrections have been applied where significant. Photometric observations on the $UBVR_JI_J$ system have been found and compared with synthetic colors; standard errors of ±0.044, ±0.019 and ±0.031 mag. are found for U-B, B-V and R-I, respectively. The results would appear not to be of the highest photometric quality.

The catalog by Jacoby, Hunter and Christian (1984) was made on the No. 1 0.9-m telescope at Kitt Peak National Observatory using the Intensified Reticon Scanner ("IRS"). Continuous spectra of rather high resolution are produced, but the limited dynamic range of the instrument forced the choice of either observing faint stars or using neutral-density filters; they chose the former limitation, and the stars range from V = 8 to 11 mag. As a consequence, good photometric observations of the stars are rare, and directly-observed V magnitudes are missing for 42 stars, B-V colors for 47 stars, and U-B colors for 70 stars. Only 22 of the 161 stars have MK spectral types. A wide range in spectral types is covered, including luminosity classes V, III, and I. The stars are nearly all of roughly solar metallicity. Some observations were made in non-photometric conditions; mean extinction coefficients were used. Reddening corrections have been applied. Thus, the data are not of the highest photometric quality. For synthetic photometry the data are of limited value until the stars have been observed in the photometric system to be studied.

The third of the catalogs intended for population synthesis is that by Pickles (1985). The observations were made on the 1.9-m telescope at Mount Stromlo and on the AAT at Siding Spring. Several types of array detector were used; all were on conventional cassegrain spectrographs. Bright stars were observed with the telescope masked or with neutral-density filters. The near-IR observations were made during twilight; otherwise good photometric practices were used, including the measurement of extinction. The observations generally cover the range 3600 to 10000A with resolutions of 10 to 17A. 200 stars, including spectral types from O to M, and luminosity classes from V to III are included in the catalog. A range in metallicity has been intentionally included. The stars cover a wide range in brightness. Signal-to-noise ratios are lower below 3800A. All of the stars have good photometry, and many are Cousins UBVRI standards. Synthetic BVRI colors have been calculated and compared with the observations. Because of the limits in wavelength coverage, the B filter response function was truncated on the blue side at 3800A, and the R and I filters truncated on the red side at 8250A. The comparison of the B38-V, V-R82 and R82-I82 colors with observed BVRI colors show good systematic agreement and standard deviations of 0.037, 0.042 and 0.063 mag., respectively, about the regression lines. Again, we have a catalog not of the highest photometric quality. For the purposes of synthetic photometry, the catalog suffers from being available only for mean types. No reddening corrections have been applied.

The final two catalogs to discuss are those by Cochran (Cochran 1980; Cochran and Barnes 1981; Cochran 1981) and by Taylor (1984). In each of these cases, no apology need be made about the photometric quality of the energy distributions. Cochran's observations were made on the 0.9-m telescope of McDonald Observatory with a reticon; the usual techniques for good photometry were applied. The wavelength range is wide, but the blue limit of 4600A is serious for many applications. The resolution is adequate for synthetic photometry at 42A. The stars include all spectral types, but the selection was based on the criteria that they include stars with known angular diameters or be photometric standard stars. They range in brightness from V = 0.0 to 9.0 mag. They can be expected to have solar metallicites, in

TABLE I
CATALOGS OF CONTINUOUS ENERGY DISTRIBUTIONS

Catalog	Wavelengths	No.	Types
Cochran and Barnes 1981	4600 (42) 10200	Vega	AOV
Cochran 1981		16	B, A stds.
Cochran 1980		98	Phot. stds, Ang. Dia. *'s
Gunn and Stryker 1983	3130 (20,40) 10800	175	dwarfs O5-M8 giants B1-M8 a few others
Taylor 1984	3288 (32,48,100) 7000	12	G dwarfs
Jacoby, Hunter and Christian 1984	3510 (∿4.5) 7427	161	Spt. O-M; l.c. V, III, I
Pickles 1985	3600 (10-17) 10000	200	Spt. O-M; l.c. V-III

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general. Taylor's observations were made with a programmable, sequential scanner on the Crossley 36-inch telescope at Lick Observatory. In this case, the primary limitation is in spectral type; only 12 solar-type dwarfs are included in the catalog.

4. THE SOVIET CATALOGS OF CONTINUOUS ENERGY DISTRIBUTIONS

Astronomers in the Soviet Union have been active in the field of spectrophotometry, and a large number (about 1500) of stars have been observed. Considerable effort has been put into the absolute calibration of Vega and the establishment of secondary standard stars. In this section only those catalogs of energy distributions which promise to be useful for synthetic photometry will be discussed. The list given in Table II does not attempt to be exhaustive; nor does it attempt to include older material. The list probably includes all the significant catalogs published in the past eight years. All of the observations have been taken with small telescopes (about 0.5-m, or smaller) and scanning spectrometers with continuous recording on strip-chart recorders. The stars are all quite bright, ranging from $V = -1.5$ to 8.0, with relatively few stars fainter than 6th mag. The catalogs include a wide range of spectral types and luminosity classes. Because of their brightness, it is probable that most of the stars have been observed in the major photometric systems. Potentially, this set of data could be quite useful for synthetic photometry. There are difficulties, however, which obviate this use, at present. One is that the data are not yet available in a machine-readable format. But, more significant are inhomogeneities in the data: the observations were made at several observatories, which use different calibrations for Vega and the secondary standards. There have been instrumental problems (Glushneva and Ovchinnikov 1982, 83; Glushneva 1983). The calibration of Vega and the secondary standards have evolved, even in the cases of individual observatories, during the period of time covered by the observations. Some effort has been made to intercompare these and other catalogs (Glushneva and Kharitonov 1978; Glushneva, et al. 1979; Glushneva 1980; Burnashev 1982; Glushneva and Ovchinnikov 1982, 83 and Hagen-Thorn and Ruban 1982) and to compile a homogeneous master catalog (Burnashev 1982; Glushneva 1983). To review all of the above papers would take too much space in this paper.

It appears, however, that many of the effects contributing to the inhomogeneity of the individual catalogs and of the group of catalogs could be removed by careful analysis and correction of the data. Until this is done, we cannot know if the remaining systematic errors are too large to permit the data to be used for synthetic photometry. In any case, it is unlikely that synthetic photometry based upon these data will equal the systematic accuracy of the best filter photometry.

TABLE II
SOVIET CATALOGS OF CONTINUOUS ENERGY DISTRIBUTIONS

Catalog	Wavelengths (A)	Res.(A)	No.
Burnashev 1977	3200 (25) 7550	30-35	50
Alekseev, et al. 1978	3100 (25) 7375	70	303
Kharitonov, et al. 1978	3225 (50) 7975	75?	602
Burnashev 1980	3200 (25) 7550	30-35	4
Kolotilov, et al. 1980	3225 (50) 10825	35,70	15
Voloshina, et al. 1982	3225 (50) 7625	18.5	735
Voloshina, et al. 1982	3225 (50) 10825	35,70	45
Glushneva & Shenavrin 1983	3125 (50) 10825	35,70	50
Voloshina, et al. 1983	3225 (50) 7625	18.5	60
Glushneva, et al. 1984	3225 (50) 7625	18.5	72

5. CONCLUSIONS

In summary, after a review of the most promising catalogs of energy distributions found in the literature, the conclusion may be drawn that none of the catalogs have the ideal characteristics. However, all of the catalogs contain useful information which, if properly considered in the aggregate, could be used to evaluate response functions and determine transformation coefficients.

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